2013-2014 Assessment of the Army Research Laboratory

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Army Research Laboratory Technical Assessment Board

Laboratory Assessments Board

Division on Engineering and Physical Sciences

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[2] Ephrahim Garcia passed away on September 10, 2014.
[3] Wesley L. Harris, a member of the Panel on Mechanical Science and Engineering at the Army Research Laboratory, was appointed chair on September 15, 2014.

Acknowledgment of Reviewers

This report has been reviewed in draft form by individuals chosen for their diverse perspectives and technical expertise, in accordance with procedures approved by the National Research Council's Report Review Committee. The purpose of this independent review is to provide candid and critical comments that will assist the institution in making its published report as sound as possible and to ensure that the report meets institutional standards for objectivity, evidence, and responsiveness to the study charge. The review comments and draft manuscript remain confidential to protect the integrity of the deliberative process. We wish to thank the following individuals for their review of this report:

Michael D. Byrne, Rice University,
Peter M. Kogge, University of Notre Dame,
Richard M. Murray, NAE, California Institute of Technology,
C. Kumar N. Patel, NAS/NAE, Pranalytica, Inc.,
Edgar A. Starke, Jr., NAE, University of Virginia, and
Dwight C. Streit, NAE, University of California, Los Angeles.

Although the reviewers listed above have provided many constructive comments and suggestions, they were not asked to endorse the conclusions or recommendations, nor did they see the final draft of the report before its release. The review of this report was overseen by Lyle H. Schwartz, NAE, Air Force Office of Scientific Research (retired). Appointed by the National Research Council, he was responsible for making certain that an independent examination of this report was carried out in accordance with institutional procedures and that all review comments were carefully considered. Responsibility for the final content of this report rests entirely with the authoring board and the institution.

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Summary

The statement of task that guided the work of the Army Research Laboratory Technical Assessment Board (ARLTAB) is as follows:

> An ad hoc committee to be named the Army Research Laboratory Technical Assessment Board (ARLTAB), to be overseen by the Laboratory Assessments Board, will be appointed to continue the function of providing biennial assessments of the scientific and technical quality of the Army Research Laboratory (ARL). These assessments will include findings and recommendations related to the quality of ARL's research, development, and analysis programs. While the primary role of the ARLTAB is to provide peer assessment, it may offer advice on related matters when requested by the ARL Director. The ARLTAB will provide an interim assessment report at the end of Year 1 of each 2-year assessment cycle and a final assessment report biennially. The ARLTAB will be assisted by up to seven separately appointed panels that will focus on particular portions of the ARL program. Each year, up to three additional panels may be appointed to assess special topics, at the request of the ARL Director.

During the 2013-2014 assessment, the ARLTAB was assisted by five panels, each of which focused on the portion of the ARL program conducted in one of ARL's core technical competencies: materials sciences, ballistics sciences, information sciences, human sciences, and mechanical sciences. This report summarizes the findings of the Board for the 2013-2014 biennial assessment and as such subsumes the 2013 interim report.[1]

[1] National Research Council, 2014, *2013-2014 Assessment of the Army Research Laboratory: Interim Report,* Washington, D.C.: The National Academies Press.

MATERIALS SCIENCES

ARL's materials sciences span the spectrum of technology maturity and address Army applications, working from the state of the art to the art of the possible, according to the ARL. Materials research efforts and expertise are spread throughout the ARL enterprise. As the ensemble of the materials discipline and capabilities, materials science is one of ARL's primary core technical competencies.

Overall, the researchers and the management are of high caliber. Researchers appeared ebullient and passionate about their work. Most of the projects presented are excellent. The scientific soundness and the use of the fundamental sciences are outstanding. It is commendable that the ARL materials sciences area comprises a good mix of talents, ranging from experienced, savvy scientists and engineers to bright, early-career professionals. The project portfolio fits well with global thrusts and the national agenda, with research projects falling at the intersection of the pillar technologies of biotechnology, nanotechnology, advanced materials, energy, and the environment.

In today's fast-moving technological landscape, additional opportunity is presented by the challenge of effectively utilizing commercial technologies, particularly in the areas of wearability, mobility, and connectivity, which are critical to the well-being of soldiers. A systematic, structured effort to scout technologies from the private sector to complement in-house projects will be highly rewarding.

As technology marches on at an unprecedented pace, it will be important that new approaches to shortening the research cycle from science to useful product are always on ARL's radar. A concerted effort to understand future needs and to craft projects relevant to the future is the ultimate challenge and opportunity.

Researchers need to make deliberate efforts to analyze data and contemplate the theories that are behind the observed physical phenomena, test data, and modeling systems so they can effectively design the path forward for each project. Given the many exciting experimental and computationally derived results that were reported during this review, efforts to analyze data and contemplate theories relating to the data and models will further optimize the progress of research. As a first step toward this goal, the comprehensive deliberation of data analysis should be highlighted in the research efforts. This does not necessarily mean the use of advanced computational tools, but rather the incorporation of even simple mathematical analysis to further uncover trends and correlations in data, and deep diving into plausible fundamental theories. This will help advance both the materials by design paradigm and the demand paradigm.

To further document the competitive posture of the ARL research programs vis-à-vis those of comparable organizations, formal metrics are needed to enable comparison of ARL research activities with those of other government-owned research laboratories in the United States and overseas.

Working toward making the Army the best Army for 2035 and toward ARL becoming a top choice for researchers to pursue careers, further raising the ARL's national and international stature is a high priority. To this end, ARL's stature will rely on performing premier research, high productivity, the ability to attract and retain the best and brightest talents, effective communication with and dissemination of the research findings to the scientific community, and the eventual deployment of research results to Army applications. The review materials and presentations provided to the Board did not clearly explain what ARL has accomplished by way of providing better armament.

Collaboration efforts have been demonstrated both across ARL and externally. The leadership's success in recruiting energetic early-career talent is evident. Staff supporting all the projects reviewed are engaged in upward collaborative efforts to various degrees; this is commendable. More excellence can be achieved by working on the efficiency of collaboration to deliver additional focus, quality, and selection of projects. Internal collaboration across the divisions and directorates is as beneficial as extramural collaboration. ARL's move toward using a framework based on science and technology (S&T) campaign plans can enhance such collaborations.[2]

Biomaterials, Energy Materials and Devices, and Photonic Materials and Devices

The researchers and the management are of high caliber and deserve kudos. Researchers appeared ebullient and passionate about their work. Most of the projects presented are excellent and are having a pervasive impact. The scientific soundness and the use of the fundamental sciences are outstanding. Some of the projects in the portfolio are particularly impressive. The biomaterials group is making noteworthy progress, following the ARLTAB's previous suggestions to recruit a new branch chief and to begin to establish a long-term program in biotechnology. The project on synthetic biomolecular materials is enormously significant by addressing the Army's needs in situation awareness and force protection in the areas of on-demand production of biomolecular sensing materials in response to new and emerging hazardous threat materials and functional biomolecular materials that are stable in austere environments, persistent surveillance, and ubiquitous sensing. The project has already shown success by developing iterative and integrated multiscale computational biology capabilities—this is top-notch research. The project has also demonstrated for the first time rapid development of peptides as synthetic alternatives to antibody-based bioreceptors, which are difficult to produce and maintain in the field. The use of biogenerated fuel to drive a fuel cell and generate a periodic power boost is another research project important to the Army.

ARL is a technology-driven and warfighter-focused institution; developing technologies to deliver ubiquitous power and energy for warfighters is a compelling mission. The project on hydrogen production from water by photosystem for use as fuel in energy conversion devices offers promise. The project on nonnoble metal catalysts for alkaline fuel cells studies the catalysts supported on graphene. Impressive power density (300 $mWcm^{-2}$ at 60°C) was demonstrated using a Pt-free cathode with an anode of standard carbon-supported Pt. When the performance can be improved further and stability demonstrated, this could represent a significant breakthrough. For lightweight, quiet, efficient, and reliable power sources for Army applications to enhance soldier combat capability, the project on fuel cells for military applications tests and evaluates commercial technologies, namely, direct methanol fuel cell and solid oxide fuel cell (SOFC) systems. Fuel cells reduce weight and decrease the logistic burden associated with batteries. The 300 W SOFC systems, operated on propane, can be thermally cycled more than 40 times between room temperature and 800°C without significant degradation and can be heated to 800°C in less than 10 minutes. The system was successfully tested in an unmanned aerial vehicle. This has much potential for Army applications.

In the area of photonic materials and devices, the accomplishments of the project on electromagnetic modeling of quantum-well infrared photodetectors (QWIPs) are laudable. The model described explains the quantum efficiency (QE) of all existing detector structures, including the most advanced optical effects, and expresses the detector QE in terms of the material's absorption coefficient and the volumetric integral of vertical electric field. Because affordable, high-speed, high-resolution, long-wavelength infrared (IR) cameras are critically important to the Army's night vision, large-area surveillance, and navigation in degraded vision environments, the success of this project is of enormous value. As a leader in QWIP technology, ARL can leverage this achievement to develop advanced technology and to brand its leadership.

[2] Army Research Laboratory, September 2014, *Army Research Laboratory. S&T Campaign Plans. 2015-2035,* Adelphi, Md.: Army Research Laboratory, http://www.arl.army.mil/www/default.cfm?page=2401.

Another high-impact project is developing a low-cost, III-V, direct-bandgap long-wavelength infrared (LWIR) detector for night-vision technology. LWIR detection is a niche Army technology requiring dedicated equipment and highly specialized skills and tools. The research involves the growth of defect-free unstrained and unrelaxed InAsSb material on binary substrates such as GaSb, InSb, or InAs. This Ga-free InAsSb detector is expected to be a disruptive technology for the LWIR field and to potentially replace the costly II-VI-based technologies.

In ARL's physical facilities, state-of-the-art equipment and instruments are available to perform quality research work, and there is a high level of material characterization capability—for example, ultrafast terahertz (THz), nanonuclear magnetic resonance (nano-NMR), time-resolved ultraviolet (UV) materials growth and characterization—and a clean room fuel-cell laboratory, all of which are supported by trained and knowledgeable personnel. Synergistic capabilities could be strengthened further through the tie-in of facilities across divisional branches as well as through collaborations with targeted external facilities.

Electronic Materials and Devices, and Structural Materials

Research projects under this review span three families of materials—metal, ceramics, and polymers—plus an additional category of composite materials. The overall portfolio comprises short-term and long-term projects. A relatively large proportion of the work reviewed consists of high-risk, high-impact projects. The research scope covers experimental, computational, and modeling projects. In the laboratory's physical facilities, state-of-the-art equipment and instruments are available to perform quality research work, and there is a high level of material characterization capabilities and exceptional mechanical testing equipment.

In the area of electronic materials and devices, the research presented throughout the review is of high scientific and technical merit and evinces a great deal of innovation. High-profile research aligned with ARL's mission needs is evident. Staff members are working on forefront research projects that could potentially yield breakthroughs, and the work is directed toward the emerging needs of the future (2035) Army. For instance, the low-dimensionality (two-dimensional [2D]) materials program is particularly impressive, covering fundamental aspects of synthesis, characterization, device design, and manufacturing. Tuning 2D materials at the atomic scale opens enormous opportunities to design electronic properties for innovative applications through controlling surface conditions, defects, and the interfaces with other 2D materials. This is a potentially high-impact area. The piezoelectric materials program has achieved a high degree of maturity, so it is now transitioning to the implementation of unique actuators, microelectromechanical systems (MEMS), robots, and further miniaturization of low-power relays.

In the area of structural materials, the projects are at different stages of research and development, but overall the research is of high quality. The maturity of the work in the areas of synthesis and processing is commendable. Modeling has been nicely integrated into many experimental studies such as magnesium (Mg) alloy development and field-assisted processing. The project on boron suboxide ceramics stood out among many excellent presentations. The mechanical press, capable of applying up to 700,000 lb of pressure in developing lightweight armor, is an exceptionally enabling piece of equipment. The experimental work conducted in cold spraying, magnesium processing, and nanocrystalline metals is excellent, and the researchers have access to centralized characterization facilities. Researchers have made inroads in publishing their results (such as in nanocrystalline metals) in the archival literature. However, the utility of this technology for making scaled-up parts is still a matter of conjecture.

Another area that may need attention is powder technology, which appears to be a crosscutting technology at the ARL, crucially applicable to multiple projects. Whether there is a need for in-house capability and expertise in this area warrants thorough consideration.

In the context of the focus on correct modeling at specific scales and physics, notable results include the atomistic modeling, piezoelectric materials, and computational fluid dynamics (CFD) modeling for cold spray deposition. The modeling is well integrated in an overall fabrication and testing program, enabling the selection of fabrication techniques (e.g., Mg alloy development) or device manufacture (e.g., piezoelectric MEMS). A growing effort to link models at various scales and expressing different physical phenomena is producing good results, especially in the transition from smaller to larger scales (e.g., brittle material modeling or polymer coarse graining).

Many projects have an overarching theme of interfacial behavior across different classes of materials, such as nanocrystalline alloy stability, grain boundary engineering of ceramics, and the role of adhesives. This provides a unique opportunity to explore crosscutting themes and research activities that enhance the role of computational methods for mesoscale modeling, stochastics, optimization, and informatics (e.g., statistical learning and data mining), as well as experimental methods such as advanced microscopy and microstructural characterization studies.

BALLISTICS SCIENCES

There was clear evidence of a speedy response to changing needs to support the warfighter with innovations in ballistic survivability and lethality. ARL's experimental program concerning threats is quite detailed and demonstrates commendable knowledge of the evolving threats. The spectrum of armor design demonstrated a broad array of technical approaches and flexible and rapid response. ARL's staff are motivated and competent, and the staff members articulated a well-defined line of sight from their research to the mission of ARL and to the warfighter. The overview presentations for the terminal and internal ballistics areas were very impressive and provided a rationale for the diverse materials issues under investigation; the researchers have gained from the recent combat experience and lessons learned from in-theatre observations.

Several overarching opportunities and challenges were identified for ARL's enterprise in terminal and interior ballistics, including these:

- Examples of how the Army Research Office's (ARO's) individual projects fit into the Army's overall goals and relate to one another and to other ARL projects would facilitate ARLTAB's assessment of the quality of ARL's S&T work.
- A rigorous, formal internal validation program is needed for ARL to quantify the extent to which the physics within the broad spectrum of ballistics models is being developed to accurately describe the physics operative. Given the importance of such models to develop predictive design capability in support of current Army programs and further to support design of future systems, platforms, and equipment, increased emphasis on validation across all ballistics-related research topics is warranted.
- The staff is not as visible in professional societies and technical conferences as their accomplishments and scientific expertise would warrant. While obviously the sequestration and travel restrictions have negatively affected staff interactions with the outside S&T community, the lack of interactions through conferences and professional associations will have a deleterious effect on collaborative efforts and on maintaining the edge in areas of expertise; it is therefore important to continue to address this ongoing issue.
- It is important to apply increased and sustained efforts to ARL's damage and failure modeling across the spectrum of materials of relevance, given the importance of such modeling to ballistics

science and technology. These physically based damage models need to include the statistical aspects of how and where damage evolution and failure occur in a material.

It appears crucial for ARL to develop, for terminal, interior, and exterior ballistics, its strategic vision behind internal investments, program and mission deliverables, and staff planning to support the needs of the Army of the future. This strategic planning appears particularly important given that the future ground combat vehicle design pathways are fixed. For example, while glass, effectively confined, is known to have potential for contributing to the defeat of shaped-charged jets, explosive reactive armor (ERA) and even nonexplosive reactive armor (NERA) have greater potential, and ERA is already being utilized with great effectiveness.

INFORMATION SCIENCES

Autonomous Systems

For each of the key areas—perception, intelligence and planning, human–robot interaction, and manipulation and mobility—the overall technical quality of the work is high and is being recognized as such as evidenced by publication in archival journals. For most of the work reviewed, the scientific quality is comparable to that at other federal research laboratories and at national and international universities. The research staff are very well qualified to undertake the research. The laboratory facilities and the infrastructure are state-of-the-art and supportive of the ongoing research activities.

In the area of manipulation and mobility, work related to self-righting robots is of a very high caliber and also has direct applications in the field. The piezoMEMS research and associated small robotics effort is first rate, with elements—specifically, the work in motion generation at the MEMS scale—that are seminal.

The research projects in the area of perception are of a high caliber. The primary accomplishments in robotic intelligence are advances in mapping capability, control for communications, and cognition. Much of this work is being published in top journal and conference venues, which attests to the overall quality of the research.

In the area of human–robot interaction the experimentation conducted at Fort Benning has yielded an important basis for making design decisions. For example, experiments have demonstrated voice commands to be suitable for discrete actions but less so for controlling continuous processes.

It was not clear how the individual research projects in each of the four areas representing the ARL autonomous systems enterprise fit within the larger research effort. Without such a roadmap, there is very little indication that the research projects are connected either in the subareas or across the enterprise.

Atmospheric Sciences

The research portfolio for the Battlefield Environment Division (BED) includes a range of unique atmospheric science problems of vital importance to the Army that are not addressed elsewhere in the Department of Defense (DoD) or the civilian scientific community. The BED has made impressive progress in its research areas. Illustrative of such progress is the development of a laser-based tool for capturing, holding, and analyzing an individual aerosol or dust particle.

The lack of reference to atmospheric science in ARL's 20-year vision document is disturbing, however. BED currently (FY14) has 47 in-house personnel, a decrease of 9 full-time-equivalent positions since the prior review in 2012. The continual pressure to downsize has resulted in a 20 percent mandated reduction in optics research and the pending zeroing-out of very critical aerosol research. Continuation of this trend will compromise the division's ability to fulfill its responsibilities and will lead to the loss of many valuable opportunities currently available to the ARL, including crosscutting opportunities impacting other divisions.

Computational Sciences

The Computational Sciences Division (CSD) team is making concerted efforts to advance new Army-relevant directions centered on high-throughput distributed processing and the applications of modern computer science. This is a commendable approach, and CSD could consider the development of similar approaches to advance its research projects in traditional high-performance computing (HPC) and physics-based modeling.

The project on tactical HPC (cloudlets) is conceptually at the cutting edge; such work is only now beginning to receive attention in the commercial and academic research communities. To make substantial progress will require the allocation of additional research personnel to this project. New initiatives related to software-defined networks, quantum computing, and quantum networks hold promise and represent the cutting-edge research that ARL needs to pursue and investigate for potential application in future Army missions.

Understaffing at CSD continues to be a challenge, with a large number of team lead positions vacant. As a result, many projects lack a sufficient number of experienced researchers to lead, guide, and mentor the early-career researchers. It is important for CSD to fill these open senior positions to ensure the successful resolution of the many important problems that it is pursuing.

Network Sciences

There was good science and engineering in many areas of the work. Since the previous review in 2012 there has been a significant improvement in the quality of the research and the presentations and in the apparent morale of the team. The lightweight intrusion detection work is promising. The issue of burstiness in intrusion detection evinced an interdisciplinary content. Strong work is being performed in tactical communications, robotics, language technologies, and E-field measures in standoff power sensors.

The ongoing research could benefit from greater interactions within ARL. As an example, research in the area of social media and social networks could benefit from interactions with the cybersecurity area. Similarly, even a very strong area of research like the E-field and radio frequency measurement effort could benefit from greater interaction with the signal processing community within ARL. More generally, there is a good bit of effort on sensor information exploitation and fusion that could benefit from an integrated approach. These integration efforts could be enhanced by bringing greater technical diversity in the work force at ARL, in particular added strengths in the social and mathematical sciences. There are instances in which broad interactions with the external community are occurring. One such area is in language technologies, which is very well connected to the larger community.

The areas in which ARL is leading the research community need to be publically highlighted to raise the visibility of the organization. As an example, in the cybersecurity area, ARL is one of the few research institutions that have access to real data. This is a major strength and would undoubtedly attract very favorable attention. The impressive early-career scientists appear to be receiving appropriate mentoring. Some work (e.g., temporal logic for intelligent systems) was in a speculative stage but important for ARL work to remain at the cutting edge.

HUMAN SCIENCES

Simulation and Training Technology

The Simulation and Training Technology Center (STTC) is tackling a number of very challenging technical problems in the areas of training technology that have great potential to set standards across the DoD. STTC researchers are pushing the state of the art of simulation in the cloud and protocols for advanced distributed simulation.

STTC has historically been strong in computer science and engineering, and it has developed a number of successful technology-enhanced training products. The merger of STTC into ARL in 2010 brought together STTC's core competency in computer science with the Human Research and Engineering Directorate's (HRED's) core competency in the human sciences, creating huge potential for new productive synergy. ARLTAB's prior (2011-2012) assessment observed that integration of the STTC into HRED creates great opportunities for human factors influence on STTC products and STTC enhancements of traditional HRED endeavors. The merger of STTC with HRED needs to be extended, with greater emphasis on and integration of human sciences into the program of work. For the most part, the quality and outcome value of the research being carried out by STTC would benefit significantly from having more experts in human science.

Translational Neuroscience

The translational neuroscience (TN) program at ARL is a unique and important effort whose objectives, if successfully accomplished, could be a game changer for research on soldier and mission effectiveness. The TN group is tackling key technology bottlenecks to moving neuroscience from the laboratory to the field. The staff continues to grow, attracting highly motivated early-career scientists from a diverse set of universities, with the resultant benefits of fresh intellectual capital and productive competition of ideas.

Overall, the quality of the TN research presented, the capabilities of the leadership, the knowledge and abilities of the investigators and their scientific productivity, and proposed future directions are impressive. The work is well aligned with the clear and substantive mission to move neuroscience from the laboratory to real-world military settings (i.e., from the bench to the battlefield). The TN group conducts high-quality neuroscience research that is routinely validated by its publication in good, peer-reviewed journals and is on a par with work at good university neuroscience departments.

Soldier Performance and Human Systems Integration

The portfolio of research is very applied and is highly relevant to current Army needs; in general, the work in this area represents good, solid research, development, and applications. Significant gains were evident in publication rates, numbers of postdoctoral researchers, and collaborations with relevant peers outside ARL. The research work environments were impressive in terms of their unique and advanced technology capabilities to support research. Overall these are outstanding accomplishments and mark a visible advance over prior years.

The sensory perception research being addressed appears well-motivated and referenced to the extant scientific literature. Further, the science in these areas has greatly benefited from the superb facilities made available to ARL researchers, most notably, the environment for auditory research (EAR) and the computer-assisted virtual environment (CAVE). Overall, progress has been demonstrated in each of its thrust areas. The paucity of publications outside of ARL internal reports is a challenge that needs to be addressed.

Generally, the physical and cognitive performance programs are addressing practical problems and issues relevant to the Army mission. The experiments outlined were generally well designed according to solid experimental psychology principles. The research staff was very enthusiastic and seemed excited about the idea of doing translational research that has practical outcomes. Equipment and facilities available to the group are very good and are fully utilized for ongoing projects. Scholarly productivity was evidenced by some publications in academic journals.

The human systems integration (HSI) group needs to develop a scientific vision and charter that clarifies responsibilities and delineates the path for future research. There appears to be a gap in expertise in key areas within HSI. For example, the HSI group could benefit from expertise in theory and modeling in both cognition and complex systems. ARL has the opportunity to be on the forefront of the research in this area and, for the most part, the researchers are doing very interesting work. However, the current portfolio of projects within the HSI area may be too customer-driven. ARL could leverage this applied work and/or fund companion projects to advance the state of knowledge or science base for HSI as well as broaden the impact of the work beyond the immediate customers.

MECHANICAL SCIENCES

Mechanics

The laboratory facilities are impressive, including the subsonic wind tunnel and facilities supporting work in propulsion and additive manufacturing; these facilities can enable ARL to establish leadership positions in mechanical sciences. Several researchers have industrial backgrounds; this represents a strength of the research team. Recent work on damping augmentation using nanomaterials to tailor interfacial properties of critical vehicle structures is an especially strong activity.

The mechanics area needs a more robust workforce with sufficient experienced staff to mentor recently hired, less experienced staff. There is a need to delineate a clear path connecting development, laboratory testing, and full-scale testing of components and systems. ARL work is not clearly differentiated from external contractor work, and the ARL workforce is challenged by the requirement to manage local, existing ARL research and to monitor external contractor work. There is a need to accelerate full operational capability of all primary research facilities—for example, the subsonic wind tunnel. There is also a need for a local ARL capability to conceive, develop, test, and implement computational fluid dynamics simulation tools for increasing complex airframe configurations and flight regimes. Although it may be difficult to develop advanced multi-physics CFD capabilities from scratch, the relevant staff need to be sufficiently knowledgeable to assess and evaluate off-the-shelf CFD software for accuracy and predictive capability.

Propulsion

The high-pressure, high-temperature, pulsed injection facility is impressive. The high-temperature fatigue facility is excellent. The small-engine altitude facility is a very impressive, unique, and useful facility. The tribology laboratory, too, is a very useful facility. The ultrasonics method used to find potential cracks is novel and promising; it is nonintrusive and robust, even at high temperatures.

There is good applied research but little competitive fundamental research. If more fundamental research is desired, each laboratory experiment and computational program needs to be designed and constructed to answer specific fundamental scientific questions. Researchers need to be in command of previous work on related topics. Many more journal publications, with first-rate peer reviews, are needed to make a greater impact and to challenge researchers to perform at their full potential. Better mentoring of early-career researchers is needed.

Reliability and Diagnostics

ARL researchers are conducting research and developing an approach to the design of aircraft structural components with goals to reduce fatigue failures and sustainment costs associated with maintenance. The program has the potential to revolutionize the achievement of high-reliability systems. In many of the current projects it will be important to pay more attention to the underlying physics of the problem (e.g., how sensors interface with the material or structure). The ability to better predict the remaining useful life of a structure will depend critically on the ability to develop multiphysics, multiscale models (including uncertainties) and sensors that will provide relevant real-time data.

The overall technical quality of ARL's applied research and development in the area of reliability and diagnostics is very high. The virtual risk-informed agile maneuver sustainment team has a strong contingent of enthusiastic, highly capable researchers. The potential to produce fundamentally important results that would improve the reliability and survivability of Army systems is great. To demonstrate the high quality of the research and to get important feedback from other experts in the fields, it is important that research papers be submitted to top-notch archival research journals.

RECOMMENDATIONS

Recommendations to improve the overall ARL research enterprise are:

Recommendation 1. ARL should require researchers to clearly articulate the existing technical challenges in their research as well-posed problems, to formulate key questions, to identify approaches and tools, and to set out an assessment strategy. Concept maps, research baselines, and milestones that characterize the research are recommended.

Recommendation 2. To optimize the progress of their research and to set a path forward for each project, researchers should consistently analyze data and contemplate the theories that are behind the observed physical phenomena, test data, and modeling systems.

Recommendation 3. ARL should continue its efforts to be a key source of disruptive technology options for the Army of the future. Toward this end, it should balance short-term customer-driven work with innovative R&D that goes beyond current requirements.

Recommendation 4. ARL should develop a laboratory-wide verification and validation methodology, formalism, and implementation program. This program should be applied to support connectivity between theory, modeling, and experiments; refine underlying assumptions and approximations; encourage sensitivity studies, including how systems can fail; quantify margins and uncertainty; and inform small-scale to system-level experiments.

Recommendation 5. ARL should encourage a systems integration approach across its research enterprise to engender interconnectivity between ARL's science and technology campaign plans.

Recommendation 6. ARL should consider including in assessment agendas selected presentations related to new or recent starts to maximize the benefits of early feedback from ARLTAB across all disciplines.

Recommendation 7. ARL should look for additional ways to increase interaction between its researchers and leaders in industry and academia, given that limitations on travel have restricted this important professional development avenue.

Recommendation 8. ARL should encourage and incentivize publication of research in peer-reviewed journals.

Recommendation 9. As ARL continues to build its research staff, it should give attention to bringing in mid-career and senior personnel to mentor the outstanding early-career scientists who have been recruited. Effective mentoring should include engagement in selecting research directions, facilitating communication with research peers, guidance on service and committee assignments in technical societies, and enhancing career development.

Recommendation 10. ARL should convene a strategic planning group to formulate and plan research facility needs to support Army research and development objectives for the next 10-20 years.

Recommendation 11. To narrow the distance between the science and Army end-use applications, ARL should continue efforts to assure that researchers across all ARL disciplines understand future needs of the Army.

This report also identifies program-specific and project-specific suggestions, presented in Part II, and outstanding and exceptional areas, presented in Part III.

Part I

Introduction

1

Introduction

This introductory chapter describes the biennial assessment process conducted by the National Research Council's (NRC's) Army Research Laboratory Technical Assessment Board (ARLTAB). It then describes the preparation and organization of the report, the assessment criteria, and the approach taken during the report preparation.

THE BIENNIAL ASSESSMENT PROCESS

The ARLTAB is guided by the following statement of task:

> An ad hoc committee to be named the Army Research Laboratory Technical Assessment Board (ARLTAB), to be overseen by the Laboratory Assessments Board, will be appointed to continue the function of providing biennial assessments of the scientific and technical quality of the Army Research Laboratory (ARL). These assessments will include findings and recommendations related to the quality of ARL's research, development, and analysis programs. While the primary role of the ARLTAB is to provide peer assessment, it may offer advice on related matters when so requested by the ARL Director. The ARLTAB will provide an interim assessment report at the end of Year 1 of the assessment cycle and a final assessment report biennially. The ARLTAB will be assisted by five separately appointed panels that will focus on particular portions of the ARL program.

The charge of ARLTAB is to provide biennial assessments of the scientific and technical quality of the Army Research Laboratory (ARL). These assessments include the development of findings and recommendations related to the quality of ARL's research, development, and analysis programs. ARLTAB is charged to review the work in ARL's five core technical competencies (ballistics sciences, human sciences, information sciences, materials sciences, and mechanical sciences)[1] but not the work of the Army Research Office (ARO), a key element of the ARL organization that manages and supports basic research; however, all ARLTAB panels receive reports of how the research and development activities of ARO and ARL are coordinated.

In addition, at the discretion of the ARL director, ARLTAB reviews selected portions of the work conducted by the Collaborative Technology Alliances (CTAs) and Cooperative Research Alliances (CRAs). Although ARLTAB's primary role is to provide peer assessment, it also may offer advice on related matters when requested to do so by the ARL director; such advice focuses on technical rather than programmatic considerations. To conduct its assessments, ARLTAB is assisted by five NRC panels, each of which focuses on one of the core technical competencies of the ARL enterprise. The ARLTAB assessments are commissioned by ARL itself rather than by one of its parent organizations.

For this assessment, the ARLTAB consisted of six leading scientists and engineers whose collective experience spans the major topics within ARL's scope. Five panels, one for each of ARL's core technical competencies, report to the ARLTAB. Five of the ARLTAB members serve as chairs of these panels. The panels range in size from 13 to 29 members, whose expertise is carefully matched to the technical fields covered by the areas that they review. Selected members of each panel attend each annual review. In total, 100 experts participated in the process that led to this report. All panel and ARLTAB members participate without compensation.

The NRC appointed the ARLTAB and panel members with an eye to assembling a slate of experts without conflicts of interest and with balanced perspectives. The experts include current and former executives and research staff from industrial research and development (R&D) laboratories, leading academic researchers, and staff from the Department of Energy national laboratories and federally funded R&D centers. Twenty-eight of them are members of the National Academy of Engineering, and five are members of the National Academy of Sciences. A number have been leaders in relevant professional societies, and several are past members of organizations such as the Army Science Board and the Defense Science Board. ARLTAB and its panels are supported by NRC staff, who interact with ARL on a continuing basis to ensure that ARLTAB and the panels receive the information they need to carry out their assessments. ARLTAB and panel members serve for finite terms, generally 4 to 6 years, so that viewpoints are regularly refreshed and the expertise of the ARLTAB and panel members continues to match the ARL's activities. Biographical information on the ARLTAB members appears in Appendix B.

In 2013 and 2014, the five panels reviewed the following ARL core technical competencies:

- Panel on Ballistics Science and Engineering: protection, lethality, energetics, and survivability/lethality/vulnerability analysis;
- Panel on Human Factors Science: translational neuroscience, soldier simulation and training technology, soldier performance (perceptual sciences and physical–cognitive interaction), and human-systems integration;
- Panel on Information Science: autonomous systems, network sciences, atmospheric sciences, and computational sciences;
- Panel on Materials Science and Engineering: power, energy, photonics, biological sciences, electronic materials and devices, and structural materials; and
- Panel on Mechanical Science and Engineering: propulsion, mechanics, and diagnostics.

[1] For 2015-2016, the ARLTAB is charged to review the work in ARL's seven science and technology campaigns; namely, Materials Research, Computational Sciences, Information Sciences, Human Sciences, Sciences for Maneuver, Sciences for Lethality and Protection, and Assessment and Analysis.

This biennial report summarizes the findings of the ARLTAB from the reviews conducted by the panels in 2013 and 2014 and subsumes the 2013 interim report.[2]

PREPARATION AND ORGANIZATION OF THIS REPORT

The current report is the eighth biennial report of ARLTAB. Its first biennial report was issued in 2000; annual reviews were issued in 1996, 1997, 1998, and 2013. As with the earlier reviews, this report contains the ARLTAB's judgments about the quality of ARL's work (Chapters 2 through 6 focus on the individual core technical competencies, and Chapter 7 provides a discussion of crosscutting issues across all of ARL). The rest of this chapter explains the rich set of interactions that supports those judgments.

The amount of information that is funneled to the ARLTAB, including the evaluations by the recognized experts who make up the ARLTAB's panels, provides a solid foundation for a thorough peer review. This review is based on a large amount of information received from ARL and on interactions between ARL staff and the ARLTAB and its panels. Most of the information exchange occurs during the annual meetings convened by the respective panels at the appropriate ARL sites. Both at scheduled meetings and in less formal interactions, ARL evinces a very healthy level of information exchange and acceptance of external comments. The assessment panels and ARLTAB engaged in many constructive interactions with ARL staff during their annual site visits in 2013 and 2014. In addition, useful collegial exchanges took place between panel members and individual ARL investigators outside of scheduled meetings as ARL staff members sought additional clarification about panel comments or questions and drew on panel members' contacts and sources of information.

Each panel's review meeting lasted about 2.5 days, during which time the panel members received a combination of overview briefings by ARL management and technical briefings by ARL staff. Prior to the meetings, panels received extensive materials for review, including selected staff publications.

The overview briefings brought the panels up to date on the broad scope of ARL's scientific and technical work. This context-building step is needed because the panels are purposely composed of people who—while experts in the technical fields covered by ARL's core technical competencies that they review—are not engaged in collaborative work with ARL. Technical briefings for the panels focused on the R&D goals, strategies, methodologies, and results of selected projects at the laboratory. Briefings are targeted toward coverage of a representative sample of each core technical competency area over the 2-year assessment cycle. Briefings include poster sessions and laboratory tours that allow direct interaction among the panelists and staff of projects that were not covered in the briefings.

Ample time during both overview and technical briefings was devoted to discussion, which enabled panel members to pose questions and ARL staff to provide additional technical and contextual information to clarify panel members' understanding. The panels also devoted sufficient time to closed-session deliberations, during which they developed findings and identified important questions or gaps in panel understanding. Those questions or gaps were discussed during follow-up sessions with ARL staff so that the panel was confident of the accuracy and completeness of its assessments. Panel members continued to refine their findings, conclusions, and recommendations during written exchanges and teleconferences among themselves after the meetings.

In addition to the insights that they gained from the panel meetings, ARLTAB members received exposure to ARL and its staff at ARLTAB meetings each winter. The 2013 and 2014 ARLTAB meetings

[2] National Research Council, 2014, *2013-2014 Assessment of the Army Research Laboratory: Interim Report,* Washington, D.C.: The National Academies Press.

refined elements of the assessment process focused on ARL's core technical competencies, including read-ahead materials, review agendas, and expertise required within the panels.

ASSESSMENT CRITERIA

During the assessment, the ARLTAB and its panels considered the following questions posed by the ARL director:

- Is the scientific quality of the research of comparable technical quality to that executed in leading federal, university, and industrial laboratories both nationally and internationally?
- Does the research program reflect a broad understanding of the underlying science and research conducted elsewhere?
- Does the research employ the appropriate laboratory equipment and/or numerical models?
- Are the qualifications of the research team compatible with the research challenge?
- Are the facilities and laboratory equipment state of the art?
- Are programs crafted to employ the appropriate mix of theory, computation, and experimentation?

To assist ARL in addressing promising technical approaches, the ARLTAB also considered the following questions:

- Are there especially promising projects that, with improved direction or resources, could produce outstanding results that could ultimately be transitioned to the field?
- Are there promising outside-the-box concepts that could be pursued but are not currently in the ARL portfolio?

Within the general framework described above, the ARLTAB also developed and the panels selectively applied detailed assessment criteria organized in the following four categories (Appendix C presents the complete set of assessment criteria):

1. *Effectiveness of interaction with the scientific and technical community.* Criteria in this category relate to cognizance of and contributions to the scientific and technical community whose activities are relevant to the work performed at ARL;
2. *Formulation of projects' goals and plans.* Criteria in this category relate to the extent to which projects address ARL strategic technical goals and are planned to effectively achieve the stated objectives;
3. *R&D methodology.* Criteria in this category address the appropriateness of the hypotheses that drive the research, of the tools and methods applied to the collection and analysis of data, and of the judgments about future directions of the research; and
4. *Capabilities and resources.* Criteria in this category relate to whether current and projected equipment, facilities, and human resources are appropriate to achieve success of the projects.

APPROACH TAKEN DURING REPORT PREPARATION

This report represents the ARLTAB's consensus findings and recommendations, developed through deliberations that included consideration of the notes prepared by the panel members summarizing their assessments. The ARLTAB's aim with this report is to provide guidance to the ARL director that will help ARL sustain its process of continuous improvement. To that end, ARLTAB examined its extensive and detailed notes from the many ARLTAB panel and individual interactions with ARL during the 2013-2014 period. From those notes it distilled a shorter list of the main trends, opportunities, and challenges that merit attention at the level of the ARL director and his management team. The ARLTAB used that list as the basis for this report. Specific ARL projects are used to illustrate these points in the following chapters when it is helpful to do so, but the ARLTAB did not aim to present the director with a detailed account of interactions with bench scientists. The draft of this report was subsequently honed and reviewed according to NRC procedures before being released.

The ARLTAB applied a largely qualitative rather than quantitative approach to the assessment. The approach of ARLTAB and its panels relied on the experience, technical knowledge, and expertise of its members, whose backgrounds were carefully matched to the core technical competency areas in which the ARL activities are conducted. The ARLTAB and its panels reviewed selected examples of the scientific and technological research performed by ARL; it was not possible to review all ARL programs and projects exhaustively. Given the necessarily nonexhaustive nature of the review process, the failure to mention a particular program or project should not be interpreted as a negative reflection on the omitted program or project.

The ARLTAB's goal was to identify and report salient examples of accomplishments and opportunities for further improvement with respect to the technical merit of the ARL work and specific elements of ARL's resource infrastructure that are intended to support the technical work. Collectively, these highlighted examples for each ARL core technical competency area are intended to portray an overall impression of the laboratory while preserving useful mention of suggestions specific to projects and programs that the ARLTAB considered to be of special note within the set of those examined.

REPORT CONTENT

Part I of the report discusses the biennial assessment process used by ARLTAB and its five panels. Part II: Chapters 2 through 6 provide detailed assessments of each of the ARL core technical competency areas reviewed during the 2013-2014 period. Part III presents findings and recommendations common across multiple competency areas. The appendixes provide the ARL organizational chart and its mapping to the core competency areas reviewed in 2013 and 2014, biographical information on the ARLTAB members and staff, the assessment criteria used by ARLTAB and its panels, and a list of acronyms found in the report.

Part II

Core Science Competencies

2

Materials Sciences

INTRODUCTION

The Panel on Materials Science and Engineering at the Army Research Laboratory (ARL) conducted its 2013 review at Adelphi, Maryland, on June 11-13, 2013. The 2013 review addressed the areas of biomaterials, energy materials and devices, and photonic materials and devices. The same panel conducted its 2014 review of the ARL facility in Aberdeen, Maryland, on June 3-5, 2014. The 2014 review addressed the areas of electronic materials and devices and structural materials, including materials in extreme environments and multiscale modeling.

ARL's materials sciences span the spectrum of technology maturity and address Army applications, working from the state of the art to the art of the possible, according to the ARL. Materials research efforts and expertise are spread throughout the ARL enterprise. As the ensemble of the materials discipline and capabilities, the area of materials sciences is one of ARL's primary core technical competencies. In the larger context, the mission of ARL, as the U.S. Army's corporate laboratory, is to provide innovative science, technology, and analyses to enable a full spectrum of operations.

Overall, the researchers and the management are of high caliber and deserve kudos. Researchers appeared passionate about their work. ARL's work in preparing for the review was superb. The ARL director's webinar overview and read-ahead materials, presentation viewgraphs, poster materials, and laboratory tours greatly facilitated the review process. It was highly valuable to have an interactive session with the ARL director to become acquainted firsthand with the ARL's mission and goals. This is also the first review involving the new director of ARL's Sensors and Electron Devices Directorate (SEDD), whose vision and plans were presented in an energizing fashion.

The criteria for ARLTAB's assessment focus on the technical merits of the work; facilities and equipment; research talents; underlying broad-based sciences; and the desired impact and the balance of theory, computation, and experimentation. They include as well alternative directions or approaches to achieve a project's promise.

In this chapter, ARLTAB's findings are set forth in several sections that provide evaluations of groups, projects, and future thrusts and offer general observations and suggestions.

It is gratifying that some postdoctoral researchers have joined ARL as full-time employees after completing their fellowships, an indication that laboratory management is providing an attractive environment for early-career researchers. The ARL director conveyed openness to suggestions, and the SEDD director is well versed in the research at SEDD and in emerging technologies for materials.

In today's fast-moving technological landscape, additional opportunity is presented by the challenge of effectively utilizing commercial technologies, particularly as they pertain to wearability, mobility, and connectivity, which are critical to the well-being of the soldier. A systematic, structured effort to scout technologies from the private sector to complement in-house projects would be highly rewarding.

As technology marches on at an unprecedented pace, it is important that new approaches to shorten the research cycle from science to useful product always be on ARL's radar. A concerted effort to understand future needs and craft projects relevant to them is the ultimate challenge and opportunity. To this end, the materials genome initiative is one frontier that deserves attention.

Branding and marketing represent an additional opportunity worthy of consideration so that good work is not kept secret. Measures of success for the research work—for example, invention disclosures and patents, citations, and publications—need to be tracked. The *Research@ARL* monograph series on energy and energetics[1] and the materials modeling at multiple scales [2] are commendable. When it comes to publications, "merit" vs. "quantity" is another judgment to be made.

Most of the projects presented are excellent and have a pervasive impact. The scientific soundness and the use of fundamental sciences are outstanding. It is commendable that the ARL materials science talent pool has a good mix, ranging from experienced, savvy scientists and engineers to bright, early-career professionals. There appears to be good diversity with respect to gender and ethnicity. The project portfolio fits well with both global thrusts and the national agenda, with research projects falling at the intersections of biotechnology, nanotechnology, advanced materials, energy, and the environment.

As for institutional aspirations, there is no shortage of challenges and opportunities. One of the larger questions being asked is: How can ARL be a unique research laboratory that is nourished by an innovative culture? In expanding innovation, discovering new science and new technology is as rewarding as crafting new uses of existing technologies to develop advanced Army products.

Striking a balance between the projects that tackle known unknowns, driven by application and innovation on demand, and the projects that explore unknown unknowns to achieve high-risk and high-reward outcomes needs to be an ongoing effort.

Another opportunity is presented by asking how the distance between the science and the Army end-use applications can be narrowed. The ARL scientists maintain their knowledge of Army applications through direct exposure with the end-users in the field. To enhance human capital, nurturing a work environment that offers positive energy, organizational stability, and a high retention rate is essential. Establishing a comprehensive reward system is another challenge and opportunity. Several ideas that may be considered are awards (monetary and nonmonetary), internal recognition, external peer review, research freedom, laboratory-wide recognition of stature (e.g., fellowships), and dual-track career advancement.

[1] Army Research Laboratory, 2012, *Research@ARL: Energy & Energetics,* June, http://www.arl.army.mil/www/pages/172/docs/Research_at_ARL_2012_s.pdf.

[2] Army Research Laboratory, 2014, *Research@ARL: Materials Modeling at Multiple Scales,* July, http://www.arl.army.mil/www/pages/172/docs/research-at-arl.vol3-issue2.pdf.

Researchers need to consistently analyze data and contemplate theories that are behind the observed physical phenomena, test data, and modeling systems to effectively design the path forward for each project. Given the many exciting experimental and computationally derived results that were reported during this review, such efforts will further optimize the progress of research. As a first step toward this goal, data analysis needs to be highlighted in the research efforts. This does not necessarily mean the use of advanced computation tools, but rather the incorporation of even simple mathematical analysis to further uncover trends and correlations in data and deep diving into plausible fundamental theories. This will help to advance the materials by design and by demand paradigms.

To further document the competitive posture of the ARL research programs vis-à-vis those of comparable organizations, formal metrics are needed to enable comparison of ARL research activities with those of other government-owned research laboratories in the United States and overseas.

Working toward making the Army the best Army for 2035 and the ARL toward becoming a top choice for researchers to pursue careers, one priority will be further elevating the ARL's national and international stature. This stature will rely on performing first-rate research, solid productivity, ability to attract and retain the best and brightest talent, effective communication with the scientific community and dissemination of ARL research findings to that community, and, eventually, the transfer of knowledge to Army applications. The review materials and presentations did not clearly explain what ARL has accomplished in the way of providing better armaments.

Collaborative efforts have been demonstrated both across ARL and with external entities. All the projects reviewed are engaged in collaborative efforts to various degrees; this is commendable. The next level of excellence can be achieved by improving the efficiency of this collaboration to deliver better focus, quality, and selection of projects. Internal collaboration across the divisions and directorates is as beneficial as extramural collaboration. ARL's move toward the use of science and technology (S&T) campaign plans can enhance such collaborations.[3] Also, research output could be enhanced by the periodic evaluation of project feasibility and milestones.

Biomaterials, Energy Materials and Devices, and Photonic Materials and Devices

Overall, the researchers and the management are of high caliber and deserve kudos. Researchers appeared passionate about their work. Most of the projects presented are excellent and are having a pervasive impact. Scientific soundness and the use of the fundamental sciences are outstanding. Some of the projects in the portfolio are particularly impressive. The biomaterials group is making particularly noteworthy progress, following the ARLTAB's previous suggestions to recruit a new branch chief and to begin to establish a long-term program in biotechnology. The project on synthetic biomolecular materials is especially significant for the Army. It addresses needs in situation awareness and force protection in such areas as on-demand production of biomolecular sensing materials in response to new and emerging hazardous threat materials; functional biomolecular materials that are stable in austere environments; persistent surveillance; and ubiquitous sensing. The project has already done topnotch research by developing iterative and integrated multiscale computational biology capabilities. It has also demonstrated, for the first time, rapid development of peptides as synthetic alternatives to antibody-based bioreceptors, which are difficult to produce and maintain in the field. The use of biogenerated fuel to drive a fuel cell and provide a periodic power boost is another research project important to the Army.

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[3] Army Research Laboratory, 2014, *Army Research Laboratory. S&T Campaign Plans. 2015-2035,* Adelphi, Md.: Army Research Laboratory, http://www.arl.army.mil/www/default.cfm? page=2401.

ARL is a technology-driven and warfighter-focused institution; developing technologies to deliver ubiquitous power and energy for warfighters is a compelling mission. The project on hydrogen production from water by photosystem for use as fuel in energy conversion devices offers promise. The project on nonnoble metal catalysts for alkaline fuel cells studies the catalysts supported on graphene. Impressive power density (300 $mWcm^{-2}$ at 60°C) was demonstrated using a Pt-free cathode with an anode of standard carbon-supported Pt. If the performance can be improved and stability demonstrated, this could represent a significant breakthrough. For lightweight, quiet, efficient, and reliable power sources that enhance soldier combat capability, the project on fuel cells for military applications tests and evaluates commercial technologies—namely, direct methanol fuel cells and solid oxide fuel cell (SOFC) systems. Fuel cells reduce weight and decrease the logistic burden associated with batteries. The 300 W SOFC systems, operated on propane, can be thermally cycled more than 40 times between room temperature and 800°C without significant degradation and can be heated to 800°C in less than 10 minutes. The system was successfully tested in an unmanned aerial vehicle, representing a welcome upward potential for Army applications.

In the area of photonic materials and devices, the accomplishments of the project on electromagnetic modeling of quantum-well infrared photodetectors (QWIPs) are laudable. The model described explains the quantum efficiency (QE) of all existing detector structures, including the most advanced optical effects, and expresses detector QE in terms of the material's absorption coefficient and the volumetric integral of vertical electric field. Because affordable, high-speed, high-resolution, long-wavelength infrared (IR) cameras are critically important to the Army's night vision, large-area surveillance, and navigation in degraded vision environments, the success of this project is of enormous value. As a leader in the development of QWIP technology, ARL can leverage its achievement to develop advanced technology and to strategically brand ARL's leadership.

Another high-impact project is developing a low-cost, III-V, direct-bandgap, long-wavelength infrared (LWIR) detector for night vision technology. LWIR detection is a niche Army technology requiring dedicated equipment and highly specialized skills and tools. The research involves the growth of defect-free unstrained and unrelaxed InAsSb material on binary substrates such as GaSb, InSb, or InAs. This detector is expected to be a disruptive technology for the LWIR field and to potentially replace the costly II-VI based technologies.

As for laboratory physical facilities, state-of-the-art equipment and instruments are available to perform quality research work, and there are many material characterization capabilities—for example, ultrafast terahertz and nanonuclear magnetic resonance (nano-NMR), time-resolved ultraviolet (UV) materials growth and characterization, and a clean room fuel-cell laboratory, all supported by trained and knowledgeable personnel. However, synergistic capabilities could be boosted through the tie-in of facilities across division branches, as well as through collaborations with the targeted external facilities.

The sections that follow summarize the comments and suggestions for three groups of projects: biomaterials, photonic materials and devices, and energy materials and devices.

Electronic Materials and Devices, and Structural Materials

Research projects under this review span three families of materials—metal, ceramics, and polymers—plus another category, composite materials. The overall portfolio comprises short-term and long-term projects. A relatively large proportion of the work reviewed consists of high-risk, high-impact projects. The research scope covers experimental, computational, and modeling projects. In the laboratory's physical facilities, state-of-the-art equipment and instruments are available to perform quality research work, and there are excellent material characterization capabilities and exceptional mechanical testing equipment.

In the area of electronic materials and devices, the research presented throughout the review is of high scientific and technical merit and evinces a great deal of innovation. High-profile research aligned with ARL's mission needs is evident. Staff members are working on forefront research projects that could potentially yield breakthroughs, and the work is directed toward the emerging needs of the future (2035) Army. For instance, the low-dimensionality—two-dimensional (2D)— materials program is particularly impressive, covering fundamental aspects of synthesis, characterization, device design, and manufacturing. Tuning 2D materials at the atomic scale opens enormous opportunities to design electronic properties for innovative applications through controlling surface conditions, defects, and the interfaces with other 2D materials. This is a potentially high-impact area. The piezoelectric materials program is exceptionally mature, so it is now transitioning to the implementation of unique actuators, microelectromechanical systems (MEMS), robots, and further miniaturization of low-power relays.

Taking into account that projects in structural materials are at different stages of research and development, the research, overall, is of high quality. The maturity of the work in synthesis and processing is commendable. Modeling has been nicely integrated into many experimental studies such as Mg alloy development and field-assisted processing. The project on boron oxide ceramics stood out among many excellent presentations. The mechanical press, capable of applying up to 700,000 lb pressure in developing lightweight armor, is exceptionally enabling equipment. The experimental work conducted in cold spraying, Mg processing, and nanocrystalline metals is excellent, and the researchers have access to centralized characterization facilities. Researchers have made inroads in publishing their results (such as in nanocrystalline metals) in the archival literature. However, the utility of this technology for making scaled-up parts is still a matter of conjecture.

Another area that may need attention is powder technology, which appears to be a crosscutting technology at ARL, crucially applicable to multiple projects. Whether there is a need for in-house capability and expertise in this area calls for thorough consideration.

In the context of the focus on correct modeling at specific scales and physics, notable results include the atomistic modeling, the piezoelectric materials, and the computational fluid dynamics (CFD) modeling for cold spray deposition. The modeling is well integrated into an overall fabrication and testing program, enabling the selection of fabrication techniques (e.g., Mg alloy development) or device manufacture (e.g. piezoelectric MEMS). There is a developing effort in linking models at various scales and expressing different physical phenomena, which is producing good results, especially in the transition from smaller to larger scales (e.g., brittle material modeling or polymer coarse graining).

Many projects have an overarching theme of interfacial behavior across different classes of materials, such as the nanocrystalline alloy stability, grain boundary engineering of ceramics, and the role of adhesives. This provides a unique opportunity to explore crosscutting themes and activities of research that enhance the role of computational methods of mesoscale modeling, stochastics, optimization, and informatics (e.g., statistical learning and data mining), as well as experimental methods such as advanced microscopy and microstructural characterization studies.

ACCOMPLISHMENTS AND ADVANCEMENTS

Biomaterials

Synthetic Biomolecular Materials

ARL investigators have successfully demonstrated, for the first time, rapid development (in less than a week) of peptides as synthetic alternatives to antibody-based bioreceptors, which are difficult to produce and maintain in the field. This project, which used combinatorial chemistry and genetically modified *E. coli* to find peptides capable of strong binding to inorganic materials, is excellent research. For example, finding 15-unit amino acid sequences that bind strongly to metals and other target compounds will facilitate development of biosensor technology. This research addresses an important need in situation awareness and force protection such as on-demand production of biomolecular sensing materials in response to new and emerging hazardous threat materials. The collaboration with the Institute for Collaborative Biotechnologies at the University of California at Santa Barbara seems to be productive; extended visits by staff members leading to joint publication are encouraged.

Tissue Scaffolding

This is an excellent effort and certainly is of benefit to the Army because it is aimed at designing nanofibrous scaffolds that enable wound healing and regeneration of damaged nerve tissues. These scaffolds will be used for three-dimensional (3D) cell culture platforms for the study of blast-induced traumatic brain injury (TBI) at the cellular level. The tissue engineering research involves a scaffold for neural cells, and the work shows the cells aligned if the fibers are oriented, a feature well known in the field. The work is being carried out expertly; the gradient approach to place adhesive protein in the scaffold deserves further study. By far the most interesting application was that the scaffolds were used to culture neural cells, which could be exposed to a simulated blast or shock wave followed by analysis of changes in the metabolic characteristics of the cells. This research could lead to unique treatments to heal nerve injuries as well as to get a better fundamental understanding of neural damage from ballistic blasts in order to design better protective equipment.

Synthetic Biology Using Quorum Sensing

Work on harnessing the natural bacterial communication system involving the communication molecules AI-2 is relevant to the Army needs in areas such as bioterrorism, warfare, food and water safety, medical applications, and fuel integrity. The investigators use synthetic biology to engineer a bacterial sensor and to rewire bacterial communication machinery in order to develop a robust and sensitive biosensing system. Additional theoretical studies in gene circuits would help to develop better systems for a wider range of applications.

Nanocellulose

Nanofibrils of cellulose (NC) is an area of research relevant to Army needs because it has the potential for developing materials that exhibit high strength and modulus (comparable to Kevlar), controllable adhesion and dispersion properties, and nanoscale-enabled transparency. This NC product could be an excellent logistical material that is sustainable, inexpensive, bioderived, biocompatible, and eco-friendly.

Theoretical investigations (at ARL or in conjunction with outside academic collaborators) into the structure and physicochemical processes involved in the development of NC are encouraged. The work is interesting but does not seem to have breakthrough potential. While the work on improving impact strength, the ability to reinforce polymer matrices to yield transparent composites, and the synthesis of bio-based polymers is of high quality, it is not many steps beyond the current state of the art in composite technology. Also, the type of research involved in this project involves mainly chemistry and is only marginally biological (and thus not directly related to biotechnology).

Effects of Atmospheric Environmental Conditions on Bio-aerosol Properties

This project develops a system built and tested to measure the effects of atmospheric environmental conditions, including gases, sunlight, and humidity, on UV-laser-induced fluorescence spectra and the viability of bio-aerosols. This project is critical to developing useful tools for soldiers on the ground, who face serious environmental threats. However, it appears to be focused on large-scale measurement capabilities that were not distinguished from other efforts in environmental monitoring and to follow rather than lead efforts that address the need for monitoring highly mobile individual soldiers. The results to date are interesting and informative, and the fluorescence data are useful. It would be useful to consider adding other spectroscopic techniques, such as Raman scattering, to obtain complementary spectral information. Theoretical studies on the photochemical pathways and fate of the photoproducts would also help to provide a fundamental basis for the project. Atmospheric photochemistry is well known, and the study of simple bio-aerosols needs to be expanded to include the study of more complex systems. The project on bio-aerosol chemistry involved interesting, high-quality research, and it is important to tie it in with other work on modeling toxic plume development due to industrial accidents or to a bioterror event. Collaboration with scientists at other laboratories and universities is strongly encouraged.

Energy Materials and Devices

$Li_7La_3Zr_2O_{12}$ Electrolytes

Samples of high quality were fabricated by hot-pressing. They were evaluated in electrochemical cells by cycling. While the current passed at room temperature was modest (0.01 $mAcm^{-2}$), the cycling performance was stable. Some electrochemical impedance spectroscopy (EIS) was also presented. Future work is planned in evaluating electrode impedance. The refractory nature of the electrolyte is likely to facilitate the design and construction of Li batteries with a broad range of operating temperatures, similar to NaS batteries but with higher voltage and specific energy. Options also exist for further improving Li ion conductivity by doping with other ions.

Materials for Advanced Battery Chemistry

In collaboration with the University of Maryland at College Park, electrolytes were formulated for Li/S, Na, Mg, and conversion reaction materials.

In Situ Investigation into High-Capacity Alloy-Type Li-Ion Battery Anodes

The objective of this work was to systematically investigate by means of atomic force microscopy (AFM) the volume changes occurring during charge and discharge using samples of controlled geometry (size-controlled Si islands formed by microfabrication). The AFM was able to capture the morphological evolution of the islands during electrochemical cycling and showed that islands as small as 100 nm in height and diameter readily suffer irreversible mechanical degradation. It is not clear, however, how to avoid this type of degradation. Nevertheless, the approach used to systematically investigate degradation is good. Well-defined geometry is likely to allow the development of theoretical models describing state of charge and the associated volume changes.

Atomic Force Microscopy for In Situ Analysis of Li-Ion Battery Materials

The formation of a thin, contiguous solid electrolyte interface (SEI) layer is important for the satisfactory operation of Li-ion batteries. It is important that it be thin and be a reasonable Li-ion conductor but a poor electronic conductor. The layer is typically a few nanometers to ~100 nm thick. This layer is difficult to characterize. In the present work atomic force microscopy was used to image the SEI layer. This appears to be a very fruitful way of investigating the dynamics of SEI layer formation. It would add considerable value if these studies are supplemented with electrochemical tests, such as EIS.

Oxidation Stability of Electrolytes from Density Function Theory Calculations

Stability is given in terms of voltage. The work shows that density functional theory (DFT) can be used to identify the correct reaction mechanisms (and products). Calculations are in good agreement with the experimental results. This appears to be a very in-depth study. Few papers have been published to date.

Prototyping of 5 V Li-ion batteries

This work concerns the possible development of a high-voltage cathode for Li-ion batteries. $LiFePO_4$, $LiCoPO_4$, $LiMnPO_4$, and $LiNiPO_4$ were investigated using first-principles calculations. Through these calculations, $LiFePO_4$ and $LiCoPO_4$ were identified as good candidates. From the standpoint of thermodynamics, $LiCoPO_4$ is determined to be the best (highest voltage), while $LiFePO_4$ is shown to be more stable. The present work showed that a cathode containing both Co and Fe exhibited high voltage and was also stable. It appears that by suitably tailoring composition, it may be possible to achieve both good performance and good stability.

Liquid Electrolyte Li-S Battery

This is a good problem-solving project based on classic electrochemical methods to reveal qualitative mechanisms during discharge. Awareness of the effect of these materials on the entire system is an important strength of this work. There are several recent publications in high-quality technical journals.

Developing Next-Generation Thermal Batteries

The approach of this project consists of forming multilayer laminates of two metals, Ni and Al. The individual layers are a few tens to a few hundreds of nanometers thick. The relative thicknesses are selected based on the final intermetallic composition desired, which in turn is based on the heat released during the thermite reaction. Very thin layers allow attainment of very high velocities of reaction front travel (10 ms^{-1}). Ignition is achieved at one end. This is a very specialized topic but of direct relevance to Army operations.

Nonnoble Metal Catalysts for Alkaline Fuel Cells

These catalysts are supported on graphene. By suitable thermal treatment, the catalyst is pyrolyzed to change its chemistry. Impressive power density (300 $mWcm^{-2}$ at 60°C) was demonstrated using a Pt-free cathode. The anode was standard carbon-supported Pt. The work is very impressive. If the performance can be improved and stability can be demonstrated, this could represent a significant breakthrough.

Fuel Cells for Military Applications

The 300 W SOFC system operated on propane and could be thermally cycled more than 40 times between room temperature and 800°C. The SOFC system showed 4 times improvement in endurance over SOA battery. The system could be heated to 800°C in less than 10 minutes. Also, the system was successfully tested in an unmanned aerial vehicle. This represents a significant achievement for the SOFC systems and utility for military applications.

Palladium Membranes for Purification of Reformer Gases

Thin (500 nm) Pd membranes were fabricated by supporting them on lithographically patterned 15 μ thick Ni substrate having 15 μ hexagonal holes. A pressure differential of 20 psi could be maintained without rupturing the membrane. The permeation rates were comparable to or better than rates for other Pd membranes supported on other substrates (alumina, stainless steel). The reformate contained CO and H_2S as contaminants. The results are impressive. It is probably possible to use porous Ni foils (made by consolidating Ni powder). This may decrease the cost and may also improve strength, allowing for larger pressure differentials.

The use of Pd membranes for extracting hydrogen from reformer gas is investigated with the goal of reducing cost. The quality of the experimental approach is outstanding and provides a well-characterized system that can be used for fundamental studies as well as sustained engineering development. The researchers' understanding of the underlying issues is excellent, as are the qualifications of the personnel for making advances in both science and engineering. The experimental approach leads the project at present, although modeling aspects could be brought to bear for predicting hydrogen transfer rates and strain based on pressure differences, among other design issues. It may be important to extend knowledge of mechanisms associated with Pd crystal size, diffusion path through crystals versus grain boundaries, lifetime issues that might be associated with crystal ripening, and alloying effects with the support structure that may lead to degradation on the reformer gas side. There is an extensive literature on Pd membranes and their use in exploring reaction mechanisms associated with surface hydrogen. The present project could be expanded significantly to applications well beyond the one used here for purification.

Thermophotovoltaic Energy Conversion Director's Strategic Initiative (DSI)

This is an ambitious project that integrates multiple components, each of which is well-studied in the classic literature and each of which is capable of improvement. The effort benefits from vigorous pursuit with excellent insights based on knowledge of the basic phenomena that are involved. The experimental design and fabrication are excellent and make possible, in principle, a wide variety of system parameters (for example, geometry, flow rates, emitting surfaces, and spectra filters). The reaction engineering of the combustion is treated quantitatively, while the remaining components are at present characterized qualitatively. There is a good mix of experiment and early-stage modeling, and there is significant potential for improved quantitative modeling and optimization.

Exploiting Drop Resonance for Improved Condensation

In this project, experiments are carried out on vertical copper surfaces. The quality of the experimental arrangement is good, and the data measurement methods are reliable. There is an extensive literature on heat transfer in dropwise condensation, as well as on the effect of surface movement on droplets, that has yet to be brought into the project. The effect of vertical height is also important, because droplets that detach from the upper region will clear a path as they detach and sweep up additional droplets on their way down the surface. Copper forms an oxide surface, which could represent a significant variable that needs to be characterized. Similarly, the use of surfactants is critical, because they influence contact angle and propensity of the droplets to shear. While the project is still in the early stages of development, it would benefit from more detailed consideration of the underlying physical phenomena and selection of well-characterized materials for assembling the experiment. There is great potential for significant improvements in modeling and engineering correlations for predicting heat transfer rates.

Phase Change Thermal Buffering for Army Systems

The use of latent heat from phase changes to reduce cooling demand during transient heat loads is investigated in this project. This is an excellent project with an experienced investigator. It benefits from deep understanding of fundamentals across a very wide range of materials and phase-change applications, many of which are described in the literature. Numerical simulations of transient effects play a useful role in modeling transient melting fronts. The project provides a path forward for identifying improved materials with characteristics suitable for Army applications.

Integrated Thermal Solutions for Electronics Systems

In this project configurations for improved heat transfer for various types of electronic packages are investigated by means of simulation models. Chip configurations include 3D chip stacks and power chip stacking. Various levels of sophistication of modeling methods using commercial packages were developed in order to identify the most numerically efficient methods. The quality of the work and the understanding of the underlying physical and numerical methods are excellent. There is an excellent match with practical aspects of reducing the work to practice that involves knowledge of the application as well as the heat transfer fluids and materials. While the Army may have unique applications, it is likely that there are approaches reported in the literature that can be brought to bear, provided that there is in-house expertise of the quality represented in this project.

Advanced Thermal Interphase Testing and Development

This laboratory tour demonstrated that experimental methods are being designed to accurately measure temperature drops (ΔTs) that occur across interfaces. In many energy systems when multiple interfaces exist, it is important to take into account such ΔTs, because they dictate the overall heat rejection rates.

Modified Model for Improved Flow Regime Prediction in Internally Grooved Tubes

Heat transfer during two-phase flow in small-diameter grooved tubes is investigated in this project. This is an important project that has a wide range of specific applications; it requires a general knowledge of flow regimes and associated heat transfer correlations. The experimental arrangement is excellent, as are the qualifications of the personnel for experimental work. There is an extensive literature on two-phase flow in large pipeline systems as well as small-scale refrigeration systems, from which additional ideas for experimental design and analysis could be extracted. In some flow regimes associated with two-phase flow in large pipelines, the sophistication of the computational modeling has improved to the extent that the modeling has replaced experimental measurements. While the knowledge of underlying behavior in small-scale systems is presently at an early stage of development, the path forward could include a quantitative modeling component that might grow in time.

Photonic Materials and Devices

Electromagnetic Modeling of Resonant Quantum-Well Infrared Photodetector Structures

The Board noted in its 2011-2012 assessment of the ARL: "Resonator quantum-well infrared photodetectors (QWIPs) continue to be a crown jewel among the achievements of SEDD [ARL Sensors and Electron Devices Directorate], which has been able to incorporate advanced optical concepts into the detector design. SEDD has developed a better understanding of new near-field optical phenomena that has enabled the design of a QWIP structure with quantum efficiencies nearly 70 percent, doubling the previous record of 35 percent for corrugated-QWIPs. Research aimed at creating extremely low-noise."

The achievements of this project are remarkable. Twenty-five years after the invention of QWIPs, the work described amounts to a rebirth of the field. This work also comprises one of the most convincing applications of plasmonic enhancement for real, deployable technologies that have been demonstrated. QWIPs clearly have an exciting potential to impact the Army mission, with competitive sensitivity but based on mature materials technology that can provide high uniformity and high pixel counts; they also offer the potential for low-cost foundry manufacturing.

III-V Materials for Infrared

The investigations into narrow, direct bandgap III-V materials constitute one of the best projects in the Electro-Optics and Photonics Division. As a whole, this work could radically alter the applications and deployment of mid-IR detectors and focal plane arrays, with performance equal to or better than HgCdTe, because the energy band properties are likely to be more favorable to reduced dark current. Surface recombination and passivation are easier for InAs than for GaAs or InP, so this might provide additional performance advantages.

The presentation of this project was particularly outstanding, with the research very clearly put in context and the ARL contribution compellingly told. This included the history, the probable source of historical scientific confusion in the literature, and the role of compositional ordering. This team deserves commendation for leveraging the Small Business Technology Transfer (STTR) resources to further its

Auger characterization capabilities, and the team is looking forward to carrier lifetime and preliminary device results in the coming year.

This work is an outstanding example of the ways in which ARL makes unique contributions. The project's success reflects a combination of insight, effective modeling, motivation, and carefully selecting the right epitaxy technology to realize a breakthrough in technology for Army applications.

Metamaterials and Metastructures Director's Strategic Initiative

This research activity illustrated two applications of novel integrated photonics. In the work on slow-light waveguides, the innovative designs required very challenging fabrication techniques, and the results were impressive. Nonetheless, performance targets were not articulated clearly enough to assess the promise or efficacy of chip-scale slow-light devices. Additionally, the fact that the results differed by a factor of 10 from the model suggests either an opportunity for discovery or that discrepancies need to be more seriously addressed.

In the work on tunable metamaterials with active adjustable bias structure, insufficient information on performance targets and results was made available to permit adequate assessment, and it is not clear whether there is going to be a serious effort in terahertz applications at ARL or whether this work is considered to be a basic science investigation into possible new metamaterials.

Terahertz Probe of Nitride Semiconductor Opto-electronic Materials and Devices

This project described a remarkable collection of scientific results on nitride device and materials characterization and overall was a very promising exploration of new capabilities. The presentation on the project amounted to a catalog of noteworthy achievements but would have been more informative if it had discussed future directions and identified those with the greatest potential. This was a good example of high-risk work, and while it may not become a mainstream characterization tool, it might provide a capability that is not possible with other techniques.

Mid-Infrared Solid-State Laser Materials

This different method for high-power mid-IR lasers is intriguing. In particular, the elimination of thermal problems through 1.6 μ lasing is an interesting possibility. However, net quantum gain appears to be dependent on an efficient and complex combination of lasers and an optical parametric oscillator that has not yet been demonstrated. From an applications perspective, this is high-risk work.

Research Presented in Posters

The work on HgCdSe materials development for GaSb substrates appears to still be limited by Se purity. The atom optics is an outstanding example of interesting but high-risk and potentially high-impact work by a strong team making steady progress in technology platform development. The heteroepitaxy of GaN on SiC appears to have demonstrated good absorption with good low-noise avalanche characteristics, claiming 75 percent QE at 240 nm; a U.S. patent has been issued. The swept frequency and other beam-combining achievements are very promising and appear to be unique and important contributions to the field. The opto-electronic oscillator (OEO) work is very strong, and the team has unraveled some interesting new acoustic effects not typically apparent in telecom applications owing to the very low frequency offsets.

Electronic Materials and Devices

Low-Dimensional 2D-Atomic Layer Materials

The projects studying 2D atomic-layer materials are on the forefront of materials research; they are paving the way for future Army electronics applications, including low-power electronics, transparent electronics, and flexible and conformal electronics. One project, initiated in fiscal year 2013 (FY13), uses advanced Raman spectroscopy and offers an alternative means of understanding material properties by mapping the Raman spectrum of molecular-level photon and electron integrations. Another project, also initiated in FY13, is studying the electrical performance of 2D atomic-layer material. These new projects complement and support the 2D field effect transistor (FET) interface study, which delivered outstanding results and produced a Best Paper award at the 2012 International Electron Devices Meeting of the Institute of Electrical and Electronics Engineers. The project on emerging radio frequency (RF) electronic devices examines 2D materials for RF applications and van der Waals solids; and a novel device is under construction after having completed material exploration.

ARL work in 2D materials research seems to be well integrated within the overall Department of Defense (DoD) effort. The fields of 2D materials research and device physics offer several opportunities for collaboration and outreach activities with academia and with the scientific community at large, and ARL has been proactively forging partnerships with leading universities such as the Massachusetts Institute of Technology, Columbia University, and the University of Texas at Austin.

The project on low-dimensionality electronic materials and devices is timely and well recognized within the scientific community. In particular, the projects involving 2D materials, such as graphene on hexagonal-boron nitride (h-BN) and transition metals dichalcogenides (TMDs), exemplify the very productive integration of compelling fundamental science, mission-driven research, and university outreach opportunities. The program elements related to materials synthesis and device characterization appear to be progressing successfully; they make use of innovative investigative capabilities, such as Raman spectroscopy, and advanced growth capabilities, such as metal organic chemical vapor deposition (MOCVD) and atomic layer deposition (ALD).

This work also makes innovative use of Raman spectroscopy as a sensitive probe of graphene-based structures. The investigators identified a new Raman peak for graphene on h-BN. The other aspect of this work was studying trilayer graphene. One stacking is insulating while the others are metallic. Interestingly, the investigators demonstrated that they could drag the boundary between different stackings using a scanning tunneling microscope (STM). This is excellent basic science that could lead to novel applications, and the effort could serve as a model for other projects. This work also demonstrated the development of an excellent Raman scattering measurement system with high spatial resolution that has enabled the excellent characterization of both graphene on h-BN and molybdenum disulfide (MoS_2) on polymers. The research team also discovered that not only does the stacking order (A-B-A-B vs. A-B-C-A-B-C) in multilayer graphene determine its optical and electronic properties but also that this stacking and phase can be reversibly switched and moved by applying an external bias field. This finding has already resulted in the publication of several high-visibility articles and is well coupled to the applied project on performance of 2D electronic materials.

In the project on understanding the electrical performance of stacked 2D atomic layered materials, the ARL researchers were integrated within a larger team of university collaborators, but they have clearly carved out their own research topics. A variety of noteworthy scientific advances were made during the course of this project. The investigators on this project were able to fabricate functional logic circuits based on chemical vapor deposition (CVD)-grown MoS_2. This was achieved both on silicon dioxide

(SiO_2) and on a flexible substrate. Analyses were performed to understand the performance limitations due to fabrication flaws. Other outstanding basic science issues were addressed in this context. Specifically, the investigators characterized the changes in conductivity due to grain boundaries. Additionally, they discovered that MoS_2 is contracted by 1.3 percent when free-standing than when deposited on a substrate.

The project team has been working its current focus for about a year, and they have demonstrated not only simple back-gated transistors but also front-gated devices that require far more sophistication to process. They have also enabled demonstration of an inverter, a ring oscillator, Negated AND or NOT AND (NAND) and Negated OR (NOR) gates, and a static random-access memory (SRAM) cell. The research team went through three iterations of MoS_2 growth on different polymer substrates that are optically transparent and completely flexible and that make the MoS_2 now possibly the best 2D layered material approach for low-power electronics. This project has moved from being one among many to being one of the leaders in 2D electronics, showing very impressive results in a very short time and advancing the state of the art in materials and in the application of 2D materials for electronics.

The project on analysis of 2D FET interfaces to optimize efficiency and speed led to a breakthrough in the field—namely, the discovery that by using a 2D layer a few atoms thick from source to drain (S-D), transistors can be turned off when the S-D is very small. This cannot be done if bulk material is used for the S-D, as is usually done. This approach leads to a higher density of transistors on the chip and to better efficiency and speed: As such, it represents a new type of transistor that promises future advances.

On-Chip Energetics: Porous Silicon

This is a mission- and customer-driven project, studying how porous morphology drives reaction and the effects of morphological parameters on the desired results. The project is engaged in a potentially enabling technology: the generation of thermal energy in modular initiators by using porous materials (e.g., silicon). The reaction rates can range from slow burns to the upper limit of acoustic velocity of the porous material.

Successfully delivering thermal energy on demand would be an important and very valuable achievement for the Army.

Emerging Technology for Power-Efficient Electronics

This mission-driven project represents important basic research that could enable mixed signal operation (RF and digital circuits on same chip) on gallium nitride (GaN). This approach would reduce power consumption, size, and weight, and could also enable a system on a chip (SOC). This modeling and calculation effort could be integrated with other experimental and fabrication efforts.

Piezoelectric Materials for Frequency-Agile Radio Frequency MEMS Front Ends

ARL is a world leader in the piezoMEMS field, providing state-of-the-art materials, fabrication, modeling and simulation, and device prototyping.

This mission- and customer-driven project has been ongoing for several years. It is an enabling MEMS technology applicable to switches, resonators, transformers, tunable filters, phase shifters, and tunable passives for secure communication and phased-array radar systems, as well as for improvised explosive device (IED) detection.

The project uses the state-of-the-art piezoelectric materials processing and device fabrication capabilities, in conjunction with modeling and simulation, to develop high-performance, frequency-agile RF MEMS components—common, low cost, reconfigurable hardware for tactical radios, IED detection, and missile systems.

The project investigator has forged extensive collaborative ties with other agencies and academia and has disseminated research results through technical publications and patents.

Magnetic Metamaterials: New Concept, Modeling, and Applications to Low-Profile Wideband Antenna Design

Significant progress has been made in magnetic metamaterials. Accomplishments include the development of very low profile (3.3 in.), wideband ultrahigh frequency (UHF) (250-505 MHz) magnetic metamaterial antennas, which can replace the large, very visible whip antenna now used on Army vehicles; low-profile, wideband UHF (300-1200 MHz) electromagnetic bandgap (EBG)-backed antennas; and collapsible, umbrella-shaped spiral antennas for satellite communications with simple feed design.

Structural Materials

Silicon Carbide–Aluminum Metal Matrix Composites

Work on SiC-reinforced aluminum matrix composites shows the successful implementation of the more highly loaded composites accomplished by rolling. There is good characterization (in situ scanning electron microscope [SEM] with crack initiation and propagation) and finite element modeling (FEM).

Cobalt-Free Tungsten Carbide

This new project to develop environmentally sustainable ("green") materials for armor-piercing (AP) projectiles has identified viable materials and has been performed in collaboration with industry. Concerns about potential carcinogenic properties as well as any cleanup requirements of Co-containing tungsten carbide (WC), utilized in the cores of AP rounds, has motivated research into the development of binders for WC that do not contain Co. Research at ARL is exploring routes for the fabrication of non-Co-containing binders; each of the routes is being explored with the objective of benchmarking it against the performance of current WC-Co cores.

Boron Suboxide Ceramics

Because of its higher hardness and comparable elastic modulus, boron suboxide (B_6O) is a potential replacement for boron carbide (B_4C). This experimental program is geared toward processing of B_6O and is closely coupled with a computational program. One of the advantages of processing B_6O rather than B_4C is the lower temperature required for hot pressing, which reduces the overall production cost.

Ion-Containing Polymers

Research in this project uses reaction-induced phase separation to synthesize membranes having co-continuous hydrophilic and cross-linked hydrophobic domains. The work has resulted in the synthesis of membranes that have high charge transport, improved mechanical properties, and water vapor transport.

The researchers have determined key attributes of alkaline stable cations (acidic protons, aliphatic cations) and have identified cations with over 1,000-hr half lives at 88ºC in 1 *M* sodium hydroxide solution. The work also disproved steric hindrance as a most effective strategy for stabilization.

Nanocrystalline Iron and Other Metal Alloys

The team has developed a high-quality program for thermodynamically stabilizing the grain size of nanocrystalline metals. The underlying concept is to create close to equilibrium grain boundaries (GBs) by lowering the GB energy through the addition of a second element. This concept was proposed years ago in Germany but had not been realized until the recent ARL work. Production of engineering materials has placed this project in the lead of this internationally competitive field. The project uses simple models to screen candidate alloy materials. After selection, the second element is introduced by ball milling. In-house ball-milling facilities appear to be sufficient for this project. This process is a practical method for large-scale production. This research project has developed an alloying strategy for the control of grain size and achieved significant improvements in properties vis-à-vis state-of-the-art nanocrystalline alloys.

Magnesium Alloys

This project has demonstrated significant progress toward the goal of developing Mg alloys that possess increased strength and fracture toughness for armor applications. This research represents a well-planned program combining modeling, process development, process scale-up, and characterization efforts. The utilization of viscoplastic self-consistent (VPSC) modeling to guide the equal channel angular pressing (ECAP) design and process route optimization is particularly praiseworthy. Ties to university researchers, including Johns Hopkins University and Monash University, are well focused in the area of understanding the microstructure/property relations in Mg alloys, such as AMX602, that have improved properties but do not contain rare earths. The project's approach of utilizing ECAP processing to refine the grain structure appears fruitful and is supported by the significant grain size reductions realized so far.

Cold Spraying

Cold spraying of metals is a technology that was invented in the mid-1980s in the former Soviet Union. It is a versatile process for applying metal coatings to substrate surfaces. Typically, fine particles (1-50 μm in diameter) are accelerated in a supersonic gas stream to velocities up to 1,000 m/sec. Upon impact with the substrate, plastic deformation of the particles yields a dense deposit that strongly adheres to the substrate. The process has been used most successfully to deposit aluminum, copper, and titanium on a wide range of substrates. Using robotic control, uniform deposits can be made on flat or profiled substrates. The technology has already found application in the repair of machined parts. ARL's cold spray research has advanced from a laboratory-scale demonstration to a pilot-scale operation. Beyond that, the ability to fabricate shaped pieces by combining cold spraying and additive manufacturing technologies has been demonstrated. For example, a cone-shaped Al alloy article with excellent surface finish has been fabricated—something that no other laboratory has been able to do. This is an impressive achievement and opens exciting opportunities for in-field refurbishment of worn-out parts and even the replication of components or parts that have failed in service.

Tungsten Alloys

Since the Gulf War demonstrated that cleanup of depleted uranium after warfare is both hazardous and costly, research into the development of alternatives to projectiles made of depleted uranium, an area of focused research at ARL and other Army laboratories for over three decades, continues. The current focus on ultrafine-grained W or W alloys is showing some progress. The coupling of experimental process development efforts and DFT computational modeling addressing approaches to increase the ductility of W by examining W-rhenium analogs, including W-zirconium and W-titanium, is noteworthy.

Energy Coupled to Matter

This is a large-scope and long-term project involving a variety of external process parameters that could affect and change the characteristics and properties of materials by modifying their microstructure under a set of target conditions. The project focuses mostly on innovative synthesis, processing, and manufacturing processes under extreme conditions, including high electric and magnetic field environments. The project's general strategy is to use extreme environments to tailor the microstructure of materials during processing in order to develop materials by design and on demand with superior and/or optimized properties. Current examples include electric-field-assisted sintering (EFAS), microwave processing, and flash sintering, as well as the rapidly evolving field of additive manufacturing. This project is currently in the exploratory stages of development and execution; while promising, it appears somewhat unfocused and would greatly benefit from a clearly articulated scientific strategy and scientific roadmap. As the fundamental principles and design rules governing materials processes in extreme E&M environments are being established on a scientific basis, it is expected that the definition of such a strategy will improve and be brought into a sharper focus. This project would also benefit from a better integration of in situ diagnostics and characterization, as well as modeling and simulation.

This is a relatively new program (1 year) that has produced few results, but strong staff leadership and good vision can enable the project to collaborate with strong external U.S. government and university programs to define the best facilities for ARL to develop for investigating high magnetic and electric fields, microwave, acoustics, light, temperature, pressure to control phase chemistry, and nanostructuring of materials. ARL is also focused on developing in situ characterization tools, which are essential for understanding how to create novel materials by applying new high-energy sources during synthesis.

Electric-Field-Assisted Sintering

EFAS has reached its highest level of maturity at ARL, where an integrated pilot-scale unit for the production and consolidation of nanopowders of metals and ceramics has become operational. However, much remains to be done to establish sintering mechanisms. In particular, the very high heating rates achievable in this process introduce complex thermal-electrical gradients, which result in gross heterogeneities in the sintered structures that strongly influence properties and performance of the final products.

The investigators have developed a coupled thermoelectric-sintering modeling framework for two EFAS machines (vacuum chamber with furnace and open air). They have also instrumented an open-air EFAS machine to ensure repeatability and record temperature(s), current, and ram displacement during a run for high-fidelity modeling. Their immediate effort is to explore the effect of electric current on diffusivity and grain growth in light metals and ceramics.

Another project is exploring the impact of EFAS in a single-step processing operation for producing bulk materials from powders. In this process the powder is heated by the application of electric current under applied pressure. This process has demonstrated success in consolidating bulk nanocrystalline and other traditional materials that are difficult to sinter, such as ceramics and refractory metals.

Encapsulation Technology

This project presented an effort to combine metal matrix composites with monolithic ceramic tiles and structural steels to achieve engineered armor packages possessing improved ballistic performance. Improved specific strength and modulus in hybridized materials systems was realized. This project has established the basis for designing large-scale protective systems for land-based vehicles. The investigators have developed prototype designs that show much promise.

Composite Adhesive Design

This project is establishing the foundations for a data-driven framework for designing materials for adhesives. The investigators have managed the difficult and arduous task of developing a large and vetted data set for engineering properties where the provenance is well defined and formatted into a 100 percent digital retention framework.

Grain Boundaries in Ceramics

This program is supported by a complementary ab initio atomic simulation effort. The work to date has been focused on synthesis and exploring different processing routes such as colloidal processing and sputter deposition for depositing amorphous silica and boron suboxide onto the surfaces of boron carbide powder particles. They have successfully used hot-pressing and spark plasma sintering methods to successfully consolidate boron carbide powders to high densities. To date an exploratory microstructural characterization effort has been initiated using transmission electron microscopy (TEM).

Piezoelectric Materials

The research targets understanding of the materials structure that leads to the intriguing properties of piezoelectric materials starting from first principles. Currently the project is at the level of ascertaining the effects of grain geometry on continuum properties.

Silicon Carbide

The research currently concentrates on molecular dynamic simulations of SiC systems with new force laws that provide better results on prediction of shock response and sintering.

Boron-Based Ceramics

The modeling work in this project is part of close collaboration with the processing and synthesis group; these two groups have collaborated well in initiating a project to develop boron-based ceramics. Even though their entry into a well-researched area, especially B_4C, is only recent, significant progress has been made is setting up the mechanism for understanding the behavior of these very complex materials. These materials could have a large impact on the development of armor owing to their high hardness and low density if the issue of low fracture toughness can be resolved. Even though these materials have been studied for a long time, the defects in them are not well understood. The opportunity for materials design is enormous here. Expertise in this area appears to be available at ARL. Although not as far along as the nanocrystalline metals project, some samples have been made and characterization started. At this point the micrographs show silica at the boundaries, but no mechanical measurements have been made. It is too early to assess the impact this work will have, but it is an exciting research area being pursued by an appropriate team of highly qualified scientists, who have done a nice job of calculating elastic moduli and solution energies for a number of impurities.

Multiscale Modeling of Polymers

This FY14 project is aimed at the development and validation of multiscale models to elucidate the effects of the fibrillated microstructure of ultrahigh molecular weight poly-ethylene (UHMWPE) fibers on the unique properties that govern their exceptional ballistic-resistant characteristics. The project developed a computational framework for fibril-to-fiber length scales and subsequently made preliminary correlations between the modeling and fiber twist-tension experimental data on Dyneema. The researchers' pursuit of the advances of multiscale modeling of collagen and Kevlar fibers with various approaches that do not provide a rigorous treatment of fibril-to-fibril interactions to the modeling of UHMWPE is commendable.

Atomistic Modeling of Polymers

In this research program polymers are modeled by molecular dynamics. In order to simulate the polymer chains, the coarse graining method is implemented. Reactive force fields were added. This approach is state of the art in atomistic/molecular modeling and was applied to polyurethane urea, polymer composites, and the design of new composite materials. For example, SiO_2 nanoparticles were added to polymers, and their effect on the mechanical properties was established.

ARL Enterprise for Multiscale Research in Materials

There is a broad joint ARL-funded program involving Johns Hopkins University (for experiments and magnesium), California Institute of Technology (for modeling), Drexel University (for polymers), the University of Delaware (for composites), and Rutgers University (for ceramics). ARL is in position to capitalize on the strengths at these universities. Processing, where ARL is very strong, is primarily conducted in-house. The materials under investigation are divided into four groups: metals (including Mg by ECAP, nanocrystalline metals via powder and consolidation, and cold spraying technology); ceramics (boron carbide and boron suboxide); composites; and polymers (UHMWPEs).

The materials in extreme dynamic environments program is in place, with collaborations occurring at the experimental (processing, testing, characterization) and computational levels. Not much effort is being devoted to analytical approaches. The Mach Conference on materials in extreme environments, organized by Johns Hopkins University, showed that the participating groups are actively engaged and generating new results.

OPPORTUNITIES AND CHALLENGES

Biomaterials

The hiring of a new branch chief might improve the focus and critical mass in the Biotechnology branch. One of the important elements of developing a collaboration is having a leader who is well recognized in the scientific community. Therefore, in addition to the new branch chief, ARL will also need a scientifically recognized leader who can provide the scientific vision, direction, and connections to lead this program in the right direction for ARL. The Biotechnology branch will need more resources and personnel to reach critical mass. It is still a small group that will need some time to grow and find its way. Internally, the branch could reach out to personnel inside ARL and develop joint biorelated projects, grants, and other activities. Also, it would be helpful to hire more mid-career scientists if funding is available. In the meantime, the branch can take advantage of other Army programs, such as the Institute for Collaborative Biotechnologies and the soldier nanotechnology programs. New interactions with other Army-supported institutes, such as the Institute for Soldier Nanotechnology at MIT, are also encouraged, and the new cooperative research and development agreement involving Johns Hopkins University, the Center for Innovative Technology, the University of Delaware, and Penn State University could be initiated.

Since the Biotechnology program is relatively new, it is premature to evaluate it against the other more mature programs (e.g., the Photonics program). It appears that the Biotechnology branch still needs a defined vision and differentiation from other laboratories and universities. Then, over time, it can become like the Photonics program. The three focus areas discussed in the Biotechnology branch's presentation (biotools, biotargets, and human factors) are excellent topics that reflect a long-term, wide-ranging vision; however, these topics are still too broadly defined and will need to be further narrowed in order to benefit from current expertise at ARL. The main focus seems to be on biotools, but this was not spelled out in the general presentation. The four thrust areas for bioinspired materials mentioned in the presentations—energy, detection, and force protection; robust networks; structural awareness and evolving threats; and cognitive nanoscience and transformational medicine—are ambitious for a relatively small biotechnology program. Since these thrusts require a much stronger level of research commitment and resources, a further downselection and narrowing of programs that better suit the resources and capabilities of ARL is required. The Biotechnology program is not only newer but also much smaller and has fewer financial resources to build upon than its counterpart branches in the rest of ARL; however, it could make much better effort to connect to and leverage some of the strongest programs in ARL, in particular the Photonics program. The new Biotechnology branch has now a unique opportunity to refine its vision and focus it on collaboration.

The Biotechnology branch could benefit from greater collaboration with outside groups to define a unique place for itself with relevance to Army needs and where its researchers become leaders, not just followers. The branch needs to seek new areas that have direct relevance to the mission of the Army. This search could be stimulated by initiating and hosting quarterly seminars with the participation of leaders in the field. Of particular interest is the work being conducted at MIT on bioinspired batteries using phages and carbon nanotubes and work at Cambridge University and Imperial College London that is subjecting pig tissues and cells to impulse loading to determine the effect of shock waves. Such work could provide insights that are relevant to the mission of ARL.

Energy Materials and Devices

Increasing the use of atomistic modeling and mesoscopic (continuum) modeling represents a great opportunity to complement many of the outstanding experiments that are under way.

DFT calculations have already been useful in understanding the stability of electrolytes, SEI layer formation, and the development of high-voltage cathodes. In addition to DFT calculations, there is also an opportunity to conduct mesoscopic modeling of entire electrochemical systems. For instance, charge-discharge cycles of a Li-ion battery or analysis of the performance characteristics of a fuel cell require solving a number of coupled equations. A comprehensive approach to system-level modeling will likely lead to new insights, which will help identify fundamental materials-related issues that in turn require further investigations. These areas offer excellent high-risk, high-reward options.

Considerable work on DFT is under way in other parts of ARL. The work would be improved by integrating the disparate efforts or by hiring researchers with expertise relevant to individual areas.

Pd membrane is another example of an opportunity. The use of Pd membranes for extracting hydrogen from reformer gas is being investigated, with the goal of reducing cost. The experimental approach leads the project at present. Modeling aspects could be brought to bear for predicting hydrogen transfer rates and strain based on pressure differences, among other design issues. It may be important to extend knowledge of the mechanisms associated with Pd crystal size; diffusion paths through crystals versus diffusion paths through grain boundaries; lifetime issues such as might be associated with crystal ripening; and alloying effects with the support structure that may lead to degradation on the reformer gas side. The present project could be expanded significantly to other applications well beyond the one used here for purification.

Multiple functionality of a structure appears to be another exciting area of research. The concept is to design a structural component (e.g., the wing of an aircraft) to do multiple functions. The main function is mechanical (support structure), meaning that strength, toughness, and modulus are the important properties. By designing composites with interspersed electrodes, one can also store energy as capacitors or supercapacitors.

Nonnoble metal catalysts for alkaline fuel cells also present opportunities and challenges. The objective is to synthesize organic-based catalysts containing Fe for oxygen reduction reactions. These catalysts are supported on graphene. By suitable thermal treatment, the catalyst is pyrolyzed to change its chemistry. The anode was standard carbon-supported Pt. If the performance can be improved further and stability can be demonstrated, this could represent a significant breakthrough. A computational component could strengthen this area, specifically in catalyst design. Long-term stability of these catalysts is a challenge.

Photonic Materials and Devices

A substantial fraction of the work in the photonics portfolio can be characterized as high risk in the sense that it appears to be quite speculative or to have a long-term horizon. One good example of strong work in this category is the work on cold-atom optics, but there are many other examples as well.

There are fewer projects that exhibit high risk by addressing the following questions: Will a broad investigation into a new area of study yield anything interesting? Will an unproven concept demonstrate any useful level of efficacy, independent of specific Army performance goals? The payoff for such basic work would be in finding applications for the Army at some point in the future that cannot be well-predicted today.

In many cases, the photonics work at ARL seemed to evince an aversion to risk and a low tolerance for failure. In these cases, ARL seems to have adopted a "fast follower" approach, whereby most of the work comprises investigations into whether external scientific advances can be successfully mapped onto the Army mission. This is entirely consistent with elements of ARL's definition of innovation, but it may be more symptomatic of a predominantly top-down project selection. Other peer laboratories may have a more bottom-up approach, with decisions on entirely new approaches being made at the investigator level.

ARL could improve the marketing of its work in the photonics area. While the story of ARL photonics can be compelling, the overviews and core competencies lists appeared to catalog activities rather than to articulate capabilities, accomplishments, and impact. The breadth of work is commendable, but ARL needs to find ways to tell the world where it is truly outstanding, how it wants to be measured, and the context of its work. In many presentations of the photonics work, the connectivity to technology fielded by the Army was not strongly articulated; it would help to highlight the success stories.

There seemed to be a culture of soft-selling evident in the photonics work. For example, the recent game-changing advances in QWIP technology have catapulted ARL to the world's number one spot for this technology. Presentations could include charts to show the competition, and this work could be very successfully highlighted in the international scientific community. The recent advances in narrow bandgap III-V work are also highly provocative and could be very successfully promoted in the outside technical community to raise the prestige of ARL. Businesses understand this kind of promotional activity, and ARL could emulate their approach.

Electronic Materials and Devices

Low-Dimensional 2D-Atomic Layer Materials

In the work on low-dimensionality electronic materials and devices, most of the applications of 2D electronics will require improvements in materials and a large scale-up of materials size, uniformity, and quality to achieve an integration level of at least millions of devices operating at speeds up to 10 GHz to address any meaningful applications. This would represent a game-changing opportunity. This fundamental project, focused on atomic layer characterization, is critically important if such progress is to be realized.

The investigators have positioned themselves at the interface between materials science and condensed matter physics. There are many new monolayers being isolated as the overall field matures, and the investigators have already taken an appropriate interest in phosphorene. One of the challenges is that this field moves with blazing speed. Given the limited manpower on this project, careful decisions need to be made to effectively balance new exploration, device optimization, and collaborations.

The project on understanding the electrical performance of stacked 2D atomic layered materials was initiated in 2008 to study the potential of carbon nanotubes (CNTs) for low-power electronics. At that time, there were significant challenges to first separate the metallic and semiconducting CNTs and then fabricate more than the most primitive transistors, so in 2011 ARL switched to graphene. While ARL fabricated back-gated graphene field-effect transistors (FETs), this was not a leading technical effort, so in 2013 the project switched to growing MoS_2 2D materials and fabricating impressive transistors and simple but important integrated circuits (ICs). This is an interesting success that showed the evolution of materials and an approach that reflects well on both the research staff and management. There are excellent opportunities for incorporating this technology into very lightweight, low-power wearable electronics and displays. As in the case of low-dimensionality electronic materials and devices, most of such applications will require relatively high-performance electronics, so further device optimization and scale-up from the relatively simple circuits already demonstrated to large-scale integration of at least millions of devices operating at speeds up to 10 GHz are necessary.

On-Chip Energetics: Porous Silicon

The role of integrating additive manufacturing, which can be valuable to the project, is not clear. The outcome of the project is expected to deliver thermal energy on-demand systems for the Army and for other applications. This requires the successful execution of experimentation—for example, in reaction control.

Emerging Technology for Power-Efficient Electronics

This effort appears to be a good niche area of research for ARL to pursue in the context of GaN technology, where much related, but not exactly the same, work is already going on around the world. The Defense Advanced Research Projects Agency (DARPA) Compound Semiconductor Materials on Silicon (COSMOS) program would be achieving similar goals by allowing mixed material on the same substrate. It would be beneficial for ARL to explore how its project relates to, and is synergistic with, DARPA's COSMOS program.

Piezoelectric Materials for Frequency-Agile Radio Frequency MEMS Front Ends

Several opportunities exist in the RF MEMS area, and ARL is in a good position to move aggressively into this field and to consolidate its leadership.

Magnetic Metamaterials—New Concept, Modeling, and Applications to Low Profile Wideband Antenna Design

This research effort uses engineered materials (metamaterials) and electromagnetic surfaces to achieve low-profile designs for Army antennas. Metamaterials can step up the radiated power of an antenna, enabling miniature antennas. Several opportunities exist and ARL is in a good position to move aggressively into this field.

Structural Materials

Silicon Carbide–Aluminum Metal Matrix Composites

The challenge for this project is to address critical science and engineering issues that are not addressed by the vast body of literature that already exists in the field of particulate metal matrix composites. This was one of the few posters that explicitly identified the need for a formal feedback mechanism and for optimization to develop robust modeling. This reinforces the need for optimization methods to be included in the overall materials research program.

Cobalt-Free Tungsten Carbide

Addressing environmental and safety concerns while maintaining performance requirements for non-cobalt-containing WC cores for inclusion in AP rounds is technically challenging. The manufacturing approach being pursued appears to have been carefully considered, in particular the potential for a nano-iron binder, which appears to be very promising and presents some unique opportunities to remove Co from the WC binder phase.

Boron Suboxide Ceramics

There are considerable challenges in the scale-up of the processing of these B_6O powders. This experimental effort, combined with the computational DFT work and the mechanism-based research being conducted by other groups at ARL, constitutes a worthwhile and serious pursuit. The integration of the three efforts represents an opportunity for success in this arena.

Ion-Containing Polymers

To address oxidative, thermal, and humidity cycling concerns, the investigators have proposed incorporating compounds 10 and 14 (or compounds like them) into ion exchange membranes and fuel cells and investigating chemical stability in the actual fuel cell environment. The challenge here will involve establishing a link between chemistry, processing, and microstructure.

Nanocrystalline Iron and Other Metal Alloys

The research group identified an opportunity: the ability to create bulk parts and materials. With the promise of enhanced properties and advancing manufacturing, there is a strong need for characterizing and modeling the underlying mechanisms to fully exploit this opportunity. The team has assembled a wide array of tools, from microscopy to first-principles calculations, to support this work, and the next step is to build up and enhance the integrative science that links the modeling and characterization to achieve a predictive, multiscale materials by design approach. The synthesized material is characterized using a number of techniques, including TEM. Apparently there are no technically qualified scientists at ARL to perform TEM measurements, so an outside source is used. It would be extremely useful for this project and many other materials science projects at ARL to have a 3D atom probe.

Magnesium Alloys

Before they can be used in armor applications, Mg alloys will have to be made strong enough and with good enough fracture toughness in large plate form to supplant the Al alloys currently in service in vehicle platforms. Attainment of this goal would mean a huge opportunity for Mg in the lightweighting of armor and vehicles. Once Mg alloys that meet the strength and toughness requirements have been developed, the challenges of corrosion, erosion, and fatigue will have to be tackled, so that the alloys can be widely applied for vehicular armor. ARL's planned path forward—the installation of a crucible furnace and rolling mill facilities to support Mg alloy development—is appropriate.

Cold Spraying

ARL's cold spray research has advanced from a laboratory-scale demonstration to a pilot-scale operation. Beyond that, the ability to fabricate shaped pieces by combining cold spraying and additive manufacturing technologies has been demonstrated. Rapid implementation in the field of this new integrated spray-deposition process is warranted. The impressive progress in cold spray technology is leading to applications such as the repair of Mg helicopter components and the reactive munition (shaped charges) that can be deployed in the BattleAx system. The Mg ECAP program has potential, but it is doubtful that the increase in strength derived from the reduction in grain size below 1 μm will be significant and will justify the process, which has an inherent difficulty and is very energy-intensive. The nanocrystalline research is very contemporary and an outgrowth of the doctoral work of some participants. The challenge is to find applications for this processing methodology.

Tungsten Alloys

Increasing the inherent low fracture toughness of W and its lack of shear-banding driven rod resharpening behavior remain a grand challenge. Exploitation of modeling approaches to understand the atomic bonding and operative mechanisms underpinning these weaknesses in W is a promising modeling and experimental manufacturing process development activity. The researchers need to consider the applicability of super-hard-faced WC/Co alloys as inserts in kinetic-energy projectiles. These materials are available commercially in various sizes, shapes, and forms. A typical super-hard facing consists of a high fraction of diamond or cubic boron nitride particles in a ductile metal matrix, thereby imparting fracture toughness (bend strength) to the graded-composite structure.

Energy Coupled to Matter

Owing to the nature and the scope of the project, one of challenges is the planning vis-à-vis the target goals—for example, which material to study, which field-assisted parameters to study, and what are the determining factors, milestones, and success criteria.

The researchers need to continue investigation and development of high magnetic and electric fields, microwaves, acoustics, light, temperature, pressure to control phase chemistry, and nano-structuring of materials. The research team also needs to pursue the development and implementation of in situ characterization tools.

The investigators have correctly noted that a key challenge is the need to develop a fundamental understanding of mechanisms that influence field–material interactions. The approach is to implement a complex array of modeling tools, including thermodynamic modeling, DFT modeling, and phase diagram simulations. Further thought needs to be given to how the results of such modeling will be integrated.

Electric-Field-Assisted Sintering

This research is aimed at understanding and control of sintering kinetics to better address challenges in the reproducible fabrication of high-quality parts, particularly those of complex geometries. Without a near-net-shape capability, the applicability of this new technology will be seriously limited. In today's industry, it is not sufficient to make preforms, and then to resort to post-thermomechanical treatments to produce the desired shapes.

Encapsulation Technology

Development of improved (in performance and cost) kinetic energy (KE) armors requires the concurrent development of the materials of construction, design of the structure, and the processes utilized to fabricate the armor system in addition to the development of predictive computational modeling to support armor design and validation via ballistic testing. From a basic science perspective, this project is a good example of hierarchical design of hybrid materials, where the fundamental principles of micromechanics, shape, and form at an engineering scale and basic materials properties are optimized with respect to ease of processing and manufacturing. There exists an opportunity to develop this project as a template for other multiscale design projects.

Composite Adhesive Design

This program could be readily expanded by exploring a probabilistic relationship between failure modes and loading history. This could help to address the lack of understanding of the physical phenomena at multiple scales that govern high-stress and high-strain-rate material performance, resulting from the paucity of validated linkages between experimental and computational research tools at critical length and time scales.

Grain Boundaries in Ceramics

Boron carbide is an immensely complex material, with unmeasurable (and probably variable) stoichiometry, unknown defect structure, unknown impurity content, uncharacterized grain boundary structure, and a tendency to amorphize or melt. The greatest long-term challenge in the program is to find the few keys to performance enhancement—if they exist. In the short term, both the B_3C and the B_3C-SiO_2 materials require substantial microstructural-scale analysis, including electron backscatter diffraction (EBSD) to uncover texture and grain boundary crystallography, energy dispersive x-ray spectroscopy (EDS) for identification of phases, TEM for grain boundary segregant structures, and—ideally—atom probe, also for grain boundary segregants. Some of these can be performed in-house, including on the new scanning electron microscope-focused ion beam (SEM-FIB) system. Others will require external collaboration. The researchers indicated that they aim to explore the science that enables the engineering of grain and interphase boundaries in low-density boron icosahedra–based ceramics like boron carbide and boron suboxide for improved fracture resistance. To meet this challenge, a detailed microstructural program where microscopy and spectroscopy are used as research tools and not just for routine characterization will be key. Although prior work in the field of grain boundaries in other ceramic systems such as nitrides was acknowledged, to ensure that this project has the maximum impact for both the Army mission as well as advancing the field scientifically, there needs to be a more refined set of objectives as to what aspects of the microstructure, especially in terms of grain boundaries, will be explored. Topics to consider include but are not limited to the impact of processing chemistry on intergranular film thickness, wetting and evolution of grain boundary geometry and dihedral angles, and chemical characterization of bonding states at grain boundaries via electron energy loss spectroscopy. When linked to property measurements such as high-rate deformation, this project could have an important impact on many basic science studies.

Boron-Based Ceramics

Because this study requires an extensive survey of large systems, computational resources are a limiting factor. While computer time has not been an issue to date (the investigator has used high-performance computing [HPC] resources within the DoD laboratories), the decision to use a genetic algorithm optimization scheme in the next stages of the project will tax current central processing unit (CPU) cycle availability. Management needs to look at a variety of options inside and outside ARL, including dedicating appropriate resources to this program. Computational throughput has also been limited by a shortage of software licenses. Apparently, a cutback in the number or type of DFT software licenses has limited the number of computational replicants that can run simultaneously. This will become critical as the next stage of the project commences. ARL needs to investigate solutions, including purchasing more licenses, negotiating the license agreement to allow multiple replicants per license, or considering open source software such as Abinit (with the understanding that this will require some retrenchment).

This project has a high degree of risk, because the small computational cell size used in ab initio methods may not be able to capture the complex and potentially nonperiodic phenomena in this large unit cell material. High risk is appropriate for a basic research project, but realistically evaluating the potential for this approach to solve the problems of interest needs to be a component of the project. The basic concept is to weaken the GBs to improve fracture toughness. The DFT calculations are reasonably well focused and use service-oriented architecture techniques. There appears to be an issue with respect to use of the Air Force computer system, pertaining to the Vienna Ab-initio Simulation Package (VASP) and/or CASTEP[4] licenses. This issue needs to be resolved.

Multiscale Modeling of Polymers

Development of predictive models of the mechanical behavior of UHMWPE will afford improved opportunity to maximize UHMWPE fiber use in armor applications. A challenge in modeling subfiber mechanics is to gain an understanding of the defects within UHMWPE fibers, their length scale, and the linkages between manufacturing and defect distribution and their effects on subfiber and fiber mechanical behavior. Researchers need to continue addressing the gap between molecular dynamics modeling and fiber behavior.

Atomistic Modeling of Polymers

Shock wave propagation through these polymers was investigated. This modeling approach needs to be coupled to experiments in order to advance the field.

ARL Enterprise for Multiscale Research in Materials

The success of this broad collaboration hinges on the ability and desire of participating scientists to physically visit the institutions and have extended (2 weeks or more) visits that are periodically repeated. This is more easily accomplished at the graduate student, postdoctoral, and junior scientist levels. If such a program of visits is not established, the universities will pursue their different and diverging paths with a significant diminution of results. The danger (for each institution) of conducting incremental work

[4] CASTEP is a commercial and academic software package that uses DFT with a plane wave basis set to calculate the electronic properties of crystalline solids, surfaces, molecules, liquids, and amorphous materials from first principles.

and repeating work that has been done before is real, and the challenge to the participating researchers is to seek new areas.

OVERALL TECHNICAL QUALITY OF THE WORK

Knowledge of materials is the foundation of designing, constructing, and manufacturing useful products that meet target purposes in functional as well as aesthetic qualities and characteristics. Superior knowledge spurs superior products. This knowledge must be continually built and augmented through creative, innovative, and ingenious studies.

In general, ARL's materials science research, being dedicated to address the Army needs, includes those from the state of the art to the art of the possible. Materials research efforts and expertise are spread throughout the ARL enterprise. It is a crucial core competency and a crosscutting discipline.

To achieve an optimal impact, ARL has tried harder to strike a balance between projects that tackle known unknowns, driven by application and innovation on demand, and projects that explore unknown unknowns to achieve high-risk and high-reward outcomes. The technical merits of research projects and the caliber of researchers have also demonstrated upward momentum.

Several leading and high-impact scientific studies as outlined in this report show tremendous promise and potential breakthroughs for future applications to benefit, protect, facilitate, and empower soldiers of the world's unrivaled armed force, the U.S. Army. The following are outstanding and exceptional areas in materials sciences.

Critically important to the Army's night vision, large-area surveillance, and navigation in degraded vision environments, the electromagnetic modeling of quantum-well infrared photodetectors (QWIPs) work is exceptionally valuable. Affordable, high-speed, high-resolution, long-wavelength infrared cameras will be one of the fruits of this project. ARL is the world leader in QWIP technology.

To support development of lightweight, quiet, efficient, and reliable power sources for Army applications to enhance soldier combat capability, the project on fuel cells for military applications tests and evaluates commercially made technologies—namely, direct methanol fuel cell (DMFC) and SOFC systems. The technology reduces weight and decreases the logistic burden associated with batteries. This represents an upward potential for Army applications and an outstanding value.

The work on synthetic biomolecular materials is highly significant for the Army. The project has already shown success by developing iterative and integrated multiscale computational biology capabilities for in silico studies and studies on the evolution of material interfaces. This is innovative and ingenious work.

To explore potential breakthroughs that could meet the emerging needs of the 2035 Army, the low-dimensionality (2D) materials program covers fundamental aspects of synthesis, characterization, device design, and manufacturing. Tuning 2D materials at the atomic scale opens enormous opportunities to design electronic properties. This is a potentially high-impact area.

To develop lightweight armor, ARL's mechanical press capability of up to 700,000 lb of pressure is unique. This is exceptionally enabling test equipment that facilitates materials discovery and development.

Biomaterials

The technical quality of the research and personnel in the biotechnology branch seems highly variable and ranges from good to excellent. The researchers are very knowledgeable and capable, and they have a very good understanding of the relevance of their research to Army missions. The scientists and engineers in the biomaterials area are remarkably enthusiastic and effective. Their research productivity is more than adequate in general and excellent in several areas such as applied molecular biology and biosensor development.

The photonics programs are more mature and have good projects and personnel, with a couple of projects being world-leading efforts; the biotechnology effort is newer and as such needs careful nurturing. The overall quality of the research in the biotechnology program has greatly improved over the past year and is excellent in several areas. These include the excellent research on synthetic biomolecular materials and the search for extremophile dry-tolerant, thermostable proteins for sensing applications. Several studies involving applied molecular biology are well chosen and have great potential.

Some projects reflect good underlying fundamental science; others do not involve basic understanding. If the research is conducted at ARL with outside help, systems and synthetic biology could be an exciting area if it can include protein engineering, synthetic biomaterials, and extremophiles. The Biotechnology branch could closely couple with the well-established photonics groups, which have outstanding laboratory resources and equipment. Further collaboration with outside researchers is also encouraged. For some projects, the addition of theoretical studies to accompany the experimental work would be very useful. The ARL has outstanding laboratory facilities and equipment, and the experimental research there reflects the excellent work of ARL staff and efficient application of these outstanding resources. The Biotechnology branch is also well equipped to do classical molecular biology and biochemical research. The nascent systems biology and some of the computational modeling of protein structures represent some basic computational and theoretical elements of the program. However, if this branch begins to conduct research at the interface of the biological and physical worlds, it would discover many opportunities for the integration of theoretical, computational, and experimental observations and results.

Further collaboration needs to be pursued with other research institutions, including universities, to add some theoretical studies and obtain improved fundamental understanding of the processes being investigated. Collaboration with organizations where Army-sponsored research is conducted (for example, MIT, University of California at Santa Barbara, Johns Hopkins University, and the Center for Innovative Technologies) is encouraged. These collaborations would energize the talented researchers and provide a good opportunity to conduct collaborative research and write joint papers, which would enhance the reputation of ARL in the global scientific community.

Energy Materials and Devices

The scope of the research was impressive, covering a broad spectrum of materials physics relevant to Army technologies. In general, the quality of the research reviewed was high. The quality of the scientific content of the presentations and the overall selection of topics were impressive. However, some of the specific projects presented in previous years were not presented in sufficient depth during the current review. An example is the power platform for flapping wings (microautonomous systems). Some update on the status of this topic would have been useful, especially given the significant focus on it over the last couple of years.

Overall, in the materials sciences discipline, the quality of the scientific research is excellent, reflecting a broad understanding of the underlying science. There was more effort devoted to understanding and monitoring global research activities than in previous years. Increased collaboration with external organizations within the DoD community, in the industry, and in the academic community is also notable.

The question on the mix of low-risk and high-risk research to reach an optimal balance continues to be a discussion item. Nonetheless, the project portfolio does indicate a wide array of work embracing high-risk and lower-risk research.

Photonic Materials and Devices

The science and technology in this area are strong, with some examples of world-class, breakthrough work. As exhibited in the posters and presentations, ARL's technical work is outstanding, demonstrating both breadth and depth. The researchers showed clear and deep understanding of their fields and they evinced understanding of their particular work in both its applications context and its place on the world research stage.

Electronic Materials and Devices

Low-Dimensional 2D-Atomic Layer Materials

The overall technical quality of the work presented in this cluster of projects is outstanding. The research project on low-dimensionality electronic materials and devices demonstrated outstanding technical achievements in characterization of 2D layered electronic materials and the discovery of external bias change of the stacking structure in multilayered graphene on h-BN. There are a good number of highly visible publications on this work.

The project on understanding the electrical performance of stacked 2D atomic layered materials is an example of the high quality of the ARL research portfolio in 2D layered electronic materials and devices. In 2011, the investigators switched from studying carbon nanotubes to graphene. In 2013, the investigators recognized the importance and relevance of MoS_2 and embarked on this journey. Since then the investigators have contributed significantly to the scientific literature and made substantial progress on building functional devices. This research is a success, as evidenced by the 12 publications that were produced in the course of this work, 6 of which featured an ARL researcher as either the first or the last author. The technical quality of the work is consistently very good, from the foundation of understanding and developing the growth of MoS_2, to device modeling and fabrication, to realizing small demonstration circuits required for logic operation. This project is well supported and coupled to the scientific fundamentals project on low-dimensionality electronic materials and devices. The project exhibits high-quality scanning probe microscopy (SPM) and Raman characterization of the MoS_2 materials, theory work on 2D materials, and the effects of surface and edge states on mobility.

On-Chip Energetics: Porous Silicon

The projects were found to be of high quality. An additional merit of the project is its use of the ARL clean-room facility, a valuable ARL capital investment.

Emerging Technology for Power-Efficient Electronics

The investigator is extremely competent and is capable of advancing the state of the art in this promising research area.

Piezoelectric Materials for Frequency-Agile Radio Frequency MEMS Front Ends

The project is of very high technical merit. The leader of the effort has been working on MEMS at ARL for more than 15 years, is very capable and knowledgeable about the technology, and is a leading expert in the field.

Magnetic Metamaterials: New Concept, Modeling, and Applications to Low-Profile Wideband Antenna Design

The projects collectively are of very high technical merit. Prompt success of the effort can offer immediate benefits to the Army by reducing the profile of antennas mounted on Army vehicles, helping to limit their visibility.

Structural Materials

Silicon Carbide–Aluminum Metal Matrix Composites

The technical quality of this work is good, with complementary experimental, characterization, and modeling (FEM) components.

Cobalt-Free Tungsten Carbide

The green WC project entails manufacturing process development, materials characterization, and performance optimization. The effort appears well planned and technically focused, and the project is on track to produce meaningful binder replacement options.

Boron Suboxide Ceramics

The program is of high quality, with beneficial collaborations with Rutgers University (for synthesis) and Johns Hopkins University (for TEM). High-quality TEM is an essential component of this program.

Ion-Containing Polymers

This work shows promise in advancing important engineering problems. To meet the challenges and opportunities, this project can build on a multiscale paradigm both computationally and experimentally. The work would be strengthened by also considering a modeling/theoretical foundation when choosing compounds to explore experimentally.

Nanocrystalline Iron and Other Metal Alloys

This group has disseminated its technical results by publishing in a large number of high-quality publications. Now that a number of material combinations have been identified, it is a natural extension to utilize semiempirical potentials to calculate the stability and structure of GBs in specific materials systems. This work would help to define process parameters and quantify the reliability of these novel materials. In-house expertise for this extension is available at ARL. This project is one of the best materials research projects presented during this review. The project shows a good application of fundamental science to critical manufacturing problems.

Magnesium Alloys

This project has made excellent progress over the past 3-4 years, in particular as demonstrated by its 12 in. × 12 in. × 1 in. processed plates.

Cold Spraying

This work had been going on at ARL for a number of years. Its results are significant, and the research is leading to patentable technology and could lead to industrial applications. Two applications are of special interest:

- For reactive munitions, ARL has been able to codeposit Ni and Al powders in a shaped charge. These powders can react exothermically but are prevented from doing so by the ambient temperature of the process. However, the formation of a jet could initiate the reaction, increasing the energy of the warhead. Similarly, shells made with Ni, Al, and a third mystery component could react after fragmentation or upon impacting the target, increasing the lethality of the weapon.
- For helicopter gearbox repairs, a single gearbox casing costs around $800,000, and so it is advantageous to repair these magnesium alloy components, which can be done by cold spraying. This technique is applicable to the more than 4,000 helicopters in service for the U.S. defense.

Tungsten Alloys

Replacement of depleted uranium (DU) remains a complex materials science challenge strongly driven by political and environmental cleanup realities. The current ultra-fine-grained W and W alloy development efforts, including powder purity improvement and powder consolidation methods, appear warranted and are worthy of further research. Excellent progress has already been made in this challenging materials development area. In particular, the embedded WC/Co insert appears to be a solution to the oblique-angle impact problem. Building on this achievement, there is the prospect of further improvements in performance by the use of inserts of super-hard-faced WC/Co alloys.

Electric-Field-Assisted Sintering

A computational modeling approach to EFAS is being developed to understand and control sintering parameters to achieve reproducible structures and properties for complex parts. The model is helpful in guiding EFAS development, particularly in addressing challenges associated with process scale-up and optimization, leading eventually to full-scale manufacturing. This research is well targeted and likely to yield results of major technical importance.

Energy Coupled to Matter

The team is excellent and exhibited good judgment in defining projects. The project evinces a close connection of computational modeling to couple to and define an optimal approach for the proposed experimental work.

This program has provided critical capabilities for ARL. While it is in its early stages, it would be useful to develop projects that distinguish it from other groups here and abroad. To enhance the quality of the program it has to be competitive with other laboratories. For instance, some thought needs to be given to where ARL can carve out a research niche for itself—say, in developing new materials or in exploring fundamental physics that no other groups are exploring.

Encapsulation Technology

The combination of purposefully selected structural materials in combination with metal matrix composites and monolithic ceramics to achieve lightweight, multi-hit-capable armor systems is a very fruitful line of research. The work has progressed well; it now needs to move to the next phase, where the design is guided more strongly by analytical and stochastic-type modeling. Adding a theoretical component to the design would also help to ensure the long-term success and impact of the project.

Composite Adhesive Design

This project is at its early stages, and the investigator has established a program that can serve as a template for a data-driven approach to materials design. The project has the ability to uncover unexpected new correlations in structure–processing–property relationships. If the project moves to the next stage, from building a data repository to incorporating analytical tools to interpret that data for models, then the project can significantly accelerate the transition from experimental validation and data management to materials design. This project is one of the few, if any, that explicitly call for building stochastic/statistical and informatics approaches to materials design.

Nanocrystalline Alloy Microstructures

This group has also disseminated its technical results in a large number of high-quality publications. Now that a number of material combinations have been identified, it is a natural extension to utilize semiempirical potentials to calculate the stability and structure of GBs in specific materials systems. This work would help to define process parameters and quantify the reliability of these novel materials. In-house expertise for this extension is available at ARL.

Grain Boundaries in Ceramics

This project is exploring the fundamental issue of GBs in engineering ceramics that goes far beyond the specific chemistry of the material system. The work is off to a good start and is addressing the critical issues of materials synthesis and processing and ensuring that the provenance of the materials is well established before embarking on a detailed mechanical and microstructural characterization of interphase boundaries in boron-icosahedra-based ceramics. The overall technical quality is strong, and the problem is compelling and has significant growth potential. In contrast to the modeling component of this effort, the experimental component is not discovery-directed basic research but, rather, science-guided development, and there is a clear line of sight from the technology to the customer. Thus, this project has an appropriate balance between basic research and development.

Piezoelectric Materials

A good foundation has been established for continuing work on the hard problem of linkage to atomistic descriptions.

Silicon Carbide

The effort has led to validation of single crack propagation and bifurcation, and it sets a good foundation for analysis of more complex crack propagation scenarios.

Boron-Based Ceramics

The overall technical quality of this work is strong. It is very positive to see ARL adding to its modeling portfolio at this length scale. This is an area that can grow substantially. Missing at this time are the calculations of intrinsic defects, although this information may be available in the literature. Interaction of impurities with intrinsic defects may be critical in these materials and is an effect well suited to investigation by DFT. The research team has a good background in materials science as well as DFT expertise. This is a combination rarely found and is a strong advantage for this project. GBs and amorphization will be difficult to study with DFT, owing to their complexity. More empirical methods, calibrated with DFT, can be used to examine these complex structures. This project has taken up the great challenge of predicting structure and properties of bulk boron suboxide (B_xO) and B_xO grain boundaries. Accomplishments include construction of the B_xO simulation cell (168 atoms), development of a GB simulation cell (~500 atoms), a survey of bulk dopants in B_xO, and calculation of elastic constants in pure and doped B_xO. The results have been analyzed in depth, and a journal paper is in progress. This work has a line of sight to the effort to apply grain boundary engineering to B_xO, but it is better categorized as basic research. As such, the contributions of this relatively new project are substantial and strong.

Multiscale Modeling of Polymers

This new project represents a well-conceived multiscale project displaying strong initial progress. Continuing leverage of experimental and modeling insights and techniques from medical research on collagen is expected to prove beneficial.

Atomistic Modeling of Polymers

Seventeen peer-reviewed publications resulted from this work, a significant accomplishment by the project's enthusiastic early-career participants.

ARL Enterprise for Multiscale Research in Materials

The technical quality is high, but the challenges are daunting as well. Although a significant component of computational modeling is present for the four classes of materials under study (metals, ceramics, polymers, and composites), there is limited evidence of true multiscale modeling. This is a challenge that is recognized by ARL and that will require significant effort going forward.

3

Ballistics Sciences

INTRODUCTION

The Panel on Ballistics Science and Engineering at the Army Research Laboratory conducted its review of ARL's terminal ballistics program on August 20-22, 2013, and its review of energetics, interior, and exterior ballistics on July 15-17, 2014. This chapter provides an evaluation of ARL's ballistics (including energetics) sciences core technology competency portfolio.

ARL's ballistics scientific and engineering research efforts during 2013 and 2014 span both basic research that improves fundamental understanding of scientific phenomena and technology generation that supports interior, exterior, and terminal ballistic and energetic developments and fielded system upgrades. ARL's energetics and ballistics mission scope is centered within the Weapons and Materials Research Directorate (WMRD) and the Survivability and Lethality Analysis Directorate (SLAD). These directorates execute their mission of leading the Army's research and technology program and analysis efforts to enhance the protection and lethality of the individual soldier and the Army's advanced weapon systems.

ACCOMPLISHMENTS AND ADVANCEMENTS

The ARL has a strong record of achievement and timely support of the warfighter as it develops advanced capabilities for defeating many types of enemy targets and platforms over many years, and the recent and ongoing work described in this review of ballistics demonstrates how ARL continues to build on its tradition of excellence in protecting the warfighter.

The reviews in 2013 and 2014 were divided into topic areas described in technical keynote presentations and posters covering materials for interior, exterior, and terminal ballistics, energetics, penetration mechanics, humans in extreme ballistic environments, and computational terminal ballistics. The oral and poster presenters demonstrated considerable knowledge of the technical areas addressed, displayed strong enthusiasm for their work, and dedication to the missions of ARL supporting the warfighters and national defense. ARL's efforts in energetics, interior, exterior, and terminal ballistics address both fundamental and urgent Army warfighter needs of great importance. The linkages between the research and technology presented and the ties to Army military vehicles and weapons were clearly demonstrated. The *Research@ARL* monograph series on energy and energetics[1] and materials modeling at multiple scales[2] are commendable. Specific accomplishments and advancements in each of the topical areas during the 2013 and 2014 reviews are summarized below.

Materials for Terminal Ballistics

The overview presentations for the materials for terminal ballistics area were very impressive and provided a rationale for the diverse materials issues under investigation; the researchers have gained knowledge from recent combat experience and lessons learned from in-theatre observations. The study of small munitions, specifically striving to build linkages between materials and ballistic performance, was very impressive; ARL is encouraged to continue to pursue this direction as a pathway to increased predictive capability. Continued modeling and simulation (M&S) efforts to bridge the boundaries between mesoscale and microscale are encouraged. The organizational effort to encourage students in the science, technology, engineering, and mathematics (STEM) fields and to provide existing personnel with international and university connections is also very positive.

Many of the materials for ballistics programs reviewed were very impressive. For example, investigation of next-generation Al alloy armor and the evolution of the Eglin armor steel are both promising research topics. Aluminum alloy armor design and the materials manufacturing technology for these alloys with superior ballistic performance are key to controlling material and fabrication costs while supporting lighter weight technologies for the Army. Research to develop an Al alloy with desirable performance but with reduced costs is key to this strategic direction in armor and vehicle design. The use of THERMOCALC, a state-of-the-art thermodynamics modeling program, to modify the Al alloy 2139 composition, particularly by reducing its silver content, is very promising. Continuing to partner with industry on alloy development to achieve an Al alloy with desired yield strength, fracture toughness, and formability at a lower cost is the right direction for this research. Altering the alloy chemistry of cast Eglin armor steel with the aim of using this material for underbody blast resistance is a very promising technology to address both increased blast performance and reduced manufacturing and assembly costs. The manufacturing capability developed for net-shape single-piece underbody manufacturing was very impressive. Simulations of the solidification during casting and, after that, the blast performance using currently available M&S tools, along with experimental testing as an integral part of the development process, were both technologically state-of-the-art and aimed at addressing important Army vehicle needs.

Exploration of the utilization of nanocrystalline alloys for shaped-charge liners appears to be a very promising avenue of research. Nanocrystalline metals offer the possibility of improved properties (strength, ductility) for shaped-charge applications. Fabricating these materials in bulk by means of powder processing is challenging because grain growth occurs even at low temperatures. In this project, the investigators exploit a thermodynamic approach to stabilizing nanocrystalline grains by populating grain boundaries with a solute element that decreases grain-boundary free energy. To achieve this goal,

[1] Army Research Laboratory, 2012, *Research@ARL: Energy & Energetics,* June, http://www.arl.army.mil/www/pages/172/docs/Research_at_ARL_2012_s.pdf.

[2] Army Research Laboratory, 2014, *Research@ARL: Materials Modeling at Multiple Scales,* July, http://www.arl.army.mil/www/pages/172/docs/research-at-arl.vol3-issue2.pdf.

the investigators developed a simple thermodynamic model for grain-boundary free energy and applied it, pairwise, across the periodic table. From this pairing of binary alloys, copper-tantalum was chosen as a candidate material. Ductility was better than that of microcrystalline samples. A warhead prototype has been fabricated that may represent one of the largest bulk components ever fabricated with a uniformly nanocrystalline grain structure. Next, the warhead will be tested. This achievement represents a significant advance in the nanostructured materials field and an impressive achievement for ARL.

ARL work involving the multiscale modeling of noncrystalline ceramics and glass is seeking to develop a physics-based multiscale modeling capability to predict the performance and optimize the design of noncrystalline ceramics and glasses not yet synthesized. A specific goal is to develop a fundamental understanding of why certain chemically substituted glasses exhibit enhanced resistance to penetration by shaped-charge jets and other ballistic threats. This research relates very strongly to the glass research effort, which is focused on shaped-charge jet/glass interactions; it is possible that at some point certain results from this study could support the glass research activity. Of particular note was the team's ability to leverage the work of other institutions, including new results in nanotechnology, applying experimental equipment from geophysics—for example, the diamond anvil cell—and interacting with glass manufacturing R&D teams. This team is striving to work across multiple scales, from nano- to mesoscale, and there is significant opportunity in ARL's efforts to integrate the basic science described during the review with the glass research application work and the experimental tools.

Since 2007, ARL has been developing novel fabrication technologies to advance three-dimensional through-thickness reinforcement (3D-TTR) woven fabrics and composites; the goal of the work has been to enhance ceramic composite armor performance by reducing the ballistic damage zone around the impact point. This research is focused on integrated manufacturing and modeling and simulation efforts that, if successful, will result in materials-by-design tools that enable development of lightweight protection systems. This is more likely to be a structures-by-design than a materials-by-design achievement, but the work can be useful for the development of 3D-TTR hybrid composite armor. It is forward-looking and promises to achieve practical armor system design using advanced concepts of 3D reinforcement. Achievement of this goal will require ARL to develop its own internal weaving capability to implement the architecture suggested by modeling or to do it by teaming with industry. It will be important for ARL to strategically determine which of these two courses of action it deems most promising.

ARL has a long history of projects aimed at elucidating the property–performance relationship of armor ceramics and their applicability to armor design and ballistic enhancement. The armor ceramic projects are pursuing both an understanding of damage evolution mechanisms in silicon carbide-new (SiC-N) under dynamic loading and the use of nondestructive testing to quantify microstructure features within the ceramic, in particular the glassy phase along grain boundaries. SiC-N has been shown to fail under dynamic loading via intergranular fracture. This observation, coupled with its superior ballistic behavior compared to other armor ceramics, led the researchers to conclude that the intergranular grain-boundary film (IGF) is key to better ballistic performance for boron carbide (B_4C). Linkage of these observations with further utilization of in situ diagnostics seems a promising approach to quantifying the details of how these ceramics operate during ballistic impact. It will be beneficial to link the damage evolution studies with other research where nondestructive testing using impedance spectroscopy has been shown to be able to identify overperforming and underperforming SiC-N. Using scanning probe microscopy, the researchers were able to map the conductivity of grain-boundary phases in the ceramic studied. Quantification of the relationships among microstructure, defect type, and distribution of nondestructive characterization data, and ballistic behavior in armor ceramic materials is a laudable goal if used to support lot-acceptance testing for ceramic armor components. This nondestructive testing needs to be closely tied with both traditional ballistic testing and postmortem material damage analysis.

Penetration Mechanics

ARL presented an array of evolving fundamental and applied projects focused on the science of penetration mechanics; the development and implementation of new imaging and velocimetry diagnostics aimed at the quantification of penetration linked to lethality; and a view into the continuum-level models under development for ceramic material response that attempts to bridge the scale from meso to macro.

The utilization of advanced diagnostics to quantify the time-dependent penetration behavior of ceramics is both innovative and crucial to the development of models capturing the physics involved in armor penetration and thereby seminally important to design from the perspectives of both survivability and lethality. ARL's team designed a multiple-head flash x-ray system for real in situ observations of projectile penetration into a ceramic armor surrogate. Rate of observation has been enhanced to obtain better imaging resolution. Because absorption scales with sample thickness, the team has also adapted a novel photon Doppler velocimetry (PDV) technique to track projectile penetration travel into the sample, enabling larger target studies. The x-ray technique was used to determine dwell time during initial penetration and how that can be used to design stacked ceramic armor.

ARL's ceramic material model development work was highlighted in several poster presentations. Innovative mesoscale models from actual material reconstructions are under development to inform macroscale continuum models. Improvements were made in coupling of constitutive models to the host codes to better handle the failure and fracture of materials. In one example, a predictive tool using the Kayenta ceramic model was developed to predict the response surface associated with material shear deformation as a function of load. Results of limited ballistic tests performed to test the model showed good correlation with model predictions. This modeling effort is of a high standard, as demonstrated by the authors' peer-reviewed journal article. In addition, work involving finite-element modeling (FEM) of tungsten carbide (WC) penetration into silicon carbide (SiC) was well integrated with experiments performed at various rates and with increasing complexity that favorably predicted dwell transition and penetration velocities in the high-rate loading regime. Adaptation of the plasticity model (Kayenta), originally developed for geological materials, to model the mechanical response (tensile failure) of WC reflects innovative modeling through incorporation of the material model development into shock physics finite-element analysis. This work is well connected to material modeling work conducted at Sandia National Laboratories and the University of Utah. It is important to step up efforts to demonstrate how this knowledge and these insights will contribute to the design of armors effective in defeating WC projectiles.

Research into the development of depleted uranium alternative projectiles, including in a segmented-rod form, has been an area of focused research at ARL for over a decade, when it became clear that cleanup of depleted uranium after warfare is both hazardous and costly. There has been little choice politically, therefore, but to investigate means to further enhance the ballistic-impact performance of conventional tungsten heavy alloy (WHA). A significant achievement has been the development of a rigid-body penetrator, in which the strong and tough WHA contains one or more embedded inserts of very hard tungsten carbide/cobalt (WC/Co). Extensive impact testing has demonstrated that the location of each insert in a segmented-rod WHA is critical to achieving optimal ballistic performance at oblique angles of attack. The use of aligned short segments minimizes or eliminates the susceptibility of a long rod to the bending stresses experienced following oblique impact. Excellent progress has been made in this challenging area. In particular, the embedded WC/Co insert appears to be a solution to the oblique-angle impact problem. Building on this achievement, there is the prospect of further improvements in ballistic-impact performance via the use of inserts of multimodal-structured WC/Co and diamond-hard-faced WC/Co. Notwithstanding this progress, there are strategic needs for further development in this area, given the evolving stratagems of the Army surrounding future weapons and vehicles; these needs are addressed later in this chapter.

ARL's successful application of new experimental instruments and diagnostics in new size and time-scale regimes—including optical photography, flash x-ray cineradiography, and new imaging techniques from other institutions such as the national laboratories—to the quantification of in situ penetration into armor is exciting, and ARL is to be congratulated for actively pursuing these diagnostics. Collaboration with the national laboratories has included the application of models and codes and the use of experimental facilities and instrumentation techniques, both of which are very positive; the project using Los Alamos National Laboratory's proton radiography facilities and applying Lawrence Livermore National Laboratory's PDV technique are particularly noteworthy. Both efforts appear to be especially successful. The principal opportunity (and challenge to ARL management) is how to effectively expand and accelerate this work.

The focus of the imaging and velocimetry technique development for impact studies is to identify, enhance, evolve, and develop current state-of-the-art diagnostics to increase information gathered about material state, structure, deformation, kinetics, and dynamics during impact and penetration experiments. Specifically, this work is addressing imaging diagnostics that push toward greater spatial and temporal resolution, laser-based interferometry diagnostics that probe interactions at enhanced temporal resolution, and diagnostics that can identify material state in a multiple-material mixed environment. Techniques being addressed include high-speed flash x-ray cineradiography, proton radiography, x-ray phase contrast imaging, and multicolor flash x-ray computed tomography that has the potential to resolve multiple materials in a reconstructed 3D space that is critical to predictive model development. The Army Research Laboratory Technical Assessment Board (ARLTAB) strongly encourages this effort, which is expected to enhance ARL capabilities important to advancing fundamental understanding of impact/penetration phenomena.

Research investigating phase field modeling (PFM) of fracture and twinning in brittle solids addresses an area relevant to the fracture of ceramic armor materials. This is good and interesting fundamental materials work. The motivation behind this research is the observation that polycrystalline armor materials such as ceramics and metals often demonstrate twinning and transgranular fracture at the single-crystal scale. In very high strain rate situations, even brittle materials can undergo plastic deformation, by dislocation motion and deformation twinning as well as fracture. To investigate the competition between twinning and fracture, a PFM has been developed and tested on single-twin and single-fracture events.

For twinning, the free-energy functional includes the elastic field, which changes nontrivially upon twinning, competing with a twin/matrix interfacial free energy. For a single twin forming under an indenter, this model captures both reversible and irreversible twinning. For fracture, the free-energy functional involves a balance between the elastic energy released and the surface formation energy—that is, a Griffith criterion for fracture. Crack initiation and opening were demonstrated in various notched sample configurations. This research is a new application of PFM and offers a promising method for probing shock behavior in complex microstructures. Although the ultimate payoff may be several years in the future, it is an effort worth pursuing. This fundamental research project is building a foundation for future modeling and is considered promising. PFM is a good addition to ARL's suite of computational capabilities.

Composite model development to support ballistics predictive capability is being pursued via numerical models aimed at understanding how the woven portion of the armor package can be optimized to increase penetration resistance. This research specifically addresses implementation of a woven fabric model to simulate the response of soft armor to the impact of a debris cloud generated by buried charge, such as that from an improvised explosive device (IED). Improvements being made to the material model based on experimental work by ARL and its academic partners, introducing stochastic variation in the fibers and reductions in stiffness and strength due to the weaving process, are innovative and worthy of continued investment. Work is needed to effectively apply the experimental results to further refine the model and to verify its validity and value.

Determination of the mechanisms controlling penetration in lightweight materials is key to achieving future lightweight armors for both personnel and vehicle protection. Results presented for aluminum alloy 1100-O showed that for a 30 percent cold-rolling reduction, a dislocation cell structure was observed; for 70 percent reduction, the cell density increased and a laminar microstructure began to emerge; and for 80 percent reduction, a fully developed laminar structure was formed. This correlation enabled the variation of spallation pullback velocity with shock resistance, with peak shock stress to be investigated for each Al alloy microstructure. For the 30 percent reduction, the variation with shock stress was not monotonic, whereas for the microstructures with higher dislocation content, the variation in shock resistance increased or at least did not decrease with increasing shock stress. This work provides a possible window into the effect of microstructure on blast resistance. The interaction with university and international research partners was a strong point. The project demonstrates a solid step toward developing an understanding of the effects of microstructure on Al alloy armor blast resistance using M&S tools. The work reflects good leveraging of interactions outside ARL.

Humans in Extreme Ballistic Environments

The humans in extreme ballistic environments activities appear to be well organized, the technical strategy is well posed, and the current state of science and technology in this area is well defined. The design, modeling, and testing of the warrior injury assessment manikin to test the effects of extreme acceleration and loading effects associated with underbody vehicle blast is an area unique to Army mission challenges and well connected to warfighter needs. This innovative and collaborative effort to collect data required for predicting injuries to support the design and sensor placement on anthropomorphic test devices is to be commended. Ties to the medical communities to map current wartime injuries and subsequently inform vehicle and warfighter equipment to reduce injuries and enhance survivability are excellent. ARL is to be commended on the excellent partnering with university and external experts related to how experiments are conducted and data collected. The program appears to be well run and technically sound, but there appears to be insufficient collaborative activity on the physiological effects of kinetics to inform research on what kinetics can be tolerated—for example, the limits for traumatic brain injury (TBI).

The project on evaluation of the effects of blast and ballistic protection on soldier performance included modifications to two soldier equipment items that improved warfighter protection. These items included a helmet support device (to address the tendency of the head to drop forward under the burden of the helmet and night vision goggles) to maintain the helmet in an optimized position for protection and a mandible guard addition to the helmet. The team demonstrated that the mandible guard interferes with common weapon aiming and firing and thus presents an integration challenge. These investigations included both live soldier tests and laboratory assessments. The live soldier tests were performed on a soldier sitting in a chair and a soldier navigating an Army obstacle course. Both projects represent innovative and timely attention to addressing warfighter needs and are examples of excellent integrated research and technology applied to short-term warfighter needs.

The project on soft protection/continuous fiber woven composites is addressing a critical near-term warfighter need for groin protection that balances protection, comfort, and flexibility. Various available aramid yarns, knits, and felt constructs are being systematically investigated for groin ballistic protection, starting with insights gleaned from the U.K. underwear options already deployed. The scientific and engineering approach to addressing this near-term warfighter need offers very promising options, and exploration of additional fabrics and weave alternatives is encouraged. Teaming with industry appears particularly crucial to this endeavor.

Two projects, one theoretical and one experimental, are addressing head protection through strongly coupled modeling. The integrated approach for improving low-velocity-impact head protection via an ARL-developed FEM for head impacts while wearing a helmet is responsive to a key Army priority; such low-velocity impacts may be a result of falling or of exposure to an explosive event. Present helmet pads are effective for impacts at about 10 fps, but the objective of the ongoing work is to increase impact energy absorption from <10 fps up to tens of fps to 150 *g*. To date, the model has been validated with experimental results in the range 10-14 fps, with interest in extending the validation for <1 to 20 fps. The modeling results presented have indicated pad characteristics that may meet goals, primarily for frangible or frangible elastic materials. Alternatively, an external helmet load-bearing fixture has been conceived. Both novel concepts have been prototyped, and there has been some initial testing. Such out-of-the-box thinking is to be lauded, but it is also reasonable to question whether a helmet is ultimately the correct approach or whether some form of back- or shoulder-mounted head protection device would perhaps be a more effective solution. This project appears to be an excellent example in which the numerical model supports experimental concepts and corresponding experiments verify the model and concept. What makes it a special case is that this work informed out-of-the-box conceptual thinking about external supports for the helmet and even a replacement of the helmet with shoulder- or back-supported head protection. ARL is encouraged to continue pursuing this area of science and engineering.

The work on modeling of the head/helmet system subjected to blast and ballistic loads is leading to the development of a computational framework to define loading response to the head and the interaction with helmets as input to neuro-network analysis. Improvement and further development of the computational effort for both the helmet and the coupling to the head is encouraged. This is in line with the view of the ARL team, which recognizes the limitation of the current model and the importance of exploring new ideas for improvement and linking them to the *g*-force-loading helmet design project.

The use of a torsional Kolsky bar to evaluate high-strain-rate characteristics and quantify the mechanical properties of viscoelastic polymers at very high strain rates has been reported in the scientific literature. This project is in support of quantification of the high-rate mechanical response of human tissues to facilitate the development of constitutive models to describe such tissue subjected to extreme loading. Such polymers could be used as synthetic surrogates for biological tissues and are therefore of interest to experimental and modeling efforts looking at ballistic and blast effects on the body. The experimental measuring techniques are complex, and the Army is on target in attempting to develop this capability. Unfortunately, the Army investigators could not replicate the analysis reported in the literature. The finding, if true, is disappointing and important, because mechanical characterization methods at these strain rates are difficult and few. While it is understandable that alternatives are not readily available, it seems that a more rigorous follow-up is warranted. The Army is one of a very few organizations with a mission need for such data. Without more analysis of the Army modeling efforts and plans, one can discern neither the absolute necessity for such data nor the degree of accuracy required, but it seems certain that competence in this area is vital for the military. ARL is encouraged to continue to explore both experimental techniques/diagnostics and constitutive model development in the area of tissue mechanical behavior.

A finite-element approach was developed to numerically model the forces of a bottom explosion on the warfighter's foot and leg below the knee. The resolution of the computational elements supported modeling of all the bones and the soft tissue. Existing data were consistent with the model, so that both the model and data have been shown to yield a result indicating minimal foot damage for a short impulse of low amplitude and low acceleration but major damage for a much larger amplitude impulse over a longer loading time. The team expects to refine the model and further compare it with experimental data; however, it is nearing sufficient validity to support examination of floor protection concepts that could reduce the impact from under-vehicle blast loading on the soldier. Work to explore extension of the model to evaluate blast effects on the upper leg and torso and potential means for mitigating those effects seems promising. This project presents an excellent example of a combined theoretical and experimental approach to developing a basis for relatively timely and inexpensive engineering trade-offs of concepts to improve vehicle design and safety systems.

The project on methodology for evaluating small-caliber systems involves the application of a previously developed modeling tool to a newer small-caliber weapon. The predictions of the work are comparable to experimental results to the degree necessary for the field. The speed and ease with which this work was completed is ample evidence of the utility of the model for addressing practical military ballistic and warfighter weapon needs. It is, however, difficult to see a clearly defined research component in the current work. Any innovative steps in the construction of the model are years in the past and were not presented. This does not detract from the accomplishments or the successes of this project, but it is not clear what further fundamental development of the model is planned or needed.

The project applying survivability analysis to body armor decisions using the operational-requirements-based casualty assessment (ORCA) code analyzed the torso for vulnerability to frontal ballistic trauma. The analysis was repeated for two body armor configurations. This analysis provided data that could be used to compare the protective benefits of the larger armor against the drawbacks of weight and bulk. A similar analysis was used to compare injury and disability with and without protective undergarments. These data help bolster the case for these safety devices to protect the soldier in the field. It will be important to apply the ORCA code to all classes of warfighter protective equipment deployed in theatre as well as to new equipment being designed and tested, and to clearly link the applications to the effort to validate the ORCA code.

Computational Terminal Ballistics

The lethal mechanisms and the blast and ballistic protection projects provided an interesting and reasonably comprehensive review of the broad scope of ARL work in these areas. ARL has a strong record of achievement over many years in developing advanced capabilities for defeating many types of enemy targets, and the recent and ongoing work described is building upon its tradition of excellence. The ARL effort to examine small combat units and scalable effects in the context of new and effective systems appears particularly well conceived and thoughtfully planned.

The glass research presentation described in depth work being conducted to develop an advanced fundamental understanding of the fracture behavior of glasses during penetration by a shaped charge jet and details of the interactions between the jet and the fragmenting glass. The effectiveness of glass, whether self-confined or mechanically confined by other materials, to resist penetration by shaped-charge jets has long been known and is generally attributed to a dilatancy (bulking) effect, but the excellent experimental and computational work described builds on prior knowledge, particularly work conducted at ARL more than 20 years ago. This project involves a research strategy using highly resolved experimental investigations and high-fidelity computational modeling. The project incorporates state-of-the-art constitutive mechanical models developed at ARL aimed at discovering a mechanism for disruption of shaped-charged jets in glass targets. As such, it is establishing a suite of experimental and computational tools that might be applicable to a variety of extended studies. This is outstanding work exemplifying how experimental study and modeling can effectively use discovery science and research to drive innovation. This research is comparable in technical quality to that of other leading laboratories.

The computational terminal ballistics overview described exciting new work focused on the effects of electromagnetic (EM) fields on the formation and breakup of shaped-charge jets. The phenomenon, initially discovered through computational analyses and subsequently examined computationally in some detail as well, will be better understood through systematic investigation in a series of well-structured experiments. The presentation had two major components: a broad overview of computational ballistics and specific results for computational model employment and development for EM armor applications. ARL has enhanced the ALEGRA multiphysics code from Sandia National Laboratories to incorporate ceramics modeling (Kayenta), extended FEM, Lagrangian material tracking, coupled optimization software (Dakota), and magnetohydrodynamics robustness and new materials.

In the computational modeling effort for EM armor, specific accomplishments included successfully applying the enhanced ALEGRA model to assess the behavior of EM armor, identifying correspondence and important differences with experimental results and developing a prototype design for a compact power source. This project exemplifies how ARL is utilizing and extending the best National Nuclear Security Administration modeling tools to address Army mission projects and deliverables. Coupling of these predictive tools with the combat vehicle vulnerability analysis modeling appears to be an area where a game-changing predictive modeling tool suite could be developed; it could positively impact phenomenological and operational system implementation and performance modeling of the future ground combat vehicle (GCV).

The EM "squish" phenomenon was newly recognized as having potential value in helping to make an advanced capability more effective. The basic physical mechanism is understood, and the Sandia model is used to explore alternative configurations aimed at optimizing the effect. This is the same model, however, used for the jet-induced plasma investigation, which is known to have a discrepancy that may also be relevant to this effect. One expects that the requisite modification of the model mentioned for the jet-induced plasma will also be required to achieve significant further progress in exploring the squish phenomenon.

The project on flow strength of polymers modeling focuses on atomistic modeling to FEM and is an excellent start to interfacing atomistic and continuum models of polymer mechanical behavior. Expansion of this modeling multi-length-scale approach is strongly encouraged as a path forward to address the distinctive behavioral differences at high strain rates exhibited by polymeric materials.

The modeling and simulation of military operations on urban terrain (MOUT) target penetration project has completed some target analysis and quantified the margin of error. In order to match experimental data, researchers had to divide the solution space and solve the equations using two different techniques. That they were able to predict results within 10 percent is considered to be a strong and very promising technical ARL accomplishment.

The project on reduced-order modeling of underbody blast is an in-house effort that developed a simplified modeling approach amenable to rapid determination of blast-loading histories on critical Army targets. Simplified assumptions are made that attempt to represent the essential aspects of impulse loading without resorting to a detailed three-dimensional (3D) computation of the blast response. This modeling is useful for rapid turnaround system evaluations. Linkage of this modeling to a testing program that evaluates the effectiveness of the modeling is clearly necessary to validate the accuracy and to quantify the margin and uncertainty of the model. The project has also determined a set of analytical solutions that could be used for verification of the simplified numerical model and its mathematical implementation. This work represents a step beyond pure empirical modeling that may be appropriate for Monte Carlo or system analysis. The simplifications that are used impose a degree of uncertainty in defining loading histories, however, because impulse is an integrated quantity and the uncertainties may be acceptable for some system evaluations. Key to this effort is determining the limits of the applicability of the simplified model approach.

The jet-induced plasma characterization project clearly represents a discovery science project. It is based on a particular concept that guides the parameters of interest. It includes an experimental investigation to characterize the plasma. A Sandia model was employed by Sandia collaborators to capture the characterization in a model of the plasma jet. This comparison and modeling and experiment resulted in the discovery of an apparent discrepancy. Further experimental measurements have begun to determine the source of the apparent discrepancy. As more data are obtained, Sandia plans to revise the computer code and expects that modification to require significant effort. In the meantime, the experimental results have provided evidence that can advance the concept. While much remains to be done to complete the investigation, the next step would be to explore a practical implementation approach to armor protection.

Demonstration of the utilization of reduced-order modeling of underbody blast for estimating and evaluating lower limb soldier injuries in vehicles subjected to blast loading is both important and timely to inform new vehicle design considerations. The project illustrated completed-scale impulse tests of flat plates and V-hulls to validate underbody models, which were used to support analyses of alternatives for joint light tactical vehicles and to inform design strategies for the GCV. Reduced-fidelity models to support system engineering trades and program planning and execution decisions are an extremely important line of model development.

The project on novel penetrator efficiencies is focused on segmented penetrators. It also involves the development of extending rod penetrators. Segmented penetrators were the topic of intensive study at least 20 years ago, but the largely proof-of-concept effort was of limited success. One of the challenges is defining appropriate and credible baselines for comparison, which are greatly needed. The researchers on this current updated look at segmented penetrators appear to understand the importance of developing credible baselines for comparison. Some results to date with respect to achieving and maintaining desired separation in flight and segment colinearity during penetration are promising. The potential benefits of segmented rods may become increasingly evident as impact velocities extend well beyond the current conventional ordnance velocity regime of ≥1,600 m/s. A particularly interesting means for extending the rod close to the target and locking the segments together has recently been transitioned to the U.S. Army Armament Research, Development and Engineering Center (ARDEC) for possible application in next-generation kinetic energy (KE) and depleted uranium (DU) replacement programs. As noted for segmented penetrators, it is imperative that credible baselines be established for performance comparisons to monolithic, nonextending rods.

In the vehicle protection armor modeling project, the goal is to explore armor concepts using modeling and simulation to gain a fundamental understanding of the mechanisms at work and how ARL can exploit them to defeat current and future threats to Army platforms. Proven modeling and simulation tools can be extremely useful in exploring advanced armor concepts. Such tools have been in a continual state of evolution for many years, with much of the work being conducted at the Department of Energy national laboratories. The overall validity with respect to both large-scale deformations and specific material behaviors, as well as the ability of the models to effectively model target/threat interactions for a range of threat types—KE, shaped charges, explosively formed penetrators (EFP), and blast—is critical. This is important work that will be helpful in guiding ARL armor concept development efforts and setting the stage for follow-on, well-defined, proof-of-concept experiments and subsequent advances. Establishing and maintaining a strong link between this modeling work and system testing as validation is key to the development of effective predictive design capabilities. Implementing existing multiphysics modeling capabilities to simulate explosive armor performance, exploring several design possibilities, and conducting appropriate comparative experiments as a basis for modifying the model parameters represent a promising start to the development of a tool for designing explosive reactive armor.

Development of modeling tools for both metallic armor and 3D hybrid composite protection systems appears to be an outstanding contribution to practical armor system design using advanced strength and damage models for metallics and ceramics and concepts of 3D composite reinforcement. The metallic modeling provides computationally based guidance for alloy development for armor applications. Combining strength and damage models followed by a parameter sensitivity analysis to determine which material parameters are most important for reducing penetrator damage in an aluminum (Al) and a magnesium (Mg) alloy represents a strong systematic approach to providing insight into armor design and performance. This analysis demonstrated that the work-hardening parameters characteristic of these materials are most important for new materials design, with failure strain ranked as next in importance. To implement the architecture suggested by 3D composite modeling, it will be important to strategically address the development of weaving capability within ARL.

Energetics

The advanced energetics program that has been undertaken by ARL is an ambitious effort to achieve the next generation of high-energy energetics, which can lead to greatly improved energy densities and new formulations supporting core Army needs. Energetics in the energy density range above that of conventional explosives is a strong strategic choice central to ARL's mission, and it is an area where relatively modest investment, if continued over a number of years, could make the laboratory a national leader. In terms of staffing and program direction, it is worth exploring the potential for tapping into the knowledge and experience of synthetic chemistry professionals, particularly by hiring from within the pharmaceutical industry. In the area of synthesis there is much to gain from leveraging outside resources, both industry and universities, and working to build ties to them.

The early results from the program are encouraging, and the staff currently in the program are excellent. It is important, however, that ARL expand support for this area through new hires and support for external collaborators. One of the primary goals of the advanced energetics initiative was to attract early-career scientists into this field, and ARL has been successful in hiring new explosive formulation and synthesis expertise into its workforce. In addition, ARL's investment in multiscale modeling of energetics as an enabling technology is impressive, and ARL is certainly among the leaders nationally in this effort, alongside Los Alamos National Laboratory and Sandia National Laboratories. Continued development of these tools and of a coupled theory–experimental–simulation–validation program is important to strengthen and nurture the multiscale energetics modeling efforts.

ARL's energetics team outlined a rational approach to the important problem of identifying candidate molecules for novel energetics. This group has recently been formed, but early progress is promising. Tetranitroglycoluril (TNGU) appears to be a good starting point for a more comprehensive investigation, and this work is encouraged. Explosives based on TNGU and related molecules have demonstrated potential for reducing sensitivity to accidental initiation while maintaining high energy density. In addition, the x-ray analysis of the amorphous polymorph of poly-CO produced in the diamond anvil cell revealed a short range order that was reproduced with a density functional theory (DFT) model. This is a significant step in understanding this elusive material.

New laboratory-scale methods for quantification of the explosive performance using laser-induced shock waves show great promise. The laser-generated shock-wave test to measure explosive performance of milligram quantities of energetic materials has demonstrated good correlation between measured blast wave velocities with conventional large-scale measurements of detonation velocity for a wide range of previously-studied energetic materials. The method has also been utilized for the characterization of new energetic materials available only in milligram quantities, yielding results that are consistent with the expected performance of new, disruptive energetic materials synthesized by ARL. This work has provided ARL, and perhaps other laboratories, with an inexpensive, very-small-sample-size screening test for the experimental energetic materials being developed. Although the scientific basis for it is still being established, this method appears to be a promising tool for the identification and quantification of new energetic materials.

An optical method to monitor the reactions of metals in explosive materials has been developed and demonstrated with a boron/potassium nitrate (B-KNO_3) powder mixture. The two-camera method with wavelength filters was used to monitor boron oxide (BO_2), as well as material incandescence. This has enabled the first visualization of a key B reaction in real time. This work provides a new tool for optimizing metal-energetic material mixtures and can be applied to systems beyond the B-KNO_3 test case. This research is impressive as a scientific study that also has very useful applications to energetic material research; the researcher is an expert in his field.

The modeling efforts across the energetics research area are showing growth and progress. The coarse-grained modeling research aimed at predicting the response of microstructured energetic materials demonstrates the need for this approach based on the large computing time required for a direct atomistic simulation. If successful, this development could reduce computation time by one or two orders of magnitude. The concepts in this research have been developed in the soft matter/polymer communities, and this is the first effort at extending them to hard energetic materials. The basic approach is to idealize the material as a hard sphere that interacts with its neighboring spheres by forces that are derived from an atomistic analysis of the compound in question. The idealization loses information about the interactions, and effects of the lost information are accounted for in the model by introducing random forces between the spheres. A model for chemical reactions, assuming the sphere is a perfectly stirred batch reactor, is also incorporated so that detonation can be modeled. A problem of a planar shock was analyzed using the model with 384,000 spheres and was compared with a full atomic simulation with 8,064,000 atoms; good agreement was found.

The large-scale DFT analysis of nanodiamonds to investigate molecular surface configurations that were then subjected to collision and implosion conditions is interesting research. The numerical modeling for large-scale DFT analysis demonstrated that this is a useful technique and gave encouraging results. Although these extended molecular solid models did not include stored strain energy, future work is being planned to use this modeling approach as a framework for investigating potential energy release mechanisms, and this extension needs to be pursued. Further efforts in the development of physically based energetics models are needed.

The High Performance Computing Institute (HPCI) research, funded by the U.S. Army's ARDEC, represents a new idea in modeling that aims to eliminate the system-specific models used in existing models. The goal is to define a physics-based multiscale model starting at the atomistic level and progressing through a succession of scales to the continuum level. ARL is currently addressing issues from atomistic through mesoscale to meet criteria established by ARDEC. ARL has completed and validated the atomistic model against a finite element simulation. The coarse graining method development needed to reach the mesoscale is in process, but the microscale issues have not been fully solved and need to be further examined.

The optically measured explosive impulse project represents the first nonintrusive, high-resolution optical measurement of the blast wave pressure profiles. The idea is to use a high-speed digital video camera to visualize by Schlieren methods the decay of an explosively generated blast wave. Careful calibration of the Schlieren system and image processing is used to quantitatively interpret the images of the blast wave. This test configuration required compensating for optical system response, the light source intensity distribution, and fabrication of multigram, spherical test charges. The result is a sequence of high-resolution images of the spatial distribution of index of refraction behind the leading shock wave. The index of refraction distributions can be further interpreted to provide pressure-time histories that can be integrated to provide impulse. This technique appears to offer significant advantages over the conventional methods of using an array of piezoelectric pencil gauges, particularly in the near field, where protecting the gauges from vibration and impact is a challenge. The technique is being validated against conventional pencil gauge data, and continued efforts to develop quantitative optical measurements of blast waves are strongly encouraged.

Interior Ballistics

Much progress has been made in ARL's core technologies germane to experimental investigations and modeling of gun interior ballistics. The experimental programs designed to investigate large-caliber gun ammunition (ammo) vulnerability and hot climate ammo responses represent important technological areas for ARL research. In the case of ammo vulnerability, it was determined that direct jet injection was the major factor in the detonation of an ammo compartment. However, penetration of the compartment did not always create catastrophic events, and to date, based on the experimental data collected, an empirical model via curve fit to the data has been constructed. The development of physics-based models aimed at capturing the controlling mechanisms of ammo compartments subjected to off-normal events is crucial to the attainment of a true predictive capability rather than the current curve-fitting approach.

The optical methods of measurement extending from the shock wave impulse to muzzle flash and muzzle blast are intriguing areas of research. The projects in this area represented ingenious use of classical optical methods with modern cameras and imaging processing. The results tie in nicely with other projects on modeling muzzle blast and flash, and they provide experimental data on explosive performance for very small amounts (milligrams) of experimental explosives.

The in-house modeling efforts in the interior ballistics have greatly benefited from the long history of efforts at ARL, which is the leader in interior-ballistics modeling. ARL modeling tools are being effectively used for advancing gun technologies and related efforts. Extension of interior ballistic models to muzzle blast and mechanics of gun barrels/deformable projectiles shows good promise. Predictive model development in this area could be enabling for design innovation that can lead to significant improvement in gun performance and the ability to take advantage of potential improvements in propellant performance that are being pursued in other projects.

Modeling of tank ammo utilizing the German technology of perforated, coated propellant grains that feature temperature compensation to ensure peak pressure within safety limits in hot climates is one example of a promising line of research. The long-standing problem of high ambient temperature (hot climates) resulting in muzzle pressures that are significantly higher and can exceed design limits continues to be a key issue relating to ammo safety. The Germans have developed a perforated propellant grain configuration with each perforation having a specific filling material and heat compensating end-coatings. This is applied to a particular experimental 120 mm round. The results of firing tests showed the desired moderation of peak pressure over a wide range of ambient temperatures. However, the physics of the operative mechanisms within this technology remain poorly understood, and the models are not predictive. A multiphase, multidimensional model is therefore being developed to better understand the physics of this design for ambient temperature insensitivity and to also serve as a basis to explore more affordable alternative grain configurations for this and other types of rounds. The modeling results to date have been experimentally correlated with test data on the behavior of individual grains and with a representative multigrain large-caliber round configuration. This line of research appears both fruitful and central to ARL's mission.

The NGen code has been utilized in conjunction with the Abaqus commercial finite element code to analyze tapered-bore guns. Tapered-bore guns offer the possibility of greater muzzle velocity and compact length with no parasitic mass (no Sabot). A tapered-bore gun consists of a full-bore section and a tapered section. The effects of the length of the full bore and the tapered sections, and the taper angle, need to be assessed and predictive models developed. To explore this, an internal ballistics code, NGen, was coupled with a commercial solid mechanics code, Abaqus, explicitly to analyze projectile deformation. The results demonstrate that this is a way to identify the effect of base pressure and swage pressure on the deformation of the projectile and to determine the muzzle velocity. Modeling the interaction between two complex nonlinear processes poses a significant challenge. Initial results from this first coupling of an internal ballistics code with a structural mechanics code are promising.

Modeling of the complex chemical dynamics operative in solid rocket propellants represents a compelling area of research. A complex model of the chemical kinetics and fluid dynamics of the many reactions that define the explosive reaction of ammonium perchlorate-hydroxyl-terminated polybutadiene (AP-HTPB) has been developed. The model is detailed enough to define conditions under which the explosive reaction can be safely released under pressure as high as 15,000 psi (the current safe limit is 2,000 psi), making an increase of pressure to 5,000 psi attractive. The work is an excellent example of computational chemistry that adds significantly to our understanding of chlorine oxide chemistry and is relevant to other problem areas of halogen-oxygen reactivities. The methods employed are relevant to the understanding of other energetic material combustion kinetics and will aid in the optimization of explosive systems.

Exterior Ballistics

The presentations and posters provided in the area of exterior ballistics were excellent. The work represents solid applied R&D that is thoughtful and innovative. The balanced use of empirical/experimental and analytic/modeling approaches is exemplary. Although there are challenges with validation, most of the posters presented modeling informed by empirical testing and vice versa. Moreover, the staff is diligently applying codes—for example, computational fluid dynamics (CFD)—developed outside ARL rather than incur the expense of internal development.

The work on global positioning system (GPS)-guided munitions, specifically M-code receiver testing, is an area where ARL has established a leadership position. At present, the effort appears focused on testing that uses key expertise at ARL. This activity could inform decisions on which critical 6.1 and 6.2 problems to solve in the future.

The efforts on Tobit Kalman filter and the effects of canard interactions are particularly noteworthy. These efforts represent new techniques for guidance systems that are independent of the GPS challenge problem. This project developed simulation using commercial software (CFD++) of subsonic aerodynamics of a model projectile (unclassified shape) with canards and fins and the computed aerodynamic coefficients and determined classical aerodynamic stability coefficients. It also determined that interaction of the wake of canards with fins destabilizes the original configuration and has proposed changes in the geometry of the canards and fins to eliminate this instability. The project then verified the effect of predictions with numerical simulations and validated the results against wind tunnel testing. This program represents a solid effort in aerodynamic engineering with a payoff for guided projectile design. It is a good opportunity for providing staff with basic research topics in fluid dynamics that can help them build their careers and enhance ARL's foundational research for next-generation ballistic designs and models.

The project on coupled jet interactions for maneuvering flight behavior has developed simulations using commercial software (CFD++) to simulate the coupled aerodynamics of a maneuvering body (supersonic M = 2 finned projectile) with 6 degrees of freedom (DOF) rigid body dynamics. The simulations have incorporated maneuvering accomplished by transient supersonic jet injected transversely to the flow near the front of the projectile. Comparison of the fully coupled simulation with a traditional aerodynamic response coefficient matrix has been used as force and moment inputs to 6 DOF rigid body simulations. These simulations examined interactions of the jet wake (vortex pair) with the fins and predicted steady effects on the aerodynamic coefficients. The effective angle of attack compares reasonably well between the fully coupled and response coefficient computations; significant differences were observed for angular orientation (yaw/pitch angle trajectories) in certain cases. The project has demonstrated that the coupling effect may be important in some parameter ranges. This is a good start on a project in aerodynamic engineering that would have a good payoff for guided projectile design. The success of this project requires validation with careful experiments. Separating fundamental flow physics issues from vehicle design would be another excellent opportunity for providing staff with basic research topics in fluid dynamics that could help them build their career and enhance ARL's foundational research for next-generation ballistic designs and models.

The project on compressive sensing infrared (IR) is exploring the application of compressive sensing encoding to spinning projectiles. There appear to be three motivators: using sensors with a small number of pixel elements (current technology in high-speed IR); compression of information for rapid transmission over a data link; and imaging in a rotating reference frame. The ideas used are an extension of standard compressive sensing methods to a rotating sensor. A concept has been identified and some numerical modeling carried out to examine issues in the proposed encoding scheme associated with various sensor configurations and encoding schemes. This is an exploratory project at an early stage. Compressive sensing is an appropriate research topic, and the methodology is technically sound.

The project enabling vision for projectile-image-based navigation seeks to identify important performance characteristics of an optical seeker on a mortar round against a moving target. Key challenges to the design of such a directed projectile include very high *g* forces on the electronics at firing, the initial field of regard covering the uncertainty ellipse from earlier targeting data, image updates of the designated target as the round rotates, and potential impacts of atmospheric, background, and motion effects on the optical image resolution. Although in the early stages of characterization, progress has been made laying out key operational parameters and performance characterizations.

OPPORTUNITIES AND CHALLENGES

An overarching consideration in assessing specific research activities ongoing at ARL is whether the work can reasonably be expected to solve short-term critical warfighter needs encountered in theatre or is focused on the long term with some potential to contribute significantly to the eventual development of advanced capabilities important to meeting the operational Army's warfighting, peacekeeping, and perhaps other mission needs. If these goals cannot be met, attention can be redirected to other areas.

The opportunities and challenges are presented here in two categories: (1) overarching topics related to ARL's overall science and technology (S&T) enterprise in terminal ballistics and (2) specific opportunities and challenges tied to particular terminal ballistics thrust topics or projects.

Overarching ARL Topics

The materials presented did not always provide details of the programmatic ties and interplay with ARL's integration into the 6.1 (basic research) to 6.7 (operational system development) S&T infrastructures. These details would provide a richer context in which to assess the potential ability of the research to meet current Army needs and support the Army of the future. Further, how ARL is leveraging the Army Research Office's (ARO's) investment to support the near-term and long-term Army strategic vision was not always clear across all the projects presented. Examples of how individual projects fit into Army overall goals and relate to one another and to other ARL projects would facilitate the ARLTAB assessment of the quality of ARL's S&T work. One area the overall strategy does not address is the need to identify core, differentiated capabilities where ARL experiences minimal competition and the ARL capability is excellent. Some of these areas are obvious: for example, energetics and interior, exterior, and terminal ballistics. However, the strategy needs to devote dedicated and concerted efforts to highlighting these capabilities. Although the advance of technology places a premium on selecting new areas in which to develop capabilities and expertise, there is a danger of overlooking the existence of challenging research problems in established areas.

ARL has for a long time been primarily consumed by the needs of the warfighters engaged in ongoing conflict. That meant that most programs and projects were directed at near-term deliverables, usually engineering solutions to battlefield problems. Evaluating the quality of such work is a matter of looking at the technical quality and the compromises necessary to deliver the product in a timely manner. Now ARL has effectively transformed its programs into strategic thrusts that support Department of Defense (DoD) strategic areas. The speed of this transition and the way the new directions were presented and developed are impressive. However, longer-term strategic programs demand a more detailed description of the implementation strategy. ARL is not the only player in these programs, and it is not known where the critical responsibilities lie. During its assessment of ballistics sciences the ARLTAB has had trouble differentiating ARL's real goals from its aspirations. The engineering projects are integrated into larger programs, but the time scales or criticality of the project elements were not clearly elucidated. Even long-term science programs need some reasonable near-term objectives. In the future more attention could be devoted to these issues in the program overviews, where the ARL role and the critical paths could be shown.

Model validation, which requires concurrent research of materials properties and performance, was insufficiently defined and elucidated during the review for the majority of the projects presented. Some excellent examples of validation were shown at some level, such as in the MOUT project, but this was not seen throughout the review. Validation of models remains spotty, and at times just a computer-based visualization of a model was presented with few or no quantitative comparisons to data. Often it seemed that validation was being carried out, but the specifics of the validation approach were not presented. Presentations instead provided qualitative arguments based on visual comparison of model and experimental outputs. This is a prime area in which ARL needs to develop and promulgate general principles for model validation on which all researchers at ARL can draw. There is need for an ARL-wide approach to the utilization of models to conduct sensitivity studies. This is crucial to provide guidance in the design of experimental studies, particularly for the selection of materials and variation of parameters.

Details of complex material and structural models matter, but these, along with the basis for choosing model parameter values, were seldom discussed. When there is considerable simplification of geometry or assumptions about material behavior, it is important to provide data justifying such approximations. The success of a model in reproducing a visual image of the overall phenomenology is not the same as validation. It is important to achieve validation on a project by project basis. Is validation sought for that project's scope of work to determine whether a detailed comparison with quantitative data is warranted, or is validation for this project deemed to be the ability to predict trends in response or performance so as to map out regions that would define and limit experiments?

A rigorous formal internal validation program is needed within ARL to quantify the extent to which the physics within the broad spectrum of ballistics models is being developed to accurately describe the physics operative. Given the importance of such models to develop a predictive design capability in support of current Army programs and future systems, platform, and equipment development, increased emphasis on validation is warranted. In addition to the need for an ARL-wide strategic approach to model validation, methods are needed to quantify the margin of uncertainty (QMU) for these models. For example, it is not clear how the ORCA and MUVES-S2[3] models are validated. During the 2014 review, specific details of the validation methodology remained inconsistent, although more connectivity between theory, experiment, and modeling was shown. Presentations provided insufficient details on how ARL's models are formulated and validated; the sensitivity, if known, to key parameters and variables; and the statistical variations to be expected. Uncertainties need to be consistently presented in the form of error bars, confidence intervals, or similar measures when comparing models and data. There is a need for sensitivity studies to identify key parameters. For example, sensitivity analysis appears to be strongly warranted in the modeling of the tapered barrel research project aimed at exploring the importance of bullet constitutive behavior as it relates to friction.

ARL staff continue to be less visible in professional technical societies and technical conferences than their accomplishments and scientific expertise warrant. The continuing budget restrictions and uncertainties, sequestration cuts, and travel restrictions have negatively affected staff interactions with the outside R&D community, albeit 2014 showed an improvement over 2013 even as it remains significantly below levels that existed prior to implementation of the restricted conference attendance policy. Lack of interactions through conferences and professional associations will continue to have a deleterious effect on collaborative efforts and on maintaining the edge in its areas of expertise. This will continue to negatively affect morale and opportunity cost, and it will pose serious consequences to staffing retention and hiring in the future if the situation is not reversed. In the poster presentations there were examples of technical work that suffers from a lack of external collaboration. Moreover, ARL's strategic focus on innovation through adoption and development of scientific ideas and insights from the scientific community cannot be applied to solve Army problems if their focus is predominantly forced inward. If this situation is sustained, a not-invented-here syndrome will be nearly impossible to avoid in the future, leading to in-house reinvention of wheels that would be better brought in from outside. Continued efforts to push back on this situation is in ARL's and the Army's interests.

ARL's damage and failure modeling across the spectrum of materials of relevance is less technically evolved and therefore less predictive than the strength and equation-of-state modeling capabilities within ARL presented during the review. It is important to increase efforts in this area, given its importance to ballistics science and technology. Physically based damage modeling needs to include the statistical aspects of how and where damage evolution and failure occur in a material. This includes identification and modeling of the damage and failure mechanisms in biological and soft materials that as a newer field represent a challenging scientific problem. It is also important to explore strengthening the staffing and collaboration in this area with external university and national research laboratories and the medical community.

[3] Modular UNIX-based Vulnerability Estimation Suite (MUVES-S2) is a software-based modeling tool.

Materials for Terminal Ballistics

It appears crucial for ARL to develop strategic thinking behind internal investments, program and mission deliverables, and staffing to support the ability of the Army to meet the national security mission needs of the future. This strategic thinking appears particularly poignant as the future GCV design pathways are fixed. For example, while glass, effectively confined, is known to have potential for contributing to the defeat of shaped-charged jets, explosive reactive armor (ERA) and even nonexplosive reactive armor (NERA) have greater potential, and ERA is already being utilized with great effectiveness. Ceramics similarly can be very effective, but only when very effectively confined, which currently makes them too expensive for implementation in vehicle protection applications. The key questions are therefore these: Which of ARL's current areas of S&T are sufficiently mature in the area of materials for terminal ballistics to meet current and projected performance criteria in specific applications? Which have been found, for reasons of performance or cost, not to warrant further continued effort at the expense of new S&T areas? Better characterizing and qualifying the materials ARL receives from various suppliers will help ARL to make engineered systems that deliver the expected performance.

It is important to identify the microstructural features to measure and the property or properties in next-generation aluminum alloy armor that correlate with ballistic performance. It may be strength and (quasi-static) fracture toughness as measured so far, but that remains to be verified. Assessing the ballistic performance of a developed alloy is crucial to determining whether research on the alloy needs to continue.

Mechanical performance of nanocrystalline alloys for shaped-charge liners will certainly be a function of microstructure, which in turn arises from processing. The research would benefit from a grain-scale modeling component, including both microstructural evolution (sintering and grain growth) and mechanical response (ductility). When combined, these models can not only predict resulting structures but also suggest optimized microstructures. This may be a much more efficient approach than iteratively reprocessing to optimize material properties. The Office of Naval Research (ONR) has some interest in these systems. The possibility of partnering with the Navy on this topic is worth investigating. It would be worthwhile to expand the research to include variations in the volume fractions of the constituent phases. Near 50:50 compositions are likely to deliver bicontinuous nanostructured composites, in which the constituent nanophases are interpenetrating in three dimensions. Such composite structures are extraordinarily resistant to grain coarsening at high temperatures, thus opening an opportunity for high-strain-rate superplastic formation, as observed for a tricontinuous oxide ceramic.

The 3D-TTR hybrid composite armor development effort appears to be a structures-by-design development effort rather than a materials-by-design effort, although the research is viewed as having merit. Since this effort has been under way for more than 5 years, however, it is reasonable to ask what significant achievements it has recorded to date. Has clear proof-of-concept been established? This armor system has a very complex structure and geometry that will be extremely time-consuming to model at the level of the fiber or even the yarn. Considerable simplification will be required, and each level of simplification will require validation by some carefully designed experiments. This level of validation has not yet been done and has not even been planned. Without such diligence, the utility of modeling for further refinement of these woven composite systems is compromised.

All composite armor studies utilize existing fiber chemistries and processes, unchanged by the fiber industry for the past several decades. Translating the 3D-TTR effort from structure-by-design to material-by-design will require the incorporation of fiber chemistry and processing expertise, either developed in-house or accessed externally. Given the paucity of new fiber development by fiber manufacturers, next-generation materials will likely need to be developed in-house at ARL.

The deliverables to be gleaned from elucidating the property−performance relationship of armor ceramics were insufficiently defined to show what the prior program accomplished. What results have been obtained that suggests this program will provide results useful to the Army? While one possible use could be to support lot-acceptance testing for ceramic armor components, it seems unlikely that it could replace traditional ballistic testing for this purpose. Ballistic testing remains a key acceptance/rejection basis for ceramic-enhanced small arms protective inserts (ESAPI) used in body armor. The strategic direction of this project needs to be evaluated.

The project on ceramic microstructures for enhanced ballistic protection appeared to be retreading old ground. The work has shown that ceramics with fine grain size and IGFs have better ballistic performances than those with coarser grain sizes and limited or no IGFs. This work would be significantly enhanced by the use of transmission electron microscopy (TEM) to characterize grain boundary structure and chemistries, because the IGFs are believed to be key to intergranular fracture. Grain size and IGF effects on fracture have been extensively studied, and the researchers need to integrate the knowledge amassed in this extensive literature into their analysis. This program covers a large array of materials, ranging from commercial aluminas (why these aluminas were chosen was not clear) to B_6O, AlB_{12}, $AlMgB_{14,}$ and composites. At present there is little fundamental perspective. What is new and promising about this work? Are ARL researchers aware of previous work published in the open literature or in government reports that has been done assessing microstructure vs. ballistic performance?

The goal of the project on advanced materials and processing for soldier protection is to identify the high-rate mechanisms, materials, and architectures and the innovative processes and concepts for enabling quantifiable improvement in key aspects of soldier-borne protection for head and body. The focus on improved composite designs for helmets, which is exploring the effects of existing, commercial polymer yarn constructs for better ballistic protection while using state-of-the-art modeling to identify improved yarn ply orientation patterns, is very positive and forward thinking. While integration of this modeling with other types of body armor or lightweight vehicle armor was not discussed, it needs to be strongly encouraged even if the current goal of defeating of a 7.62-mm small arms threat represents a perhaps insurmountable objective in a helmet of a tolerable weight, although if this engenders outside-the-box thinking it may be a boon to future research. In the advanced materials and processing for soldier protection project, the focus was on a ballistic helmet capable of defeating theater-relevant small arms threats, new insight and approaches to mitigating the shock and adverse impulses associated with impact, and an ESAPI system solution capable of meeting the objective threats at a 10 percent lighter areal density. The goal of achieving a ballistic helmet capable of defeating 7.62-mm small arms threats, which is very likely achievable only at a total helmet weight that is intolerable to a user, poses a virtually insurmountable challenge. A 10 percent reduction in areal density for ESAPI body armor is a realistic goal, but the strategic planning needed to achieve this goal was not described in detail. The Defense Advanced Research Projects Agency (DARPA) spent many millions of dollars trying to reduce body armor weight to circa 3.5 lb/ft^2 goal a decade or so ago, and minimal reductions were achieved. The objectives of this project need to be evaluated on a continuing basis.

Penetration Mechanics

ARL's penetration mechanics program is an ambitious effort aimed at merging state-of-the-art modeling with new experimental diagnostics. This is a great challenge that could advance the science of penetration mechanics. Predictive capability, however, will only be achieved if bridging the scales from a modeling perspective is strongly pursued, coupled with a strong program in material damage evolution and failure modeling.

The time-dependent penetration behavior of a ceramics project described application of a flash x-ray and PDV to reverse ballistic testing of metallic penetrators into subscale ceramic targets; this effort represents a positive application of evolving diagnostics to Army problems. PDV appears to be a useful new tool for large-sample studies able to track particle velocities over longer time intervals than velocity interferometer system for any reflector. This body of work provides real-time data that are critically needed for model development and, thereafter, verification and validation. Although the x-ray technique has been used for years, its use in materials studies remains critical. The PDV work appears to be a key new tool in future ballistic testing, but only if tied to quantitative analysis of the deformation and fracture mechanisms during terminal ballistic experiments and then as input to improving computational models applicable to lethality and protection technologies. Dwell was first recognized as a notable consideration in the performance of hard-faced armors at Lawrence Livermore National Laboratory (LLNL) in the late 1960s. ARL initiated work focused on dwell many years ago. A critical question is: What has dwell-centric research to date achieved toward the development of superior ceramic armor materials? A portion of ARL's research in this topical area could not be briefed to the panel except at a baseline level due to classification restrictions. This suggests opening discussions with the National Research Council (NRC) to arrange for a focused classified technical assessment of the science within this topical area.

The development of models for ceramic materials is an activity of critical importance at ARL if it can lead to the creation of a predictive capability for the application of ceramics and other materials in Army armor and lethality systems. Much work has been carried out by a number of organizations over many years, including focused work supported by DARPA, that have not achieved the goal stated for the modest ARL effort. ARL claims that improvements have been made in the coupling of constitutive models to the host codes in order to better handle the failure and fracture of materials. What advances with respect to predictive capability have been achieved? ARL also claims that a variety of simplified ballistic experiments that examine the time-dependent failure of materials have been conducted to validate the improved material models and codes. What have these experiments shown? No details that would elucidate these questions were presented, and perhaps, as mentioned above, this suggests establishment of a focused effort to provide a scientific assessment of this research area in a classified venue.

Research in DU alternative projectiles is a project crying out for strategic planning and context definition for future Army needs and ties to Army strategic planning for new vehicle designs. The presenter stated that significant progress continues in developing nanocrystalline W-based composites as replacements for DU materials. However, few specific accomplishments were cited, perhaps because classification restrictions limited the briefings. Nevertheless, research to develop non-DU projectile materials having at least comparable performance has been under way for more than three decades. Other ARL work included in the DU-replacement effort that is directed toward improving the performance of (sheathed) WC-based projectiles against oblique targets may be of some value. The researchers need to consider the applicability of diamond-hard-faced WC/Co alloys as inserts in segmented WHAs. These materials have been under continuous development for decades, and today they are the materials of choice for drill bits in the oil- and gas-exploration industries. They are available commercially in disc-shaped forms for drag bits and as profiled inserts for roller-cone bits. The diamond-hard facing is actually bonded with Co, as is the underlying compositionally graded WC/Co, thus imparting fracture toughness (bend strength) to the graded composite material. Another option is a multimodal-structured WC/Co, which can be fabricated by the liquid-phase sintering of mixed powder compacts, even though the Co content is <2.0 wt-%; normally, at least 10 wt-% Co is required to ensure complete densification, which incurs a weight penalty. A denser WC/Co insert that is harder and tougher would be advantageous.

For KE penetrator applications, presenters did not explain what they have gained by recently focusing on nanocrysalline materials. The researchers noted in this briefing that the engineering properties of these new materials remain quite poor. They exhibit minimal ductility and toughness and resist efforts to integrate them into KE projectiles. It may be that this challenge cannot be surmounted. Work with sheathed penetrators was also mentioned. This area was also explored extensively at least as far back as the early 1980s. The presenters did not evince much awareness of prior work in this research area or of lessons learned pertinent to the present effort, albeit again the technical content of the ARL presentation may have been restricted because of classification issues, suggesting the need for additional assessment at the appropriate classification level.

Phase field modeling (PFM) of fracture and twinning in brittle solids is tied to the observations that polycrystalline armor materials such as ceramics and metals often demonstrate twinning and transgranular fracture at the single-crystal scale. In this work, phase field theory and numerical simulation are used to model these phenomena, which could provide a payoff for the Army in the long run. This project would benefit from interaction with ab initio or empirical atomistic modeling as well as experimental work; it could supply data for input (surface energies, for example) as well as information for validation (twin size, nucleation mechanisms). This work would benefit from integration with the academic PFM community. Collaboration and insights into the state of the art currently available in this area is yet another casualty of the ill-advised government policy that restricts conference travel. In PFM, interfaces are diffuse, which may affect fracture propagation (by smearing the crack tip discontinuity). The effect of the diffuse interface on fracture predictions merits attention. The extent to which this work might ultimately benefit the ARL mission needs to be articulated.

Assessment of the quality of the composite model project and its ties to strategic Army objectives is difficult because the work is at such an early stage. The goal of creating a method for evaluation of optimal, feasible, and cost-effective fabrics is appropriate. The stated steps to improve and validate the model are essential but have not yet been taken. Examination of the composite model development to date leads to several strategic investment questions: Will the model represent knitted materials as well as woven? Will it be possible to validate this model for nonrepeatable experiments or experiments with a large QMU? Will the model be able to effectively represent laminates of materials?

Researchers on the project on tailored mechanisms for light armor ballistics articulated their goal: to develop a fundamental understanding of the deformation mechanisms and failure processes active under shock loading conditions for light armor materials such as aluminum and magnesium and then, using key discoveries, to control ballistic performance. Dynamic fracture testing, using plate impact assemblies, was conducted on as-received 1100-O aluminum cold-rolled to 30, 70, and 80 percent reduction to study the effects of microstructural evolution on spallation response. While an understanding of the relationship between processing and the microstructure and blast resistance of aluminum alloys is interesting as physical metallurgy, how it could lead to improved armor was not spelled out. Further, the real purpose of this work—in other words, its value to the Army—is unclear. After decades of working with metals such as aluminum for armor applications, the M134, the Sheridan tank, and the Bradley fighting vehicle and of seeing their vulnerabilities to mines, rocket-propelled grenades, KE threats, and IEDs, it seems appropriate that ARL is finally looking to develop a fundamental understanding.

Humans in Extreme Ballistic Environments

The strategic, integrated system approaches to both the warrior injury assessment manikin (WIA-Man) and humans in extreme ballistic environments seem headed toward significant near-term improvements in soldier protection. The fundamental underlying research was not described in detail, so it is not clear whether a breakthrough in the understanding—for example, of the cause(s) in traumatic brain injury—might lead to further breakthroughs in armor protection. Linkages to more modeling and simulation are encouraged as a way to facilitate more predictive performance capability development. Data on physical differences between male and female skeleton and body structure are now required to complete a female war fighter manikin development program.

The project on evaluation of the effects of blast and soldier protection measures on soldier performance faces several challenges. The research was not connected to research at other institutions (e.g., aviator helmet research across the DoD or to sports helmet research elsewhere) to foster the best innovation. The metrics for physical performance were insufficiently defined, and no quantitative results were presented. There was no sign of substantive interactions with other institutions performing human performance modeling, testing, and simulation. Overall, what was presented was a series of demonstrations rather than a description of basic scientific research or engineering development. This line of investigation is important, and if the quantitative rigor of the work can be enhanced, there is great potential for it to make a significant contribution to the field and to the engineering of soldier equipment.

The soft protection continuous-fiber woven composites project is strongly tied to yarn and fabric mechanics expertise, which is not available in-house but could be brought in through consultants. It was unclear how much deformation of the fabrics studied would be equivalent to fabric penetration; this information is important for model validation. Understanding of the complex parameters that lead to fabric comfort is also expertise that does not exist in-house but could be accessed by engaging consultants. A question arises: Would it be worthwhile for ARL to consider developing a broader in-house manufacturing capability to support related projects and equipment development in the future?

The project on an integrated approach for improving head protection against low-velocity impacts is focused on the need for energy dissipation over a broad range of low-velocity head impacts. It resulted in the helmet pad investigation; it has also led to a novel shoulder-supported fixture and has called into question whether in the long term a helmet is the optimal solution for warfighters. This opens the door to new ideas for devices supported not only by the neck but also by or only by the shoulders or back (a space helmet) of the warfighter. Such approaches might help solve the low-velocity problem, might provide support for the increased helmet weight necessitated by cameras and electronics, could provide a basis for increased ballistic protection, and could support more electronic functionality. Continued research in this area is encouraged. Linkages between this project and the modeling effort addressing the head/helmet system subjected to blast and ballistic loads are suggested as a positive avenue for research. Assessing the validity of neuronetwork analysis is so challenging that it is not likely to produce short-term applications.

The project on applying survivability analysis to body armor decisions appears to be simply using an existing tool for design analysis. The model did not produce quantitative data that were not self-evident. Being shot in the torso (or femoral artery) is bad, and the closer to the heart and lungs, the worse is the effect. Smaller armor protects less of the torso. Wearing protective shorts prevents groin area injuries more effectively than not wearing them. The case for applying computational models (instead of mere design rules) to these problems needs to be made much more strongly. ORCA does not appear to include modeling of armor and its effects; to simulate armor, the projectile velocity is simply attenuated based on data from experiments or other models. Coupling ORCA to ballistics models would extend its utility as a design tool. Integrating ORCA with some of the more physical models being developed in the WIAMan project appears to be a fruitful avenue of research.

Computational Terminal Ballistics

The computational terminal ballistics presentation could have been made more effective by systematically addressing the modeling of KE penetrators, shaped-charge warheads, and EFPs in sequence—

specifically, stressing the differences in their lethal penetration mechanisms and clarifying why each type of penetrator is effective against a particular target. This would have effectively set the stage for the blast and ballistic protection overview that followed the presentation. The fact that the ARL ballistics modeling uses approximately 87 percent of Army's high-performance computing (HPC) resources and approximately 65 percent of DoD resources overall is a serious challenge for future computational modeling. Although a plot of HPC resource growth was displayed, there was no analysis to show that the future computing capabilities would be adequate for ARL needs much less new HPC needs that might emerge across the DoD enterprise.

For the project on vulnerability analysis of GCVs, more information on consideration of operational systems would have been helpful. Throughout many of the terminal ballistics briefings and posters, reducing the weight of combat vehicles through lighter armor and faster and more effective lower-caliber munitions was central to ARL's strategic vision. However, it appeared there is no clear set of objectives associated with the operational concept options, just an interest in providing options for performance versus size and weight to the requirements community. It seems that a common vision for cost and weight reduction, while at least maintaining capability, would have provided a useful context for assessing this work.

The jet-induced plasma characterization effort is simultaneously a high-risk and potentially high-payoff project. The physical characterization is still under way, so the potential payoff is a long way off. Even if successful and able to move to a higher level of technology readiness, the concept would necessarily be only one element of a layered capability. The project is an ongoing collaboration between ARL and Sandia. The results of experiments show promise, but the phenomena have not yet been fully characterized, and continued modeling and validation are strongly encouraged.

If the EM squish phenomenon turns out to be promising, and if follow-on exploration with a laboratory prototype shows the approach could be feasible, this approach could enhance other experimental efforts. The effort is presently a numerical investigation using a model shown in another project to be lacking in a key area of physical characterization. Until that model is corrected and there is an understanding of the impact of the correction on the model's accuracy, this phenomenon needs to also be investigated experimentally. Even then, for the amount of additional equipment required, the improvement in advanced capability may not be as significant as predicted by the original concepts.

The project on flow strength of polymers, covering the length scales from atomistic through continuum, would benefit from collaboration with the existing polymer rheology and molecular modeling communities. The results need to be applied to anisotropic systems and other chemistries. Validation of the model against experimental data is crucial.

Both of the projects on reduced-order underbody blast modeling contained many simplifications in the modeling. Further development may be necessary to expand the range of applicability for the modeling approach. There was no clear indication of specific progress on these projects since a review conducted by the ARLTAB in May 2012. Plans for model validation were not discussed, and plans for future accreditation by the U.S. Army Test and Evaluation Command were not satisfactorily explained.

The LF2XA explosive model parameterization approach is appropriate for ideal explosives; however, this explosive is likely a nonideal energetic material. Hence the variable reactive burn modeling needs to be regarded with skepticism. The calibration of this model was done using highly resolved CTH Eulerian computations.[4] However, the re-parameterization of the model in ALEGRA to replicate the CTH results may be the result of insufficient numerical resolution. Further verification of the modeling is required.

[4] CTH is a multimaterial, Eulerian, large deformation, strong shock wave, solid mechanics code developed at Sandia National Laboratories.

Model calibration is linked to sustained planar shock experiments, and the applications to other shock loading conditions—that is, thin pulse or nonplanar projectile loading—may be far enough removed from the conditions of the model calibration. This work follows a traditional approach in computation of shock-initiated reactive flow. Although there are recognized weaknesses in this approach, it may be sufficient for many studies.

The researchers working on novel penetrator efficiencies who look at segmented penetrators appear to understand the importance of developing credible baselines for comparison, and some results to date are promising with respect to achieving and maintaining desired separation in flight and segment colinearity during penetration. The potential benefits of segmented rods may become increasingly evident as impact velocities extend well beyond the current conventional ordnance velocity regime of ≤1,600 m/s. The work on extending the rod penetrator is also interesting, reflecting progress since earlier investigations of its potential. A particularly interesting means for extending the rod close to the target and locking the segments together has recently been transitioned to ARDEC for possible application in next-generation KE and DU replacement programs. As noted for segmented penetrators, it is imperative that credible baselines be established to allow comparing performance to that of monolithic, nonextending rods, and validation to experiments is crucial. Strategic planning of S&T to support future Army needs for advanced KE is also crucial.

The armor modeling efforts described are important work and clearly will be helpful in guiding the development of ARL armor concepts while setting the stage for follow-on, well-defined, proof-of-concept experiments and subsequent advances. Finding measurable performance parameters so that the model predictions and experiments can be quantitatively compared is very important. Quantitative validation of the modeling, or at least of its ability to qualitatively predict changes in penetration resistance with changes in design parameter, is also seminal to this effort. Use of the results of the modeling to develop simpler, much less computationally intensive, predictions of penetration resistance that can be used for vehicle-level assessments appears to be an important avenue of pursuit.

Researchers on the project on armor material modeling and optimization stated that their goal was to determine which material properties have the most influence on the ballistic performance of lightweight military specification metals; they noted that the goal will be realized by taking a design-of-experiments approach to modeling and simulation. Overall, the optimization effort seems sound, but to have an impact it will be important to translate the findings to the materials community for implementation.

Energetics

Striking the right balance when considering disruptive energetics is important. The advertised orders of magnitude gain in performance (in terms of energy release per unit mass) potential seems challenging; enhancing energy densities by 30 to 100 percent within a 5- to 10-year time frame seems ambitious. Since there has been relatively little gain in energy density since CL-20[5] was discovered nearly 30 years ago, it appears to be a formidable task to surpass these energy densities in a relatively short time. Perhaps aiming for gains of a few percent would be more realistic. Nonetheless, thinking outside the box is needed to advance this field. On the other hand, gains of up to 50 percent are plausible with a long-term, focused effort supported by sustained additions in staffing and further investments in infrastructure. Caution needs to be applied to avoid overselling this program and raising expectations too high. Increases of only 10-15 percent in density with CHNO explosives or propellants would represent a major improvement with significant implications for combat systems.

[5] CL-20 is a nitroamine explosive.

Extended solids, of which poly CO is but one example, are intriguing materials that could provide the basis for an entirely new and more powerful class of energetic materials. Little is known, however, about many of the properties that will determine their practicality let alone the methods for large-scale production. In addition, the current emphasis on poly-CO seems excessive compared to that warranted by other efforts, such as investing in scale-up versus discovery targeted at more practical systems or theoretical efforts aimed at establishing more useful bounds on possible energy. This is high-risk, high-payoff research that belongs in the portfolio with more moderate risk approaches. Given the difficulties of scaling up high-pressure synthesis, it would be prudent to aggressively pursue alternative synthetic routes such as plasma discharge or laser shock. If one of these should be successful it would have a tremendous impact on all phases of the work. The list of unknowns in this area is formidable; not least is the understanding of how to release the energy inherent in the material within the desired time scale. There are many problems associated with formulating a practical product, and the fundamentals of doing so are largely unknown. The modeling is too premature to assess whether sufficient energy can be obtained from the release of strain energy. ARL staff members are well aware of these issues and appear capable of addressing them. However, a more balanced strategy developed jointly by staff and ARL management would be highly warranted.

It remains a challenge to prove that a substantial gain in energy release can be realized with many of the new materials under investigation. This is particularly the case for nanodiamond energy. Considering the nanodiamond data to date, there appears to be little evidence from the modeling that these materials release substantial strain energy. The kinetic barriers to formation are unknown and difficult to assess. Optical access to the larger volume cell is difficult, which means that there is no way to measure the progress of the reaction, while larger diamonds that would allow in situ measurements are prohibitively expensive. Data mining of the numerical simulations needs to be done to assess the potential for energy release. In addition to releasing energy, an advanced energetic concept such as nanodiamonds must also release a copious quantity of gas to be useful as a propellant or warhead component. It is unclear whether this material will truly represent a viable energetic material as traditionally used in a fragmenting warhead or as a propellant additive. At this point, it appears uncertain whether this is a reasonable route for an enhanced energetic.

Similar approaches are being initially applied to explore the performance improvement of non-hydrogenic boron. Designing the spherical samples with sufficient materials for uniform ignition remains problematic. A more sensitive, higher speed camera is on order to increase data rate and measurement space; the spherical samples and the camera both appear to be critical for this effort. The spectroscopic and photographic approaches of other work, reported during the poster session, can provide complementary data. The spectroscopy can be performed in parallel with the optical Schleiren approach. Leveraging all of these techniques consistently across all the energetic development efforts within ARL would provide a basis for cross comparison to support value and performance assessments.

The orthoamides present a particularly challenging target class of molecules. There are very few synthetic approaches in the literature, and few other groups are working on them. Consequently, complete success is not assured, but the risk is moderated by the fact that any knowledge generated will be of lasting value to the field and the potential payoff could be substantial. ARL needs to take a leadership role in this area. The fact that others are not working in this area makes it even more important for ARL to maintain this effort because of its fundamental importance to the ARL mission. Even though early results are encouraging and the investigators seem very capable, it is difficult to speed up progress. Progress on this research topic will probably be limited by the small pool of trained and creative chemists working in ARL on this material. Beyond the obvious means of adding staff, ways need to be found to enlarge the community engaged in related research. Perhaps support for students or postdoctoral researchers in academia could be targeted to this area. More attention to this work at the appropriate conferences could also help to increase the number of collaborators.

The coarse-grained modeling effort needs to be extended in several ways to be more realistic. For example, directionality (i.e., anisotropy) and nonuniformity of the material needs to be accounted for. A method of incorporating defects would be a crucially important addition. Defects appear paramount to understanding and modeling the nanodiamond and tetranitroglycoluril (TNGU) materials. In coupling reduced-scale modeling to the continuum scale, the link from the mesoscale to the statistical scale has not been included. This is the scale where effects like defects and localization predominate. For example, energy localization to form hot spots is due to interactions of internal boundaries, and these are extreme states in statistical representations. Capturing these effects is critical to understanding reactive behavior. Coarse-grain modeling with the inputs of information from the smaller scales (i.e., atomistics) does not provide the complete link to traditional continuum models. More thought and development at this level needs to be done. The ultimate aim is to incorporate information from a coarse-grain model into a continuum-scale model for analyzing a wide range of geometries and loading conditions. This is a major challenge.

It will be important to identify at what stage and for what range of conditions comparison with experiment rather than with another numerical model needs to be carried out. In doing this validation, a quantitative comparison is needed under conditions that test the predictability of the model. It would be useful to identify specific milestones and an estimate of when this might be achieved in order to be able to assess progress toward the overall goal. From the standpoint of HPCI, challenges exist in adding back effects lost when moving through the coarse-grain scale.

Interior Ballistics

The physics in interior ballistics is complex and can appear daunting; substantial work has been done in this area, but further study of certain crucial areas is critical to developing new predictive capabilities or enhancing current ones. One example is the modeling of the fracture and the localized effects of contact with propellant grains; another example is the need for mesh adaptivity as interior ballistic models are being used to treat more complex propellant geometries and extended to muzzle blast prediction. Tools for adaptive mesh refinement exist in the open literature that could be readily included in this modeling effort. Although several applications of the interior ballistic modeling were shown, comparisons against experimental data tended to be qualitative rather than quantitative. There is a need for quantitative validation and a systematic treatment of uncertainty rather than simply comparing observational data with simulation results. Based on the past and present activities at ARL, there appears to be sufficient experimental data for model validation in the interior ballistics area, and systematic quantitative comparisons with the database are strongly encouraged.

In the area of large-caliber tank propellant, further work to complete the validation could provide a basis for developing designs that are less expensive than the German grain design (e.g., via 3D printing) and that are scalable to other caliber weapons. To some extent, experimental validation is expected to be based on developmental optical and spectroscopic test methods. These much-needed methods are also under development. Continued progress is expected, but it is not clear when the research can move to the exploration of alternative concepts. Another researcher is expected to join this research area soon. It may be desirable to further increase available resources based on the potential for substantial savings in production costs and performance improvements over a wide range of ambient temperatures for a variety of round types.

The experimental programs on small-caliber green primers and ammunition compartment vulnerability both appear to warrant increased emphasis. The green primer project is small and entirely customer-funded. Customers are unlikely to fund continued data collection, especially once their primers are seen to be noncompetitive. This is an excellent beginning of a potentially valuable effort that could be continued at low cost. The work is efficient and effective. This project seems to be managed by very competent and well-focused researchers given the constrained tasking for the project. The effort is unique and seems deserving of more freedom of scope to capitalize on the current investment. The ammunition compartment vulnerability effect is crucial to warfighter survivability and requires significant effort if predictive capability and not just curve-fitting is to be achieved. The effects of spall fragment interactions and subsequent venting configurations need to be quantitatively characterized for inclusion in the model. If the model is to be utilized for the long term and achieve predictive capability, the project will need to re-verify the assumptions when new materials are stowed within the compartment and the exact geometries of the loading are quantified. The effect on the ammo compartment of vehicle under-body blast also needs to be considered in detail. The research seems appropriate and critical to warfighter safety, but if no parameters are provided as to how accurate the model is expected to be or the end goals of the effort identified, it seems unlikely that true progress will be achieved.

In the area of advanced kinetic round modeling, important challenges involve understanding the effects of projectile shape change and incorporating a material model that can accurately simulate shape changes in the circumstances encountered, which include high pressure, large deformations, and temperature generation due to plastic dissipation. One important task is to provide a quantitative comparison with experimental results to validate the model predictions. Another is to understand the sensitivity of the predictions to material parameters and the characterization of friction between the bore and the projectile so that the minimum data needed for predictive simulations can be identified. In particular, sensitivity studies need to be conducted to determine which performance features are sensitive to material and friction properties (and in what range) and which are not. Further down the line, barrel wear and possible projectile failure (fracture and large localized deformations that adversely affect projectile performance) also need to be considered.

Exterior Ballistics

The flight sciences and the guidance, navigation, and control (GN&C) overview presentation did not communicate the motivation for the subsequent posters clearly enough to place all the exterior ballistics research in context and define the interconnections. Moreover, the low-cost thrust is not a readily credible motivator of research. It would be more accurate to describe this as research into guided munitions with relaxed component performance and tolerances. If the problem were simply a matter of introducing less costly components, the production contractor would as a matter of course pursue this approach to increase its profit margin on fixed-price production contracts. In addition, the GN&C techniques presented in the overview were not placed in context of the intended long-term objectives or ARL strategy. There are new methods and old methods and different scopes of applicability—what works in a surface-to-air missile may be inappropriate in a gun-launched round. Presumably, ARL's GN&C scope includes all Army air and ground vehicles. Should the munitions GN&C efforts dominate ARL research because the WMRD is focused on ballistics?

A number of the junior staff presenting in the exterior ballistics poster session would be well served by participating in a mechanism whereby they can learn of past R&D in missiles and munitions guidance and flight dynamics. Two potential approaches include mentoring by senior staff and regular peer review sessions with other researchers from across the U.S. Army Research, Development and Engineering Command (RDECOM) at both the senior and entry levels. Examples include exposure to DARPA's and other DoD laboratories' automatic target recognition research, which has been under way for over two decades, and GN&C approaches in currently deployed (and in some case retired; e.g., Pershing II guidance) missiles and munitions.

The image-based exterior ballistics projects are aimed at characterizing a system concept for a mortar round with an optical sensor to home on and intercept a moving land vehicle. This is a problem that ARL is uniquely qualified to explore. There is little previous work on missile targeting and guidance for this short-range, short-time engagement with such a low-cost round. The initial characterization is self-consistent in defining and circumscribing the system concept to meet the challenge. This includes defining the seeker field of regard, which covers the evolving ambiguity ellipse from the time of receipt of the (moving) target coordinates to when the seeker begins to look; the requisite optical resolution for target recognition; and the effects of atmospheric flow, turbulence, and vibrations on image quality. The next research steps identified by ARL include exploration of effects and requisite technologies in more detail. Using imaging to guide rotating projectiles is a component of the ARL long-term strategy of placing GN&C in all projectiles and represents an opportunity to extend GN&C to a large number of projectiles. Some of the challenges are to make imaging sufficiently robust for the projectile launch environment, useful for a wide range of targets, and to lower its cost. There is opportunity to develop optical sensing techniques that would enable guidance on spin-stabilized projectiles—a large subset of ARL munitions. It is unclear what role this effort will play in the overall strategy of developing GN&C solutions for current and future Army munitions.

However, a more detailed understanding of the operational environment (e.g., variety of targets, expected countermeasures, and the red force/blue force mix) could better inform which technical risks should become GN&C research priorities and which risks are likely to be resolved with present technologies. For example, if both red and blue tanks are in proximity, as seems to be the example target set of the poster presentation, differences in configuration and atmospheric degradation may imply a significantly higher sensor resolution than determined in the initial analysis. Overall, this is an excellent area to explore as the Army moves beyond the recent land wars, and the work is of very high quality. It would be helpful for management to be more explicit about its vision of the battlefield of the future to better focus follow-on research priorities.

As for the development of advanced aerodynamic performance control algorithms, the basic flow physics of canard wake–vehicle interaction remains to be elucidated. The challenge is to have a fundamental focus when examining generic issues of how the wake interacts with the boundary layer on the body or fin to change the pressure distribution as well as cause flow separation. Upcoming experiments planned in the water tunnel could be used to gain an in depth understanding of this. Quantitative data are needed to validate numerical simulations beyond looking at spin-up rate. There are substantial opportunities for interactions with the subsonic aerodynamics community, both commercial and academic, to leverage past work on guided missiles and launch vehicles.

Further, interaction of the jet wake with fins and body is crucial to understanding how a jet influences aerodynamic forces beyond simple force balance due to the jet's momentum. A key open issue in predicting flight dynamics is the adequacy of a quasi-steady model based on traditional aerodynamic coefficients vis-à-vis a model that treats flow as fundamentally unsteady. Including fundamental unsteady effects will be important for high-speed maneuvers and jet durations shorter than the time scales needed to set up steady flow over the body. There are important issues for designing GN&C algorithms that rely on physics modeling of aerodynamics. A key challenge lies in assuring the reliability of unsteady CFD modeling of 3D flow over a very large range of length scales, particularly for the near-body and fin region with interaction of jet wake with boundary layers. Planned activities in validation will be essential to ARL's success in this area. Opportunity exists for contributing to the fundamental understanding of jet wake–boundary layer interaction flow physics. The challenge is to have a fundamental focus in examining the generic issues of how the wake interacts with the boundary layer on the body or fin to change the pressure distribution as well as to cause flow separation. If it is essential to understand extreme unsteadiness, then experiments that require significant investment will need to be carried out to time resolve these details. It is essential to partner as soon as possible with other organizations that have technical resources, including high-speed flow facilities, advanced diagnostics like 3D digital particle image velocimetry (DPIV) and surface pressure measurements with pressure-sensitive paint.

OVERALL TECHNICAL QUALITY OF THE WORK

Within the DoD and in the area of ballistic science and technology ARL has an unequaled record of achievement and timely support of the warfighter through its sustained development of advanced capabilities for defeating many types of enemy targets and platforms, and its development of increasingly lethal munitions to place adversary personnel and assets at risk while satisfying the spectrum of national security missions engaged in by the Army. ARL's efforts in ballistic science address both fundamental understandings and urgent warfighter needs of great importance to national security. ARL's personnel, facilities, and programs are the clear go-to place for the DoD and the entire defense agency enterprise in the area of ballistic science and engineering. As such, ARL is central to the national defense and needs to be supported by government at all levels.

The overall quality of ARL's applied research and development is very high. There is, as ARL management realizes, a need to focus more on the basic research that will underpin future developments, particularly now that the Army may soon no longer be fighting two wars. The time is ripe, say ARL's managers, for ARL and the Army to place emphasis on thinking strategically about what the Army wants and needs to be able to do 5 to 30 years from now. This is a good time to work on future groundbreaking advances and to emphasize incorporating progressive 6.1 research into the overall research portfolio. A plan for transitioning from 6.1 to 6.2 to 6.3 research needs to be clearly articulated and disseminated. Given the constraints on funding, a hierarchy of research priorities needs to be defined relative to the overall strategy. Projects need to be terminated when they no longer show promise or no longer play a significant role in the overall strategy.

ARL's existing S&T work in energetics and ballistics is very well served by the current Aberdeen Proving Grounds infrastructure and facilities. There was clear evidence of speedy responses to changing needs to support the warfighter with innovations in ballistic survivability and lethality. ARL's experimental program concerning threats is quite detailed and demonstrates commendable knowledge of how these threats are evolving. The spectrum of armor design demonstrated a broad array of technical approaches and flexible and rapid response. ARL's staff are clearly motivated and competent, and all the staff members articulated a well-defined line-of-sight from their research to the mission of the ARL and to the warfighter. All the briefings and posters were well presented by the researchers. For the majority of posters, the work was state-of-the-art and was properly juxtaposed with research at other institutions. As one example, this aspect of the project on multiscale modeling of noncrystalline ceramics (glass) was impressive: the team is drawing on new results in nanotechnology, applying experimental equipment from geophysicists, and interacting with glass manufacturing R&D teams such as Corning's. Similarly, the novel energetics synthesis, experimental characterization, and modeling efforts are excellent examples of a well-coordinated and integrated research program.

Many of the posters displayed in-depth collaborations with outside organizations, including other DoD laboratories, academia, and especially the National Laboratories. Collaboration with the National

Laboratories included the application of models and codes and the use of experimental facilities and instrumentation techniques. Some of the new analytical techniques and diagnostics developed to follow projectile penetration and test novel energetics were very impressive. For example, the project described in the poster on developing imaging and velocimetry techniques for impact studies used the Los Alamos National Laboratory's proton radiography facilities and applied Lawrence Livermore National Laboratory's photon Doppler velocimetry (PDV) techniques. The objective—to observe penetration phenomena at ever-smaller scales and faster times—is crucial to the development of predictive modeling capability in the area of terminal ballistics and penetration mechanics. The laser-generated shock wave test to measure explosive performance of milligram quantities of energetic materials, which was developed by ARL, is also very impressive. ARL is to be congratulated for seeking out the application of these new diagnostic techniques to provide in situ data on penetrator–target interactions as a means to model penetration mechanics, modeling validation, and characterization of energetics in a cost-effective manner. Additionally, the use of impedance spectroscopy and scanning probe microscopy for mapping grain boundaries in SiC-N was impressive.

The overall program on novel energetics is a strong strategic choice for ARL. Its thrust areas are central to ARL's mission and investment in them, if continued over the next decade, could make ARL a national and international leader. The early results from this program are encouraging, and the staff currently working in the program are excellent. Expanding activity in this area, with concomitant support in the form of new hires and external collaborators, is warranted.

The computational activities are in general well integrated into a large proportion of the research presented. Large, complex, and/or intensive calculations benefited from the use of externally developed, state-of-the-art code platforms, many from the Department of Energy. Many have been used in collaboration with other groups or national facilities, but some outstanding examples were developed in-house. There were extensive modeling efforts over a variety of length scales to follow penetrator–target interactions, muzzle blast, and interior ballistics. Reduced-order modeling is an in-house-driven program that is producing results for systems modeling. The interplay between materials and design of armor systems was well presented, as were energetics synthesis development and linkages to properties, which showed that the issue requires close collaboration between materials development, design, structure/property characterization, and computational efforts to optimize performance. To advance the state of the art, particularly in material modeling and failure modeling under conditions encountered in regimes pertinent to ARL problems and in the CFD area germane to exterior ballistics, ARL needs to collaborate on tool development if the tools are to evolve to meet Army needs. The importance of ARL's developing a laboratory-wide validation methodology, formalism, and implementation program cannot be emphasized enough. Sensitivity studies, beyond providing a way to guide and refine where experiments should be concentrated and on which materials, need to also model how systems can fail.

ARL is making good use of funds allocated to Small Business Innovation Research (SBIR) projects. Several administrators and senior technical staff cited positive experiences with various sponsored projects. In one case, a small-business entity has demonstrated, for the first time, the growth of single crystals of aluminum oxynitride. This achievement has opened up exciting opportunities for basic research at ARL. It appears that the new technology can also be applied to other difficult-to-process materials.

4

Information Sciences

INTRODUCTION

The Panel on Information Sciences at the Army Research Laboratory (ARL) is charged with reviewing ARL research in the broad areas of autonomous systems, atmospheric sciences, computational sciences (including high-performance computing), and network sciences. The panel reviewed the ARL work in autonomous systems at Adelphi, Maryland, on August 13-15, 2013; the work in high-performance computing at Aberdeen Proving Ground, Maryland, on June 23, 2014; and the work in atmospheric sciences, computational sciences, and network sciences at Adelphi, Maryland, on June 24-25, 2014.

Autonomous Systems

While there was considerable variation in both the quality and impact of the research presented, the researchers were largely aware of the progress in their fields, and that had a noticeable impact on their own work. ARL has recently recruited a number of very promising early-career scientists. Careful attention needs to be directed at ensuring that they receive appropriate mentoring and career development opportunities as they develop their individual research portfolios. The new indoor Military Operations in Urban Terrain (MOUT) facility was impressive and will go a long way toward furthering the goals of the intelligence and planning program. The tour of the ARL Sensors and Electron Devices Directorate's (SEDD's) Specialty Electronic Materials and Sensors Cleanroom research facility helped the review team understand the infrastructure support available to ARL researchers.

A summary assessment of research in each of four subject areas—manipulation and mobility, perception, robotic intelligence, and human–robot interaction—is presented in the following sections of this chapter. ARL has a leading program in the area of small-scale robotics. A demonstrated ability to design, fabricate, and test these devices gives it a place of distinction in this field. Similarly, research in the area of perception is being performed at a high level of quality. With a mission to develop machine understanding of objects, actions, and interrelationships in a specified environment, this work is critical for advancing the state of autonomous systems. Ongoing research is focused on advancing unsupervised approaches to human detection and advancing sensing and perception capabilities on constrained platforms. Research in the areas of human–robot interaction and intelligence is addressing important problems of mapping, cognition, and communication, as well as issues related to trust in autonomous systems. This research is cutting edge and comparable to work at federal, university, and industrial laboratories here and abroad, and portions of the work are poised for successful transition to applied research.

Atmospheric Sciences, Computational Sciences, and Network Sciences

The Army Research Laboratory Technical Assessment Board (ARLTAB) was tasked with evaluating the quality and impact of the ARL research program. A backdrop for this assessment was the aspirational goal outlined by the ARL director: pursuing research to support the U.S. Army to fight the war after the next. This statement speaks to a focus on fundamental research that may not have near-term applications or directly support the immediate needs of the U.S. Army. The ARL research agenda in the subject areas reviewed is both broad and diverse. The ARLTAB did not focus on the appropriateness or scope of the research agenda but noted that it needs a description of the context in which the internal research program was structured.

The linkages between in-house research, the research of external partners, and collaborative efforts are key in assessing the impact of ongoing work. This aspect could be considered for future reviews. Additional desirable adjustments to the presentation format including the following:

- Clearly articulate the problem at the beginning of each presentation. Whenever appropriate, a mathematical statement of problems is desirable.
- For continuing programs, identify how the program has changed since the previous review and indicate how recommendations from that review have been incorporated into those decisions to change. This was not a uniform practice in all presentations. Including a timeline that indicates the stage of completion for a project would also be helpful.
- Include benchmarks against which research is being calibrated. Research presentations need to identify what is unique and what new knowledge has been generated.
- Wherever possible, identify quantitative metrics against which research is to be assessed, and describe how these metrics challenge existing limitations of the status quo.

These comments notwithstanding, the work that was reviewed was of good quality. There was considerable variation in both the quality and the impact of research, but the researchers were largely aware of the progress in their fields. Related work was cited, and in some instances this awareness had a positive effect on their own work.

ARL has recently recruited a number of promising early-career scientists, and it will be important to ensure that they receive appropriate mentoring and career development opportunities as they develop their individual research portfolios. The ARLTAB panel's visits to laboratories and research facilities at the ARL were useful for the assessment process. Members of the computational sciences assessment team had the opportunity to visit the high-performance computing facilities at Aberdeen Proving Ground and to see live demonstrations of some aspects of the ongoing research. Additional visits to select facilities will be helpful to future review panels.

All elements of the research program that were assessed have continued to progress in the quality of their work, the dissemination of results in distinctive publications, and apparent overall morale. The

ARL was responsive to the earlier reviews and recommendations of the ARLTAB. This includes both recommendations related to specific projects and recommendations on how to organize their activities to enhance their research capability and improve its visibility. As an example, the Computational Sciences Division (CSD) has better integrated its research on multiscale materials modeling with experimental validation and has developed a research roadmap for its work on tactical high-performance computing (HPC) that involves short- and long-term objectives. It has also increased the number of Ph.D.'s on its research staff and the external visibility of its research by increasing the number of conference and journal publications resulting from this work. Most presenters did an excellent job of articulating connections to Army operations.

A number of the exciting new research thrusts in Battlefield Environment Division (BED) study areas appear to be in response to the ARLTAB recommendations during the 2012 review. In support of these thrusts, and faced with flat or declining financial resources, BED has creatively expanded the number of postdoctoral researchers, visiting scientists and engineers, and students. This new expertise has enabled the division to pivot rapidly to exploit new research opportunities. Significant progress has been made on research projects evaluated during the 2012 review, particularly in boundary-layer research (study of particulates and aerosols, optical turbulence, and measurements). BED has successfully acquired and adapted powerful existing software tools for the verification of its numerical prediction models and has made significant advances in its suite of multiscale models.

In network sciences, there has been significant improvement in the quality of the research and the presentations and in the morale of the team. Almost all presenters did an excellent job in articulating connections to Army operations, although some presentations lacked clear problem definitions. Some of the weak projects from earlier reviews have now been eliminated. One issue from the previous review that may not have been addressed is the implementation of a support system for promoting recognition of researchers in professional societies. This needs to continue to be a priority for ARL management.

ACCOMPLISHMENTS AND ADVANCEMENTS

Autonomous Systems

All elements of the autonomous systems research program at ARL have continued to show progress, both in the quality of work and dissemination of results in high-quality publications. The program focuses on mobility and manipulation of robotic devices and on technologies that improve the usefulness of these devices, such as intelligence, perception, and improved human–robot interaction. The ARL research program is part of a larger collaborative effort involving external partners. A better definition of the role of the internal research in the overall program goals and of continued collaboration with partners is strongly encouraged.

Manipulation and Mobility

Research in the area of manipulation and mobility is closely linked to the ARL's Collaborative Technology Alliance (CTA) in Autonomous Systems,[1] where significant collaboration with those partners is to be found. Three areas were highlighted during the review: replicating locomotion found in biological systems to improve robot mobility, autonomous manipulation of robots, and piezomicroelectromechani-

[1] There are currently two active CTAs related to autonomous systems: Micro Autonomous Systems and Technology (MAST) and Robotics.

cal systems (piezoMEMS) technologies to develop small-scale robotic systems. New updates on the project related to the CANID robot,[2] mimicking the movements of a canine hound, were presented. The primary thrust of the new development was the addition of a flexible spine to the robot. This is a challenging and interesting project, and the addition of this key degree of freedom to a walking robot is a good idea, because it more closely resembles the complexity found in nature. There needs to be a concerted effort to better understand the physics of this machine. Researchers have proposed low-order models for the system, and it might be fruitful to continue this line of inquiry. Good modeling will be imperative in any numerical simulations required to explore gains that are possible and to guide the focus of new experimentation.

Work related to self-righting robots is of a very high caliber and also has direct applications in the field. This was evident from the fact that the project was conceived through interactions with soldiers who are often confronted with the task of retrieving immobilized robots in combat. The research seeks to develop solutions for a broad class of physical conditions that affect stability of mobile robotic platforms. The current focus is on examining the underlying mechanical issues of self-righting in a quasi-static environment. It was not clear how the upright, stable position would be sensed on a sloping surface, where self-righting is most likely to be needed. ARL's consideration of dynamics in 2014 is applauded.

The piezoMEMS research and associated small robotics effort are first rate, with elements that are at the vanguard of this field. The robotic devices under development with integrated piezoelectric materials demonstrated work that is at the forefront of MEMS design, fabrication, and experimentation. Specifically, the work in motion generation at the MEMS scale is seminal. Large-amplitude motions are being created at the micron scale using integrated actuators, structures, and electronics cofabricated on silicon. Techniques and approaches to generating articulating limbs with integrated flexure hinges and actuators represent advances in the engineering of MEMS technology. This has broad implications and applications to numerous MEMS systems—for example, MEMS-based microscale sensors and instrumentations such as mass spectrometers on a chip, drug delivery systems, and chemical assay analysis, where controlling microfluids is critical. The work being performed by ARL in the piezoelectric actuation of MEMS will impact more than just the creation of bioinspired microscale robotic systems.

Perception

The research in perception is of a high caliber. The work focuses on developing techniques that allow for describing the robot's environments from sensor data. While there has been considerable progress toward describing environment for the purpose of mobility, deriving higher-level descriptions such as subtle cues and references that distinguish different behaviors and intents, recognition of specific classes of objects and features that are directly relevant to tactical behaviors, and labeling of object, feature, and terrain classes remain a challenge.

The current research plan is focused on three critical areas: perception on constrained platforms, robotic intelligence, and human–robot interaction. As for sensing and perception on constrained platforms, the scale and size of the platforms being explored in the autonomous systems enterprise pose technical challenges in sensor design. Sensors have to deliver the requisite accuracy and precision for surveillance and navigation, but they also have to reconcile with power limitations on smaller platforms. Other problems being addressed in the perception area include detection of humans in still images and strengthening object and material recognition capabilities, including an ability to recognize actions and

[2] CANID is a quadruped designed to test hypotheses regarding dynamic bounding using an actuated compliant spine mechanism.

imminent actions. The latter is based on scene parsing and action grammar and represents an interesting approach. The problem of developing real-time human detection algorithms is important, because existing approaches are based on supervised learning techniques that are computationally cumbersome. In operational environments that may be diverse and exhibit large variations, computational efficiency is an important consideration. The unsupervised learning approach used in this work is more efficient but may still yield false positives, and additional work is required to overcome this drawback. The basic approach for each of the research tasks is fundamentally sound, breaking new ground. Results of this research are publishable in archival literature, and the work is on a par with research being done at universities and other laboratories. The researchers are aware of related work being done elsewhere and recognize deficiencies in their individual approaches. Each presented a good plan for the future activities.

Robotic Intelligence

The primary accomplishments in robotic intelligence are advances in mapping capability, control for communications, and cognition. Much of this work is being published in top journal and conference venues (including the *International Conference on Robotics and Automation*, the *Institute of Electrical and Electronics Engineers Proceedings*, and the *International Journal of Robotics Research*), which attests to the overall quality of the research. Former students funded by the CTAs have been recruited to ARL and are important contributors to the research effort. Some of the 6.1 (basic) research projects are also making their way to 6.2 (applied) research, an important step before transitioning this work to the field.

In long-duration, three-dimensional (3D) mapping and navigation, the principal focus is on the development of a laser-based approach to 3D mapping that combines features from three existing mapping techniques. Demonstrating the effectiveness of the approach by deploying it on physical robots is an important accomplishment. Another thrust of intelligence research is on developing robust methods for control of mobility and communications. The primary focus of this effort is the development of a centralized, optimal solution of mobile node positions, subject to point-to-point communications constraints. While promising results were presented, additional details are necessary, particularly for issues such as scalability and whether such issues impose limitations on the proposed approach. Research in intelligence is also examining new cognitive architectures for robotic control. This work is focused on developing a new cognitive architecture that combines long-term memory, working memory, and perception. The mapping problem is driving this development, but it is difficult to understand how the cognitive approach improves mapping performance.

Human–Robot Interaction

In the area of human–robot interaction (HRI), research at ARL is looking at design issues for safe operation of autonomous reconnaissance systems in complex environments. The emphasis of this effort is human factors experiments to investigate interaction with, and control of, multiple autonomous systems. The design of interfaces is an important aspect of this investigation. Studies are focused on graphical user interfaces (GUIs), multimodal interfaces (including voice), and telepresence with stereovision and haptic interfaces. The experimentation conducted at Fort Benning has yielded an important basis for making design decisions. For example, experiments have demonstrated voice commands to be suitable for discrete actions but less so for controlling continuous processes. Similarly, the research has demonstrated how audio cues in 3D improve situation awareness in telepresence tasks.

The RoboLeader project continues to be an important component of the ARL HRI program. The research draws on a large body of experimental work related to evaluating the effectiveness of autonomous and semiautonomous control of teams of robots. The RoboLeader intelligent system was evaluated in this context and shown to provide benefits from the standpoint of both task performance and workload management. Testing with humans showed individual differences in performance: People with good spatial ability and significant videogame experience had better situation awareness of the mission environment. The results have implications for personnel selection and training and for user interface design.

Another research thrust in the HRI arena is bringing greater understanding of automation actions to the human in the loop. The focus of this effort is the use of visual display screen overlays to communicate robot perceptions and intentions to a human operator during an automated navigation task. The experimental approach is sound and based on prior studies of shared mental models and automation transparency. Results of this work support the use of such visual aids to reduce teleoperation occurrences, teleoperation times, and subjective workload.

The HRI group's publications reflect a broad understanding of the science and research conducted elsewhere—related work is cited and contributions are placed in context. The group has also edited a book, *Human-Robot Interactions in Future Military Operation*,[3] which includes input from external sources, including academia. It also has a demonstrated record of successfully transitioning its work to the U.S. Army Tank Automotive Research Development and Engineering Center (TARDEC) robotics programs.

Atmospheric Sciences

The U.S. Army faces many challenges to its future dominance on the battlefield, including environmental impacts on operations, which are chiefly concentrated in the atmospheric boundary layer. The research portfolio for the BED includes a range of unique atmospheric science problems of vital importance to the Army that are not addressed elsewhere in the Department of Defense (DoD) or the civilian scientific community. The division's projects are concentrated in three critical areas: atmospheric sensing, including aerosol sampling and properties, and optical imaging and processing; atmospheric dynamics, including turbulence physics and fine-scale observations; and atmospheric modeling applications, including mesoscale and microscale models, data assimilation, and verification/validation. The BED has made impressive progress in each of these research areas.

Model of Atmospheric Boundary Layer Environment

The Atmospheric Boundary Layer Environment (ABLE) research model has been under development for about 3 years and is currently undergoing rigorous testing as a direct numerical solution (DNS) to the Navier-Stokes equations of fluid dynamics at grid resolutions fine enough to resolve the full range of turbulence down to the dissipative range, known as the Kolmogorov microscale. Once completed, the ABLE modeling system will be a primary research tool for understanding, characterizing, and predicting the evolution of the turbulent boundary layer in time and space. Innovative numerical methods, such as the Lattice Boltzmann method, are being introduced to adapt ABLE for highly complex terrain and urban conditions and to support various physics options. A special feature of ABLE is that it provides a modeling framework extensible to other BED atmospheric modeling systems, such as BED's Weather Running Estimate–Nowcast (WRE-N) model, to maximize parallelization efficiencies and to be adaptable to a variety of novel computing platforms. In this context, it is more useful than an existing well-

[3] Michael Barnes and Florian Jentsch, eds., 2010, *Human-Robot Interactions in Future Military Operations,* Burlington, Vt.: Ashgate Publishing Company.

tested DNS/large-eddy simulation (LES) system. Direct assimilation of lidar wind observations within ABLE is projected as a possibility for the future. This innovative work is of high quality, comparable to that in the universities and other major laboratories. The research team is well qualified and adequately supported.

Advanced Artillery Meteorology for Army and Marines

The advanced artillery meteorology system represents a mature BED project in model development and adaptation that harvests and exploits research emerging from within ARL and from the wider research community in mesoscale modeling, data assimilation, and observation sciences. Once tested and validated in this data-assimilating modeling system, improved capabilities are transitioned to operational status at the Air Force Weather Agency (AFWA) to support Army applications around the world. The project has played a vital role in improving the accuracy of both traditional artillery and rocket-assisted munitions, while decreasing costs and manpower in the field. The current project represents the ongoing evolution of Profiler, the first Army artillery meteorology system to use data from a numerical prediction model. ARL has assisted the Army and Marines in development and evaluation of the follow-on laptop version, the Computer Meteorological Data-Profiler. Ongoing work is focused on gathering and analyzing meaningful performance metrics for the currently fielded laptop system.

Aerosol Sampling

The aerosol sampling project is motivated by the need to understand and mitigate the adverse effects of combustion products and other aerosol constituents on soldier health in Army theaters of operation. The atmospheric science community has a large effort in correlating aerosol composition with health effects. Ongoing work represents the first step toward achieving a correlation between these two areas of interest while specifically focusing on Army-related sites. Although the project team did not present information beyond the identification of aerosol composition as a function of particle size and day (time), it is clear that careful thought regarding the application of the data in a larger context (e.g., source apportionment and health effects monitoring) has already occurred. This research adds a significant component to the larger atmospheric science community's efforts to correlate aerosol composition and health effects.

Applied Anomaly Detection Tool

The anomaly detection project is an excellent example of how the understanding and characterization of the atmospheric environment can be successfully linked to the social-cognitive aspects of information science to develop practical and effective methods to improve soldier safety in hostile environments. Begun with both ARL mission and customer-driven funding, and utilizing expert insights from in-theater expertise of veteran soldiers, the project originally provided a training simulator in which soldiers learned how to recognize potential anomalies in color, texture, and other parameters of the terrain that could reveal hidden sites of roadside improvised explosive devices (IEDs) under various atmospheric conditions. More recently, the project has been extended to provide automated real-time decision support for soldiers in the field, giving them real-time warning to avoid imminent threats. The concept is now being extended to give warning of threats aloft using a range of environmental information as inputs. The work is both important and of the highest quality.

Effects of Atmospheric Conditions on Bioaerosol Viability and Optical Properties

This project focuses on understanding the fate of various bioaerosols as they are exposed to conditions in the atmosphere. A combination of laboratory and field-based experiments is used to obtain basic information to characterize the effects of gases, sunlight, and humidity on the viability of the bioaerosol constituents. The work results from a solid, collaborative effort between BED's Atmospheric Sensing Branch, the Johns Hopkins University, Texas A&M University, and Sandia National Laboratories. The area of bioaerosols is particularly important to the broader atmospheric science community, and few studies exist to examine the heterogeneous interactions of these particles and effects on particle viability. Useful results have been obtained, including distinct changes in fluorescence level for bioaerosols exposed to different concentrations of ozone and water vapor. Variations in the fluorescence signals have been correlated with changes in the viability of the biological particle simulants.

The experimental techniques used in this work are sound. Researchers have conducted experiments using both clean laboratory air as well as actual ambient air samples. The use of actual ambient air likely resulted in additional chemistry that may not have been well represented in the laboratory experiments.

Data Assimilation Advances Supporting Nowcast Modeling

This effort focuses on developing strategies for integrating atmospheric data into existing and future ARL atmospheric models. Specific emphasis is given to assimilating Meteorological Data Collection and Reporting System (MDCRS) and Tropospheric Airborne Meteorological Data Reporting (TAMDAR) aircraft observations over the continental United States (CONUS) in WRE-N as a means of determining their practical value to short-term forecasts (Nowcasts). A key for Army applications is the ability to improve performance in data-poor regions. Though simple and easily adapted to new domains, scales, and environments, the observation nudging technique used in the WRE-N model is dated. The significant computational constraints under which the WRE-N operates preclude use of the more sophisticated approaches at this time, such as three-dimensional variational (3DVAR) analysis, increment analysis updating, and 4DVAR or variants of Kalman filtering.

Ongoing numerical experimentation is focused on determining the best radius of influence and weighting strength for assimilating the temperature and moisture data; testing indicates that the optimal choices for nudging weight and radius of influence may be case-dependent. The quality of the research is high, given the constraints mentioned earlier, and the researchers are clearly knowledgeable about the field of data assimilation.

Detection of Ultrathin Clouds

This research seeks to understand and differentiate the bulk properties of particles with sizes comparable to optical wavelengths and to quantify their impacts on the Army's electro-optical systems. Transparent cirrus clouds fit this category, as do super-thin water clouds nearer the surface and various ensembles of aerosols. Given such diversity of causation, this is a long-term effort aimed at identifying contributors to the scattered signal in active remote sensing (e.g., lidars) or passive sensing (e.g., optical receivers). In this initial stage it is an inverse scattering problem, where a range of physically plausible solutions are matched against existing observations of known or expected particle type and distribution. The model of agglomerated spheres is unique, and it produces results that can explain the measurements without resorting to case-dependent parameters. It is computationally intense, but once done for a single particle and at various orientations and compositions, it is relatively simple to obtain the result for the bulk properties that lidar or optical instruments would sense.

The work is a fundamentally important part of the diagnosis of what is where in the atmosphere and seeks to provide an explanation of why. As for the question of why, the polarimetric signatures used in the work are convincing and capture the gist of the physical reasons. The quality of this effort is on a par with that of similar work by others dealing with, for example, classification and quantification of precipitation particles in clouds and inferred from polarimetric radar signatures. The challenge remains verification, because there are no compatible in situ sensors to use as standards. The investigators are on the right path as evidenced by the quantitative agreement of modeled polarimetric properties with the observed ones.

Human Vulnerability Forecasting

The human vulnerability forecasting project is a new focus to couple multiple sources of natural environmental data with data on human activity in order to identify potential correlations between human vulnerability occurrences (responses) and specific environmental variables (predictors). This project is in the data-gathering and initial analysis stages, and the team is currently evaluating two different computational approaches. The first approach developed a prototype forecasting software system to ingest environmental data automatically while simultaneously ingesting human activity data in the form of dates and activity type(s). The second approach makes use of the statistical learning tool Random Forest to derive a predictive model. The ability to model human behaviors based on specific environmental conditions has tremendous upside potential by providing tactical ground units with a new source of predictive intelligence for safe and effective execution of highly dangerous operations. The fact that there have been no publications or conference/workshop presentations from this project is to be expected, given the project's newness. It is also noteworthy that the project team includes an active-duty Army senior officer, whose operational insights provide a valuable user's perspective to the project.

Real-Time Atmospheric Imaging and Processing

The achievement of collimating beams from several lasers for the purpose of increasing power density while reducing instrument size is significant. In particular, the use of beam tails from the hexagonal sources arrangement to collimate the beams has paid off, as demonstrated in action. Considering that these are the first attempts, 70 percent efficiency is impressive, and it is realistic to expect greater than 90 percent efficiency in the very near future. The development of an agile electronically steerable laser beam would be among the first of its kind.

The use of signal processing schemes has been integrated into this capability. The lucky region fusion algorithm for mitigating the effects of turbulence along the propagation path has progressed since the last review in 2012. This technological enhancement, made possible by real-time computations on field-programmable gate arrays, increases the overall capability in optics at the ARL.

Meteorological Sensor Array at White Sands Missile Range

This development project is designed to establish, in a phased deployment approach and in response to previous ARLTAB recommendations, multiple regular arrays of instrumented meteorological towers, initially in and near the White Sands Missile Range (WSMR) complex. Especially important and unique is the addition of above-ground observing assets (e.g., triple lidars and unmanned air systems) that have the potential to provide considerable detail aloft to augment the ground-based towers. In addition, the new sensor array designs are expected to maintain some flexibility to allow adaptation as modeling needs for verification data continue to evolve. The phased approach is sound and thoughtfully considered, and a clear context was provided for creating the network. The principal objective is to provide ground-truth data for the verification and validation of weather forecast models at the scale (1 km horizontal spacing) and with the geometry (Cartesian grid) of a native model grid, as is typically used by WRE-N. Additionally, the sensor array will provide a persistent framework for studying the atmospheric boundary layer in semiarid, complex terrain. Installation of this network has the potential to highlight ARL in the international research community in terms of observations, atmospheric boundary layer research, and numerical modeling and validation of the boundary layer.

Multiscale Turbulence in the Atmospheric Boundary Layer

The objective of this study is to learn how the anisotropy of atmospheric turbulence (that is, different turbulence along the altitude in the atmosphere) affects the transport of momentum, heat, and moisture in the boundary layer. The project focuses on the larger scales of turbulence, which are well known to be highly anisotropic but have nonsteady, nonuniform characteristics that affect fluxes through the boundary layer and near the surface. Rigorous data analysis and theoretical analyses are the preferred means of study. LES and DNS provide additional numerical means of investigating turbulence anisotropy, but anisotropic processes and evolution have remained poorly understood. As a result, anisotropic effects are only partly accounted for in most numerical models. ARL has proposed a new approach for investigating turbulence anisotropy that combines multiresolution decomposition and anisotropy of the Reynolds stress tensor analysis and tensor invariants. This research approach divides and analyzes the turbulence motion at different scales. The study allows investigation of the decay of larger and presumably more anisotropic eddies into smaller scale eddies, which are more nearly isotropic.

The work is of very good quality and has the potential to be integrated into BED's fine-scale numerical modeling in WRE-N and ABLE, notably for better determination of the characteristics of the outer length scale in the surface layer. Recent findings have been published in *Boundary-Layer Meteorology*, attesting to its quality.

Real-Time Detection of Nerve Agent Stimulants Using Multiwavelength Photoacoustics

This project seeks to develop a novel form of laser photoacoustic spectroscopy to rapidly detect the presence and concentration of complex gases. Nerve agent simulants (e.g., dimethyl methyl phosphonate) were utilized as test cases. Pursuing the goal of a practical field-deployable system, researchers have modified a traditional photoacoustic system that analyzed an enclosed air sample in steady state to detect trace gaseous species. The modifications included the development of a flow-through, nonresonant photoacoustic cell for continuous sampling. Perhaps the most innovative modification is the system's use of three separate lasers at different wavelengths, which extends the available analytic range into the mid-IR region. Currently, the system is able to detect the simulants at concentrations down to 5-15 ppm, but new adaptations and experiments are expected to lower the detection threshold by an order of magnitude. It is theoretically possible to add more lasers to broaden the analytic range, improve the accuracy of the response spectra, and further lower the threshold of detection. ARL researchers hope to be able to detect nerve agent simulants and other gaseous compounds in concentrations down to parts per billion, which would dramatically enhance soldier safety on the battlefield. The research is both innovative and of high impact.

Nowcast Model Assessment

Objective verification of numerical prediction models at the scales of interest to the Army is especially difficult. In response to prior ARLTAB recommendations, BED is now making use of the Model Evaluation Tool (MET) software developed by the National Center for Atmospheric Research (NCAR), which is widely used by the meteorological research community for verification of numerical weather predictions. In addition BED has adopted the Geographical Information System (GIS), which is well adapted for the unique and challenging model verification problems at horizontal scales finer than 1 km. Taken together, MET and GIS provide BED with expanded and flexible verification options for quantifying predictive skill and assessing product value. These acquisitions have enabled BED to rapidly advance its Nowcast model assessment capability to approach the state of the science in the operational and research communities for fine-scale atmospheric modeling.

Nowcast Modeling

The vision for the Nowcast modeling project is to give a soldier or team of soldiers the ability to enter the theater of operations with a portable computer containing a suite of numerical weather prediction models and automated tactical decision tools suitable for small-scale (tens of km) operations on the battlefield. The software system would be complete, with all the observational data and gridded model input fields the user needs to run the software on the laptop/tablet in order to generate meteorological fields and automated decision assistance products within 30 minutes.

The Nowcast modeling project is one of several observational- and modeling-based projects that constitute a comprehensive model development, adaptation, testing, and verification program. The six-person project team has also engaged with other mesoscale modeling groups around the country, including the National Oceanic and Atmospheric Administration (NOAA) Earth Systems Research Laboratory High-Resolution Rapid Refresh Model group, whose civilian users at the Federal Aviation Administration have requirements like those of the Army for small-scale, highly accurate meteorological information packaged into a useable format for the end user. The project team produced six ARL reports and two conference/workshop papers over the last 3 years. However, this work could be submitted to a suitable, high-value, peer-reviewed journal for vetting by the rest of the mesoscale modeling community.

Quantified Weather Impacts and Friendly vs. Threat Advantage

The goal of this project is to develop a quantitative, highly granular weather effects display system to enable a more intuitive, flexible, and informed interpretation of weather impacts upon operations and personnel. Such a system would replace a legacy decision assistance system, Integrated Weather Effects Decision Aid (IWEDA), which has deficiencies related to arbitrary boundaries and inflexibility to adapt to mission priorities. The proposed approach will allow meteorological parameters affecting the mission impacts to be weighted as desired by the user, with transitions between severity levels depicted as linear, quadratic, exponential, or other, as appropriate. In addition to providing a smoother impact continuum, this project introduces the important innovation of allowing a direct comparison of which side, friendly or threat, has the advantage or disadvantage vis-à-vis forecasted adverse weather conditions.

Computational Sciences

The structure of the Computational Sciences Division (CSD) includes both a substantial facilities component that serves the high-performance computing (HPC) and networking infrastructure needs of ARL, the Army, the DoD, and a growing research component focused on interdisciplinary computational science. The CSD team is making concerted efforts to move forward new Army-relevant directions around high-throughput distributed processing and the applications of modern computer science. This is a commendable approach, and CSD could consider the development of similar approaches to advance its research projects in traditional HPC and physics-based modeling. Projects were presented along five themes: programming models for distributed processing on heterogeneous architectures, tactical HPC, multiscale materials modeling around dislocation dynamics and defects, modeling mobile networks, and emerging areas.

Programming Models for Distributed Processing on Heterogeneous Architectures

This research focuses on developing programming models and associated runtime systems to allow near-real-time distributed processing on heterogeneous architectures. Establishing near-real-time situation awareness through the use of contemporary programming models and networked heterogeneous computing architectures could lead to significant and game-changing battlefield advantages. The use of portable application programming interfaces (APIs)—extremely important because HPC architectures are constantly changing—coupled with stable APIs is consistent with state-of-the art HPC thinking. ARL's focus on tactical ad hoc HPC architectures is novel; tactical and ad hoc features are not fully accounted for in classical HPC architectures, which are well-defined, static interconnect topologies with well-behaved bandwidth characteristics. Moreover, CSD's investigation and use of different types of heterogeneous computing architectures (e.g., general-purpose central processing units (CPUs), general-purpose computing on graphics processing units, Xeon Phi, and low-power ARM processors[4]) along with programming models and run-time systems that leverage existing and well-funded industry standards (e.g., open computing language) ensure that the research applies to existing and emerging HPC architectures and leverages the best that the industrial and academic research has to provide.

Overall, this work is likely to be an important part of ARL's portfolio going forward, and its continued development and enhancement can be leveraged across different projects.

Tactical HPC (Cloudlets)

The objective of this research is to develop a comprehensive infrastructure for deploying and using advanced computational capabilities on the battlefield. The research has primarily focused on addressing some of the fundamental questions regarding the optimal placement of mobile computing resources and on how to identify the routes that these resources should follow in order to maximize the throughput of the computations and data transfer rates. In particular, the project on tactical cloudlet seeding considers the optimal placement of a limited number of mobile computing resources to increase the soldier's capability at the tactical edge. The problem formulation is sound. Key strengths include their plans to explore a variety of algorithmic approaches that offer a range of trade-offs between computation costs and quality of solution. CSD has made significant progress in better defining its concept of tactical HPC

[4] ARM processors are a family of 32-bit microprocessors developed by Advanced RISC Machines, Ltd., that power a wide variety of electronic devices, including mobile phones, tablets, and multimedia players.

(cloudlets), an area that holds the promise of providing significant operational capabilities in the field. The work has the potential of making a significant impact.

Multiscale Materials Modeling

CSD has made significant progress in work related to multiscale modeling and simulation techniques, and has applied these methods to modeling materials dislocations in microstructured crystals and multiscale computation of electron transport. The projects on computational materials science with two-scale hierarchical models and the simulation of dislocation dynamics are generally sound. In particular the problem of enhancing the scalability of scheme to model dislocation dynamics of complex microstructures appears to hold the potential for serving multiple applications, including those involving gallium nitride (GaN) materials, other electronic materials, and metallic-ceramic composites. In addition to the numerical methods and algorithms, the research has developed a software framework that employs multiple principles that have been developed in the broader computer science community but have not previously been applied for large-scale scientific problems. These include dynamic scheduling to achieve load balance (and potentially fault tolerance) and memorization to avoid repeated computation. The overall scientific work is of very high caliber; it reflects a broad understanding of the basic science and combines disparate techniques. It reflects an appropriate mix of theory, computation, and experimentation.

Modeling of Mobile Networks

CSD has made significant advances in modeling mobile networks by combining simulation and emulation with experiments. This work has resulted in the development of a parallel version of the NS-3 simulator software, and the EMANCE software has been used to emulate Army radio models that have been transitioned and used by the U.S. Army's Communications-Electronics Research, Development and Engineering Center (CERDEC) and other DoD organizations. Related to that is the work on real-time radio frequency (RF) realistic propagation modeling and simulation that is used by CERDEC and the Naval Research Laboratory for network modeling and jamming applications. The scientific quality of the research presented is comparable to that of leading federal, industry, and university laboratories. ARL researchers evinced a clear understanding of the underlying science that supports the research activity. The quality of the research team in both depth and breadth of knowledge is strong, but the number of research personnel assigned to each project was less than that allocated to similar research projects in other federal and industrial research organizations. Overall, the project is coming to closure and is being transitioned from a research to a development project.

Emerging Areas: Software-Defined Networks and Quantum Computing and Networks

CSD has initiated projects to explore research issues in two emerging areas: cybersecurity in the context of software-defined networks (SDN) and the field of quantum computing and quantum networks.

Access to a secure network is mandatory if the future warfighter is to use data to make effective offensive and defensive battlefield decisions. CSD's effort in this area examines automatic (cognitive intelligence) detection of various network attacks and how such detection can be used in the context of SDNs to protect the network through automatic reconfiguration. The results, when they become available, will be implemented on ARL's current Cisco SDN routers. This is an important area of network research, and early research results are promising.

The research on quantum computing has the potential to be significant. The investigators translate a classical Boolean satisfiability (often abbreviated SAT) problem into a spin chain whose ground state can be interpreted to be an instance. The idea of using quantum algorithms to apply to SAT, one of the canonical classically exponential NP-complete (NP refers to nondeterministic polynomial time) problems, would not only give another example of a powerful quantum algorithm but also be generally useful in that SAT solvers have been applied to a wide range of concrete problems. The second step of this work to extend SAT to first-order predicate calculus will yield not only a generally useful algorithm for application but also a general approach to programming quantum computers in a natural way. This work represents some original and exciting thinking.

Network Sciences

Research presentations in network sciences were organized in the three broad areas of communications, sensing, and operational management of networked robotic systems. There was good science and engineering in many areas of the work. Since the previous review in 2012 there has been significant improvement in the quality of the research and of the presentations and in the apparent morale of the team. The lightweight intrusion detection work is promising. The issue of burstiness in intrusion detection evinced an interdisciplinary content. Strong work is being performed in tactical communications, robotics, language technologies, and E-field measures in standoff power sensors. Almost all presenters did an excellent job of articulating connections to Army operations. In some instances, however, presentations lacked clear problem definitions and suffered from poor articulation of the problem. Some weak projects have, appropriately, been eliminated since the 2012 review.

The areas in which ARL is leading the research community need to be publicized to raise the visibility of the organization. As an example, in the cybersecurity area ARL is one of the few research institutions that have access to real data. This is a major strength and would undoubtedly attract very favorable attention. The impressive early-career scientists appear to be receiving appropriate mentoring. Some work (e.g., temporal logic for intelligent systems) was in a speculative stage and such interesting work would provide good candidates for future presentations.

Multiagent Adversarial Games

This emerging project seeks to develop a simulation platform to quantify different tactical strategies. The goal is to gain insights into best strategies and to provide training technologies. The team has applied different perspectives that include behavioral game theory, dynamic behavior and strategies, simulations based on cognitive architectures, individual and small group (scalable) conditions, and formalizations. This study is led by ARL's Human Research and Engineering Directorate.

Overall, the formulation of the problem was clear, the technical quality of the work was good, and the work is directionally new and relevant to the Army.

Data-Driven Analysis of Collaboration Structure and Evolution

The research goal is to use topological (e.g., homology) properties of social networks (i.e., network representations of relationships) from data sets to gain insights into coalition formation and decision making in groups. Data sets used include the Digital Bibliography and Library Project (DBLP) computer science (CS) bibliography, and certain group e-mails. This project has been ongoing for some years; the main contribution of the work lies in strong collapsing, an algorithmic advance for computing coverage in sensor networks. The research team is well qualified and aware of related work in the field.

Tactical Communications

A number of projects were organized around the common theme of tactical communications in generally harsh environments. The range of research in this context spanned low to very high frequency (VHF) and optical communications, as well as communications-enabled measurements that are used to control robots in new tactical environments. This exemplary body of work puts ARL at the cutting edge of tactical communications research. Among the many positive attributes of this work, these communications techniques are developed and investigated in the context of specific, interesting Army applications. The researchers were well aware of related work in the field, and they have established good external collaborations (such as with the University of Michigan in the area of small antennas) when appropriate. There is also excellent synergy within the extended ARL group, as evidenced by joint publications. The research group enjoys good external visibility, as indicated by members serving in an editorial capacity for special issues related to the subject matter (for example, the special issue on robotic communications and collaborations in complex environments, published in 2013).

Temporal Logic for Intelligent Robots

This is exemplary, early-stage work that promises to deliver considerable impact. The goal is to develop a planning system for intelligent responses by robots to new events. The work uses linear temporal logic to interface between high- and low-level planners. The decomposition and interfacing between high- and low-level planning is a novel approach. The work is synergistically linked to other ARL research on mapping for robots, and it is well integrated within a much larger project, Adaptive Collaborative Sensing, with the Naval Research Laboratory (NRL) and the Air Force Research Laboratory (AFRL), within which its niche is well defined. The work also benefits from connections to external university work, for instance, in the use of a Cornell University toolkit.

Operational Management of Networked Robot Operation

This research explores how cognitive and network information can be combined to influence decision making. This is done in the context of the robotic operation manager's role, where the task involved a decision maker deciding whether to follow a path or not, given five cues about the environment that might include an improvised explosive device (IED). A rudimentary experiment with a 2 (time pressure/no time pressure) by 2 (bandwidth reduction/no bandwidth reduction) design was established, and 16 participants performed the experimental protocol.

Dynamics of Trust and Information Sharing

This research thrust seeks to enhance and improve the distributed decision making capability within the Army, particularly in an environment where competitive advantage is obtained through effective communications in a network of distributed and informed sources. The research examines and builds the scientific foundations for such decision making. Researchers have looked at key questions related to trust, including how trust influences the behavior of social, information, and communication networks. This work is part of the Network Science Collaborative Technology Alliance (CTA) and is performed in collaboration with researchers in the ARL Social Cognitive Network Academic Research Center (SCNARC). Researchers have developed metrics by which to gauge trust, models that describe trust propagation in a network, and trust management protocols. According to ARL, its work in this area has received significant external attention and accolades in the form of best paper citations.

The poster presentation on this topic lacked a clear articulation of the problem, the mathematical basis for the proposed solution, and comparisons with competing methods that demonstrate how the approach yielded superior results. There are some good ideas behind this research, and these need to be highlighted more effectively. How this research thrust fits in to the broader context of network science research also needs sharper definition.

OPPORTUNITIES AND CHALLENGES

Many of the presenters did not describe well how their research projects fit within the larger research context. Without such a roadmap, there is very little indication of the connectivity of the research projects, either within the subareas or across the enterprise. The ARL research effort is part of a larger collaborative effort involving external partners. A better definition of the role of the internal research in addressing the overall program goals and continued collaboration with partners are strongly encouraged. There is an expectation that the ARL strategic plan with several campaigns and crosscutting research initiatives will provide a better framework in which the research can be contextualized. In particular, it may shed light on the process by which research projects are selected. The presentations provide only the individual researchers' motivations in problem selection; the strategic dimension is often missing.

ARL would do well to include other cross-divisional and cross-directorate projects that leverage the multidisciplinary composition of the laboratory workforce. These are vital to building a strong external presence for ARL, and such collaboration needs to be a priority for the laboratory management. A combination of top-down efforts complemented by invited ideas from researchers has been successfully implemented in other large research organizations. However, the support for such initiatives will require a broadening of the discipline base. Certain disciplines, notably the mathematical sciences and the statistical sciences, cry out for infusion of new talent. Similarly, social scientists, especially those trained in mathematical and quantitative analysis, would bring considerable value to social-cognitive sciences research and to the design and interpretation of experiments. Game theory has grown to be dominant in many areas of interest to the Army, such as understanding and shaping social relationships and behavior, and even networking. ARL could draw from the economics, mathematics, and computer science communities to strengthen its base in game theory.

In some areas of research, particularly in the computational sciences, many of the projects have a considerable software development component, which is currently being done by the researchers working on the project. This may not be the best use of their time; it is important for ARL to build capacity for software development by hiring programmers who can work in close contact with scientists on systems and algorithms.

ARL can do more to enhance its external visibility. This could begin with encouraging greater exposure for the research staff and their work to the outside world. The limitations placed on researchers' travel to conferences is damaging to the mission of the ARL. Inability to network and meet with colleagues not only compromises the growth of research staff but also denies ARL the opportunity to brand itself in the areas of its strength. It also contributes to an insular trend in the research program. If its researchers cannot travel to conferences, greater attention could be paid to organizing onsite workshops involving a larger external research community, and possibilities of onsite short courses. ARL's hosting of seminar series at the laboratory is a good first step in this direction.

ARL needs to leverage its scientific leadership in certain areas, such as tactical communications, machine translation, and tactical robotics, by offering incentives for academic and industrial researchers to collaborate. Such incentives could be funneled through ARL's open campus initiative and could possibly involve the use of ARL's laboratory facilities. ARL needs to consider designating senior members of staff to act as official liaisons with individual university departments. Their task would be to build relationships with faculty and students, which begins by facilitating a two-way flow of information and gaining familiarity with ongoing research and students who are contemplating joining the workforce.

Autonomous Systems

It was not clear how the individual research projects in each area of the ARL autonomous systems enterprise—manipulation and mobility, perception, robotic intelligence, and human–robot interaction—fit within the larger research effort. Without such a roadmap, there is very little indication of the connectivity of the research projects either within the subareas or across the enterprise.

The internal research efforts at ARL are being performed against the backdrop of a research roadmap that includes contributions from partners and contractors. It would be useful to clarify this context in order to better understand any gaps that might exist in the research approach. Other specific opportunities to improve the overall research enterprise include the following:

- Require researchers to clearly articulate the existing technical challenges in their research and how and why the proposed tools and methods are likely to resolve those challenges.
- As ARL continues to build its research staff, give some attention to bringing in mid-career and senior personnel to mentor the outstanding early-career scientists who have been recruited.
- Look for additional ways to increase interaction of its researchers with leaders in industry and academia, given that limitations on travel have restricted this important function.
- Focus on developing a mature framework to guide the conception, design, development, and testing of small, unmanned autonomous systems, including definitions of pertinent parameters and their domain (values).
- Encourage a systems integration approach across its research enterprise to engender interconnectivity between ARL's science and technology (S&T) campaign plans.

At a fundamental level, ARL can take additional steps to enhance the quality and impact of its research efforts. There is a trinity in research and development: analysis, computation or simulation, and testing. Analysis is essential, and there is room for improvement on this front, before one proceeds with numerical simulation or building and testing artifacts. Results from analytical modeling can guide the subsequent steps in development and identify possible missteps; this analytical component needs to be integrated into the approach to research. For example, it is not enough to build a robot and begin to generate a gait similar to that of an animal—one must understand the physics behind the energy converted in a machine when using such a method of locomotion.

Manipulation and Mobility

In the area of manipulation and mobility, there is need for a more coherent approach to vehicle design and development. It would appear that while many excellent issues are being addressed, the overall approach is somewhat ad hoc. For instance, there is an absence of nondimensional scaling in platform design. Characterization of the fundamental physics of flying vehicles—length:diameter ratio, drag polar, coefficients of lift and drag, and power requirements—must be part of the basic design philosophy. Similarly, metrics for system performance evaluation in generalized terms, such as actuation efficiency, propulsive efficiency, hover power loading, power:weight ratio for the actuator, endurance, and specific energy of the fuel source, would add focus to coupled systems and vehicles to include physics-based performance attributes. For robot systems, the specific resistance or cost of transport for any locomotive machine, natural or man-made, is a measure of a machine's locomotive efficiency. It would be beneficial for ARL to encourage this traditional thinking as part of the research mindset.

There is an opportunity to perform simulations of robots and vehicles based on analytical models of the physical systems operating in different environments and to include uncertainties in these models. The models can further be coupled to real control systems, leading to hardware-in-the-loop control design. The ARL may need to consider procuring development hardware, such as D-Space, for robotic controller development. Such systems would accelerate results and allow the integration of complex, nonlinear controllers, based on traditional sensors and sensor fusion, states of the machine, learned behaviors, and complex logic of state machines. Once developed, successful controllers could be programmed, at which point the developmental kinks will have been sorted out, to perform laboratory and field tests of the new controllers.

Integration of systems components is essential to the robotics research area. The system is much more than the sum of its components—nonlinear interactions, sometimes stochastic in nature, can have significant impact on overall operation. In this context, an integrated approach (systems engineering) is a fundamental (6.1 level) domain of research. Such an approach will also allow researchers to best trade concept options against the desired output or value functions. There is an opportunity for the ARL autonomous systems enterprise to assume the leadership in advancing a highly quantitative and scientific approach to systems engineering as it relates to integration of systems components into the robotics research area.

Other general approaches for consideration related to this area of effort may be summarized as follows:

- Notionally establish a family of small robots (ground and air) of varying size (between 1.0 g and 100 kg) and define and reach both the baseline and performance goals for each robotic class. These specifications could be based on a limited selection of potential Army scenarios or vignettes.
- Establish a directed robotic mobility propulsion effort to unify and direct activities required to produce very high-power and high-energy-density systems.
- Establish an integrated design and optimization methodology (considering key parameters like energy, power conversion efficiency, and locomotive efficiency) for the design of these highly integrated robotic systems. The interdependence of all the subsystems will quickly become clear to the researchers as they try to categorize future robotic systems.
- Consider the establishment of a robotic mobility systems integration laboratory. This laboratory would allow for the integration of complete physics-based air and ground mechanics models of selective robots with candidate control systems in a simulated real-world operating environment.

Perception

Although the mission statement pertaining to perception research is rather broad, the actual ongoing focus is restricted to a rather narrow set of problems. It was not clear if this focus was driven by gaps or deficiencies identified by the Army or how the work fits with contributions from partners. As an example, perception needs to support more than obstacle avoidance; it needs to support a richer semantic understanding of terrain that would be useful for people as well as autonomous vehicles. Furthermore, there is a need to address scalability issues with regard to sensor capabilities, such as varying fidelity and power requirements with size. Sensors provide measurements of data pertinent to the operational environment. For autonomous behavior, however, it is necessary to process these physical measurements to glean information. In the area of unsupervised human detection, researchers need to explore a hybrid supervised/unsupervised algorithm that would not only be computationally efficient but could also curtail the number of false positives that the current approach seems to yield.

Sensors are also linked to communications. The processing and communications power available to a single platform determines what is transmitted—measurements, processed data, or commands. The work on parsing and action grammars could benefit from transmitting unknown constructed images over a communication network to a node with greater processing capability and reference data. In this context, focus needs to be directed at combining scene parsing, scene surface layout analysis, and 3D reconstruction to advance the state of the art in overall scene understanding.

It may be useful to place bounds on the problem dictated by mission requirements. This would help identify quantitative metrics against which progress in research tasks can be measured. Ongoing research in perception is aimed at enabling cooperative interaction between robots and humans at multiple levels. Accomplishing this within a mission context, accepted military doctrine, and social norms of the society in which the soldier-robot teams operate is a major technical challenge.

Robotic Intelligence

Overall, the research programs in intelligence reflect a broad understanding of the underlying science and research conducted elsewhere. However, researchers need to more clearly state the scientific problems they are addressing and the metrics they are using for evaluation. The work also needs to be properly placed within the current state of the art. Presenters need to better articulate the primary contributions of the research and how the presented approaches achieve those contributions. The recently hired Ph.D. researchers need to better clarify how their new work at ARL is going beyond their dissertation contributions as students.

More broadly, the challenges of robot intelligence specific to the needs of the Army need to be clarified. While the three areas related to mapping, control for communication, and cognition are important, they do not provide a perspective for the ARL vision for robotic intelligence for Army applications.

In the work on long-duration 3D mapping and navigation, there is a need for justification of why the approach performs better for this problem of long-duration mapping, including identifying metrics against which progress can be gauged. The scalability issues with the approach were correctly identified, and it will be interesting to see how the proposed strategy of forgetting parts of the map helps address this problem. In the area of robust control of mobility and communications, it is important to calibrate the performance of the approach against related methodologies in the fields of mobile ad hoc networking and optimization. There could be some important linkages of this work to the network sciences CTA, and that could present opportunities for leveraging.

The design of new cognitive architectures for control can play an important role in robotics. However, it is difficult to understand the benefit of this cognitive approach to the mapping problem. Many working solutions for mapping exist that do not make use of cognitive solutions, and it is not clear how such an approach improves mapping performance. The approach could instead be motivated by a different application domain requiring more high-level cognition, such as a scenario that entails going to the back of a building and watching a door for persons of interest.

Human–Robot Interaction

In the area of HRI interface design, the breadth of experiments is clearly commendable. The experiments, however, are conducted as separate efforts and employ different tasks. This limits the ability to draw meaningful insights from the results. For example, an Android touchscreen interface was compared to an Xbox controller, and separately a speech interface was compared to manual navigation through a GUI. An opportunity exists to place these experiments and results within a larger context and to interpret results across experiments to provide more general design guidance.

In HRI research efforts related to understanding automated system actions, the initial experiments provide encouraging results for simple task scenarios involving few factors at a time. There is a need for follow-on experiments that validate the use of visual aids when performing more complex tasks, particularly in a multitasking environment, and on dismounted soldier interfaces.

It is important to conduct more basic research that takes advantage of ARL's unique access to soldiers. As all of the services move toward the inclusion of more robot systems, it is necessary to conduct the basic research that will allow these systems to be effective and efficient members of the team. It was heartening to note the existing collaborations with researchers in cognitive architectures and perception. This model needs to be replicated across other projects at the 6.1 level, where HRI can help guide the development of capabilities that are still very difficult to achieve without a human in the loop (e.g., perception work). Even with increased system capabilities, both in terms of intelligence and perception, there will still be a need for a soldier to interact with the robot systems. The nature of the HRI will change, from remote operation to a supervisory role and, eventually, to interaction with the robot as a team member. HRI, however, will remain the key to the effective deployment of robots in the Army and other services.

The HRI group would benefit greatly from wider exposure. ARL could consider sponsoring a workshop that would discuss HRI from the soldier's perspective. In addition to inviting academics and people from the other service laboratories, sponsors of HRI research from other agencies such as the Office of Naval Research, National Science Foundation, Army Research Office, and Defense Advanced Research Projects Agency could bring valuable insight to this effort.

On a more general level, much of the work presented was mature; new opportunities for providing input and feedback on projects that were in their inception stage could be beneficial to the overall research enterprise.

Atmospheric Sciences

Future Army needs for environmental information and decision aids, particularly in aerosol and optics research—which is vital for understanding, collecting data within, and predicting the atmospheric boundary layer—would be significantly compromised unless adequate resources needed to build on the excellent and innovative studies currently under way are provided. The ARL team has developed a laser-based tool for capturing, holding, and analyzing an individual aerosol or dust particle. The ability to trap particles, expose individual particles to atmospheric oxidants, and monitor changes in particle morphology, chemical composition, and optical properties is highly significant and at the cutting edge of developments. This work alone has the ability to propel BED's Atmospheric Sensing Branch to the forefront of the atmospheric chemistry community. However, ARL may not be able to exploit fully this remarkable technology because of major cuts to BED's funding for aerosol and optics studies now planned for 2015 and 2016.

The lack of references to atmospheric science in the Laboratory's 20-year vision document is noteworthy. There is significant interdependence among the various elements of the atmospheric science research portfolio. For example, future advances in boundary layer turbulence and predictive modeling development are linked to aerosol studies, and these ultimately have an impact on imaging and optics. Eliminating aerosol research, which is exceptionally novel and of high quality, could significantly impact the other areas. BED needs to strengthen its efforts to communicate the interdependency of the major branches of its research and their individual and collective value for improving the Army's ability to understand and exploit environmental information to its advantage.

Most appropriately, DoD is directing significant resources in the newly emergent area of big data, with a special focus on data analytics. The atmospheric science community has been working with big data sets and extracting information for predictive purposes for many decades. It is important that the atmospheric sciences team has a seat at the table along with the computational and information sciences areas, with each sharing its history and capabilities so as to maximize synergy and rate of progress.

The transition of prediction technologies to operations is unusual in that the Air Force is responsible for providing operational weather products and services for Army operations. Matured predictive technologies developed in BED are passed to the Army Research, Development, and Engineering Centers in preparation for their implementation into the Air Force operations suite. Therefore, any evaluation of BED's effectiveness in this arena must take into account the collaborative relationship between Army and the Air Force and its effect on the technology transition efforts. Research in this arena is further complicated by the need to come up with immediate technical solutions to pressing operational problems of Army users.

There needs to be an emphasis on enhanced communications between division leaders at the laboratory, especially with a focus on possible synergistic activities and avoiding duplication of effort. As an example, it may not be advisable to spend considerable resources studying and developing ways of mitigating human heat stress in BED while the advanced materials group in another division is working on a new self-cooling suit that would achieve the same goal.

Atmospheric Boundary Layer Environment Model Development

A number of challenging issues need to eventually be resolved for ABLE to provide useful LES Nowcasts in the complex environments necessary for actual Army applications. For example, the existing subgrid-scale (SGS) closure scheme would likely be acceptable for grids as fine as several tens of meters, but a more sophisticated SGS may be necessary for the types of complex applications envisioned. Additionally, it is certain that the cyclic lateral boundary conditions commonly used in conventional LES systems cannot be adopted for real-case predictions in highly complex terrain. It would be useful to review the literature on realistic noncyclic lateral boundary problems for possible adaptation into future work. Extension to or coupling LES with deep convection models capable of modeling moist turbulence is also a possible topic for future long-term consideration.

Advanced Artillery Meteorology for Army and Marines

The difficulty in acquiring suitable firing-range data, in addition to the necessary atmospheric data, is a concern. This type of information is not easy to extract unless the artillery trajectory and wind profile data are automatically collected and stored for later analysis. If coordinated with a carefully planned set of weapons test-firing and special upper-air meteorological data, the new meteorological sensor array under development at WSMR may help provide the type of data sets needed to perform this type of definitive validation. Fuller potential of this work may be realized by transitioning to the newer BED models under development, specifically WRE-N and ABLE.

Aerosol Sampling

A significant challenge in the aerosol sampling work is to obtain real-time measurements that can be correlated to immediate effects on the warfighter. The project team has given thought to developing field-deployable systems to obtain real-time aerosol composition information that would be deployed for this purpose. Research also needs to be directed at obtaining a better understanding of heterogeneous (gas-particle) interactions to help quantify uncertainty in the reported chemical concentrations.

Effects of Atmospheric Conditions on Bioaerosol Viability and Optical Properties

Additional work is needed to examine the mechanisms of interactions with ozone (O_3) and with hydroxy (OH) radicals. This may involve laboratory studies where different mixtures of chemicals can be controlled. The project team has already developed a plan to conduct field-based experiments that would allow them to effectively assess the mechanisms of inactivity as a function of atmospheric chemical properties.

Data Assimilation Advances Supporting Nowcast Modeling

Further testing over a range of weather conditions and over various types of terrain is needed to determine whether a single optimal set of nudging weights and radii of influence is indeed acceptable. Data starvation experiments would be revealing, especially if conducted over a data-rich environment, such as the CONUS, where the rest of the data can be used for thorough evaluation of impacts.

It would be useful for the research team to perform experiments identical to those now being conducted with observation nudging but instead using one or more of the sophisticated data assimilation techniques now available. This is important for showing how differences in quality relate to computational complexity/domain size and location/run time; demonstrating the required trajectory of computing to meet future needs; and identifying ways of improving upon observation nudging. Additionally, as part of its data assimilation program, BED needs to consider undertaking the design of observing system experiments and observing system simulation experiments that would help answer such questions. In addition to the emphasis on model assessment via statistical approaches for measuring skill, there is a need to assess the value of forecasts. Fine-scale forecasting requires confrontation of the value/skill paradox, and ARL needs to collaborate with other groups that are dealing with this same challenge, such as the use of object-oriented verifications. The NCAR MET verification software, already imported and used by BED, provides a ready path for such collaborations.

Real-Time Atmospheric Imaging and Processing

It might be possible to adapt the technology to quantify turbulence along the path. The cumulative propagation effects (i.e., the distribution of power projected perpendicularly to the propagation) are related to the turbulence along the path. It is necessary to explore the feasibility of retrieving turbulence properties from such projections. Other methods for de-blurring images have been developed by the image processing community, and it would be helpful to present a comparison of the lucky fusion algorithm with these other techniques.

Development of a Meteorological Sensor Array at White Sands Missile Range

The addition of one or more upwelling infrared (IR) sensors would be quite valuable for capturing the diurnal structure of the atmospheric boundary layer and would help to increase the value of the network for broader ARL applications. Additionally, the network would be ideally suited for the use of mobile Doppler radars as an adjunct to the planned lidars and other above-ground sensors, especially during intensive observing periods. Maintaining the equipment and recording, archiving, and quality-checking the data streaming from an observing network of this magnitude will be a daunting task, despite BED's long history of atmospheric monitoring at WSMR. ARL could beneficially investigate direct collaborations with operators of large existing mesonets, especially with regard to data quality control, management, and availability of replacement components needed to operate and sustain an extensive network on this scale. It may be useful to consider embedding future installations of the network within other existing networks to leverage their infrastructure and share costs. An enormous range of scientific and technical expertise as well as monetary resources will be required to operate and maintain the network.

Multiscale Turbulence in the Atmospheric Boundary Layer

More attention needs to be given to identify the specific weaknesses in existing turbulence parameterizations within BED Nowcast models, whether it be those used for all turbulence scales, as in a mesoscale model, or those used for the subgrid-scale closure in LES.

Real-Time Detection of Nerve Agent Stimulants Using Multiwavelength Photoacoustics

Additional investigations to examine the effects of atmospheric chemistry, in particular the effects of O_3 and NO_x on the compounds of interest, are under consideration. Additional work is needed that specifically focuses on the potential interferences of OH radical chemistry with the sensing of the chemical agents of interest.

Nowcast Model Assessment

The problem of meaningful model evaluation at the scale of 1 km or less is particularly challenging, and BED is encouraged to assess existing model verification techniques for any gaps or weaknesses for its Nowcast model applications. There are relatively few examples of prediction verification for turbulence, boundary layer depth, and the range of variability in the boundary layer for wind, temperature, and moisture. Developing a comprehensive approach to identify previously ignored or underassessed boundary layer quantities of interest for Army operations, and developing appropriate verification techniques that leverage and extend the existing software would be valuable contributions.

Quantified Weather Impacts and Friendly vs. Threat Advantage

The project represents a welcome upgrade, but the team faces significant challenging questions: What is the best way to depict transitions between impact classes? How difficult will it be to incorporate the analogous threat-side thresholds? Are the measures of impact the same or different for friendly and threat forces, and on what basis? As noted with the advanced artillery meteorology project, the appropriate type of system verification and validation data will not be available unless rigorously defined field testing or an automated data collection scheme can be developed and executed by the team. There may be some benefit for team members to engage with researchers in the Next Generation Air Transportation System (NextGen) program who are developing automated decision assistance tools for air traffic managers to assess the adverse impacts of weather.

Computational Sciences

The overall research portfolio represents a good mix of projects covering ongoing high-impact areas of computational science research as well as emerging areas in which both the traditional HPC infrastructure (large center-based HPC resources) and nontraditional high-performance computing platforms (mobile/distributed heterogeneous computational nodes at the battlefield) can be leveraged to provide to the Army unique and novel capabilities.

A crosscutting area of opportunity exists around interoperable high-throughput run-time systems. Such run-time systems already play an integral role in the research related to programming models, distributed heterogeneous architectures, tactical HPC, and characterization of materials properties. This area needs to be considered a core research area so as to bring about a significant enhancement of capabilities and development of enabling technology for various computational and big data problems. There is a need to define the basic research problems, articulate strategies for sound software development, determine milestones and measures of success, and develop plans for field testing and pathways for deployments. There needs to be a concomitant focus on building close collaborations with outside entities working in this area to ensure that their work informs and is being informed by related research efforts.

The project on tactical HPC (cloudlets) is designed to provide capabilities and address issues that the commercial and academic research is just starting to consider. However, the number of research personnel assigned to work on this project is considerably smaller than what is required to achieve its objectives and make meaningful research and operational (via realistic proof-of-concept implementations) contributions. In addition, the research in this project could leverage some of the ideas that are being developed in the context of off-loading some computing power-intensive operations from cell phones to the cloud. Though this academic and commercial research is rather simple and deals with nonadversarial settings, it can still inform some of the design and algorithmic decisions. ARL research will benefit from getting data on soldier usage models through early-stage testing while development options remain flexible. It is also important to consider uncertainty in input parameters. Consequently, in addition to traditional linear programming, CSD needs to also explore techniques for optimization under uncertainty, including chance-constrained optimization and recourse optimization.

In the multiscale materials modeling area, it will be important to analyze fundamental limits to scalability and opportunities around data assimilation before investing in significant implementation efforts. Additionally, having professional software developers involved in the project will likely lead to a product that can be utilized more broadly in Army applications.

To provide meaningful cybersecurity capabilities, the research needs to quickly transition to detecting more sophisticated attacks such as distributed denial of service, Internet protocol (IP) spoofing, and misaligned packets.

CSD has initiated promising new projects related to software-defined networks, quantum computing, and quantum networks. These areas represent cutting-edge research. CSD is applying its computational expertise on addressing computational and methodological bottlenecks associated with analyzing very large data sets. The general area of data-intensive computing (big data) represents an application area in which CSD needs to focus in order to allow Army warfighters to obtain complete situation awareness and to respond in real time.

A key challenge is the understaffing in the CSD. More than 50 percent of the team lead positions are vacant, and many of the researchers are early-career. The branch chiefs are working as team leads, but they shoulder many disparate responsibilities in the various projects. As a result, many projects lack a sufficient number of senior, experienced researchers to lead, guide, and mentor the young researchers.

Network Sciences

In general, the quality of the presentations was quite good. It was clear that the presenters were working from a template to provide context about their projects. In some cases, there was no clear problem definition. A more effective standard format would summarize what problem is being solved, why it could be important, what is the state of the art, and what is being addressed in a given project. For ongoing projects it would be helpful to know what progress has been made since the previous review.

Some of the work presented was insular, however, and could benefit from more connections to outside work, including that being done in academia, industry, and other government laboratories. This was particularly true in the areas of social media and social networks, but also in other fields as well. As an example, in the area of cybersecurity, there is a plan to build a supervisory control and data acquisition (SCADA) test range, which may duplicate outside efforts (e.g., the SCADA test-bed at the Idaho National Laboratory). Such insularity lowers the effectiveness of the Army's investment in this research.

Greater interaction within ARL would be beneficial in some cases as well. As an example, research in the area of social media and social networks could benefit from interactions with the cybersecurity area. Similarly, even a very strong area of research like the E-field and RF measurement effort could benefit from greater interaction with the signal processing community in ARL. More generally, there is a good bit of effort on sensor information exploitation and fusion that could benefit from an integrated approach.

There is a need to diversify the talent pool in ARL to bring a broader range of ideas to some problems by adding strengths in areas such as the social sciences and mathematical sciences. There were instances in which broad interactions are already occurring. One such area is language technologies, which is very well connected to the larger community. Similarly, the work on temporal logic for intelligent systems has strong connections to NRL and AFRL.

The work on multiagent adversarial games is in the early stages, and so there are shortcomings. For instance, the context is not very dynamic, and the use of real-time feedback, which must be critical in tactical situations, is not overtly modeled. There is a wealth of relevant literature that could be consulted related to dynamic environments, adversarial intent, the impact of context, and individual versus small group differences. The simulations and modeling conducted had to rely on limited data and much speculation. Consequently, this research needs to have the best hypotheses tested with empirical data to see if it will have any real value.

In the project on data-driven analysis of collaboration structure and evolution, the results and methods are interesting, but it is not obvious whether the project is achieving its stated goal of understanding networks in unfriendly environments and detecting inefficiencies in tactical communications. The project could more directly benefit from the use of data sets that better align with these objectives.

In the project on operational management of networked robot operation, it was not clear from the presentation whether this was a between-subjects or within-subjects design. Nevertheless, the number of participants was too low to draw any meaningful conclusions. Other shortcomings of the study included only 5 cues out of 16 available (degrading the task condition), and fitting too many parameters for the ACT-R model.[5] Because ACT-R had to fit too many parameters, perhaps a different approach to human cognitive modeling could be pursued. If more participants were included, then signal detection theory

[5] ACT-R (short for "Adaptive Control of Thought—Rational") is a cognitive architecture: a theory for simulating and understanding human cognition. Researchers working on ACT-R strive to understand how people organize knowledge and produce intelligent behavior.

could be applied. Similar to the current approach of the robot operator giving advice, research related to a judge-advisor system might be particularly powerful.

In the broad areas of social media and social networks, industry (e.g., Google and Facebook) is investing significant resources on research. ARL will be better served by focusing on niche areas that are important to the Army and needs to yield on the more general problems that are being heavily researched elsewhere. There is some concern at ARL's Computational and Information Sciences Directorate (CISD) that leadership and responsibility for the area of social networking have been delegated to the Network Sciences CTA, and that ARL has not developed a pool of in-house talent to perform research that complements and leverages the work being done by the CTA. Besides needing additional social networking experts with strong analytical skills, ARL security protocols appear to limit the ability of the researchers to access the appropriate software needed for this work.

Research related to trust management and quality of information needs a better articulation of the conceptual framework and a clearer statement of the problem that is being solved. This is a promising area of research for ARL and could benefit from inclusion of social networking and social media experts with strong analytical skills. The work as presented did not effectively establish a case for why a trust management framework was necessary; the impact was lost in the jargon of trust management and value of information. Better use of Army-pertinent examples can forcefully establish the importance of the work and help to identify challenges that need to be overcome in ongoing research.

A related crosscutting thrust could be automated extraction and analysis of implicit canonical features in data. This could be useful to ground the value of information research. The image analysis group's approach to value of information is automated extraction of features followed by statistical analysis to identify and quantify anomalies. There is also ongoing work on use of automatically extracted features in low-resource language research.

Another potentially productive area of related research is to add a social network layer to the cybersecurity tool set that models organizational and command structure and to exploit natural language analysis capabilities. ARL would benefit by including research on a mathematical foundation for system cybersecurity in its science of cybersecurity research.

The project on a fuzzy logic approach for value of information focuses on how intelligence analysts use information in making recommendations to operational commanders. The particular emphasis of the work was on examining the way information was valued by the intelligence analysts. A fuzzy logic approach was used to model the value of information. While this approach can be effective by appropriately tuned quality function deployment (QFD), there is a need to compare the effectiveness against that of competing methods. In particular, switching from fuzzy logic to a Bayesian or other probabilistic or information integration modeling system would be useful. A complementary effort at ARL using Bayesian statistics for information integration was also presented, and this represents a natural pathway for possible collaboration.

The focus on cloud computing, which is primarily covered in the CSD, is an important thrust. Given the tremendous size of the problem and the embedded opportunities, however, an enlarged and integrated effort with network sciences is needed. In the external networking community, the design and control of data centers has been recognized as a research area of some significance; ARL needs to realize the scale of the challenges and opportunities that this offers.

There is considerable interest in research initiatives that integrate (1) materials science for new sources of renewable energy (e.g., solar cells) and (2) energy storage devices with energy management in networking (such as ad hoc routing of packets via nodes with adequate energy reserves) to provide assurance that tasks are completed. ARL is well positioned to conceive a broad, multidisciplinary, cross-organizational initiative in this area. This research would also have relevance to the issue of energy efficiency in data centers, which is a big problem in itself.

OVERALL TECHNICAL QUALITY OF THE WORK

In the area of autonomous systems, the piezoMEMS research and associated small robotics effort is first rate, with elements that are at the vanguard of this field. Specifically, the work in motion generation at the MEMS scale is seminal. Large-amplitude motions are being created at the micron scale using integrated actuators, structures, and electronics cofabricated on silicon.

In the area of atmospheric sciences, the development of a laser-based tool for capturing, holding, and analyzing an individual aerosol or dust particle adds a unique ability to monitor changes in particle morphology, chemical composition, and optical properties under changing atmospheric conditions. This work positions the ARL at the forefront of the atmospheric chemistry community.

In the area of computational sciences, the work related to multiscale modeling of materials, simulation/emulation of mobile networks, portable programing models and run-time systems for heterogeneous architectures, and tactical high-performance computations represents the state of the art.

In the area of network sciences, the work related to trust and quality of information has received broad recognition in the technical community. Similarly, the work on cybersecurity is of the highest quality and benefits from ARL access to real data.

Autonomous Systems

Many of the ARL internal research projects in the autonomous systems enterprise are of very high quality and have benefited from engagement with other research institutions, including partners in the CTAs. For each of the key areas—perception, intelligence and planning, human–robot interaction, and manipulation and mobility—the overall technical quality of the work is high and is being recognized as such by virtue of publication in archival journals and proceedings of recognized conferences and symposia. Also, the *Research@ARL* monograph series on autonomous systems[6] is commendable. For most of the work reviewed, the scientific quality is comparable to that being conducted at other federal research laboratories and at universities here and abroad. The research staff is very well qualified to undertake the research projects and is broadly aware of the state of the art in the field and ongoing research at other institutions. A number of research scientists have been newly recruited, and they promise to contribute to an exciting future for the ARL. Mentorship for these early-career scientists will be of paramount importance for their long-term success at ARL. The laboratory facilities and the infrastructure are state-of-the-art and supportive of the ongoing research activities.

Atmospheric Sciences, Computational Sciences, and Network Sciences

In general the quality of the work is high, and the research is having an impact. The trend in the overall quality of research is positive. There has been a dramatic improvement in quality since the 2010 review, although there are still pockets of research that need to be brought up to expected standards.

The work is on a par with that at other government laboratories. Specifically, research in areas of multiscale modeling of materials, simulation/emulation of mobile networks, portable programming

[6] Army Research Laboratory, 2013, *Research@ARL: Autonomous Systems,* July, http://www.arl.army.mil/www/pages/172/docs/Research@ARL_Autonomous_Systems_July_2013.pdf.

models and run-time systems for heterogeneous architectures, and tactical HPC are state-of-the-art. This represents a significant and continued improvement and is a clear indication that CSD's leadership and its research staff are making CSD a leading organization in computational science.

Seminal work is being conducted in deploying laser optics for the study of aerosols. Capabilities developed and demonstrated in this work were at the cutting edge of research in this domain. Work related to multiscale modeling of materials, simulation/emulation of mobile networks, portable programing models and run-time systems for heterogeneous architectures, and tactical HPCs represents the state of the art in the field. In the area of network sciences, the work related to lightweight intrusion detection in the context of cybersecurity is important. This work is novel and has potential for future development. The work on burstiness in intrusion detection represented a novel combination of statistics and computer science, and it has a strong basis in science and a good potential payoff. The research related to tactical communications, the work in robotics, the work in language technologies, and research on E-field measures in the standoff power sensor project was also strong.

The research being conducted in several projects by the Atmospheric Sensing Branch is of an exceptionally high quality, addresses cutting-edge problems, and can be applied to meet both internal Army needs as well as the needs of the larger atmospheric sciences community. Of particular note is the quality of the ABLE modeling research that is contributing to the fundamental understanding of turbulence anisotropy. Similar quality of work was evident in the project related to data acquisition at the Nowcast model scale, and data assimilation in the Nowcast model. The work related to data assimilation capabilities for very fine scale domains promises to be at the forefront of science in this field.

In some areas, the work leads that of academic institutions. As an example, in the area of network defense, ARL has a natural advantage in having access to a facility that provides actual data. Similarly, ARL research generates papers, patents, and other products that, in an academic setting, would be considered essential to establishing the impact of the work. Broader comparison against work in academic institutions is more difficult, because the ARL work and its objectives differ somewhat in nature and style, with academia focusing on graduate education. Overall, both the number and quality of journal publications seem to be increasing over previous years. Also, the *Research@ARL* monograph series on network sciences,[7] and imaging and image processing[8] are commendable. Conference presentations have declined for reasons discussed above. Although the work is of high quality, this is a fragile situation. Careful cultivation of the research culture and appropriate mentorship of the research staff are essential to place this progress on a firm foundation. Some of the presentations and research thrusts could be improved by better articulating and defining the methods that will be used to assess their results and the approaches against which they will be compared.

[7] Army Research Laboratory, 2013, *Research@ARL: Network Sciences,* March, http://www.arl.army.mil/www/pages/172/docs/ResearchARL_March2013.pdf.

[8] Army Research Laboratory, 2014, *Research@ARL: Imaging & Image Processing,* January, http:// www.arl.army.mil/www/pages/ 172/docs/Research@ARL_4_Imaging_Jan2014.pdf.

5

Human Sciences

INTRODUCTION

The Panel on Human Sciences at the Army Research Laboratory (ARL) conducted its review of ARL's Simulation and Training Technology Center (STTC) at Orlando, Florida, on June 18-20, 2013; its review of ARL's translational neuroscience program at Aberdeen Proving Ground, Maryland, on June 11-13, 2013; and its review of the soldier performance and human systems integration programs at Aberdeen Proving Ground, Maryland, on July 8-10, 2014.

Simulation and Training Technology

Broadly stated, the mission of STTC is to enhance readiness through research and development of applied simulation technologies for learning, training, testing, and mission rehearsal. The overall goal is to understand and opportunistically integrate the human science implications of these activities in order to optimize the behavior of individual soldiers and of small units or teams. One of the constituent goals is to understand and develop immersive technologies that are both operationally effective and cost effective for training and mission rehearsal, and to transition the next generation of modeling and simulation technologies to the future.

The STTC research program has four components:

1. *Adaptive training technologies program*. Its objective is to design, develop, apply, and assess artificially intelligent agent technologies—such as adaptive tutoring and virtual human tools and methods—to enhance training effectiveness and reduce costs. An important emphasis is on developing tools that allow others—researchers, instructional designers, training developers, and trainers—to efficiently author new training modules so that artificial tutors can be created for different training needs as they arise. The effort to develop a broadly applicable framework has

produced the STTC's generalized intelligent framework of tutoring (GIFT), which is a useful tool for the development and evaluation of intelligent training systems.

2. *Synthetic natural environments program*. Its objective is to enhance physics-based synthetic environment modeling, with a particular emphasis on dynamic effects such as changes in weather and lighting.
3. *Training applications.* The objective of this work is to create and test physical models and software-based simulations for diverse training applications such as medical triage, dismounted soldier operations, or training on specific ground platforms.
4. *Advanced distributed simulation program*. Its objective is to conduct R&D work in the area of software design to create a common core infrastructure and tool set to enable distributed and collaborative services in modeling and simulation. The long-term goal is to perform R&D aimed at integrated software architecture to support modeling and simulation across the Human Research and Engineering Directorate (HRED) and beyond.

This assessment is ARLTAB's first in-depth review of the STTC since its merger with the ARL's HRED in 2010. During the 2011-2012 review cycle, several STTC programs were presented as part of a broader review at the ARL HRED at Aberdeen Proving Ground, Maryland. The ARLTAB's 2011-2012 report observed that integration of the STTC into HRED would create great opportunities for human factors influence on STTC products and STTC enhancements of traditional HRED endeavors. The report suggested that the STTC and HRED increase their focus on human factors in training and continue to integrate STTC technical competencies with HRED skills in human factors research.

While some progress toward this goal was evident in the present assessment, the merger of STTC with HRED needs to be taken to the next level, with greater emphasis on integration of human sciences. The design and development of effective training systems is an inherently interdisciplinary enterprise necessitating an early and balanced collaboration between computer science and human science.

The installation of the STTC commander as deputy director of HRED is a commendable, vital step to integrating two strong organizational capabilities and cultures to the benefit of both ARL and the Army.

Translational Neuroscience

The goal of the translational neuroscience (TN) program is to integrate modern neuroscience with human factors, psychology, and engineering to enhance the understanding of soldier function and behavior in complex operational settings. TN is a unique and important effort whose objectives, if successfully accomplished, could be a game changer for soldier and mission effectiveness.

TN has concentrated its efforts on three research thrusts:

1. *Brain–computer interaction (BCI) technologies.* Enable mutually adaptive brain–computer interaction technologies for improving soldier–system performance.
2. *Real-world neuroimaging*. Assess those aspects of brain function that can be usefully monitored outside the laboratory setting and assess and/or develop the technologies that are best suited for this purpose.
3. *Brain structure–function couplings.* Translate knowledge of differences in individuals' brain structure and function to understand and predict differences in task performance.

From 2009 through 2013, the TN group made significant gains in publication rates and quality (from 16 publications in 2009 to 44 in 2013, including an increase in publications in peer-reviewed journals from 6 in 2009 to 17 in 2013); numbers of postdoctoral researchers (from 2 in 2009 to 11 in 2013); outreach and mentoring activities (from none in 2009 to 7 in 2013); and level of external funding (from $730,000 in 2009 to $10,750,000 in 2013). On these measures, the group has attained a level found in neuroscience groups at many first-tier academic institutions.

Soldier Performance and Human Systems Integration

The elements of soldier performance that were assessed were these:

- *Sensory perception*. The goal of research in this area is to understand the perceptual requirements of interpreting unaided and aided visual, auditory, and tactile signals in complex, dynamic, militarily relevant environments.
- *Physical and cognitive performance.* The goal in this research area is to investigate the physical and cognitive burdens on soldier performance and to develop design guidance for mitigating negative effects.
- *Human systems integration (HSI).* The goal of research in this applied area is to develop and enhance human performance modeling tools that enable early, cost-effective insertion of HSI criteria into acquisition requirements.

ACCOMPLISHMENTS AND ADVANCEMENTS

Simulation and Training Technology

The STTC mission is to improve training efficiency and effectiveness through technology. The projects briefed reflect an ongoing emphasis on technology for training the dismounted soldier, which is arguably the most difficult technical challenge and the area of greatest need in the Army today and for the foreseeable future.

STTC is tackling a number of very challenging technical problems in training technology, such as how to make tutoring systems that adapt to individual learners, how to best manage instructional experiences, how to make synthetic entities behave more intelligently in training simulations, and how to make training simulations more interoperable.

Many areas pursued by the synthetic natural environments technology group have great potential to set standards that other programs (and other Services) can follow. These areas include simulation in the cloud and terrestrial databases. The advanced distributed simulation (ADS) group therefore has a unique opportunity to generate guidelines or protocols for future developments across the DoD in these areas. For example, documenting the methodology, process, definitions, performance metrics, and validation tests for running simulations in the cloud, and identifying standards and technology to accomplish this, would establish a standard approach for the community.

The STTC work is significant and valuable in specific application domains (e.g., simulations of battlefield medical situations), as well as in the design of general tools for simulation (e.g., the generalized, intelligent framework for tutoring [GIFT]) to make it possible for others to rapidly create new training modules for areas with new content. Laudable progress has been made to date in the development of GIFT and in the incorporation of this framework into the computer game Virtual Battle Space II, used by the Army for training.

Translational Neuroscience

Over the past 6 years the TN group has received consistently high marks from ARLTAB and has been repeatedly cited as a model for how a new group can effectively be developed at a government research laboratory.

Publication rates and journal quality have continued to rise to impressive levels and represent a very significant accomplishment. While further improvement in the quality of journal publication is urged, the TN group's productivity is on a par with what might be expected from recognized academic institutions working in the domain.

The TN group has successfully attracted more outside funding and now enjoys a level of external support that matches that of most first-tier academic institutional groups in neuroscience. This is an outstanding accomplishment.

The number of postdoctoral fellows in the program originating from first-tier academic institutions has grown considerably. Overall, the program now employs an impressive group of early-career scientists. The consistent investment in the growth of access to intellectual capital is exemplary.

In 2012, HRED completed the renovation of its Aberdeen headquarters. This renovation included the construction of the new MIND laboratory for the neuroscience group. Although somewhat smaller than would be ideal, this lab is an excellent state-of-the-art facility that is well built and well equipped. It is likely to prove to be an excellent facility for the group in the years to come.

Brain–Computer Interaction Technologies

While ARL's program in brain–computer interaction (BCI) technologies is only a few years old, it has made significant strides in fundamental research and in the development of applications. ARL has carved out an appropriate niche in the BCI community and is well positioned with a clear emphasis on enabling practical BCI systems for soldier support. The decision to explore the integration of other sensing modalities—for example, electrocardiography (ECG), electromyography (EMG), galvanic skin response (GSR), and eye movements—into EEG-based BCI applications is conceptually strong and innovative. Overall, BCI has the potential to lead theoretical and practical breakthroughs in achieving maximum application performance with minimum invasiveness.

The applications and demonstrations shown indicated clear evidence of innovative fundamental and systems-based research. In particular, the integration of rapid serial visual presentation (RSVP) with the RAVEN system (RSVP-based adaptive virtual environment with neural processing) represents a significant fundamental advance. The cross-validation of performance estimates from two tasks (driving and RSVP) is a significant achievement, showing the generalizability of the work across multiple BCI applications. The application of transfer learning to train EEG classifiers using data from previous subjects is innovative and appropriate and has the potential to significantly reduce individual-specific training time needed for BCI systems. The use of sliding windows in hierarchical discriminant component analysis (HDCA) to deal with temporal variability in BCI responses is well considered and solves a significant practical problem in the performance of these systems.

Real-World Neuroimaging

The real-world neuroscience group outlined a project to develop novel EEG measurement technologies and supporting algorithms. The project goal is to design systems for specific tasks rather than a single system that can work in all contexts. Some substantive directions of the work were described, among them to overcome real-world limitations for use of the electrode system so that it works with hair, slips on and off easily without significant setup, and has high enough sensitivity to capture the signals necessary for the specific task. Overall, project goals and potential applications were clearly articulated and progress to date was illustrated by demonstrations.

Brain Structure–Function Couplings

Finite-Element Head Model

The finite-element head model project involves a rigorous method for incorporating anisotropic properties of biological tissue into a finite-element model for use in the development of head protective systems. This is an important goal for which the neuroscience group appears to be well qualified. The group evaluated this model using real brain-pressure data sets from a cadaver study conducted several years ago. The results demonstrated that the model was considerably more accurate than had been expected. A suggested future direction would be to model the diffusion tensor imaging (DTI) abnormalities from the postmortem brains of individuals with blast or concussive injuries. The effects of an intact, living vascular system, cerebrospinal fluid channels, and interstitial pressure gradients might yield a very different outcome than is seen in impact-damaged cadavers.

Functional Connectivity Project

The TN group appears to have made significant headway in assessing several tools for causal modeling in EEG data. These are state-of-the-art tools that have not been well tested or validated for EEG use anywhere else, and the TN group is doing a solid job of identifying the strengths and limitations of these approaches. Given the central role EEG plays in HRED's translational portfolio, undertaking this validation is an excellent use of resources. The approach is sound, and the tools seem to be undergoing reasonable validation.

Phase Synchronization Tools in Electroencephalography

The TN group has made good progress in assessing tools for measuring and identifying phase synchronization in EEG data. These are tools that have not been well tested or validated anywhere else. Given the central role EEG plays in the TN portfolio, this project reflects an excellent use of resources. The approach is sound, limitations of the tools seem to be well identified by the research, and methods for maximizing EEG signal in a fieldable device are being developed.

Decision Making in the Field Project

Using advanced psychological models of decision making in a simulated checkpoint screening task, the TN group is assessing the degree to which mission or task biases can be adjusted by instruction and incentives. The work is of very high quality and Army-relevant. It will likely provide important data about how soldiers and officers take mission instructions into consideration and how effectively they can adapt their behavior to the needs at hand, and it might even offer insight into training effectiveness. In the future, the project needs to be expanded to disentangle expertise effects from task difficulty effects, and it also needs to allow for assessing the difference between soldiers and civilians in these kinds of tasks.

Soldier Performance and Human Systems Integration

In general, significant gains were evident in publication rates, numbers of postdoctoral researchers, and collaborations with relevant peers outside ARL. Awareness and effective leverage of the pertinent research literatures were clearly in evidence in most areas. The research work environments were impressive in terms of their unique and advanced technology capabilities to support research. The research staff were confident and passionate about their work, and, in particular, ARL has done a commendable job by hiring clever postdoctoral researchers who are self-motivated and excited about the research. It was also evident that ARL has acted on earlier ARLTAB suggestions to good effect (e.g., by initiating a seminar series featuring external and internal speakers). Overall these are outstanding accomplishments and mark a visible advance over prior years.

Sensory Perception

The research is conducted in three major thrust areas: fundamental sensory capabilities of the soldier; methods, devices, and technologies for aiding perception; and advanced approaches for augmenting perception.

Overall, the presentations and posters were clear and focused and benefited noticeably from an organized approach and a consistent template for conveying the information, which facilitated the panel's ability to process the information and ask relevant questions.

Progress has been made in each of the three thrust areas. Specific achievements include (1) an empirical characterization of the probability of detection of low-contrast, moving images in the far visual periphery; (2) the completion and report of several studies evaluating the effects of headgear and hearing protection on sound localization; (3) the completion and report of studies on listener perception of small arms fire; and (4) the completion and report of studies investigating unconventional modes of communication (bone conduction and the tactile modality). Important future work is being planned to understand how soldiers recognize and interpret relevant operational and battlefield sounds in complex natural scenes.

In general the research design of the reported studies appears appropriate for the specific goals for which they were intended, and the psychophysical methods employed, if not always the most accurate or efficient, appear at least adequate. Some of the work has been published in premier scientific journals (e.g., Pollard et al., 2013,[1] and Tran et al., 2013[2]), a good indicator of the quality and significance of the research.

On the whole, the research questions addressed by the reported studies were well motivated and in keeping with the general charge of this group. Each question also gained significance by its ability to be identified, more or less directly, with a broader research question aggressively pursued in the scientific research literature.

The research greatly benefited by the superb facilities made available to ARL researchers, most notably, the environment for auditory research (EAR) and the computer-assisted virtual environment (CAVE). The research also appeared to benefit from reported collaboration with investigators at several universities across the nation.

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[1] K.A. Pollard, P.K. Tran, and T.R. Letowski, 2013, A free-field method to calibrate bone conduction transducers, *Journal of the Acoustical Society of America* 133(2):858-865.

[2] P.K. Tran, T.R. Letowski, and M.E. McBride, 2013, The effect of bone conduction microphone placement on intensity and spectrum of transmitted speech items, *Journal of the Acoustical Society of America* 133:3900-3908.

Physical and Cognitive Performance

The presentations and posters were very well prepared, organized, and executed. Generally, the programs in this area were addressing practical problems and issues relevant to the Army mission. The experiments were generally well designed according to solid experimental psychology principles. They included good quantitative biomechanical measurements (e.g., projects on the effect of physical load and environment on soldier performance and on the effect of weapon recoil on marksmanship) and some good examples of competent and sophisticated data analysis (e.g., the project on estimating soldier ground reaction forces using activity monitor acceleration). The research staff were very enthusiastic and seemed excited about the idea of doing translational research that has practical outcomes. Scholarly productivity was evidenced by some important publications in academic journals of the just-mentioned projects.

Human–Systems Integration

Improved Performance Research Integration Tool (IMPRINT) is an important human–systems integration (HSI) tool and a signature program of ARL and has had widespread use and considerable continuity for more than 20 years. Since the last ARLTAB review, ARL's HSI group has collaborated with systems engineers, which is necessary for the continued advancement of this tool.

HSI researchers have been working on several mobile applications that show great promise. Of particular note is the Work Activity Observer, which is a mobile application that can be downloaded for free. This appears to be an easy-to-use tool that holds promise for the collection of collaboration data for applications outside the military.

There are two postdoctoral researchers planned within the HSI team, and they, like the other postdoctoral researchers hired by ARL, appear to be highly energetic and enthusiastic. The expertise of these researchers complements that of the existing HSI team.

HSI researchers have leveraged expertise from external institutions, which helps them in areas in which they may lack strength. Of particular note is the current collaboration with Dr. Matthews of the University of Central Florida, a renowned expert in human performance and stress.

OPPORTUNITIES AND CHALLENGES

Simulation and Training Technology

General Opportunities and Challenges

The Role of Human Sciences

Training simulation and human behavior representation are inherently interdisciplinary R&D domains that would clearly benefit from the integration and balancing of insights and the connection of ideas from the diverse perspectives of the computer sciences and the human sciences. It is evident that STTC has its strong suit in computer sciences. The paucity of the human science research presented to the review panel made it equally evident that, as it stands, STTC is weak in this area—for example, cognitive and perceptual psychology and human factors—and is losing the potential benefits that often come from the fusion of alternative technical frameworks and approaches driven by human sciences. For example, human sciences identify a wealth of variables and data in the areas of sensation and perception (visual, auditory, tactile, olfactory); attention; problem solving and decision making; learning;

motivation; emotion and mood; social factors; human workload; human factors/ergonomics; psychometrics; individual differences; and cognitive modeling—all relevant to immersive learning, adaptive tutoring, performance in synthetic environments, and assessment of performance.

The merger of STTC with HRED was a very well conceived decision by Army management that needs to play out more effectively than it has to this point. The main challenge lies in the integration of STTC into HRED in a manner that is useful to both. The human sciences, available more generally at HRED, need to be considered early in the requirements phase and then throughout the design of simulation and training systems. The training technologies being developed have significant implications for humans and their ability to acquire task-critical skills and to become proficient performers. It is difficult to design training software without an appropriate understanding of the instructional objectives and human responses to the training environment. For example, how can one know how much fidelity is needed in different aspects of the simulation without understanding the impact of fidelity on learning and retention? Other vital areas that would benefit from considering human sciences include expertise and the elicitation of expert knowledge, identification of training objectives, feedback, team cognition and learning, student and expert models, learning processes, transfer, and retention.

Insular Community

As described above, the technical challenges faced by STTC are multidisciplinary. Though there is a valuable concentration of simulation and training expertise in Orlando, STTC needs to engage and leverage the broader national and international simulation and training research communities as well. A large component of the STTC R&D staff appears to be bred and trained by a handful of local institutions. As a result, they appear to be somewhat insular with respect to the communities of practice from which they draw. The ARL STTC team needs to consciously recruit at all levels from outside "Team Orlando." Constraining recruiting and hiring to the military, local industry, and local universities will lead to isolation from ideas current in the broader S&T community. While there is evidence of senior leadership participating in occasional international conferences, wider engagement of the research staff with the broader national and international research community through publications, invited speakers, scholars in residence, conferences, internships, and postdoctorate positions is warranted.

The problems being tackled by STTC are large, complex, important, and currently relevant to the modeling and simulation community. However, there are also many researchers working on these issues in academia and in other military laboratories outside the STTC environment. STTC researchers need to clearly define and focus their efforts within the broader scientific community, identifying precisely where they expect to advance the state of the art. It was not clear where the original research presented fit (or was framed) within the broad base of existing scientific literature. Although some work was described as applied research, the value case was not established with respect to specific Army training applications and problems.

STTC is in a unique position to enable collaboration between military-subject-matter experts, trainers, and trainees with computer scientists and simulation specialists. Developing training technology with specific users in mind and developing an in-depth understanding of their needs (as was done by STTC in the medical simulation area) would lead to more focused research and more useful results. Some of the ways to accomplish this might include applying human factors models of task requirements and human capabilities/limitations, identifying relevant individual differences, testing prototypes, soliciting feedback from trainees and subject-matter experts, and collaborating on design and testing. It is important to maximize opportunities to engage with military-subject-matter experts and users at training centers, battle labs, and similar venues. While current budgetary and policy constraints are self-evident, external engagement needs to be a management priority.

Relationship with the Institute for Creative Technology

The STTC is the government program manager for a University Affiliated Research Center, the Institute for Creative Technology (ICT) at the University of Southern California. The ICT receives 100 percent of STTC basic research (6.1) funding and needs to be integral in addressing some of the STTC's basic research questions. It was not clear, for example, how STTC requirements are communicated to ICT or how ideas feed down from ICT to STTC. This is obviously a relationship that can be exploited to broaden perspectives in both directions: people closer to the user community and people closer to research. The ICT, however, is assessed by a separate Army assessment board, and the ARLTAB was not asked to review the ICT.

Publications

STTC's output of peer-reviewed publications is low. Aside from the work presented in the area of adaptive tutoring, which identified a half dozen reports in venues other than DoD-related conferences, STTC presenters identified almost no publications contributed by the work presented. Publications are more than a simple indicant of quality. Active publication systemically drives quality in S&T cultures and organizations. Engagement in the publication process subjects the research to rigorous review, generally improving it and increasing quality. Furthermore, publications encourage project completion deadlines, polished results, and thoughts about the next steps in R&D. They are also a means to increase visibility in the research community.

It is important that STTC aim to publish in high-quality venues—for example, in top journals and at conferences that require full papers, where each paper is reviewed by two to four outside reviewers (not on the program committee). Its papers could then be indexed in catalogs and collections that are available to students and researchers (e.g., *IEEE Explore* and *ACM Digital Library*).

Observations on Individual Projects

Immersive Learning and Intelligent Tutoring

The goal of the Learning in Intelligent Tutoring Environments (LITE) group is to develop an adaptive, computer-based tutoring system that selects optimal instructional strategies to meet the specific learning needs of individuals or teams; assesses trainee attributes (e.g., progress, behaviors, and physiology); uses these attributes to classify states and predict learning outcomes (e.g., performance, skill acquisition, and retention); and then adapts the instruction to influence learning. This is clearly an important and challenging problem for the STTC, and the general approach the LITE group has taken to the problem seems to fit well with the broader mission of the STTC. The approach is to develop a flexible, modular system that can be used by individuals who are not computer experts to support a broad range of different point-of-need training challenges.

There are some challenges for this broad area. First, the complexity of the problem being tackled requires a multidisciplinary approach. As discussed earlier, there was little evidence of expertise in the areas of human cognition, attention, motivation, emotion, or perception outside those listed as external advisors to the program. These areas of expertise need to be intimately involved in all stages of this type of research. Secondly, it appears that little progress has been made on the immersive aspect of tutoring. From the presentations it was obvious that a large investment in effort has already been made in investigating a few specific factors such as "voice of God" (i.e., a computer voice not identified with a virtual team member or instructor provides feedback to the trainee) versus socially grounded tutoring, windowed versus embedded tutoring, and navigation by mouse versus joystick. However, it was not clear why these particular factors have taken on such importance in light of the many other factors that are more likely to enhance the immersive experience. Among these would be sensory inputs (full field of vision, auditory stimuli, tactile stimuli, and, for some applications, olfactory and gustatory stimuli) that provide cues and feedback relevant to a trainee's decisions or actions and that facilitate the transfer of training to real-world situations. Another challenge and area of concern was the lack of attention to the issue of readiness for general and online training. The assessment of learner readiness, temperament, and personality has been shown to be a critical step in the pedagogical development of training materials; given the normal and expected diversity in learner backgrounds, it deserves to be a priority.

Adaptive Tutoring Research

The adaptive tutoring research initiative is focused on tutoring technologies that can equal or exceed skilled classroom instruction or skilled human tutors. The focus on tutoring technologies tailors learning activities to the state of the learner or group of learners using adaptive machine-learning methods. Overall, the vision for this research is very ambitious, and the issues being addressed are very important, such as modeling cognitive and affective states, instructional management, and the rapid development of expert models. The research group has apparently reviewed a wide range of existing work in intelligent tutoring, is building on what exists, and seems to be grounded in both empirical and theoretical work. The research studies presented were focused on motivational issues related to stress or boredom that might be translatable to dismounted individuals in complex and team missions. What were not clearly stated was how the R&D agenda is being driven by specific Army training needs and how some of the ICT work on training is being incorporated.

The domain of adaptive tutoring research is enormous. The research program would benefit from a tactical evaluation and staging of subgoals. For example, to what degree should the focus be on tutoring individuals in specific skills versus tutoring and training platforms for multiple agents or teams? The issues, solutions, and products could be quite different. Discussion with the STTC group indicated that the priority was on team training. However, the product cited as very successful was a mobile improvised explosive device (IED) trainer that was primarily for training individuals to recognize IEDs using preprogrammed training regimens.

Another issue is the degree of simulation fidelity required for successful adaptive tutoring. The demonstrations implicitly assumed that very high visual fidelity is desirable and will improve effectiveness of training. However, high-fidelity visual displays may not be the limiting aspect of tutoring environments where joysticks or other simplified tools of action are used to, for example, replicate the physical movements of the agents. If the idea is to train sequences of behavior or logical decision trees of a mission plan, then perhaps visual fidelity, which may be too expensive, could be reduced in favor of focusing on training properties more critical to transfer to real missions. This is yet another illustration of the need for integrating more human sciences into the R&D effort.

A third issue is whether to focus on training for general situations or for preparatory rehearsals for actual missions. Training for general scenarios might be very useful; for example, the practice of responses to low-probability event structures that would infrequently be encountered in a real situation yet must be among the trainee's repertoire for robust performance. In this case, there is little necessity for integration of real three-dimensional (3D) terrain mapping or urban mapping of specific locations. On the other hand, if the goal is a preparatory rehearsal for a mission, software support that is effective in integrating real-world mapping data may be quite important.

Effective adaptive tutoring is likely to increase the interplay between computer science approaches and human science specialists in relation to the delivery of sensory inputs, the biosensing of the emotional or motivational state of the individual, learning theory, and adaptive testing. It would be useful to identify several high-priority, prototypical applications as benchmarks for testing development. The project must incorporate human testing and evaluation early in the design stage when deciding about where to spend resources in the development of technological systems so as to maximize human learning and performance.

Overall, this group is cognizant of the need to integrate knowledge from the existing literature and has done a fine job engaging the academic side of intelligent tutoring at well-selected conferences that are likely to provide far more rigorous reviews than DoD conferences. The group has been effective in establishing a board of advisors made up of distinguished subject-matter experts from industry and academia. These advisors can serve them well if effectively used as critical and constructive reviewers of their ongoing and planned research. Overall, this team exhibited a strong sense of teamwork and passion for the research as well as an attitude strongly supportive of the development of technical skills and the education of junior scientific members.

Generalized Intelligent Framework of Tutoring

The GIFT framework is a laudable effort to establish a general framework for intelligent tutoring. The GIFT demonstration illustrated a computational platform early in development that ambitiously aims to provide a structured environment for the authoring and managing of individual and complex multiactor team tutoring by individuals with less specialized technical and programming skill. The framework was outlined, but no details were presented on its significant components, such as the expert or student models or the selections of instruction. A wide range of sensors and the limitations of those sensors were discussed. However, there was no justification for the sensors that were selected with respect to their relevance to learning the task at hand. For example, is a full-motion platform that enables the trainee to experience walking in the game justified if a joystick is adequate for what the trainee needs to experience for the task at hand?

GIFT has potential to become a useful and important framework for embedding results from the center's research and solving some of the Army's training problems. It is also early enough in development to reconsider its design priorities—that is, to consider implementing a truly adaptive assessment and training system within a pedagogical model that could better drive the system in the direction of the tutoring, training, and simulation problems, which are the highest priority of the Army.

An alternative might be to consider studying and integrating truly adaptive aspects of existing tutoring products in domains such as mathematics and knowledge space theory. These applications map dependencies between target skills or knowledge (skill A generally precedes skill B) and use probabilistic testing to first assess current knowledge and performance and then to determine what might best be trained next. The knowledge spaces of the military training applications may be flatter and less complex than domains in mathematics, but they might still exhibit strong content structure. Knowledge structure approaches, if applicable, could provide important information about readiness to learn subskills that could be critical in effective use of time on training. Trainee performance data may validate content structure analyses and need to be considered an important tool in product development. Further, to the extent that many aspects of military training have already been codified in procedures and sequences of training activities, there may already exist structures for starting to define the relevant content domains.

Explicit Feedback with Game-Based Training

Current game environments provide only implicit feedback. To enable explicit feedback, STTC has embedded intelligent tutoring functions in games through embodied pedagogical agents (EPAs). This represents an effective use of an existing technology investment (Virtual Battlespace 2 [VBS2]) to perform studies and collect data. Since the VBS2 gaming system is becoming more prevalent in the Army, integrating GIFT with it is a good strategic move for future tutoring, because trainees will have a common platform they can use for a range of tasks. The integration of GIFT enables them to collect information in real time for after-action review and to correct trainees in real time so they do not repeat erroneous behavior.

The study on EPAs presented was an excellent example of the use of the human sciences to design intelligent tutors. The study was grounded in social cognitive theory and was a simple, well-designed test of the increased efficacy of embodied agents in providing feedback. EPAs were used as instructors or team members from different sources (e.g., GIFT or embedded in the game). The idea of GIFT turning a player in the game into a tutor appears to be a very natural way for a trainee to learn—that is, from other teammates (albeit virtual). In this study, simple verbal feedback was about as effective as embodied agents feedback. This simplified the demand characteristics of instructional game design in contrast to the literature, which suggests a larger impact for embodied sources. However, it may still be that an actual embodied agent (e.g., a military expert) could be more effective in, say, transfer, suggesting the need for further study.

Modeling Learner Mood in Real Time Through Biosensors for Intelligent Tutoring Improvements

This study is based on the idea that if the stress levels of individuals could be tracked and classified in real time, then training regimens could be monitored to advance training without triggering a stress response. The study included a number of biomarker measurement devices, including sonar (for distance measurements), a device for measuring pupillary response of the eye, a heart rate sensor, a higher-end electroencephalogram (EEG) system, and an inexpensive, 14-channel, simple EEG system. Trainees completed tasks and periodically self-reported their stress state. Several data-mining techniques, including simple regression and several machine-learning clustering techniques, were tested for their ability to learn to classify the biosensor data using the trainee rating as the target. This is essentially a test of the success of several different classification algorithms. The results had yet to be tested with the usual forms of classification cross-validation, nor had the quality of classification been determined with different subsets of biosensor inputs, highly relevant if the aim is to classify trainee reactions based on small numbers of inexpensive sensors.

The development of simple biosensor-based assessments of stress has the potential to make useful contributions to monitoring trainees. The project would benefit from the inclusion of human science specialists in physiological response monitoring for EEG and heart rate and pupillary dilation to place the data mining of biosensor measures for classification within large literatures related to human physiological responses.

Synthetic Natural Environments

The research programs in synthetic natural environments are focused on computer technical developments that will generate large-scale, realistic, immersive environments. The researchers cite the need to integrate 3D information about environments and the detailed information required to simulate urban warfare environments in high resolution. The goal is to incorporate and simulate weapons and machine impacts in these environments, which requires sophisticated models of the physical world. For example, models of building strengths and stressors in the urban environment are necessary to implement realistic consequences of simulated interventions.

Real-Time Dynamic Physical Effects in Army Synthetic Environments

The project demonstration in this area clearly illustrated the need for faster computations in order to create useful environments with realistic physical effects. There are interesting elements to this work. One is the ability to adjust fragment grid size to achieve performance. Another is accepting (for now) simpler models (without drag) to achieve subsecond results with full knowledge that more powerful processors will allow more faithful models in the future. However, the approaches presented did not take advantage of current and newer hardware architectures, such as graphics processing units (GPUs). All the work presented was based on traditional central processing unit algorithms. STTC needs to advance its research in this area toward the more general trend in the computing community if it wants to remain a leading research group in this discipline.

Terrain Generation

It was indicated that the current state of the art of terrain database generation is costly, slow, and complex and not up to the challenge posed by the need to dynamically represent high-resolution urban terrain. The ambitious challenge addressed by this STTC effort is the assumed need for effective and low-cost representations of terrestrial line of sight; dismounted and mounted maneuver; weapons effects; close air support; intelligence, surveillance, and reconnaissance; and communications. However, it was not fully evident that the fundamental requirements of tactically relevant ground force simulation are best served by the stated objectives: to minimize cost, complexity, storage, and licensing fees. Perhaps it would have been more illuminating if the case had been based on a critical evaluation of contemporary practice against the inherent interoperability requirements of live, virtual, constructive, and gaming simulation.

Cited plans for future research included rapid database generation for mission planning, exploitation of comprehensive feature extraction from lidar[3] and hyperspectral imagery, and real-time processing of aerial- and ground-collected data. There was no evidence of STTC expertise in this area; STTC needs to pursue aggressive evaluation and exploitation of contemporary geospatial data sources such as Urban Feature Data Level 3, Specialized Urban Topographic Data Store, and Multinational Geospatial Co-production Program products from the National Geospatial-Intelligence Agency or the Homeland Security Infrastructure Program. Like the presentations on real-time dynamic physical effects in Army synthetic environments, there was little discussion about how newer hardware architectures, computing methods, and management approaches could help with this work.

[3] Lidar is a remote-sensing technology that measures distance by illuminating a target with a laser and analyzing the reflected light.

Human Representation

STTC reported on work to improve the physical representations of humans—for example, representation of human gestures and movements in distributed simulation, which are a serious shortcoming in current systems. However, the progress achieved since 2010 was not made evident.

The reported work with Soar, which is aimed at enhancing the intelligence of agents in order to enable consistent social cultural behaviors, is commendable.[4] However, the degree of social and behavioral realism for synthetic forces continues to be a challenge and a concern. The complex challenge of modeling creditable tactical behavior in computer-generated forces requires ongoing collaboration and engagement between military subject-matter experts, computer scientists, and human scientists. In particular, there needs to be explicit guidance from cognitive and behavioral scientists on the level of realism and fidelity in training applications. For example, in training simulations that involve interaction of avatars with foreign agents, emphasis on the facial expressions, pupil dilation, body language, and other features is paramount; if resources are limited, it is important to scale back other less critical features of the environment.

Future research areas in synthetic natural environments cited by STTC included improved immersive capabilities involving acoustics and tactile feedback support (haptics). Distributed simulation systems as early as SIMNET achieved considerable perceptual stimuli from dynamic acoustic cues (e.g., munitions effects, vehicle operations). Such auditory inputs are critical for monitoring and maintaining situation awareness. Background sounds are sometimes a critical cue. For example, lack of normal activity played a big role in alerting experienced soldiers to potential terrorist threats in Afghanistan and Iraq. STTC's stated intention to pursue investments in localized acoustic, haptic, and olfactory stimuli is appropriate.

Advanced Distributed Simulation Research

Overall, the challenges addressed by the advanced distributed simulation (ADS) research group are of great importance to the simulation community and the Army training mission. This group has very strong skills and backgrounds in computer science and software engineering, which gives it a great foundation for designing and building stable, well-engineered simulation systems. Computing technology is changing rapidly, and the ADS group needs to track and leverage leading advances in industry because it will not be able to accomplish the needed advances on its own. The STTC group has developed some important strategic relationships with the information and communications industry (e.g., Intel). Moreover, the shared computing infrastructure in Research Park is a great resource to leverage for managing costs.

The ADS group has a good appreciation of existing standards, commercial off-the-shelf technology, and open source tools that it can leverage to enable it to focus on the new developments that are needed. Examples of this include modeling and simulation (M&S) standards from the Simulation Interoperability Standards Organization, virtualization, cloud computing infrastructure, and others. However, keeping up with technology evolution will be a continuing challenge. For example, there was no mention of work with GPUs or of any intent to implement parallelization or to leverage multicore processors. Also, there was no mention of big data, analytics, or computational social science, all of which are relevant to the work the group is pursuing. It could be that partners in Research Park with whom it is collaborating already cover these technologies. Having a technology roadmap would help ADS to determine which partners to leverage for those technologies important to achieving program objectives.

[4] Soar is a cognitive architecture used to model different aspects of human behavior.

Overall, the ADS group appears to be staying reasonably abreast of research in the simulation community. This gives it an appreciation of open technology issues that need to be addressed, such as the behavior of semiautomated forces, simulation in the cloud, and realistic locomotion in virtual environments. The group's publications appear to be mainly in connection with nonacademic, nonrefereed conferences. It needs to branch out to academic-type conferences, where the review process is more considered and thorough. This will also expose it to a broader range of work in the M&S and computing community beyond that being accomplished in Orlando and at the University of Central Florida.

The Science Behind Executable Architecture Systems Engineering

The executable architecture systems engineering (EASE) project is tackling some very difficult and important problems in training simulation interoperability and is focused on creating an easy-to-use environment for running simulations in the cloud. While STTC is not developing any of these simulations, it is developing the approach and methodology to easily set up and run the simulation.

While this is recognized as an important problem to resolve, the group did not present clear evidence that the approach taken can succeed given the scale and complexity of the experience provided by real training environments. The presentation's high level of abstraction made it difficult to determine how much of the work is focused on infrastructure and how much on simulation interoperability issues. For example, simply having an infrastructure that enables simulation to communicate is not the same as semantic interoperability. It appears that this has been initially designed for a very limited, known set of simulations to simplify the overall problem. However, it was not clear whether there is intent to expand the set of simulations to lesser known systems or, if there is, whether the project's methodology is capable of addressing them.

One of the features of the proposed system is to provide users with a simple interface where they can answer questions about what they are trying to accomplish (e.g., purpose or scenario), after which the simulations are automatically set up in the cloud. One such question proposed for presentation to the user concerned the necessary level of fidelity. Given how fidelity is defined and mapped to a given simulation, it could be very challenging for a user to know what fidelity is needed from a training perspective.

This area of research opens for STTC a real and strong opportunity to lead future developments in synthetic natural environments by using its research efforts to generate guidelines and protocols on how simulation software needs to be developed, aimed at the long-term goal of an integrated infrastructure in modeling and simulation.

Training Applications

Live Training Research Objectives

This project was focused on potential technological improvements in the widely used laser tag live training systems. Challenges exist, for example, with respect to the extension of firing trajectories from direct line of sight and improvements in positioning information relative to the target. Current weaponry increasingly uses nonlinear trajectory targeting that requires computational solutions rather than direct sensing. A related goal is to more clearly understand which parts of targets have been hit, and this requires extended sensor arrays and damage models that might predict survivability of human agents or functionality of larger-scale equipment such as tanks or vehicles.

The importance of this work to the Army was well communicated, particularly with respect to the importance of identifying and avoiding friendly fire incidents. Future developments stemming from this project could provide identification information for friendly agents and a processing system that would support large-scale, complex, multiagent situations.

These projects were tightly coupled with widely used training technologies, and the described projected improvements in next-generation modules and sensor arrays involve fairly straightforward, though important, technology upgrades. This technological development track needs to incorporate human science and human factors input to effectively address questions such as: Which functions should be assigned to the human and which should be automated? When should human judgment override a computer-aided decision? How should such decisions be communicated? Answers to such questions will provide boundary conditions for any new systems.

Next-Generation Common Multiple Integrated Laser Engagement System

This work deals with the specific issue of weapons' targeting precision using laser propagation. The presentation focused on the laser propagation and signal detection science and did not address the human user (shooter and victim) element of the system or how this might play into training. The research team comprises engineers without representation from the human factors perspective. This was evidenced by the quest to achieve realism without addressing the assumptions underlying its value to training.

Dismounted Soldier Training Research Objectives

The objective of this advanced technology development (6.3-level R&D) program is to support Training and Doctrine Command (TRADOC) Warfighter Objectives to improve virtual immersion, locomotion, and avatar intelligence for training dismounted soldiers. STTC is addressing important challenges for the effective use of mixed reality, including the volume and weight of backpack needed to do the computation for the training, locomotion using joystick interfaces, and comfort issues associated with heads-up displays. These systems raise many questions about which aspects need to be simulated from a training effectiveness perspective. For example, what are the implications of not representing with adequate fidelity the auditory, tactile, or olfactory sensory cues in training and rehearsal activities?

Improving the intelligence and realism of synthetic entities (e.g., opposing force) in simulations and training games is an important issue and has generated a great deal of research. As it did for the other projects it presented, STTC conveyed the idea that realism is a reasonable goal for its own sake and worth the cost. A huge issue from the human sciences perspective is this: What level of realism suffices in time of high stress, particularly tempo-related stress, where high quality may not be possible owing to sensor and computational constraints such as dynamically changing terrain? Will the current warfighters insist on videogame visual quality in a training system if training stress can be raised to approximate that of action in the field? How important is simulating more realistic motor performances, fatigue, or stress through general levels of noise and other inputs? What is good enough in which situations?

Medical Simulation for Training Research Objectives

The medical simulation technologies used in training for medical interventions provided a model case for front-end analysis of downstream application needs and a model of the use of technology to provide suitable training and general exposure to individual medical personnel. This "full recurrent cycle" process—applying, sequentially and recursively, assessment, planning, implementation, and reassessment—seemed a model that could be extended to other research programs.

Several of the demonstrations entailed very detailed renderings of hypothetical environments. This raised interesting questions about whether these are necessary for effective training and whether they might constrain training to these unnecessarily detailed representations and, in effect, reduce the transfer of training. Evidence was not presented to permit determination of whether joystick interfaces are sufficient or whether more emphasis should be placed on the natural sensing of motions and their translation into virtual reality environments.

The STTC work in this area appeared strongly linked to actual needs of the medical instruction community. Researchers said that they had had to find the gaps in needs and knowledge themselves. Of particular note are the efforts this group made to observe at the Multiple Amputation Trauma Trainer at the Army Medical Center in order to better capture the relevant parameters for their simulation scenarios. As a result, they developed strong ties to the medical training community, understood its needs (e.g., instructor overload), and developed training systems that have been successfully transitioned to field use for medical training.

Use of Holography in Medical Training

This project examined the requirements for holographic representations of the human body for medical training. This is a new and potentially expensive technology that needs to be weighed against alternative technologies (e.g., motion-based animations of human body and brain systems now available in inexpensive applications for cell phones or iPads) that could prove as effective as or even more effective than holography from a cost and training perspective.

Incorporating odor into medical training simulations is a relevant consideration, because numerous studies have revealed that unexpected or unpleasant odors can be a significant distraction in the field. Prior training that includes exposure to malodors that could be encountered is a way to immunize the warfighter or medic against the loss of concentration or attention as well as to minimize the likelihood that the odors can become associated with stress and later serve as triggers for trauma. There is also significant benefit in augmenting training by multisensory information beyond the medical domain, because warfighters can encounter unusual, unexpected, or unpleasant odors in a variety of deployment settings.

Virtual Locomotion Concepts and Metrics Study

The stated objective of the work is to achieve natural and humanlike locomotion in virtual space. The study team seemed well abreast of the current state of this technology and related research, and it has been able to effectively create a complex, real experimental condition against which to compare the virtual techniques. The experimental conditions included a good selection of movement gestures, including jumping, squatting, crawling, and climbing; the data show that the encumbrance of real gear makes some gestures difficult, just as it makes some real locomotion hard. It is well documented in the literature that users want to be able to move in any direction while gazing in a different direction. Locomotion techniques that do not allow this separation of view direction and movement direction are, in a sense, noncompliant with respect to best practices and ought not to be included in testing designed to find the most natural locomotion technique.

High-Fidelity Character Autonomy for Virtual Small-Unit Training

This work was presented using realistic dynamic behaviors and intelligent decision making based on situational context and the decisions made by other players. STTC is using the Joint Simulation Bus developed by the Office of Naval Research (ONR) to allow connectivity with different game engines. The game environment is a potential constraint due to the product's behavior (i.e., the conceptual model established for the game world). Another potential constraint came from the selection and use of a legacy system and architecture that had originally been developed based on different assumptions and technology than are currently available. Therefore, it was not clear how this product would benefit training.

Translational Neuroscience

Many of the challenges in the TN program represent opportunities to do more of what the group is already doing.

Brain–Computer Interaction Technologies

BCI technology based on neural recordings has emerged over the past 15 years as an important subfield of both TN and bioengineering. This is evidenced by the dramatic increase in the number of publications and presentations related to BCI techniques in neuroscience journals and conferences.

ARL's mission focus on healthy soldiers poses an interesting challenge for BCI research, since the common goal of most BCI research is to treat or assist patients with sensory, motor, or cognitive disabilities. Hence, instead of using BCI technology for control as most clinically relevant BCIs do, the TN group has focused its efforts on the detection of mental states such as fatigue (state-based BCIs) or of external events such as relevant targets in a visual scene (event-based BCIs). Because their goal is to assist healthy soldiers in the field, the ARL researchers have resorted to the only currently viable noninvasive technology, namely, EEG electrodes placed on the scalp.

The BCI program is largely predicated on the assumption that computers and humans have complementary strengths (e.g., processing throughput versus higher-level reasoning and reliability and objectivity versus flexibility and situation awareness) and that hybrid systems leveraging BCI have the potential to achieve performance levels that neither a computer nor a human could achieve individually. This is a compelling notion, but it is not fully clear how the ongoing efforts and future plans specifically leverage, demonstrate, and validate it. There is the opportunity to do so, for example, by comparing the RAVEN system performance using RSVP-based BCI against state-of-the-art machine vision and automatic target recognition (ATR) algorithms. Such a comparison would show that the flexibility and situational awareness of humans greatly contribute to a computer system's ability to detect and recognize targets and other items of interest.

While the performance estimate cross-validation work is technically impressive, it is important to note that these systems are effectively detecting performance (often with significant delay) rather than predicting it in a temporal context. This may not be inherently problematic, given that some applications may benefit from BCI-based performance detection if performance assessment is not possible through other means. The group's claims to have the ability to predict poor performance before it begins to set in (e.g., early detection of fatigue that may lead to poor performance) need to be tempered. In point of fact, the current BCI system cannot determine if the brain is in a state that leads to poor performance or if the brain is just reacting to the poor performance (but see Baldassarre et al., 2012).[5] The goal of this

[5] A. Baldassarre, C.M. Lewis, G. Committeri, A.Z. Snyder, G.L. Romani, and M. Corbetta, 2012, Individual variability in functional connectivity predicts performance of a perceptual task, *Proceedings of the National Academy of Sciences* 109(9):3516-3521.

research is ambitious and laudable and will necessitate a deeper understanding of the brain response and/or a demonstration of true temporal performance prediction.

Given that the BCI technology program is still in its infancy, the advancements in individual projects are impressive. However, the emphasis of the presentations on such projects made it difficult to appreciate the long-term vision of the program and the nested fundamental research questions and application goals that will be addressed as the program matures.

Reliability has become an important concern in the BCI field as is evidenced by the Defense Advanced Research Projects Agency's (DARPA's) program in reliable neural interfaces. For BCI systems to become widely used in clinical and nonclinical applications, it is crucial that electrodes continue to record stable signals from relevant brain areas for at least months and ideally for many years. This is a particularly serious problem for invasive electrodes, where foreign body reactions and the intracranial environment can affect signal quality and stability. For noninvasive EEG electrodes, the exact electrode placement can vary slightly every time the EEG cap is removed and reattached. The TN group needs to investigate whether its EEG-based BCI systems that have been calibrated for a particular subject can continue to detect relevant states and events over weeks to months without resorting to recalibration of the decoding algorithm.

It is widely assumed that field potentials recorded from different EEG electrodes provide partially redundant information. Redundancy is important because it can buffer these BCI systems from catastrophic failure and allow for graceful degradation. On the other hand, redundancy may allow BCI systems to transmit data from a smaller number of electrodes, thereby reducing the bandwidth requirements, which may be particularly relevant for wireless transmission. The ARL needs to explore the degree of redundancy in its systems by examining state- and event-detection performance as a function of the number of electrodes used, much as researchers who use invasive electrodes perform "neuron-dropping" analyses.

On a related note, it would be useful to explore the spatial organization of information content across the scalp. Are there certain cortical regions that provide more accurate detection information than others? Is the information distributed evenly across the scalp? For example, there is evidence from single-cell recordings in nonhuman primates that neurons in the inferior temporal (IT) cortex modulate their firing rates to targets that are to be searched for in a complex scene in a visual search paradigm. Responses are enhanced in IT neurons that "prefer" the target, whereas responses are suppressed in neurons that do not prefer the target. Do EEG electrodes located over the temporal lobe provide better target detection capabilities than electrodes over the occipital, parietal, or frontal lobes? This suggestion to exploit the redundancy of multielectrode signals can be viewed as an alternative to source location, discussed above.

The applications of the BCI systems that were presented were limited to state- and target-detection requiring no more than 1 bit of information. It might be useful to explore opportunities to extract richer information content than can be available with EEG alone or together with other biosensor technologies. For example, would it be possible to detect multiple levels of fatigue, attention, and arousal? Could EEG systems be used to detect states associated with subjects' ability to acquire information or to learn? Could the RSVP target detection system be expanded to detect more than one target class? For example, an operator might be looking for two different types of aggressors in a visual scene and respond differently to each.

Although their target detection system based on RSVP is quite impressive, it will be important to validate it against several control conditions to ensure that the improvement in search speed is attributable to target detection from the EEG system. One control condition would be to compare search speed using randomly sorted images that are not sorted via the EEG system. Another control condition would be to compare search speed using different machine vision and automatic target recognition algorithms to perform the sorting of images with potential targets instead of the EEG system. Such comparisons would help validate the larger claim that hybrid human–computer systems, leveraging their complementary strengths, can perform better than either system alone.

Real-World Neuroimaging

The TN effort to develop nonproprietary dry electrodes is a very challenging area wherein a breakthrough could significantly impact medical EEG, human factors, neuroeconomics, and neuromarketing and likely lead to important new applications. The integration of electrode technologies with thoughtful statistical analyses for the purpose of artifact detection and classification could bring important and valuable contributions.

The TN group has designed a very sensible balance of projects in the portfolio and has organized a strong international collaboration to help achieve the group's goals. Among these goals are the following:

- *Phantom head development.* The work in support of the EEG phantom presents a good opportunity to perform standardized testing. The goal of having a real-world system requires the group to do viable real-world testing that extends to different levels of sweating and motion.
- *High-risk dry-electrode project*. Given the focus on dry-electrode pads as a key impediment, it would be useful to conduct analyses of the computational and energy requirements for a real-world system. For example, how much energy, processing power, communications capability, and data storage will be required? Furthermore, will new algorithms be required to handle the additional challenges of the real-world environment?

The current-generation dry-electrode system is in an early stage of development. The published time series from the electrode that was initially provided did not include measurements of brain waves. Fortunately, the panel was updated with sample brain wave recordings collected in real time. These indicated that while the overall stability of this dry electrode is impressive, the signals are very small. They detect large artifacts, and it is not evident that cortical potentials are being picked up.

The TN group needs to compare the scalp measurements of these electrodes with other active dry EEG electrode systems (e.g., Gtec medical engineering) to ascertain the advantages and disadvantages of different approaches. Should there be significant differences in the scalp data, say in the signal-to-noise of averaged event-related potentials measured using the different dry electrodes and wet electrodes, the group might further make measurements of impedances and signals, humidity and perspiration testing (i.e., salt bridges), electromagnetic interference, and a standard 10-20 system for comparison of topography with the wet system to check for antenna effects from high-impedance electrodes.

The group needs to continue to consider alternative electrode types and analysis and signal enhancement methods that can reduce artifacts from electrode movement. Measures for evaluating signal quality need to be developed, and the TN group needs to ensure it is aware of and understands the lessons learned from prior work in this area.

Relevance to Protection from Traumatic Brain Injury

While the ARL is focused on the performance and protection of healthy individuals (it has noted that medical conditions are outside its mission), the problems that the group does focus on are relevant to performance and life-threatening situations that are commonly encountered by Army personnel and that are poorly understood. For example, a major threat to the performance of military personnel, during peacetime as well as wartime, is traumatic brain injury (TBI), particularly mild traumatic brain injury. Reports of soldiers recently returned from combat in Iraq found that 22.8 percent had sustained a TBI and that most of these were mild. The TN group has the potential to model and predict which areas of the brain are most susceptible to various mild TBIs and can in turn use these data to help guide the design of protective gear to militate against these injuries.

Obviously the work by TN could be of significant value with respect to identifying areas of TBI. For example, moving this work beyond impacts that might result from a blunt object striking a forehead could lead to techniques for identifying areas of brain damage when the injury is not detectable by routine imaging.

Soldier Performance and Human–System Integration

The portfolio of research is much applied and is very relevant to current Army needs. These needs could be better balanced by the addition of basic science efforts that get ahead of the current requirements. Current applied research often depends on past fundamental research. Therefore, strategic investments in basic science today can provide the options for responding to future requirements. Perhaps the relationships built through customer-driven work can be leveraged for support of the science needed to solve emerging and potential future problems.

In a similar vein, one would hope that there is an appreciative yield from past investments in research that is sufficiently mature for transition. However, the linkage between the research and applied functions of ARL human sciences is not apparent. For example, the Army's manpower and personnel integration (MANPRINT) program could provide an accessible transition path for maturing human-science-based technologies—for example, from the soldier performance and equipment advanced research (SPEAR) and EAR facilities.

ARL could better capitalize on its historic role over many decades of investing and innovating in military human sciences and engineering. It is generally accepted in the research and development field that past investments in fundamental research have led to important applications that were not anticipated at the time that the work was undertaken. It is quite probable that current proposed game changers—for example, programs sponsored by the Defense Advanced Research Projects Agency (DARPA) and the Iron Man suit program—have been enabled by specific advances gained from ARL's legacy of research and technology investments. An exercise that identifies and maps these linkages could be a worthwhile exercise for proposed new investments in fundamental science.

Generally, the ARL portfolio, as presented in this review, represents good, solid research, development, and applications. However, there were no individual efforts that stood out as especially innovative and exceptional.

Sensory Perception

The reported increase in use of the EAR facility by external parties involves some limited collaborative efforts between ARL staff and external investigators.

With a few exceptions, evidence of progress was given in the form of ARL internal reports, papers from meeting proceedings, and papers in preparation or in review. This group needs to be challenged to publish more of its work in mainstream, peer-reviewed scientific research journals, which is probably the best indicator of the quality and significance of the research.

The paucity of publications outside of ARL internal reports also causes the research of this group to appear somewhat insular. Reinforcing this view is the apparent lack of collaboration among researchers within the group. As described, the work on vision is largely conducted independently of the work on audition, and the work on audition is largely independent of the work on tactile modality. While this is a natural requirement of certain specific research questions, the broader charge to this group requires significant interaction among these sub-specialties. It is also worth noting in this regard that the reported collaboration with investigators outside ARL often involved no more than participation on a student's dissertation committee.

The restrictions on conference attendance (except for postdoctoral fellows) impair the ability of the working scientists from gaining prepublication knowledge of what is being done in their field or from obtaining important feedback on their current efforts. A seminar series bringing in outside speakers shows progress toward solving this problem; however, attendance at either a generalist or specialist meeting can, in a few days, expose the scientist to dozens of new discoveries and ideas, well ahead of publication in the literature.

Several projects were led by engineers who did not have formal training in human experimentation, and this significantly affected the quality and interpretability of the work. Experimental psychologists (or experimental researchers from allied fields) need to be part of the design process from the start, either as team members or as internal consultants.

Given the complexity of the charge given to this group, future progress will almost certainly require a significant multidisciplinary, collaborative approach involving individuals with expertise in the areas of engineering, physics, psychology, and the social sciences. The ARL's open campus initiative appears directed to this goal, and the sensory perception researchers may stand to benefit by doing what they can to take advantage of this initiative.

There is expressed interest in and there have been efforts toward integrating other sensory modalities into this group (e.g., olfaction). Given the complexity of the environment surrounding the modern warfighter and the wealth of current knowledge regarding multimodal interactions, these efforts need to be amplified; to this end the team is encouraged to seek out experts in areas that are not represented or are underrepresented at HRED. The efforts of a group working on multisensory cybernetics appears to hold promise for progress in this area, but it will be important that they are integrated at early stages with the researchers conducting fundamental sensory studies.

The International Multisensory Research Forum provides a platform for scientists from around the world who are interested in how different senses interact and how their input is integrated to communicate with one another. There are numerous laboratories training graduate students and postdoctoral researchers in this area, and it would be beneficial for ARL to consider hiring a few such individuals who could be positioned to work with and across the auditory-visual-tactile (and eventually, olfactory) research groups.

Physical and Cognitive Performance

Understanding the Effects of Physical Load

A number of high-quality research projects are being conducted in this area. Participating researchers are enthusiastic and feel that they are making a difference in improving soldier performance. There are a number of issues that are not currently addressed, but the team is well aware of the challenges ahead. For example, the portable measurement system used to estimate the ground reaction force can generate a huge amount of data that makes it impossible to analyze data manually and effectively. There also appear to be some limitations and concerns with the use of the CAVE for testing: tasks performed in the CAVE facility suffer from more errors and poorer performance than tasks performed on the computer or in the real environment. This was most apparent in the presentation describing a study on the effect of physical load and environment on soldier performance, and it raises questions about the utility of a two-dimensional (2D) display for extrapolating effects to real-world soldier environments.

One major obstacle in conducting physical load experiments is securing soldiers to participate in the research program. Although the group claims to have maximized the use of available soldiers for this purpose, the low participation rate makes it difficult to understand the entire spectrum of the soldier population in terms of age and gender. There are alternatives recommended to mitigate this effect. For example, if soldiers have other duties and cannot come to the laboratory, maybe a portable laboratory could be designed that allows researchers to acquire the data in the field. Additionally, attempts could be made to conduct research in parallel to gather as much data as efficiently as possible using the limited available soldiers. For example, estimation of vertical ground reaction force from accelerometers can be completed in parallel with measurements of horizontal ground reaction force, thereby enabling one set of experiments to obtain data for both projects.

Under the current Army command system, medical-injury-related research projects are not part of the ARL mission. Peak performance and injury can sometimes be separated by a thin margin. For example, a tired soldier may not be able to effectively use his/her muscle to protect his/her bones and joints, and so it becomes easier to sustain an injury. Setting such constraints could waste resources when trying to identify the source of injury. It can be imagined that the current group can only exercise a soldier to a fatigue stage, while the medical research group may push slightly further to identify the threshold of injury. The Army would benefit from more collaboration between ARL researchers and Army medical teams to reduce waste and identify physical markers as indicators for injury prevention.

In order to disseminate the knowledge gained in the current group, several outreach activities are being done with other teams within the Department of Defense (DoD) and with international organizations. The list of activities is impressive and deserving of continued encouragement.

Understanding the Effects of Cognitive Load

Soldier performance as a product of biodynamics and cognition is an important way forward. To succeed using this paradigm, it would be very helpful to have stronger theoretical frameworks from cognitive science for developing hypotheses and for generalizing results to new situations. While highly focused experiments are useful for solving practical problems, it is difficult, if not dangerous, to generalize to other situations and problems without the guidance of theory to identify how new factors interact. The experiments described during the review were narrowly defined by customer-driven military applications; more basic research is needed to prepare for solving future problems.

Therefore, the research program needs to effectively leverage theories from cognitive science and higher level cognition (e.g., decision sciences). In particular, two areas could be useful for theoretical guidance. One is the work on decision models that provides a theoretical basis for predicting the relations among choice accuracy, decision time, and confidence. This refers to the extensive work on what are called sequential sampling and accumulation models of decision making (also known as random walk or diffusion models of decision making). The second theoretical area that is important to consider is perception action models of motor movement that arise from the ecological psychology work. It would also be worthwhile to integrate more work on team decision making.

More broadly, the program needs a bigger and stronger vision for organizing the next generation of advances, and the researchers need continued encouragement to be ambitious and attempt more dramatic improvements—for example, bigger advances in the improved performance research integration tool (IMPRINT) program and more empirical validation of the integrated system predictions.

Equipment and facilities available to the group are very good and are fully utilized for ongoing projects. However, such facilities are also available in a number of university settings, and the group may want to consider the acquisition of high-end facilities to establish its exceptional quality as a leading laboratory. For example, the motion analysis system could be equipped with even faster speed of motion data acquisition to better understand impact. Also, augmenting the 2D virtual reality with a three-dimensional (3D) system could be very useful for advancing research in this program.

Human–System Integration

The HSI group needs to develop a clear scientific vision and charter that clarifies responsibilities and delineates a path for future research. This vision would best be developed in parallel with the current mission of addressing customer needs by identifying opportunities where specific customer needs can drive more general research questions.

There appears to be a gap in expertise in key areas within HSI. For example, the HSI group could benefit from expertise in theory and modeling in both cognition and complex systems. In general, some of the work could greatly benefit from a stronger link to current research. Some research areas (e.g., adaptive interfaces) have evolved tremendously over the past 5 years; keeping up to date on ongoing research is vital to avoid unnecessary duplication. For example, the work on development of the next generation of adaptive interfaces seemed to be quite preliminary and conducted in a very insular manner. It does not appear to take into account numerous recent studies on adaptive interfaces.

It is important that HSI researchers continue to leverage the expertise of postdoctoral researchers, other ARL colleagues, and other research institutions to fill gaps in the training and knowledge of their research staff.

ARL has the opportunity to be on the forefront of the research in this area, and, for the most part, the researchers are doing very interesting work. However, the current portfolio of projects within the HSI area may be too customer-driven. ARL could leverage this applied work and/or fund companion projects to advance the science base for HSI as well as broaden the impact of the work beyond the immediate customer. Specific customer needs will often have broader research questions embedded within them, and effort is needed to identify and address them to the extent possible within project and funding constraints.

In the past, ARL has been a leader within the military services in advancing HSI, specifically in the development of the MANPRINT tools and techniques. Continuing to invest in this area can help the HSI group to be on the forefront of development of modeling and analytical tools to support effective human systems integration. In particular, there are opportunities to leverage the specific applied work they are engaged in, so as to (1) advance the behavioral science that is needed to inform HSI issues (e.g., innovations in adaptive interfaces; tasks that may increase the likelihood of injuries); (2) perform the fundamental work needed to establish the validity of the models and tools they are developing; and (3) expand the impact of the work within and beyond their immediate Army customers (e.g., via development and validation of more generic models or guidelines).

IMPRINT

A compelling scientific vision is needed for the IMPRINT tool. The existing work appears to be piecemeal and customer-driven. IMPRINT is an important tool that has the potential to contribute significantly to the HSI community. For instance, there are currently very few quantitative tools for HSI that can provide detailed information on cognitive performance. To realize its potential, however, the

IMPRINT group needs to broaden its base of expertise beyond systems engineers and human factors scientists to include additional interdisciplinary collaborators, based on the topic areas being addressed.

The IMPRINT tool needs to have the capability to measure and model cognitive performance beyond speed, accuracy, and cognitive load. There is a specific need for more detailed models of cognitive performance in many potential areas of application. For example, modeling the decision to switch from an M4 to an M14 weapon could clearly benefit from understanding the cognitive requirements of tasks beyond mental workload (e.g., decision making, situation awareness, and communication). Many tasks, like this one, are predominantly cognitive in nature, and modeling them using IMPRINT in its present form will be limiting.

As part of the vision for IMPRINT, it would be useful to identify the most critical future research areas and develop a plan for validation for an overall model, not just separate plug-in modules. Studies that focus on improving IMPRINT and testing the validity of each component as well as the overall model would be very useful. Likewise, it might be useful to identify and address the more general research issues associated with federating models that contain different levels of detail and different views of a system—for example, IMPRINT and unified modeling language models. Given the limited resources within HSI to conduct more fundamental research in this area, bringing external experts together for an IMPRINT workshop could help chart a way forward for both future research and overall model validation.

In the project presentations researchers did not provide an obvious link between the traditional HSI tools (e.g., IMPRINT) and the survivability research (e.g., the operational-requirements-based casualty assessment [ORCA] model), but in discussions, several HSI researchers were able to elaborate the connection. More specifically, many injuries are related to the specific tasks, and HSI can contribute to this knowledge by identifying the tasks that have the greatest impact on performance.

The HSI group could collect and document successful case studies that show measurable impacts of their work with citations to other tools and human sciences research. For example, there is a paper from the Coast Guard that won a best paper award (the 2012 David Meister Award at the Human Factors and Ergonomics Society Meeting) with the use of IMPRINT, and such success stories could help showcase the value of IMPRINT.

The HSI group is commendable for continuing to refine and improve the usability of its models and tools such as IMPRINT and for using these tools to support specific Army applications, but the research being conducted could have broader impacts.

OVERALL TECHNICAL QUALITY OF THE WORK

Effective human system performance is essential to Army mission effectiveness, and ARL's investment in quality research and development in the human sciences has potential for significant impact on the present and future Army.

The natural tension between the comfortable technology pull of customer-driven work and the disruptive potential of innovating through technology push needs to be better balanced toward impacting the Army of the future.

The core quality of the research presented, the capabilities of the leadership, the knowledge and abilities of the investigators, their productivity, and proposed future directions are continuing to advance on a positive vector. The facilities are, for the most part, state-of-the-art, and, in general, the researchers demonstrated outstanding and effective leverage and collaboration with the broader scientific communities.

Simulation and Training Technology

STTC has historic strength in computer science and engineering and has developed a number of successful technology-enhanced training products. The ARLTAB's assessment recognized these accomplishments and also examined how the performance of the STTC might be improved by integrating additional scientific expertise, exposure to new or alternative scientific approaches, and tactical consideration and staging of project goals.

Overall, STTC has a clear and substantive mission with many important and unique objectives. The problems being tackled by STTC are large, complex, and important and have huge potential value to Army mission readiness and effectiveness. Technical problems include identifying, for example, how to develop tutoring systems that are adaptive to individual learners, how to best manage instructional experiences, how to make synthetic entities behave more intelligently in training simulations, and how to make training simulations more interoperable. STTC researchers are pushing the state of the art of simulation in the cloud and protocols for advanced distributed simulation (ADS). The ADS group has a unique opportunity to lead future developments across the DoD in these areas. The STTC work is demonstrably significant and valuable in specific application domains (e.g., simulations of battlefield medical situations), and the design of general tools for simulation (e.g., the generalized intelligent framework for tutoring [GIFT]) makes it possible for others to rapidly create new training modules for new content areas. Laudable progress has been made to date in the development of GIFT and in the incorporation into this framework of the computer game Virtual Battle Space II, now being used by the Army for training.

The Orlando-based leadership and scientific research groups exhibited a high level of professionalism, commitment to high technical standards in their projects, and a broad appreciation of their role in enhancing military and human outcomes. The esprit de corps and desire to integrate innovative and effective research strategies were notable in both research teams and leadership. Investment in professional development and training of junior scientists was a priority of the program. The STTC is an excellent research unit that embodies high technical standards and strong operational attitude.

Much of the work presented represents an interesting intersection of M&S with computer science. In this context it is important that computer science be recognized as broader than software development: It includes artificial intelligence, intelligent systems, parallel and distributed systems, social media, online learning communities, digital media and gaming, big data and analytics, computing performance, networking, graphics, and visualization. Many research groups at STTC tend to focus on a specific problem domain and simply and selectively use computer science disciplines to create better simulations. Owing to the breadth of work being done at STTC, the staff members are in a unique position to establish themselves as one of the leading research groups working at the intersection of M&S and computer science. While basic research is done by the ICT, STTC can still (and needs to make the effort to) integrate research from ICT and others, as well as innovate in the application of these technologies into real-world programs. This would require achieving a broader view of the intersection of computer science and M&S and creating a technology roadmap and strategy for how to accomplish this goal.

The research presented by STTC would, to varying degrees, benefit from integrating human science experts (e.g., human factors and cognitive scientists and social psychologists) into the research teams. For example, one of the goals of the simulation technology group is to push the envelope of simulator fidelity, whether it is the number of live users using the system or the physical realism of the system. Some of these issues are mainly technical, but in many instances they could benefit from human science experts. For example, knowledge about human perceptual limitations could steer simulator designs and, in turn, not waste bandwidth pushing unnecessary data. Conversely, it could also reveal areas where computational resources should be concentrated (e.g., in auditory realism). Related to this is the idea of satisficing in simulator design. That is, what level of fidelity is adequate for satisfactory training to occur? Overall, some of the areas could benefit from a systems-engineering approach that views the simulator not just as hardware and software but as a complete system of interdependent elements that includes human operators.

The incorporation of human science approaches and human science professionals in the research teams and in the specification of internal standards could enhance the human science expertise of the researchers, augment functionally engaged scientific advisory arrangements, and expand training opportunities for both senior and junior scientists.

A strong related suggestion is that STTC work to improve the quality of its user study designs, including design of the data analysis. The studies it conducts are costly, and it is vital to be certain that they are both gathering sufficient data on the critical variables of interest and performing well-designed statistical analyses. Technologists are not trained experimenters and will likely benefit from expertise identifying proper independent and dependent variables, measures, and study design elements such as between- or within-subject, needed sample size, and elimination (or mitigation) of confounders. This is another area where closer engagement by human science researchers can pay off, because these subject-matter experts are generally well trained in experimental design and statistical analysis of both quantitative and qualitative data.

Translational Neuroscience

Overall, the quality of the research presented, the capabilities of the leadership, the knowledge and abilities of the investigators, their scientific productivity, and proposed future directions are impressive. The work is well aligned with the clear and substantive mission to move neuroscience from the laboratory to real-world military settings—that is, from the bench to the battlefield. The TN group conducts high-quality neuroscience research that is routinely validated by its publication in recognized, peer-reviewed journals and is on a par with work at a good university neuroscience department.

The TN program is a unique and important effort that is tackling key technology bottlenecks to moving neuroscience from the laboratory to the field. For example, they are exploring the integration of other sensing modalities—ECG, EMG, GSR, and eye movements—into EEG-based BCI applications; approaches to overcome real-world limitations for use of the electrode system so that it works with hair, slips on and off easily without significant setup, and has high enough sensitivity to capture the signals necessary for specific tasks; and the development of nonproprietary dry electrodes, which, if successful, could significantly impact medical EEG, human factors, neuroeconomics, and neuromarketing and could lead to important new applications.

The group leadership is highly effective and qualified, and there is a palpable energy and enthusiasm in the strong mix of early-career and mid-career scientists. The facilities are, for the most part, state-of-the-art, and the group demonstrated impressive leverage of and collaboration with the broader scientific communities at universities, industry, and other government laboratories.

Soldier Performance and Human Systems Integration

The quality of the research presented, the capabilities of the leadership, the knowledge and abilities of the investigators, and proposed future directions continue to improve. The facilities are, for the most part, superb, and collaboration with the broader scientific community is generally good. Overall, ARL has the opportunity to be on the forefront of the research, development, and applications in these areas for the DoD and, for the most part, is doing interesting work. The work is generally solid, but perhaps a bit closer to turning the crank than being out on the cutting edge in the areas of interest. This is, no doubt, a function of the customer-driven nature of the projects that constitute much of the portfolio. ARL could leverage a portion of these assets for support of higher risk fundamental science that advances the state of knowledge and/or developments aimed at leading the way with challenging innovations.

6

Mechanical Sciences

INTRODUCTION

The Panel on Mechanical Science and Engineering at the Army Research Laboratory (ARL) conducted its review of ARL's mechanical sciences research and development portfolios at the Aberdeen Proving Ground, Maryland on May 28-30, 2014. The areas of mechanical sciences that were assessed were mechanics, propulsion, and reliability and diagnostics. During the 2013 review, the panel supported the assessment of the autonomous systems; the results of that assessment are presented in Chapter 3.

ACCOMPLISHMENTS AND ADVANCEMENTS

Mechanics

The laboratory facilities are impressive, including the subsonic wind tunnel and facilities supporting work in propulsion and additive manufacturing; these facilities can enable ARL to establish leadership positions in mechanical sciences areas. The facilities would also be attractive to collaborators. Several researchers have industrial backgrounds; this is the strength of the research team.

Recent work on damping augmentation using nanomaterials to tailor interfacial properties of critical vehicle structures is an especially strong activity. The work contributes to useful technology, and the researchers' approach and vision bridge fundamental questions with applied research.

ARL facilities and personnel at the National Aeronautics and Space Administration (NASA) Glenn Research Center, where research on propulsion is performed, and the NASA Langley Research Center, where helicopter and tilt rotor testing are performed, are among the best in the world in these areas. The facilities have been developed in conjunction with industry and NASA over the past 20 years and can be exploited to support 6.1 and 6.2 research.

Interfacial Strain Energy Dissipation in Hybrid Nanocomposite Beams Under Axial Strain Fields

Overall, the scientific quality of this research reflects originality and is of high quality. The principal investigator is very qualified and is supported well by his team. In general a good awareness of the underlying science and of work conducted elsewhere is evident.

Adaptive Seat Energy Absorber for Active Vehicle Safety

The overall quality of this project is good. The research reflects understanding of the physics and familiarity with other work in the field. Laboratory equipment and modeling work also seem appropriate. The researcher is qualified and is making good use of the test facilities. The project shows a good mix of theory, computation, and experiment.

Structural Damping Modeling for Rotorcraft Comprehensive Analysis

This is a useful and timely project. Hydraulic dampers are the largest operations and support maintenance driver on many helicopters in the Army fleet. They are also critical to operational readiness and airworthiness of the vehicle. Elastomeric dampers are difficult to model and not thoroughly understood from a material constitutive and life prediction perspective. The lead researcher is regarded as an expert in this area. The quality of this work is high and suitable for publication in archival journals. The research is employing appropriate equipment and numerical models.

Computational Fluid Dynamics and Comprehensive Structural Dynamics Correlation with Fuselage and Wind Tunnel Walls

The research reflects understanding of the physics and familiarity with other work in the field. The researcher seems qualified, and the quality of the work seems good, evincing thorough execution. Exploration of coaxial compound rotorcraft is valuable.

Propulsion

The high-pressure, high-temperature, pulsed injection facility is impressive. The high-temperature component/fatigue facility is excellent and has been used to study surface temperature and thermomechanics. The small-engine altitude facility is a very impressive, unique, and useful facility. The tribology laboratory is a very useful facility. It provides a capability for integration of scientific issues. Furthermore, it is capable of replicating practical constraints with respect to loads, temperature, and surface curvature. The ultrasonics method used to find potential cracks is novel and promising. The method is nonintrusive and robust, even at high temperatures. The examination of diesel engines, gas-turbine engines, and associated spray combustion is appropriate.

JP-8 Diesel Injector Experiment

The examination of JP-8 fuel injection is valuable. The plan to extend experimental capability to be able to measure more than penetration length (e.g., droplet size and velocity distributions) is good. Such data are critical for validation of high-fidelity numerical simulation tools used in the design and analysis of the injectors.

Life Cycle Management

The researcher understood well the technical goals and the direction needed to achieve the goals. A good connection exists with Rochester Institute of Technology. The planned follow-up applying statistical analysis will be useful.

Gear Surface

This work was good, and a basic understanding of fundamentals was displayed. A comprehensive list of previous works was identified by the researcher.

Turbine Blade Innovation

The experimental film cooling program aimed to validate Reynolds-averaged Navier-Stokes (RANS) computational prediction. It focuses on the effects of hole geometry and is making good progress.

Reliability and Diagnostics

According to the Office of the Assistant Secretary of the Army, Acquisitions Logistics & Technology, four out of five U.S. Army systems fail to achieve reliability requirements. Correspondingly, the costs to operate and maintain Army systems are not sustainable. Fatigue is a dominant concern in aircraft reliability. Today, modeling, inspection, and replacement of components subject to fatigue failure are critical to maintaining airworthiness.

ARL researchers are conducting research and developing an approach to design of aircraft structural components with goals to reduce fatigue failures and sustainment costs associated with maintenance. The program has the potential to revolutionize the achievement of high-reliability systems and includes the following elements: stronger materials that will lead to more durable structures; intelligent materials and structures that are self-sensing (providing materials state awareness) and, in some cases, potentially self-healing, with improved mechanical properties; physics-based models of failure (including uncertainty quantification) that will provide understanding of potential damage precursors and improved diagnostics and prognostics; diagnostics and prognostics that will relate materials/structure state to the distribution of remaining life of the structure; and control systems that will, given state awareness, keep aircraft in a safe state.

There is much scientific and engineering research that needs to be completed to demonstrate the feasibility of this approach. ARL scientists and engineers are on the path to achieving this. Early results presented by the researchers are promising.

Damage Tolerance of Novel Composite Materials

This research has demonstrated the feasibility of improving structure fracture toughness and resistance to delamination of composites through the use of needling or interleaves. Tests have been conducted and showed benefits of needling and interleaves.

Dynamic Response of Topologically Interlocking Structures

This project involves the use of additive manufacturing techniques to create interlocking elements that can be assembled to sustain impact loads greater than those sustained by traditional materials. If successful, this research could lead to the design of a new class of high-impact-resistant materials. This research has made progress by using interlocking mechanisms to improve impact resistance on a simple configuration.

Additive Manufacturing of Extremely Lightweight, Adaptive, Durable, Damage-Tolerant (XLADD) Structures

Additive manufacturing of composite materials or multifunctional composites would create a new approach for making advanced composites or intelligent composites. This research has successfully demonstrated the use of 3D printing machines to fabricate composite materials.

Statistical Estimation of Sensitivity in Modeling Parameters

The main accomplishment of this project is the development of a new probability-ratio-based method for estimating sensitivity of a system with an intractable response surface that requires computationally intensive Monte Carlo evaluation. The new approach can significantly improve the computational time and cost for estimating material responses from limited test data.

Advanced Sensor Fusion

The proposed work, once completed, could lead to a good approach for life-cycle monitoring of structural integrity and lead to the zero maintenance goal. This research has successfully demonstrated diagnostic and prognostic capabilities with a suite of various sensors for structural components under static and dynamic loads. The approach is based on the utilization of a particle-filtering algorithm to compute Bayesian posterior probabilities of remaining life.

Electrical Impedance Spectroscopy for Assessing Remaining Useful Life

The goal of this project is to use electrical measurements across carbon fibers passing through a structure to detect change in loading or other incipient damage. Previous work had looked only at the real (resistance) part of the impedance to detect such changes. The research has demonstrated that the phase angle can be more sensitive to subtle changes that cannot be detected by resistance alone.

XLADD Structures

This work is developing lightweight, high-strength, multifunctional materials that can be used to integrate self-healing and sensing-based capabilities for condition monitoring and damage tolerance. This work is making good progress.

Virtual-Risk-Informed Agile Maneuver Sustainment (VRAMS)

The overall vision presented is very good and is necessary for successful implementation of online monitoring and control.

Materials State Awareness: Identification of Damage Precursors

The goal of this work is to explore smart materials to enable intelligent built-in sensing capabilities to detect damage precursors. To this end, magnetostrictive particles were embedded into composite structures. Fractographic analysis results obtained to date indicate that changes in magnetic field flux intensity have the potential to provide useful precursor information.

OPPORTUNITIES AND CHALLENGES

Mechanics

Publication in archival journals is necessary and very valuable for establishing a world- class research reputation and developing early-career researchers. The ratio of journal to conference papers needs to be appropriate.

Research tasks appear to be somewhat disconnected, and there is no common vision. It was not clear how the current topics are related to ARL's long-term vision nor was it clear how the current topics were selected. On many tasks, the duration and schedule of paths forward were also not clear. This information would help focus the teams on milestones and the management on providing timely guidance. It seems appropriate for ARL researchers to work on programs that are more than 1-2 years in duration.

There is strong opportunity for more work related to control of noise in the vehicle's interior. This fits well in the protect-the-soldier mission, aligns with published technology goals to reduce interior noise associated with lightweight drive systems and airframe, and might dovetail well with innovative damping technologies being pursued by multiple researchers in the division. There is good potential for both fundamental and applied research contributions.

The mechanics area needs a more robust workforce with sufficient experienced staff to mentor recently hired, less experienced staff. There is a need to delineate a clear path connecting development, laboratory testing, and full-scale testing of components and systems. ARL work is not clearly differentiated from external contractor work, and the ARL workforce is challenged by the requirement to manage local, existing ARL research and monitor external contractor work. There is a need to accelerate the full operational capability of all primary research facilities—for example, the subsonic wind tunnel. There is also a need for a local ARL capability to conceive, develop, test, and implement computational fluid dynamics (CFD) and simulation tools for increasing complex airframe configurations and flight regimes. Although it may be difficult to develop advanced multiphysics CFD capabilities from scratch, the cognizant staff need to be sufficiently knowledgeable to assess and evaluate off-the-shelf CFD software for accuracy and predictive capability.

Interfacial Strain Energy Dissipation in Hybrid Nanocomposite Beams Under Axial Strain Fields

Previous (1990s-2000s) work on characterization of elastomeric materials and associated device damping may provide some beneficial structure for the work. ARL's current research focuses on physical and numerical modeling on carbon-nanotube-reinforced composites. Future exploration involving bench and rotor testing is needed if there is going to be application of these materials. Appropriate facilities and laboratory equipment need to be engaged to best support the research path. ARL needs to consider the implications of amplitude dependence on operational condition. Low damping at higher amplitudes can limit cycle behavior. ARL needs to consider internal noise reduction as a potential application for damping. The preparation of descriptive papers is commendable, and submission to peer-reviewed journals will be appropriate as work continues to mature. The aeroelastic rotor experimental system (ARES) rotor test stand and the wing and rotor aeroelastic testing system (WRATS) tilt rotor test stand, both located at NASA Langley Research Center, need to be exploited further. These are world-class facilities that were developed by ARL in conjunction with industry.

Many projects reflect appropriate system-level thinking; continued evolution along this path is needed. Even fundamental research can be motivated by and grounded in system considerations. Doing so will enhance the ability to identify thrust areas that have high payoff for the Army, the Department of Defense (DoD), and the vehicle community at large.

Rotorcraft Capability Assessment and Trade-off Tool

The ARL contribution to this project and the role of Georgia Institute of Technology are not clear. Also unclear are whether the project is using existing methodology or developing new methods to expand capabilities and how the resulting tool will be validated. Without this clarity, industry and government users will not have confidence in the results. Additional research into learning what other groups are doing with trade study tools is needed. It is not clear how numerical models grounded in correlations based on past data will be useful for future designs. Special care is warranted here. The qualifications of the research team may be below the required critical mass and training level. A single principal investigator with at least a master's degree would be an acceptable start, but additional staff, perhaps with Ph.D. training, is needed. The researchers need to consider reliability, cost, and maintainability factors in their work. They also need to engage industry and other elements within the DoD as much as possible. Working on this project in an insular fashion can undermine the impact of a very important project.

Performance Bounds for Micro Autonomous Vehicles

The overall topic is useful for approximating the endurance of micro autonomous vehicles (MAVs) at various scales. Developing additional detail on the project's objectives and path forward would be helpful. Time frame, priorities, and workforce requirements need to be quantified. Considerable work has been done on MAV performance throughout the country, including some funded by the Army, but insufficient information was provided to permit judging whether the researchers have a broad understanding of the science and what other groups have done. It was also difficult, based on the information provided, to assess whether appropriate laboratory equipment or numerical models were being employed. Team members seem qualified. A conference paper has recently been written, but no details were provided, so it is not clear whether this work is intended to be published in a journal.

Technology Identification of High-Performance Vertical Takeoff and Landing Tail-Sitter Aircraft

Publication of two recent conference papers is a good sign of productivity. The research did not reflect knowledge of previous analytical or numerical research on tail-sitter performance. The only historical reference was to old designs and schematics of new ones. FLIGHTLAB[1] analysis would be sufficient. Qualifications of the researcher seem compatible with the research challenges. It is not clear

[1] FLIGHTLAB is a flight vehicle modeling and analysis tool developed by Advanced Rotorcraft Technology, Inc., Sunnyvale, California.

whether cruise performance of a tail-sitter is a meaningful research question. The design seemed similar to a standard aircraft with a canard. The research challenge lies in the transition from cruise to hover and in low-speed operational maneuvers. Apart from the Defense Advanced Research Projects Agency (DARPA) X-Plane, it is not clear whether anyone in the DoD is seriously considering a tail-sitter.

Adaptive Seat Energy Absorber for Active Vehicle Safety

The dynamic model of the occupant seemed to be a very simplified one-dimensional simulation of the crash event. There was some uncertainty about the lumbar load time histories, and it was not clear why the loads changed sign prior to impact. Also, concerns persist regarding weight trade-offs for the technology.

CFD/Comprehensive Structural Dynamics Correlation with Fuselage and Wind Tunnel Walls

Computer equipment and numerical models seem adequate, but approximately 40 hours per run on 128 cores makes design iteration difficult. Detailed goals and the timeline were not made clear. Implementation of Helios in CAMRAD II would be a step forward, if that is indeed the goal of this program. Utilization of this methodology for design evaluations of future vertical-lift concepts is going to be very time consuming with that level of fidelity. Specific questions need to be identified and the work coordinated with the Aeroflightdynamics Directorate of the U.S. Army Aviation and Missile Research Development and Engineering Center. More collaboration with the wider Army and technical communities and understanding of the challenges associated with high-speed coaxial compound configurations would be valuable.

Structural Damping Modeling for Rotorcraft Comprehensive Analysis

There is opportunity in the reliability and durability area to engage experimental facilities such as the mechanical test rigs and temperature chambers. This project provides a good opportunity for collaborations between mid-career and early-career researchers. The appropriate mix of theory, computation, and experimentation are being applied, but experimental testing to validate advanced damper models is required. The ARES rotor test stand and the WRATS tilt rotor test stand, both located at the NASA Langley Research Center, need to be exploited further.

Propulsion

The consideration of new applications associated with smaller machinery and longer operations, especially for diesel engines, is necessary. A systems overview study is required to identify specific opportunities and needs for research, especially for diesel engines. In some areas, cooperation with designers from industry or NASA can focus the research and optimize impacts under practical constraints.

High-Pressure, High-Temperature, Pulsed Injection Facility

The droplet sizing capability needs to be developed.

High-Temperature Component/Fatigue Facility

In this recently commissioned facility, surface temperature and thermomechanics have been studied so far, but the facility can be used for other studies—for example, study of the thermal and momentum boundary layer.

Small-Engine Altitude Facility

This impressive facility, which is being used to study diesel engines, can also be used for testing gas-turbine secondary power units and components (for example, compressors).

High-Speed Bearing Laboratory

This laboratory has capabilities beyond those it is presently using, which include studying the extension of time between overhauls. A plan for more fundamental research is needed.

JP-8 Diesel Injector Experiment

There is a need to identify from a systems perspective which aspects of diesel engines need improvement and to then use the findings to define research projects. There is also a need to identify new uses for diesel engines and the research that might be useful to advance the new application. It would be useful to characterize each experimental realization with the relevant nondimensional group values—Reynolds number, Weber number, gas-to-liquid viscosity ratio, and density ratio. The effects of change in upstream pressure on flow through an individual orifice in a connected group of orifices need to be explored. The literature from the diesel industry and previous research on liquid injectors and round jets needs to be studied carefully.

Diesel Injector Computations

Examination of JP-8 injection is very valuable. As noted above, there is a need to identify from a systems perspective which aspects of diesel engines need improvement and to then use the findings to define research projects. There is also a need to use the nondimensional groupings. Recent advances in high-fidelity computational tools scalable on state-of-the-art high-performance computers need to be explored. Because the length scales vary over three or more orders of magnitude, the interesting and relevant physics cannot be described with limited computational resources. A strategy is needed in which good subgrid models are developed and used to describe the final stages of atomization and vaporization.

Ducted Rotor

This is an interesting project for which new research is needed. The appropriate parameters need to be identified and used to characterize each experimental realization, for example, disk loading, duct length/duct diameter ratio, fan pressure ratio, and lip radius/duct diameter ratio. Familiarity with turbofan research would be helpful. The ground effect needs to be examined; higher power might be needed near the ground. There is also a need to explore low-speed behavior before generalizing about the effect of blade twist.

Life-Cycle Management

It is questionable whether a crack can practically be tolerated for any duration of time after it is first discovered, and this needs to be investigated further.

Gear Surface

The work would be strengthened by interactions with designers to determine the ranges of parameters of interest and constraints on them.

Hybrid Gear

The mode analysis in this interesting work is very good, but the focus needs to extend beyond the vibrational modes. An improved understanding of material limitations would be helpful. A plan for nondestructive inspection of structural integrity is needed.

Compact High-Efficiency Centrifugal Compressor

The observed behavior is the opposite of what was expected and is not understood: Efficiency decreases and stall margin worsens. There is an opportunity to explore what causes this behavior.

Turbine Blade Innovation

There is a need to examine the vast literature on film cooling. More comprehensive characterization could be helpful—for example, velocity measurements and momentum/flux ratios could be considered. More information about flow upstream in the cooling hole would be helpful.

Reliability and Diagnostics

In many of the current projects it will be important to pay more attention to the underlying physics of the problem (e.g., how sensors interface with the material and the structure). The ability to better predict the remaining useful life of a structure will depend critically on the ability to develop multiphysics, multiscale models (including uncertainties) and sensors that will provide relevant real-time data. The development of intelligent real-time diagnostics needs to follow from knowledge of physics models and sensor data. The team studying virtual risk-informed agile maneuver sustainment will need to develop a roadmap for what will be needed to advance from concept to application. To develop this roadmap, the team will need to identify milestones, timelines, and goals.

Damage Tolerance of Novel Composite Materials

The proposed method, if successful, could lead to a reduction of composite weight or an increase in load-carrying capacity. Both methods have been tried before and reported in the literature and have shown mixed benefits. Extensive experimentation and physics-based modeling will be required to examine the failure mechanisms adequately.

Dynamic Response of Topologically Interlocking Structures

The idea in this project is to use additive manufacturing techniques to create interlocking elements that can be assembled to sustain greater impact loads than traditional materials. The problem needs to be clearly defined, particularly with respect to the application, in order to size the materials properly. In-depth modeling is necessary to understand the fundamental underlying physics. It is not clear how the approach can be generalized.

Additive Manufacturing of XLADD Structures

Additive manufacturing would be a new approach for making multifunctional composites or intelligent composites. The addition of continuous fibers by additive manufacturing still needs to be demonstrated. Considerable modification of additive manufacturing machines will be necessary to achieve the project goal. Materials, processing, and integration issues related to additive manufacturing need to be carefully studied, not only the manufacturing machine. It is important to begin the move to additive manufacturing with real materials that would be used in military systems.

Statistical Estimation of Sensitivity in Modeling Parameters

The exact computational approach was not made clear. It is important that there be a mathematical or statistical demonstration of the accuracy of the method instead of relying on Monte Carlo computational results. There have been many advances recently in the quantification of uncertainty, particularly at the Department of Energy laboratories, that need to be studied and leveraged.

Nonlinear Structural Response Under Multiaxial Dynamic Loading

In this project, procedures and methods have been developed and used to conduct a series of multiaxial component tests on electronic packaged materials. The tests to date have demonstrated that the simple superposition model is not adequate to describe certain damage mechanisms and that more sophisticated models (and corresponding physical explanations) will need to be developed to predict cumulative damage of structures that experience multiaxial loading.

There is a need to develop new methods to characterize material failure mechanisms more effectively and efficiently under various loading conditions. It was not made clear whether the project is to focus on developing new test methods or developing new modeling techniques. The potential outcome of the project needs to be clearly defined.

Advanced Sensor Fusion

The structure of the model relating sensor data to life predictions was not made clear. There was no clear description of the extent to which the model is based on physics rather than empirically fitted functions. Without a physics basis, life-prediction models will be severely limited in their application. It is questionable whether the modified Paris law is really physics based.

Electrical Impedance Spectroscopy for Assessing Remaining Useful Life

It is possible that the carbon fibers can break before any damage has accrued. Perhaps using some scalar function of the two impedance components would be better than using either one alone.

XLADD Structures

There is need for physics-based models at three different length scales. Such models are important because bridging of the scales is critical to understanding damage precursors. There is a need to move this research to the study of realistic materials. There needs to be cross-collaboration with the materials group.

Virtual Risk-Informed Agile Maneuver Sustainment

Identification of damage precursors is a key component of the VRAMS concept. It will be important to identify research needs in related areas such as sensing with embedded sensors or self-sensing material, sensor instrumentation and signal processing, and relating sensor physics to damage features.

Materials State Awareness: Identification of Damage Precursors

There was no discussion about why magnetostrictive material was used. The underlying physics and the actual physical phenomenon were not made clear. Such understanding will be important to the discovery and development of effective and useful precursors. Stiffness reduction and strength reduction are serious issues that need to be addressed.

OVERALL TECHNICAL QUALITY OF THE WORK

The combined research program in mechanics, propulsion, and reliability and diagnostics has several projects whose quality vary from average to outstanding (interfacial strain energy dissipation in hybrid nanocomposite beams under axial strain field is in the outstanding category). The continued development of critically important and valuable ground test facilities like the quite subsonic wind tunnel is notable. The recruitment and hiring of outstanding new staff members greatly increases the potential of developing future research achievement.

The quality of the research would be accelerated by infusing the existing workforce with sufficient senior staff to mentor junior staff. Clearer pathways connecting basic research and full-scale testing of components and systems would also improve research quality. Critique with recommendations through exposure of research to peer review in archival journal publications will also improve research quality. Complete full operational capability of primary research facilities provides a unique resource and advantage to capture research of the highest quality.

Interfacial strain energy dissipation in hybrid nanocomposite beams under axial strain field is an exceptional area. The work here includes the characterization of carbon-nanotube-reinforced composites and associated device damping. This work is driven by physical and numerical modeling. It reflects system-level thinking and modeling. Internal noise reduction, including for rotorcraft, is a potential application for damping. Increased aeroelastic stability of rotorcraft main rotor blades is also a potential application of this research.

The quiet subsonic wind tunnel and the high-altitude test chamber are high-quality facilities.

Mechanics

Overall, the technical quality is good, and there is great potential for the mechanics team to continue to work toward excellence. The facilities and personnel at the Aberdeen Proving Ground are making progress. Many of the recently hired early-career researchers are beginning to become productive contributors and generate high-quality technical work. It is important to provide opportunities for development and effective supervision of the early-career researchers. The new facilities in Maryland have been under design and development for the past few years, and when these are coupled with adequate numbers of qualified research staff, the team could become very productive.

The researchers are doing thorough and competent work but are not generally leading the field. However, there is significant potential to do so, because the group is very talented. They could become leaders by identifying niche areas and technology solution ideas and by developing and validating the associated computational, experimental, and design tools required to answer specific key research questions. It was not clear how many researchers are engaged in theory, computation, and experiment. There appears to be more emphasis on applied research than on fundamental research. Overall, the mechanics program is not sufficiently staffed to accomplish its mission.

Propulsion

The experimental facilities are excellent and offer some unique opportunities. There is good applied research but little competitive fundamental research. If more fundamental research is desired, each laboratory experiment and computational program needs to be designed and constructed to answer specific fundamental scientific questions. In this way, the researchers will be performing more than exploratory testing or computational exercises based on questionable physics models. Researchers need to be in command of existing work on related topics. Many more journal publications, with first-rate peer reviews, are needed to make a greater impact and to challenge researchers to perform at their full potential. Better mentoring of early-career researchers is needed.

Reliability and Diagnostics

The overall technical quality of ARL's applied research and development in the area of reliability and diagnostics is very high. The VRAMS team has a strong contingent of enthusiastic, highly capable researchers. The potential to produce fundamentally important results to improve the reliability and survivability of Army systems is high. In order to demonstrate the high quality of the research and to get important feedback from other experts in the fields, it is important that research papers be submitted to good-quality archival research journals.

Part III

Crosscutting Findings and Recommendations

7

Crosscutting Findings and Recommendations

KEY FINDINGS AND RECOMMENDATIONS

The metrics by which the Army Research Laboratory (ARL), as a research organization, internally measures and quantifies the quality of its science and technology (S&T) research across the spectrum of its mission space were not provided to the ARL Technical Assessment Board (ARLTAB). The options could include the number and impact factor of publications or the number of transitions to operational use by the warfighter. The definition of such metrics and any relevant data could enhance the impact of the ARLTAB assessments.

While high-risk, innovative projects are rising, the mix of low-risk and high-risk research to achieve an optimal balance continues to be a crosscutting effort for all of ARL's S&T programs. ARL indicated that 30-50 percent of Director's Research Initiative (DRI) projects and many Director's Strategic Initiative (DSI) projects go on to become core efforts.[1] While ARL is looking for ways to encourage innovation that will impact mission-critical programs, making it safe to fail is one way to encourage innovative, high-risk projects. Strategic management discussion of the objectives and expectations for DRI and DSI projects and how these precious funds are aligned or how they feed longer-term programmatic efforts is encouraged.

ARL clearly desires to enhance its capability to innovate, and the DRI projects are a step forward with potential to shift the technical focus of ARL toward the innovative edge. Disruptive innovations with implications for military threats and capabilities appear more likely to come at the complex intersections of traditional scientific domains rather than at their center. One approach to facilitating innovation that might be considered is the formation of small interdisciplinary teams focused on addressing or defining

[1] ARL uses the DSI and DRI research projects to build new research capabilities in long-term, high-risk scientific areas with very high potential payoff for the Army mission. DSI projects are typically funded at $500,000 to $1 million per year for up to 3 years, while DRI projects are funded at $250,000 per year for up to 3 years.

high-value research challenges. Small interdisciplinary groups that work comfortably as teams are able to move past preconceived disciplinary biases and internally promote the integration of insights and the connection of ideas from diverse perspectives. Multiple disciplines looking at the same problem will benefit from alternative frameworks and approaches while interrogating the associated issues from multiple viewpoints. ARL already has the in-house intellectual assets needed to make this work. ARL's move toward using a framework based on S&T campaign plans can enhance such collaborations.[2]

The visibility of ARL staff in professional technical societies and at technical conferences is not up to the level that their accomplishments and scientific expertise warrant. While it is clear that the sequestration of government funding and travel restrictions have negatively affected staff interactions with the outside R&D community, the long-term curtailment of such interactions will have an even more significant adverse impact. Lack of interactions normally fostered through conferences and professional associations will negatively impact both collaborative programmatic efforts and maintenance of an edge in ARL's areas of expertise. This has already affected staff morale, produced opportunity costs, and will seriously impact staff retention and hiring in the future. Moreover, ARL's strategic focus on innovation through adoption and development of scientific ideas and insights from the scientific community cannot be applied to solve Army problems if the focus is solely inward, leading to internal reinvention of wheels.

Active peer-reviewed publication systemically drives quality in S&T cultures and organizations. Engagement in the publication process subjects the research to rigorous review, generally improving it and increasing quality. Furthermore, publication encourages project completion deadlines, polished results, and thoughts about the next steps in R&D. It is also a way to increase visibility in the research community.

As the intersection of modeling and simulation with experimental measurements grows, it requires the coherent treatment of verification and validation across ARL. The majority of the projects presented did not sufficiently define or elucidate model validation. Some excellent examples of validation were shown, such as in the military operations in urban terrain (MOUT) project, but this was not seen throughout the review. Too often, a computer-based visualization of a model was presented with few or no quantitative comparisons to data. Details of complex material and structural models matter, but these, along with the basis for choosing model parameter values, were seldom discussed. When geometry or material behavior is considerably simplified, it is important to provide data justifying such simplification. The success of a model in producing a visual image of the overall phenomenology is not the same as validation. To map out regions to define and limit experiments, delineation is needed on a project by project basis as to whether validation is sought via a comparison with quantitative data or via the ability to predict trends in response or in performance. A rigorous formal internal validation program is needed within ARL to quantify whether the physics within the broad spectrum of ballistics models being developed accurately describes the operative physics. Given the importance of such models to the development of a predictive design capability in support of current Army programs and future system, platform, and equipment development, increased emphasis on validation is warranted. In addition to the need for an ARL-wide strategic approach to model validation, methods are needed to quantify the margin of uncertainty (QMU) for these models. For example, it is not clear how the operational requirements-based casualty assessment (ORCA) and MUVES-S2 models are validated. The reviews often lack sufficient details on how ARL's models are formulated and validated; on their sensitivity, if known, to key parameters and variables; and on the statistical variations to be expected.

[2] Army Research Laboratory, 2014, *Army Research Laboratory. S&T Campaign Plans. 2015-2035,* Adelphi, Md.: Army Research Laboratory, September, http://www.arl.army.mil/www/default.cfm? page=2401.

The details of how ARL is leveraging the Army Research Office's (ARO's) 6.1 investment in support of the near-term and long-term Army strategic vision was not always clearly presented to the ARLTAB panels. Examples of how individual ARO projects fit into Army overall goals and relate to one another and to other ARL projects would facilitate the ARLTAB's tasking—namely, to assess the quality of ARL's S&T.

Recommendations to improve the overall ARL research enterprise are:

Recommendation 1. ARL should require researchers to clearly articulate the existing technical challenges in their research as well-posed problems, to formulate key questions, to identify approaches and tools, and to set out an assessment strategy. Concept maps, research baselines, and milestones that characterize the research are recommended.

Recommendation 2. To optimize the progress of their research and to set a path forward for each project, researchers should consistently analyze data and contemplate the theories that are behind the observed physical phenomena, test data, and modeling systems.

Recommendation 3. ARL should continue its efforts to be a key source of disruptive technology options for the Army of the future. Toward this end, it should balance short-term customer-driven work with innovative R&D that goes beyond current requirements.

Recommendation 4. ARL should develop a laboratory-wide verification and validation methodology, formalism, and implementation program. This program should be applied to support connectivity between theory, modeling, and experiments; refine underlying assumptions and approximations; encourage sensitivity studies, including how systems can fail; quantify margins and uncertainty; and inform small-scale to system-level experiments.

Recommendation 5. ARL should encourage a systems integration approach across its research enterprise to engender interconnectivity between ARL's science and technology campaign plans.

Recommendation 6. ARL should consider including in assessment agendas selected presentations related to new or recent starts to maximize the benefits of early feedback from ARLTAB across all disciplines.

Recommendation 7. ARL should look for additional ways to increase interaction between its researchers and leaders in industry and academia, given that limitations on travel have restricted this important professional development avenue.

Recommendation 8. ARL should encourage and incentivize publication of research in peer-reviewed journals.

Recommendation 9. As ARL continues to build its research staff, it should give attention to bringing in mid-career and senior personnel to mentor the outstanding early-career scientists who have been recruited. Effective mentoring should include engagement in selecting research directions, facilitating communication with research peers, guidance on service and committee assignments in technical societies, and enhancing career development.

Recommendation 10. ARL should convene a strategic planning group to formulate and plan research facility needs to support Army research and development objectives for the next 10-20 years.

Recommendation 11. To narrow the distance between the science and Army end-use applications, ARL should continue efforts to assure that researchers across all ARL disciplines understand future needs of the Army.

OPEN CAMPUS CONCEPT

The open campus initiative[3] is a strategy intended to widen ARL's presence in the broader community and to elevate ARL's national and international stature. This laudable initiative serves to facilitate interaction and enhance collaboration with the scientific community; spark new ideas through the influx of information from the scientific community; attract and retain high-caliber scientists and engineers; offer students research opportunities with the possibility of future employment; energize ARL researchers by providing new research opportunities in other laboratories; and nurture a technology transfer environment where researchers can directly or indirectly transition research to useful products.

Addressing associated potential challenges and issues will help assure the success of the open campus initiative. Increasing numbers and types of collaboration are not without cost. It is important to consider the staff time necessary to establish and maintain such collaborations, and there is a risk that such interactions can become an end unto themselves. In response to their perceptions of management's encouragement of this openness, some staff may see collaboration as a contest to amass numbers rather than decide analytically that a particular collaboration will enhance effectiveness. As the open campus initiative matures, management will need to continue to refine expectations beyond a general improvement in working conditions and atmosphere. In the early days of implementation, one can make a case for experimentation with a variety of bottom-up collaborations based somewhat on serendipity, but the measure of success is always whether mission effectiveness is enhanced by these interactions. ARL needs to continue to develop a shared understanding of measures of success by which individual interactions and the entire open campus concept will be judged, to provide guidance to the staff on the essential nature of successful collaborations.

It is also important that the open campus be a bilateral implementation; that is, in addition to hosting researchers at ARL, ARL staff need to take on temporary assignments at leading academic and industrial research institutions. Implementing an open campus as a means to increase utilization of facilities is commendable, but the sharing of facilities could crowd out collaboration and place a burden on ARL to provide administrative and low-level support to outside users. Dedicated use by outside users for technical or proprietary reasons and scheduling and priority conflicts could also diminish effective collaboration. There is also a risk that this open campus use of ARL facilities could become focused on improving capacity utilization of ARL capital assets.

Many of the principal investigators of research projects at ARL have praiseworthy working relationships with universities, industry, and national laboratories. The open campus initiative will provide a vehicle to expand these interactions. Beyond that, there are opportunities to enrich the experience of the principal investigators by establishing further collaborations and short sabbaticals where they could become involved directly in cooperative research at allied institutions. This two-way-street aspect of the

[3] Army Research Laboratory, 2014, *ARL Open Campus Opportunities*, Adelphi, Md.: Army Research Laboratory, http://www.arl.army.mil/www/pages/2357/ARL_Open_Campus_Opportunities.pdf.

developing open campus is critical to both staff development and mentoring. One-to-one interactions on a daily basis would almost certainly enhance productivity and possibly generate new ideas for further productive research. With respect to the duration of such a sabbatical, one to two weeks every year might be a good starting point. Of course, a reverse arrangement could also benefit the visiting researcher.

OUTSTANDING AND EXCEPTIONAL AREAS

The following are outstanding and exceptional areas evinced by the competency disciplines.

Materials Sciences

Critically important to the Army's night vision, its large area surveillance, and its navigation in degraded vision environments, work on the electromagnetic modeling of quantum-well infrared photodetectors (QWIPs) is exceptionally valuable. Affordable, high-speed, high-resolution, long-wavelength infrared cameras will be one of fruits of this project. ARL is the world leader in QWIP technology.

To support development of lightweight, quiet, efficient, and reliable power sources for Army applications to enhance soldier combat capability, the project on fuel cells for military applications tests and evaluates commercial technologies—namely, direct methanol fuel cell (DMFC) and solid oxide fuel cell (SOFC) systems. The technology reduces weight and decreases the logistic burden associated with batteries. This represents an upward potential for Army applications and an outstanding value.

The work on synthetic biomolecular materials is highly significant for the Army. The project has already shown success by developing iterative and integrated multiscale computational biology capabilities for in silico study and evolution of material interfaces. This is innovative and ingenious work.

To explore potential breakthroughs toward the emerging needs of the 2035 Army, the low-dimensionality (2D) materials program covers fundamental aspects of synthesis, characterization, device design, and manufacturing. Tuning 2D materials at the atomic scale opens enormous opportunities to design electronic properties. This is a potentially high-impact area.

To develop lightweight armor, ARL's mechanical press capability of applying up to 700,000 lb pressure is unique. This is exceptionally enabling test equipment that facilitates materials discovery and development.

Ballistics Sciences

ARL has an unequaled record of achievement and timely support of the warfighter within the Department of Defense (DoD) in the area of ballistic science and technology through its sustained development of advanced capabilities for defeating many types of enemy targets and platforms, and the development of increasingly lethal munitions to place adversary personnel and assets at risk while meeting the spectrum of national security missions engaged by the Army.

ARL's efforts in ballistic science address both fundamental and urgent Army warfighter needs of great importance to national security. ARL's personnel, facilities, and programs are the clear go-to place across the DoD and defense agency enterprise in ballistic sciences and engineering.

Information Sciences

In the area of autonomous systems, the piezoMEMS research and associated small robotics effort is first rate, with elements that are at the vanguard of this field. Specifically, the work in motion generation at the microelectromechanical system (MEMS) scale is seminal. Large-amplitude motions are being created at the micron scale using integrated actuators, structures, and electronics, cofabricated on silicon.

In the atmospheric sciences, the development of a laser-based tool for capturing, holding, and analyzing an individual aerosol or dust particle adds a unique ability to monitor changes in particle morphology, chemical composition, and optical properties under changing atmospheric conditions. This work positions the ARL at the forefront of the atmospheric chemistry community.

In the computational sciences, the work related to multiscale modeling of materials, simulation or emulation of mobile networks, portable programing models and run-time systems for heterogeneous architectures, and tactical high-performance computations represents the state of the art.

In the area of network sciences, the work related to trust and quality of information has received broad recognition in the technical community. Similarly, the work on cybersecurity is of the highest quality and benefits from ARL access to real data.

Human Sciences

Researchers at the Simulation and Training Technology Center (STTC) are pushing the state of the art of simulation in the cloud and protocols for advanced distributed simulation (ADS). The ADS group has a unique opportunity to lead future developments across the DoD in these areas. The STTC work is demonstrably significant and valuable in specific application domains (e.g., simulations of battlefield medical situations), and the design of general tools for simulation (e.g., the generalized intelligent framework for tutoring [GIFT]) makes it possible for others to rapidly create new training modules for new content areas.

The translational neuroscience (TN) program is a unique and important effort that is tackling key technology bottlenecks to moving neuroscience from the laboratory to the field. For example, it is exploring the integration of other sensing modalities into electroencephalogram (EEG)-based brain–computer interaction (BCI) applications; approaches to overcome real-world limitations for use of the electrode system; and the development of nonproprietary dry electrodes. The TN group conducts high-quality neuroscience research that is on a par with work at a good university neuroscience department. Success in this research has potential to be a game changer for research on soldier and mission effectiveness.

Mechanical Sciences

Interfacial strain energy dissipation in hybrid nanocomposite beams under axial strain is an exceptional area. Internal noise reduction, including for rotorcraft, is a potential application for damping. Increased aeroelastic stability of rotorcraft main rotor blades is also a potential application of this research.

The subsonic wind tunnel and high-altitude test chamber are high-quality facilities.

Appendixes

A

Army Research Laboratory Organization Chart

Figure A.1 is an organization chart for the Army Research Laboratory (ARL), and Table A.1 maps the ARL organizational chart to the core competency areas reviewed in 2013 and 2014.

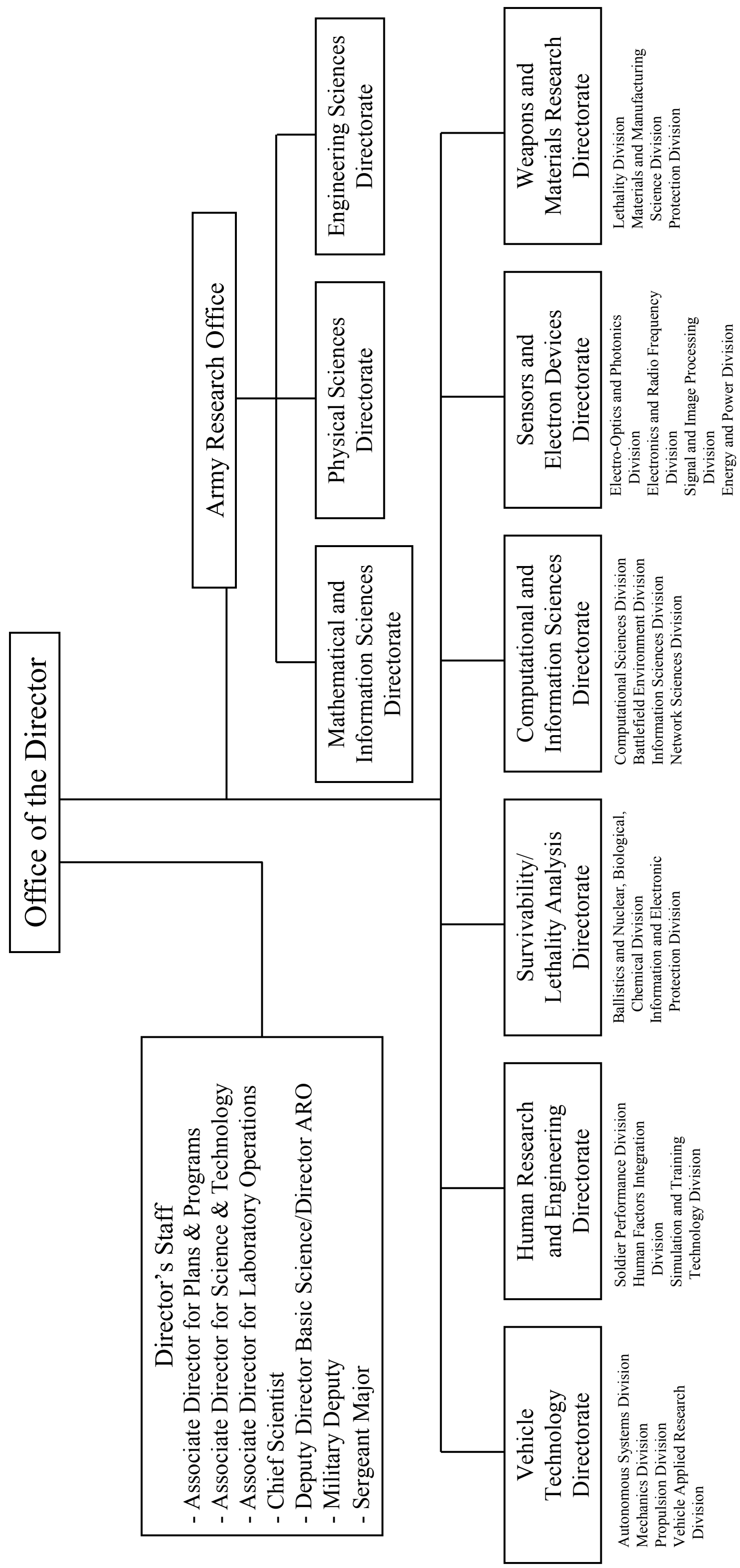

FIGURE A.1 Army Research Laboratory organization chart.

TABLE A.1 Mapping the ARL Organization Chart to the Core Competency Areas Reviewed in 2013 and 2014

Core Competency Area	Topic	ARL Directorate Involved
2013		
Ballistic sciences	Terminal ballistics	WMRD, SLAD, HRED, SEDD
Human sciences	Transitional neuroscience Soldier simulation and training technology	HRED, SEDD, SLAD
Information sciences	Autonomous systems	VTD, CISD, SEDD, HRED
Materials sciences	Energy materials and devices Photonic materials and devices Biomaterials	SEDD, WMRD
2014		
Ballistic sciences	Internal and external ballistics	WMRD, SLAD, HRED, SEDD
Human sciences	Soldier performance Human systems integration	HRED
Information sciences	Network sciences Atmospheric sciences Computational sciences	CISD, SEDD, HRED, SLAD
Materials sciences	Electronic materials and devices Structural materials	SEDD, WMRD, CISD
Mechanical sciences	Propulsion Mechanics Reliability and diagnostics	VTD, WMRD

NOTE: CISD, Computational and Information Sciences Directorate; HRED, Human Research and Engineering Directorate; SEDD, Sensors and Electron Devices Directorate; SLAD, Survivability and Lethality Analysis Directorate; VTD, Vehicle Technology Directorate; WMRD, Weapons and Materials Research Directorate.

B

Biographical Sketches of Army Research Laboratory Technical Assessment Board Members and Staff

JENNIE S. HWANG, *Chair,*[1] NAE, is the chief executive officer of H-Technologies Group and board trustee and distinguished adjunct professor at Case Western Reserve University. Her career encompasses corporate and entrepreneurial businesses, international collaboration, research management, technology transfer, and global leadership positions, as well as corporate and university governance. She has held senior executive positions with Lockheed Martin, SCM Corporation, and Sherwin Williams and has cofounded entrepreneurial businesses. She is internationally recognized as a pioneer and long-standing leader in the fast-moving infrastructure development of electronics miniaturization and green manufacturing. Dr. Hwang is an inventor and author of 350+ publications, including the sole authorship of several internationally used textbooks. As a columnist for the globally circulated trade magazines *Global Solar Technology* and *SMT* magazine, she addresses technology issues and global market thrusts. She also has served on the International Advisory Board of the Singapore Advanced Technology and Manufacturing Institute and as a board director for Fortune 500 and private companies. Over the years, she has taught tens of thousands of professionals and managers in professional development courses, providing continuing education and disseminating new technologies to the workforce. The YWCA's Dr. Jennie S. Hwang Award was established to encourage and recognize outstanding women students in science and engineering. Her formal education includes the Harvard Business School Executive Program, a Ph.D. in materials science and engineering, two M.S. degrees, one in chemistry and one in liquid crystal science, and a bachelor's degree in chemistry.

[1] Jennie S. Hwang, a member of the Army Research Laboratory Technical Assessment Board, was appointed as chair on February 6, 2014.

R. BYRON PIPES, *Chair,*[2] NAE, has been the John Leighton Bray Distinguished Professor of Engineering at Purdue University since 2004. He is a member of the Royal Society of Engineering Sciences of Sweden (1995). Composite materials have been the focus of his scholarship for the past 44 years. He has developed analytical models and carried out experiments with the objective of developing a fundamental understanding of the design, durability, and manufacture of these materials systems and structures. He served as Goodyear Endowed Professor of Polymer Engineering at the University of Akron from 2001 to 2004. He was Distinguished Visiting Scholar at the College of William and Mary from 1999 to 2001, where he pursued research in carbon nanotechnology at the NASA Langley Research Center. He served as president of Rensselaer Polytechnic Institute from 1993 to 1998. Dr. Pipes was provost and vice president for academic affairs at the University of Delaware from 1991 to 1993 and served as dean of the College of Engineering and director of the Center for Composite Materials from 1977 to 1991 at the same institution. He was appointed Robert L. Spencer Professor of Engineering in 1986 in recognition of his outstanding scholarship in the field of polymer composite materials ranging over the subject areas of advanced manufacturing science, durability, design, and characterization. Dr. Pipes received his Ph.D. degree in mechanical engineering from the University of Texas at Arlington and the M.S.E. from Princeton University. He is the recipient of the Gustus L. Larson Award of Pi Tau Sigma and the Chaire Francqui, Distinguished Faculty Scholar Award, in Belgium. He is a fellow of the American Society for Composites (ASC), the American Society of Mechanical Engineers (ASME), and the Society for the Advancement of Materials Engineering (SAMPE).

KENNETH R. BOFF is principal scientist with Socio-Technical Sciences. From 2007 to 2012, he served as principal scientist with the Tennenbaum Institute at the Georgia Institute of Technology and as scientific advisor to the Asian Office of Aerospace Research and Development (Tokyo). From 1997 to 2007, he served as the U.S. Air Force Research Laboratory chief scientist for human effectiveness. In this position was responsible for the technical direction of a multidisciplinary R&D portfolio encompassing individual, organizational, and sociocultural behavior and modeling, training, protection, and the bio- and human engineering of complex systems. He is best known for his work on understanding and remediating problems in the transition of research to applications in the design, acquisition, and deployment of systems and the value-centered management of R&D organizations. Holder of a patent for rapid communication display technology, Dr. Boff has authored numerous articles, book chapters, and technical papers and is coeditor of *Organizational Simulation* (2005) and *System Design* (1987); he is also senior editor of the two-volume *Handbook of Perception and Human Performance* (1986) and the four-volume *Engineering Data Compendium: Human Perception and Performance* (1988). He actively consults and provides technical liaison with government agencies, international working groups, universities, and professional societies. He has organized and facilitated numerous technical workshops in the United States, Europe, and the Pacific Rim focused on contemporary issues in complex socio-technical systems. He is a fellow of the Human Factors and Ergonomics Society and the International Ergonomics Association.

EPHRAHIM GARCIA[3] was a professor and director of graduate studies for the field of aerospace in the Department of Mechanical and Aerospace Engineering at Cornell University. His area of expertise was dynamics and controls, especially sensors and actuators involving smart materials with applications to robotics, energy harvesting, and bioinspired machines. Dr. Garcia served as a program manager in the

[2] R. Byron Pipes resigned as chair of the ARLTAB on February 5, 2014.
[3] Ephrahim Garcia passed away on September 10, 2014.

Defense Sciences Office at DARPA from 1998 to 2002. His programs involved the development of new types of actuation systems utilizing smart material transducers, system-level demonstrations of smart structures applied to defense platforms, morphing aircraft systems, and the development of exoskeletons for human performance augmentation. From 1991 to 1998, Dr. Garcia was an assistant and then associate professor of mechanical engineering at Vanderbilt University, where he was director of the Centre for Intelligent Mechatronic Systems, and the Smart Structures Laboratory. In this capacity he directed research in the areas of smart structures, control–structure interaction, and bioinspired robotics. From 1991 to 1997, he owned and operated Garman Systems, Inc. (now Dynamic Structures and Materials, LLC), a small engineering corporation that designed and fabricated devices in adaptive structural systems using smart materials. In 1995, Dr. Garcia was named an Office of Naval Research Young Investigator and appointed a 1993 Presidential Faculty Fellow by President Clinton. Dr. Garcia was author of more than 275 articles, book chapters, edited volumes, and books. In 2002, he received the prestigious American Society of Mechanical Engineers' Adaptive Structures Prize for "significant contributions to the sciences and technologies associated with adaptive structures and/or materials systems." Since 2006, he served as editor in chief of the *Smart Materials and Structures* journal. Dr. Garcia was a fellow of the Institute of Physics and the ASME, and an associate fellow of the American Institute of Aeronautics and Astronautics (AIEE).

GEORGE T. (Rusty) GRAY III is a laboratory fellow and staff member in the dynamic properties and constitutive modeling team within the Materials Science Division of Los Alamos National Laboratory (LANL). He came to LANL following a 3-year visiting scholar position at the Technical University of Hamburg-Harburg in Hamburg, Germany, having received his Ph.D. in materials science in 1981 from Carnegie Mellon University. As a staff member (1985-1987) and, later, team leader (1987-2003) in the Dynamic Materials Properties and Constitutive Modeling Section within the Structure/Property Relations Group (MST-8) at LANL, he directed a research team working on investigations of the dynamic constitutive and damage response of materials. He conducts fundamental, applied, and focused programmatic research on materials and structures, in particular in response to high strain rate and shock deformation. His research is focused on experimental and modeling studies of substructure evolution and the mechanical response of materials. He is a Life Member of Clare Hall, Cambridge University, where he was on sabbatical in the summer of 1998. He is a fellow of the American Physical Society, ASM International, and the Minerals, Metals, and Materials Society (TMS). He serves on the International Scientific Advisory Board of the European DYMAT Association. In 2010 he served as the president of TMS. He has authored or coauthored more than 380 technical publications.

PRABHAT HAJELA is provost and professor of mechanical and aerospace engineering at the Rensselaer Polytechnic Institute. His research interests include analysis and design optimization of multidisciplinary systems; system reliability; emergent computing paradigms for design; artificial intelligence; and machine learning in multidisciplinary analysis and design. Before joining Rensselaer, he worked as a research fellow at the University of California, Los Angeles, for a year and was on the faculty at the University of Florida for 7 years. He has conducted research at NASA's Langley and Glenn Research Centers and the Eglin Air Force Armament Laboratory. In 2003, Dr. Hajela served as a congressional fellow responsible for science and technology policy in the Office of U.S. Senator Conrad Burns (R-MT). He worked on several legislative issues related to aerospace and telecommunications policy, including the anti-SPAM legislation that was signed into law in December 2003. Dr. Hajela is a fellow of the AIAA, a fellow of the Aeronautical Society of India (AeSI), and a fellow of the ASME. He has held many editorial assignments, including editorship of *Evolutionary Optimization* and associate editorship of the *AIAA Journal*, and is on the editorial boards of six other international journals. He has published over 270 papers and articles in the areas of structural and multidisciplinary optimization and is an author or coauthor of four books in these areas. In 2004, he was the recipient of AIAA's Biennial Multidisciplinary Design Optimization Award.

WESLEY L. HARRIS,[4] NAE, is the Charles Stark Draper Professor of Aeronautics and Astronautics, Associate Provost for Faculty Equity, and Director of the Lean Sustainment Initiative at the Massachusetts Institute of Technology. He was elected to the NAE "for contributions to understanding of helicopter rotor noise, for encouragement of minorities in engineering, and for service to the aeronautical industry." He has performed research and published in refereed journals in the following areas: fluid mechanics; aerodynamics; unsteady, non-linear aerodynamics; acoustics; lean manufacturing processes; and military logistics and sustainment. Dr. Harris has substantial experience as a leader in higher education administration and management. He also has demonstrated outstanding leadership in managing major national and international aeronautical and aviation programs and personnel in the executive branch of the federal government. Dr. Harris is an elected fellow of the AIAA, AHS, and of the NTA for personal engineering achievements, engineering education, management, and advancing cultural diversity.

Staff

LIZA HAMILTON served as the administrative coordinator for the ARLTAB and the Laboratory Assessments Board (LAB) until February 22, 2014, and is now an associate program officer at the LAB. Since 2002, she has been responsible for managing the administrative aspects of panel formation, panel meetings, report publication and dissemination, and program development. In addition, she has designed newsletters, brochures, covers, and figures for numerous reports prepared by the NRC's Division on Life Sciences and its Division on Engineering and Physical Sciences. Ms. Hamilton earned a 4-year certification in musical theater performance from Pinellas County Center for the Arts in St. Petersburg, Florida; a B.F.A. in film studies from the University of Utah; a design certification from Maryland Institute College of Art; and the master of liberal arts from the Johns Hopkins University.

EVA LABRE is the administrative coordinator for the Laboratory Assessments Board in the Division on Engineering and Physical Sciences at the NRC. Since 2009, she has been responsible for assisting in the management of the administrative aspects of panel formation, panel meetings, report publication and dissemination, and program development. In addition, she has been responsible for travel expense accounting and other financial aspects of the LAB. Ms. Labre previously held administrative positions on the staff of the Committee on International Organizations and Programs in the NRC Office of International Affairs and on the staff of the Research Associateship Program in the NRC Office of Scientific and Engineering Personnel. Ms. Labre has a B.A. in art history from George Washington University.

JAMES P. McGEE is the director of the Laboratory Assessments Board, the Army Research Laboratory Technical Assessment Board (ARLTAB), and the Committee on National Institute of Standards and Technology Technical Programs, in the Division on Engineering and Physical Sciences at the NRC. Since 1994, he has been a senior staff officer at the NRC, directing projects in the areas of systems engineering and applied psychology, including activities of ARLTAB and projects of the Committee on National Statistics' Panel on Operational Testing and Evaluation of the Stryker Vehicle

[4] Wesley L. Harris was appointed to the ARLTAB on September 15, 2014.

and the Committee on Assessing the National Science Foundation's Scientists and Engineers Statistical Data System, the Committee on the Health and Safety Needs of Older Workers, and the Steering Committee on Differential Susceptibility of Older Persons to Environmental Hazards. He has also served as staff officer for NRC projects on air traffic control automation, musculoskeletal disorders and the workplace, and the changing nature of work. Prior to joining the NRC, Dr. McGee held technical and management positions in systems engineering and applied psychology at IBM, General Electric, RCA, General Dynamics, and United Technologies. He received his B.A. from Princeton University and his Ph.D. from Fordham University, both in psychology, and for several years instructed postsecondary courses in applied psychology and in organizational management.

ARUL MOZHI is senior program officer at the Laboratory Assessments Board in the Division on Engineering and Physical Sciences at the NRC. Since 1999, he has been a senior program officer at the NRC, directing projects in the areas of defense science and technology, including those carried out by numerous study committees of the Laboratory Assessments Board, the Army Research Laboratory Technical Assessment Board, the Naval Studies Board, and the National Materials and Manufacturing Board. Prior to joining the NRC, Dr. Mozhi held technical and management positions in systems engineering and applied materials research and development at UTRON, Inc.; Roy F. Weston, Inc.; and Marko Materials, Inc. He received his M.S. and Ph.D. degrees (the latter in 1986) in materials engineering from the Ohio State University and then served as a postdoctoral research associate there. He received his B. Tech. in metallurgical engineering from the Indian Institute of Technology, Kanpur, in 1982.

ANDREA L. SHELTON is administrative assistant at the Laboratory Assessments Board (LAB) in the Division on Engineering and Physical Sciences (DEPS) at the NRC. Since March 2014, she has been responsible for assisting in the management of the administrative aspects of panel formation, panel meetings, report publication and dissemination, and program development. In addition, she has been responsible for travel expense accounting. Prior to joining the LAB, Ms. Shelton previously held an administrative staff position in the DEPS Executive Office.

C

Assessment Criteria

The Army Research Laboratory Technical Assessment Board's (ARLTAB's) assessment considered the following general questions posed by the Army Research Laboratory (ARL) director:

- Is the scientific quality of the research of comparable technical quality to that executed in leading federal, university, and/or industrial laboratories both nationally and internationally?
- Does the research program reflect a broad understanding of the underlying science and research conducted elsewhere?
- Does the research employ the appropriate laboratory equipment and numerical models?
- Are the qualifications of the research team compatible with the research challenge?
- Are the facilities and laboratory equipment state-of-the-art?
- Are programs crafted to employ the appropriate mix of theory, computation, and experimentation?

To assist ARL in addressing promising technical approaches, the ARLTAB also considered the following questions:

- Are there especially promising projects that, with improved direction or resources, could produce outstanding results that can be transitioned ultimately to the field?
- Are there promising outside-the-box concepts that should be pursued but are not currently in the ARL portfolio?

The ARLTAB applied the following metrics or criteria to the assessment of the scientific and technical work reviewed at the ARL:

1. Effectiveness of interaction with the scientific and technical community
   a. Papers in quality refereed journals and conference proceedings (and their citation index)
   b. Presentations and colloquia
   c. Participation in professional activities (society officers, conference committees, journal editors)
   d. Educational outreach (serving on graduate committees, teaching/lecturing, invited talks, mentoring students)
   e. Fellowships and awards (external and internal)
   f. Review panel participation (ARO, NSF, MURI, and the like)
   g. Recruiting new talent into ARL
   h. Patents and intellectual property (and examples of how the patent or intellectual property is used)
   i. Involvement in building an ARL-wide cross-directorate community
   j. Public recognition, e.g., in the press and elsewhere, for ARL research

2. Formulation of projects' goals and plans
   a. Are tasks well defined to achieve objectives?
   b. Does the project plan clearly identify dependencies (i.e., successes depend on success of other activities within the project or outside developments)?
   c. If the project is part of a wider activity, is the role of the investigators clear and are the project tasks and objectives clearly linked to those of other related projects?
   d. Are milestones identified if they are appropriate? Do they appear feasible?
   e. Are obstacles and challenges defined (technical, resources)?
   f. Does the project represent an area where application of ARL strengths is appropriate?

3. Research and development methodology
   a. Are the hypotheses appropriately framed within the literature and theoretical context?
   b. Is there a clearly identified and appropriate process for performing required analyses, prototypes, models, simulations, tests, and so on?
   c. Are the methods (e.g., laboratory experiment, modeling/simulation, field test, analysis) appropriate to the problems? Do these methods integrate?
   d. Is the choice of equipment/apparatus appropriate?
   e. Is the data collection and analysis methodology appropriate?
   f. Are conclusions supported by the results?
   g. Are proposed ideas for further study reasonable?
   h. Do the trade-offs between risk and potential gain appear reasonable?
   i. If the project demands technological or technical innovation, are those needs being met?
   j. What stopping rules, if any, are being or should be applied?

4. Capabilities and resources
   a. Are the qualifications and number of the staff (scientific, technical, and administrative) appropriate to achieve success of the project?
   b. Is the state of the equipment and facilities adequate?
   c. If staff or equipment are not adequate, how might the project be subjected to triage (which technical thrust should be emphasized, which sacrificed?) to best move toward its stated objectives?

D

Acronyms

2D	two-dimensional
3D	three-dimensional
ABLE	Atmospheric Boundary Layer Environment
ACM	Association for Computing Machinery
ADS	advanced distributed simulation
AFM	atomic force microscopy
AFRL	Air Force Research Laboratory
ALD	atomic layer disposition
AP	armor-piercing
API	application programming interface
ARDEC	Armament Research, Development and Engineering Center
ARES	aeroelastic rotor experimental system
ARL	Army Research Laboratory
ARLTAB	Army Research Laboratory Technical Assessment Board
ARO	Army Research Office
ATO	Army technology objective
BCI	brain–computer interaction
BED	Battlefield Environment Division
CAD	computer-aided design
CAVE	computer-assisted virtual environment
CERDEC	Communications-Electronics Research, Development and Engineering Center

CFD	computational fluid dynamics
CISD	Computational and Information Sciences Directorate
CNT	carbon nanotube
CONUS	continental United States
COSMOS	Compound Semiconductor Materials on Silicon (program)
CPU	central processing unit
CRA	Collaborative Research Alliance
CSD	Computational Sciences Division of the CISD
CTA	Collaborative Technology Alliance
CVD	chemical vapor deposition
DARPA	Defense Advanced Research Projects Agency
DE	directed energy
DFT	density functional theory
DMFC	direct methanol fuel cell
DNS	direct numerical simulation
DoD	Department of Defense
DRI	Director's Research Initiative
DSI	Director's Strategic Initiative
DU	depleted uranium
EAR	environment for auditory research
EASE	executable architecture systems engineering
EBG	electromagnetic bandgap
EBSD	electron backscatter diffraction
ECAP	equal channel angular pressing
ECG	electrocardiography
EDS	energy dispersive x-ray spectroscopy
EEG	electroencephalogram
EFAS	electric-field-assisted sintering
EFP	explosively formed penetrator
EIS	electrochemical impedance spectroscopy
EM	electromagnetic
EMG	electromyography
EPAs	embodied pedagogical agents
ERA	explosive reactive armor
ESAPI	enhanced small arms protective inserts
FEM	finite-element modeling
FET	field effect transistor
FY	fiscal year
GB	grain boundary
GCV	ground combat vehicle
GIFT	generalized intelligent framework for tutoring
GIS	Geographical Information System

GN&C	guidance, navigation, and control
GPS	global positioning system
GPU	graphics processing unit
GSR	galvanic skin response
GUI	graphical user interface
HPC	high-performance computing
HPCI	High Performance Computing Institute
HRED	Human Research and Engineering Directorate
HRI	human–robot interaction
HSI	human–system integration
IC	integrated circuit
ICT	Institute for Creative Technology
IED	improvised explosive device
IEEE	Institute of Electrical and Electronics Engineers
IGF	intergranular grain-boundary film
IMPRINT	Improved Performance Research Integration Tool
IR	infrared
JP-8	jet propellant 8 (fuel)
KE	kinetic energy
LES	large-eddy simulation
Li-ion	lithium ion
LLNL	Lawrence Livermore National Laboratory
LWIR	long-wavelength infrared
M&S	modeling and simulation
MANPRINT	manpower and personnel integration
MAST	Micro Autonomous Systems and Technology
MAV	micro autonomous vehicle
MEMS	microelectromechanical systems
MET	Model Evaluation Tool
MOCVD	metal organic chemical disposition
MOUT	military operations in urban terrain
MURI	Multidisciplinary University Research Initiative
MUVES	Modular UNIX-based Vulnerability Estimation Suite (software)
NASA	National Aeronautics and Space Administration
NC	nanofibrils of cellulose
NCAR	National Center for Atmospheric Research
NERA	nonexplosive reactive armor
NMR	nuclear magnetic resonance
NOAA	National Oceanographic and Atmospheric Administration

NRC	National Research Council
NSF	National Science Foundation
OEO	opto-electronic oscillator
ONR	Office of Naval Research
ORCA	operational requirements-based casualty assessment
PDV	photon Doppler velocimetry
PFM	phase field modeling
QE	quantum efficiency
QMU	quantify the margin of uncertainty
QWIP	quantum-well infrared photodetector
R&D	research and development
RAVEN	RSVP-based adaptive virtual environment with neural processing
RDEC	Research, Development and Engineering Center
RDECOM	Research, Development and Engineering Command
RF	radio frequency
RSVP	rapid serial visual presentation
S&T	science and technology
SBIR	small business innovation research
S-D	source to drain
SDN	software-defined networks
SEDD	Sensors and Electron Devices Directorate
SEI	solid electrolyte interface
SEM	scanning electron microscope
SiC	silicon carbide
SiC-N	silicon carbide-new
SLAD	Survivability/Lethality Analysis Directorate
SME	subject-matter expert
SOC	system on a chip
SOFC	solid oxide fuel cell
SPEAR	soldier performance and equipment advanced research
SPM	scanning probe microscopy
SRAM	static random access memory
STEM	science, technology, engineering, and mathematics
STM	scanning tunneling microscope
STTC	Simulation and Training Technology Center
STTR	small business technology transfer
TARDEC	Tank Automotive Research, Development and Engineering Center
TBI	traumatic brain injury
TEM	transmission electron microscopy
THz	terahertz

TMD	transition metals dichalcogenide
TMEDA	N,N,N′,N′-tetramethylethylenediamine
TN	translational neuroscience
TRADOC	Training and Doctrine Command
TTR	through-thickness reinforcement
UHF	ultrahigh frequency
UHMWPE	ultrahigh molecular weight polyethylene
UV	ultraviolet
V&V	validation and verification
VBS2	Virtual Battlespace 2
VPSC	viscoplastic self-consistent
VRAMS	virtual-risk-informed agile maneuver sustainment
VTD	Vehicle Technology Directorate
WC	tungsten carbide
WHA	tungsten heavy alloy
WIAMan	warrior injury assessment manikin
WMRD	Weapons and Materials Research Directorate
WRATS	wing and rotor aeroelastic testing system
WRE-N	Weather Running Estimate-Nowcast
WSMR	White Sands Missile Range
XLADD	extremely lightweight, adaptive, durable, damage-tolerant