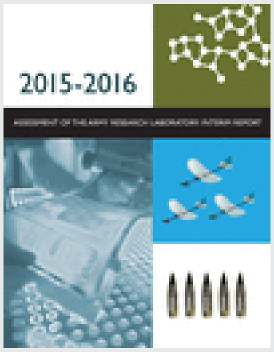

2015-2016 Assessment of the Army Research Laboratory: Interim Report

DETAILS

124 pages | 8.5 x 11 | PAPERBACK
ISBN 978-0-309-39207-5 | DOI: 10.17226/21916

AUTHORS

Army Research Laboratory Technical Assessment Board; Laboratory Assessments Board; Division on Engineering and Physical Sciences; National Academies of Sciences, Engineering, and Medicine

2015-2016
ASSESSMENT OF THE ARMY RESEARCH LABORATORY: INTERIM REPORT

Army Research Laboratory Technical Assessment Board

Laboratory Assessments Board

Division on Engineering and Physical Sciences

The National Academies of
SCIENCES • ENGINEERING • MEDICINE

THE NATIONAL ACADEMIES PRESS
Washington, DC
www.nap.edu

THE NATIONAL ACADEMIES PRESS 500 Fifth Street, NW Washington, DC 20001

This activity was supported by Contract No. W911QX-14-C-0039 from the Army Research Laboratory. Any opinions, findings, conclusions, or recommendations expressed in this publication do not necessarily reflect the views of any organization or agency that provided support for the project.

International Standard Book Number-13: 978-0-309-39207-5
International Standard Book Number-10: 0-309-39207-1
Digital Object Identifier: 10:17226/21916

Additional copies of this report are available for sale from the National Academies Press, 500 Fifth Street, NW, Keck 360, Washington, DC 20001; (800) 624-6242 or (202) 334-3313; http://www.nap.edu.

Printed in the United States of America

Suggested citation: National Academies of Sciences, Engineering, and Medicine. 2016. *2015-2016 Assessment of the Army Research Laboratory: Interim Report*. Washington, DC: The National Academies Press. doi:10:17226/21916.

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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 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:

Rodney J. Clifton, NAE, Brown University,
Nancy J. Cooke, Arizona State University,
Paul A. Fleury, NAS/NAE, Yale University,
William D. Gropp, NAE, University of Illinois, Urbana-Champaign,
Emilie M. Roth, Roth Cognitive Engineering, 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 Paul M. Bevilaqua, NAE, Lockheed Martin Aeronautics Company, who 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.

Contents

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 2015-2016 assessment, the ARLTAB is being assisted by six panels, each of which focuses on a portion of the ARL program conducted in ARL's science and technology (S&T) campaigns: Materials Research, Sciences for Lethality and Protection, Information Sciences and Computational Sciences, Sciences for Maneuver, Human Sciences, and Assessment and Analysis.

This interim report summarizes the findings of the Board for the first year of this biennial assessment; the current report addresses approximately half the portfolio for each campaign; the remainder will be assessed in 2016. During the first year the Board examined the following elements within the ARL S&T campaigns: (1) within Materials Research: biological and bioinspired materials, energy and power materials, and engineered photonics materials; (2) within Sciences for Lethality and Protection: battlefield injury mechanisms, directed energy, and armor and adaptive protection; (3) within Information Sciences: sensing and effecting, and system intelligence and intelligent systems (SIIS); (4) within Computational Sciences: advanced computing architectures, computing sciences, data-intensive sciences, and predictive simulation sciences; (5) within Sciences for Maneuver: human–machine interaction, intelligence and control, and perception; (6) within Human Sciences: humans in multiagent systems, real-world behavior, and toward human variability; and (7) within Assessment and Analysis: mission capability of systems. A second, final report will subsume the findings of this interim report and add the findings from the second year of the review, during which the Board will examine additional elements within the ARL S&T campaigns.

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. In 2013 ARL restructured its portfolio of ongoing and planned research and development to align with its S&T campaign plans for 2015-2035. ARL has maintained its organizational structure, consisting of six directorates: Weapons and Materials Research Directorate (WMRD), Computational and Information Sciences Directorate (CISD), Human Research and Engineering Directorate (HRED), Sensors and Electron Devices Directorate (SEDD), Survivability and Lethality Analysis Directorate (SLAD), and Vehicle Technology Directorate (VTD). The research portfolio has been organized into science and technology campaigns, each of which describes related work supported by staff from multiple directorates. Appendix Table A.1 shows the directorates that supported each campaign during the 2015 review. ARL's technical strategy document describes the portfolio of each campaign in detail.[1] ARL's vision is compelling and raises expectations for an innovative program of research designed to be responsive to the needs of the "Army after next." This is not yet fully evident in the portfolio currently being assessed. The reorganization of the portfolio into key focused campaigns is promising, but it may take some time to transform and mature the program of work to consistently align with new critical paths.

In general, 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. 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 all outstanding accomplishments and mark an advance over prior years.

MATERIALS RESEARCH

ARL's materials sciences efforts span the spectrum of technology maturity as they address Army applications, working from the state of the art to the art of the possible—"25 years out," according to the ARL. Materials research efforts and expertise, one of ARL's core technical competencies, are spread throughout the ARL enterprise.

Biological and Bioinspired Materials

The biological and bioinspired materials effort has grown substantially over the last 2 years. Although still small, the group has an excellent track record, including the stabilization of proteins against thermal and chemical extremes using new chemistries and methods to derive antibody-like reagents that improve antibody properties—specifically, their bimolecular recognition and binding characteristics. These accomplishments are likely to lead to further program growth. The scientific quality of this thrust area is on par with the work at leading federal, university, and industry laboratories and is a crucial part of a broader national effort in biomaterials research. Because biology is a growth area, ARL now has an opportunity to identify and recruit a critical mass of biologists, including microbiologists and polymer/organic chemists, looking well into the future to create an integrated community of researchers.

Energy and Power Materials

Energy and power materials is a mission-critical research area with a clear focus on Army needs. The effort is broad in the sense that it appreciates the importance of moving basic research to technology and reflects an integrated research approach involving experiment, theory, and simulation. As one component of this thrust, ARL researchers have developed high-quality collaborative interactions with other programs within and beyond the Army research enterprise. The portfolio of research projects supports an appropriate balance of high-risk, long-term-impact projects along with mid-term and short-term projects. There is a broad, deep coverage of different devices, different fuels, and different applications covering a wide range of time and size scales. The quality of the research projects, the staff, and the facilities is comparable to that of top research laboratories elsewhere in industrial and academic environments. Questions remain, however, about whether ARL is mobilizing aggressively enough to capitalize on ARL's own internal advances and as well as external advances made by the broader

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[1] U.S. Army Research Laboratory, *Army Research Laboratory Technical Strategy 2015-2035*, Adelphi, Md., 2014, http://www.arl.army.mil/www/pages/172/docs/ARL_ Technical Strategy_FINAL.pdf.

community—for example, are ARL's recent world-leading results on enhancement in quantum-well infrared photodetector efficiencies being translated into capability demonstrators for manufacturers and customers? Similarly, ARL may not be working to leverage advances in silicon photonics taking place elsewhere, especially with regard to heterogeneous materials. In contrast to the expansion in first-principles modeling, engineering models are underutilized, perhaps owing to limited in-house expertise in this facet of modeling.

In some energy and power applications, such as lithium-ion batteries and fuel cells, there is a broad, vigorous, fast-moving, worldwide research effort directed at identifying fundamental scientific issues and developing novel materials and entire systems. Accordingly, some too narrowly focused ARL projects need to search out and gain access to the right niche in order to have impact.

Engineered Photonics Materials

Research and development for engineered photonics materials will be essential in support of the future warfighter. Accordingly, ARL has organized a research effort in this critical area that is among the world's best. This is an impressive accomplishment in light of the technical program's inherently wide scope, which is so essential to addressing diverse Army needs, both current and future. The quality of the work presented reflects a high level of technical competence and professionalism on the part of researchers and management. This thrust area shows a good balance of high-risk, longer-term work on the one hand with, on the other hand, nearer-term, customer-driven solutions and incremental—but critical—technology refinement. This well-balanced portfolio is supported by a strong materials capability in terms of both staff expertise and laboratory or clean room infrastructure. Investments in computational modeling and simulation have been successfully implemented to complement strengths and core competencies in materials synthesis and characterization, as well as device work. All of these facilities and capabilities are being leveraged into compelling device- and application-driven work, especially in ultraviolet materials and infrared devices and device physics in both areas.

SCIENCES FOR LETHALITY AND PROTECTION

The ARL research efforts in Sciences for Lethality and Protection that were assessed span, on the one hand, basic research that improves our fundamental understanding of scientific phenomena and, on the other hand, generate technology that supports (1) battlefield injury mechanisms in human response to threats and human protective equipment, (2) directed energy programs, and (3) ballistics and blast programs that address weapon–target interactions and armor and adaptive protection developments.

Battlefield Injury Mechanisms

A better understanding of the mechanisms of injury is vital to improving protective measures, making the program on battlefield injury mechanisms an important one for ARL. This is especially true for protection of the head, about which there is considerable uncertainty concerning allowable levels of shock, which greatly affect the protective options. The most impressive accomplishment of the battlefield mechanisms/human response/human protective equipment program is that a strong cadre of scientists is at work, and a credible program is under way. A long-term vision for the battlefield injury mechanisms projects could have a philosophy to guide resource allocation and program direction. Almost all the battlefield mechanisms, human responses, and human protective equipment research topics presented had a combination of computational and experimental approaches, but the real-time interplay of experiment and computation is needed.

Directed Energy

ARL's campaign plans categorize directed energy (DE) as a focused area under the much broader category of electronic warfare (EW), in accordance with the Army's definitions. The ARL posture designations for both radio frequency-DE and laser-DE are *collaborate* rather than *lead*. The subsuming of DE under EW and a collaborate-only posture indicate that ARL has downgraded the priority of DE within its technology portfolio from its previously robust effort. The consequence of this status change was evident in the programs presented: They appear to be a small collection of seemingly unrelated projects. ARL needs to take a strategic look at the area of DE to determine its priority going forward and rethink its effort with a view to the 2035 time frame. The strategic review needs to consider future capabilities that the Army will need that DE might enable and what DE capabilities might be fielded by our adversaries for which the Army will need countermeasures. A focused ARL DE program would benefit from a systems-level study addressing future Army missions in which DE could play a role and where DE effectiveness and alternatives to DE are traded off. A highlight of the overall program in DE is the project on adaptive and scalable high-power phase-locked-fiber laser arrays. This work is a notable achievement, is recognized as such by the technical community, and appears to be ready for the next step, transition to field deployment.

Armor and Adaptive Protection

ARL has a strong record of achievement in the basic and applied sciences and the engineering of penetration and protection. The research and development described in the armor and adaptive protection area showed how ARL is building on its tradition of excellence to provide the knowledge basis for current and future Army needs in protecting our warfighters. This remains a core competency that underlies Army capabilities across the entire Department of Defense, and it needs to be preserved and nurtured. There was significant evidence of teamwork and integration among the projects in, for example, adaptive protection. Examples of the linkage between experimentation and computational modeling to provide physical insight into problems were especially noteworthy and had the potential to aid in developing new designs and exploring new concepts. Benchmarking simulations with experiments and the emphasis on bringing advanced technology (particularly in the domain of x rays) to bear on diagnostics were impressive. Developing a predictive capability for damage and fracture in metals, ceramics, and polymers underlies the efficient development of new material systems for protection from emerging penetration capabilities. At present, there is no framework that has this capability. However, experimental, theoretical, and computational advances here and elsewhere are making such a capability seem possible in the not-too-distant future. A systematic approach based on understanding the key physical processes is needed, because such a variety of material systems are becoming available.

INFORMATION SCIENCES

In the research portfolio known as Information Sciences, research projects in the broad categories of (1) sensing and effecting and (2) system intelligence and intelligent systems (SIIS) constituted the focus of the review.

Sensing and Effecting

In the area of sensing and effecting, the projects were well aligned in support of future Army missions and were focused in areas of nonimaging sensors, image understanding, sensor and data fusion, and radar signal processing. There was a significant emphasis on applications as opposed to the foundational science.

The research on acoustic sensors covers a gamut of activities focused on the application of new materials in the design of sensors to the development of innovative signal processing techniques that improve the effectiveness of the sensors. The work on signal processing extends beyond traditional sensors and is investigating the use of microelectromechanical systems-based, three-dimensional acoustical particle velocity sensors. Some of this research has been presented at recognized conferences and published in the archival literature.

The work related to image understanding was generally of high quality and is being published in respectable venues. The cross-modal face recognition work was of high quality and addressed problems relevant to Army missions. A significant opportunity exists for ARL to better connect with and provide intellectual leadership to the broader facial recognition community by creating and curating open, standardized data sets as well as challenge problems for researchers to explore.

The work related to polarization has excellent potential. In particular, collaboration in the project related to sensor algorithms for polarization imagery is representative of the potential benefits of the ARL open campus initiative. Similarly, the project on manmade object discrimination has important practical implications and recently led to a patent.

In the area of sensor and data fusion, the focus is on developing efficient techniques to fuse data from multiple sources to improve inference. In this context, research described as dynamic belief fusion allocates probabilities to sensor information based on prior performance and has shown an improvement in detection accuracy over conventional fusion methods.

Radar signal processing work was of good technical quality and showed promising results. In particular, new approaches for detecting moving personnel under tree cover and the broader issue of detecting targets obscured by artifacts have been investigated with success. The work related to nonlinear radar methods is concentrated on the use of nonlinear harmonic radar to achieve greater sensitivity across a narrow frequency band; this work has shown promise in early experiments.

System Intelligence and Intelligent Systems

Research projects in SIIS were presented in three areas: information understanding, information fusion, and computational intelligence.

The focus of information understanding is on critical methods and techniques for transforming data so as to provide useful information to the soldier. In particular, the work on temporal information extraction focuses on methods for extracting temporal relationships from text for constructing knowledge networks. The proposed approach is technically solid and has been published in prestigious venues. Projects related to activities in the network science collaborative technology alliance (CTA) include work on influence in social networks that seeks to identify mechanisms for trust formation in human networks. The emphasis of the effort has been on identifying main factors, and the work has not addressed this issue in the context of networks. Also related to the network science CTA is research related to agent-based semantic analysis in information retrieval. This thrust also includes an effort to perform language translation in an automated fashion with a goal of enhancing translation capabilities for low-resource languages. The novelty of the work centers on methods for constructing the language model.

Work on information fusion focuses on combining data from disparate sources to produce timely, actionable information for the soldier. Research related to estimating credibility through fusion of subject opinions is of good technical quality and was disseminated at a reputable conference. The work focuses on fusing multiple, inconsistent, and potentially conflicting information sources. Promising work is also represented by a project that seeks to develop an observer model for helping soldiers determine salient targets, with a special emphasis on anomaly detection in saliency models. This work draws on recent advances in image processing and neuroscience.

Research in computational intelligence is looking at interesting and potentially important problems in areas such as reasoning under uncertainty, robotic control and path planning, and models of cognition and tactical decision making. One promising approach deploys a semantic vector space for reasoning in the presence of uncertainties. The research features a combination of statistical and machine-learning methods with semantic rules for reasoning in an uncertain environment and has the potential for significant practical impact. Work on designing optimal paths for autonomous mobile robot movement has reached the demonstration level, and there is a good plan for future work that would deal with practical constraints. This is very high quality work with near-term applications.

COMPUTATIONAL SCIENCES

In the research portfolio under computational sciences, projects in the broad categories of advanced computing architectures, computing sciences, data-intensive sciences, and predictive simulation sciences were reviewed.

Advanced Computing Architectures

In the area of advanced computing architectures, research has focused on both tactical high-performance computing (HPC) and on the exploration of new and interesting computer architectures, including neurosynaptic computing, the epiphany of a many-core chip, and quantum networking. This work has important implications, but security and resilience have yet to be considered. Research on computation ferrying is exploring an important aspect of realizing ARL's vision of tactical HPC—the issue of computational tasks that could be computed on handheld devices or on mobile tactical HPC resources. Beyond establishing modeling and simulation capabilities to guide offload decisions, ARL has explored critical issues related to programmability and performance of edge (handheld) devices, particularly in the realm of open computing language programs that enhance power and performance. Research in dynamic binary translation is focused on allowing fast cross-architecture execution of binary codes, and it has yielded dramatic improvement in performance. ARL has a clear opportunity to lead the broader community and could significantly impact the Army's capability by focusing on tactical HPC.

Computing Sciences

The computing sciences group has established a strategic focus in quantum computing, parallel processing environments for large heterogeneous parallel systems, and tools to simplify application development for HPC environments. Research on the development of a threaded message-passing interface for reduced instruction set computing array multicore processors has yielded innovative solutions to the challenge of power-efficient parallel programming. The work on HPC-scaled quantum hardware description language is representative of one of the few efforts in the area of quantum networking, and it will promote the development of future systems. The computing sciences group has the opportunity to create the tools needed to optimize performance and scale for mission-critical applications and user environments.

Data-Intensive Sciences

Accomplishments in data-intensive sciences include new model order reduction methods for partial differential equations (PDE), cognitively steered exploration of solutions to PDEs at different resolution, efficient summarization and visualization of high-dimensional data sets, and concise characterization of spall damage in materials. The work on developing a high-performance, sparse, nonnegative, least-square solver advances the state of the art and leverages ARL's expertise in numerical analysis and HPC. Similarly, the work on neuromorphic computing represents a fresh and original approach. ARL researchers continue to make good advances in large, multiscale material modeling with a special emphasis on identification of damage modes. Its research approach provides a new method for characterizing spallation. The work related to the visual simulation laboratory focuses the use of a visualization-based framework to allow users to steer a multiresolution PDE simulation. The data-intensive sciences research could be strengthened by incorporating problem formulations that lead to results with theoretically grounded error bounds. Such research would contribute to ARL's focus on verification and validation in computational science.

Predictive Simulation Sciences

Important contributions have been made to developing predictive capabilities for use on the low-power computer platforms available in the field. In materials modeling, research on scalable algorithms for simulating dislocations in microstructured crystals is promising and has broad applicability for material and structural failure simulations. One of the most difficult technical challenges for this work is the problem of effective load balancing of HPC resources, and the research could benefit from consideration of new developments in adaptive parallel load-balancing techniques.

SCIENCES FOR MANEUVER

In each of the three pillars of the vehicle intelligence (VI) program—intelligence and control (I&C), perception, and human–machine interaction—the research quality was generally high. Collaboration with other government agencies, industry, and universities continues to have positive benefits. Internal personnel advancement strengthens the science capability for the VI research and development (R&D) program. Each of the three pillars of the VI program has demonstrated significant progress in advancing its R&D objectives to support the warfighter in increasingly complex environments. The R&D activities were consistent with their defined objectives. Opportunities in multiperson/multirobot scenario simulation, the teaming of autonomous systems with soldiers in uncertain environments, multispectral sensing, range sensing, contact sensing, and immersive display of robot LIDAR imagery are likely to allow ARL to be of even greater benefit to the soldier.

Inclusion of soldiers in VI field experiments is commendable. Use of more realistic vignettes and real-life simulations in experiments would be very beneficial. In particular, the use of realistic war fighting vignettes, where researchers are in the field with soldiers, provides opportunities to test and evaluate research hypotheses more thoroughly, including the revelation of previous unknowns.

Some strategic goals and tactical milestones for VI R&D programs could be made more apparent. To help quantify general progress and application-specific performance, more efforts need to be made in baselining and benchmarking.

Intelligence and Control

The I&C pillar employs innovative approaches to developing and supporting advanced technologies, algorithms, and tools in support of the warfighter effort. It invests in advancing the effectiveness and efficiency of its research personnel. It has tight couplings with the robotics CTA program and the micro autonomous systems technologies CTA program, with some specific ARL foci. The higher-level cognition that the I&C theme focuses on is aimed at enabling autonomous assets to work in the environments of relevance to the military.

Perception

The perception group at ARL has made significant headway. The perception pillar benefits from high-quality collaborations with top universities that enable successful hiring of outstanding personnel at the Ph.D. level. Its research personnel publish in top journals. The group is well aware of the current trends in the research community through participation in top, highly competitive conferences in the field.

Human–Machine Interaction

The human–machine interaction pillar's R&D program is of high quality, based on rigorous design and appropriate metrics. It benefits from a substantial increase in external and internal collaborations. Each project has its own appropriate algorithmic or experimental metrics, but the researchers did not, unfortunately, succeed in explaining the higher-level success criteria. The use of soldiers in experiments is commended. The research presented will be shifting from one-person/one-robot studies to multiperson/multirobot scenarios. This shift in research focus is appropriate as the Army moves toward use of more complex teaming architectures. This new direction highlights the need for additional research in trust and in human–machine interaction, raising questions about how one verifies software and validates systems to build confidence in the joint human–machine system, in the face of complex emergent behaviors.

HUMAN SCIENCES

The elements of human sciences that were assessed were humans in multiagent systems, real-world behavior, and human variability. A component of the Assessment and Analysis campaign portfolio on assessing mission capabilities of systems was also reviewed.

Humans in Multiagent Systems

As scoped, the area of humans in multiagent systems is very broad: It includes interactions between humans and technology and between humans and other human beings (sociocultural interactions), and it is not clear how those pieces fit together. This is an important niche area where ARL human sciences should establish competence. It has unquestioned Army relevance and is an interdisciplinary area where human sciences has a lead role to play. The key challenges are how to hold together a coherent vision for ongoing and planned research, to capitalize on useful existing baselines, and to cumulatively build to push the state of the art.

Real-World Behavior

In the area of real-world behavior, the collection and analysis of human behavioral data in dynamic, complex, natural environments is an ambitious and challenging undertaking. Not surprisingly, the accomplishments in this area are incremental given the immature state of the art and the challenges to developing the needed enabling technology and methodology. The research presented appears focused on mission-relevant problems and contexts and draws on measures from multiple domains (e.g., biomechanics, cognition, and neurosciences), consistent with the goal of addressing real-world complexity. Continued strategic investment in this area can yield significant payoffs for the Army with potential spillover benefits to other government and private sector R&D.

Toward Human Variability

Understanding and predicting human variability is an important and timely topic for investigation. Current systems are calibrated to the average performance of the average person in challenging circumstances; optimized adaptive systems might enable better use of human capacity when situations and states permit. Advances in this area reflect the availability of increasingly sophisticated techniques for behavioral and brain measurement and the development of new analytic and statistical methods that could enable adaptive systems in operational settings. This group has recruited an exceptionally strong set of researchers, including well-qualified postdoctoral and early-career scientists representing different technical backgrounds. Overall, the work in this area was of exceptional quality.

ASSESSMENT AND ANALYSIS

In the assessing mission capabilities of systems area, the work comprises human-centered engineering and decision support methods, models, and tools supported under ARL's Assessment and Analysis campaign. Most of the projects that were presented in this area are responding to the needs of specific Army customers. Commendable efforts are under way at ARL to advance assessment science by developing new models, tools, and metrics to support the acquisition and fielding of effective human–machine systems responsive to emerging missions and threats. ARL has the opportunity to be on the forefront of the research in this area; however, the current portfolio of projects in human–system integration (HSI) may be too customer-driven. ARL could leverage this applied work and/or fund companion projects to advance the state of scientific knowledge for HSI and to broaden the impact of the work beyond the immediate customers.

CROSSCUTTING RECOMMENDATIONS

Based on the 2015 reviews whose assessment is summarized in this interim report, ARLTAB offers four recommendations.

Research Portfolio, Niche Areas, and Staff Development

Recommendation 1. For each campaign ARL should provide to the review panels during the 2016 review a description of its research portfolio that describes each program and project in the portfolio. This description should include information on the project conception and initiation, project planning and scope, project performance and control, and project life cycle and should identify the percentage of each researcher's time allocated to the project, facilities and equipment required to support the work, and the inception date and anticipated completion milestone or termination date of the project. By referring to the portfolio description, ARL should provide to the review panels for each campaign answers to the following questions:

(1) What sampling strategy has ARL applied to the selections of projects to present for review? In what ways do the selected projects provide a representative sample of the portfolio?
(2) What projects represent the limited niche areas in which ARL proposes to work, in which of these areas does ARL propose to lead, and what is the rationale for its niche and leadership choices?
(3) What metrics has ARL identified to define the success of a project, and what exit criteria has ARL identified to help decide when to terminate a project?

(4) What rewards has ARL established to promote accomplishments by staff?
(5) What is ARL's approach to recruitment and development of its staff, including the approach to mentoring?

Integration of Research and Systems Engineering

Recommendation 2. For each campaign ARL should provide to the review panels during the 2016 review answers to the following questions:

(1) How does each specific project presented fit within the overall framework of ARL's research portfolio, and how are projects and programs integrated within and across campaigns so that their work is performed in cognizance of related work and their findings feed into one another and into common goals?
(2) How are systems engineering principles and processes applied across the life cycle of projects?
(3) How is face validity addressed across the design of experiments, modeling, tests, and analyses?
(4) What approaches are planned to secure military-relevant subjects for human sciences tests, experiments, and field studies?

Facilities and Equipment

Recommendation 3. ARL should work to complete formulation of 5-, 10-, 15-, and 20-year strategic plans linked to the technical goals for staffing, facilities, and capital equipment, and should present the plans to the panels during the 2016 reviews. The plan should include a 2-3 year short-term tactical plan for access to necessary computing resources.

ARL Responses to Recommendations

Recommendation 4. ARL should present to the panels during the 2016 reviews responses to the recommendations contained in this interim report.

1

Introduction

This introductory chapter describes the biennial assessment process conducted by the National Academies of Sciences, Engineering, and Medicine'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 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.

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 science and technology (S&T) campaign (Materials Research, Sciences for Lethality and Protection, Information Sciences, Computational Sciences, Sciences for Maneuver, Human Sciences, and Assessment and Analysis) 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 (R&D) activities of ARO and ARL are coordinated.

In addition, at the discretion of the ARL director, the ARLTAB reviews selected portions of the work conducted by the collaborative technology alliances (CTAs) and cooperative research alliances (CRAs). Although the ARLTAB's primary role is to provide peer assessment, it may also 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, the ARLTAB is assisted by five National Academies of Sciences, Engineering, and Medicine panels, each of which focuses on one or more of the ARL's S&T campaigns. The ARLTAB's 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 main topics within ARL's scope. Five panels, each of which focuses on one or more of the ARL's S&T campaigns, report to the ARLTAB. Five of the ARLTAB members serve as chairs of these panels. The panels range in size from 22 to 36 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. Of the total of 135 panel members, 102 members participated in the reviews that led to this interim report. All panel and ARLTAB members participate without compensation.

The Academies 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 R&D laboratories, leading academic researchers, and staff from the Department of Energy national laboratories and federally funded R&D centers. Thirty-three of them are members of the National Academy of Engineering, five are members of the National Academy of Sciences, and four are members of the National Academy of Medicine. 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 the Academies 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 2015 and 2016, the five panels will review the following S&T campaigns of the ARL:

- Panel on Ballistics Science and Engineering: Sciences for Lethality and Protection and Assessment and Analysis;
- Panel on Human Factors Science: Human Sciences and Assessment and Analysis;
- Panel on Information Science: Information Sciences and Computational Sciences;
- Panel on Materials Science and Engineering: Materials Research;
- Panel on Mechanical Science and Engineering: Sciences for Maneuver; and
- Panel on Assessment and Analysis: Assessment and Analysis.

The current interim report summarizes the findings of the ARLTAB from the five reviews conducted by the panels in 2015. The remainder of the core technical competencies will be reviewed in 2016, and the final, biennial report, which will be written in 2016, will subsume the current interim report and will add findings from the 2016 assessment.

PREPARATION AND ORGANIZATION OF THIS REPORT

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 2015. In addition, useful collegial exchanges took place between panel members and individual ARL investigators outside scheduled meetings as ARL staff members sought 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 was needed because the panels are purposely composed of people who—while experts in the technical fields covered by ARL's S&T campaigns that they review—were 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 were targeted at coverage of a representative sample of each of the ARL's S&T campaigns over the 2-year assessment cycle. Briefings included poster sessions that allowed direct interaction among the panelists and staff of projects that were not covered in the briefings.[1]

Ample time during both the overview and the 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 2015 ARLTAB meeting refined elements of the assessment process focused on ARL's S&T campaigns, 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 can be transitioned ultimately to the field?
- Are there promising outside-the-box concepts that could be pursued but are not currently in the ARL portfolio?

[1] Agendas of the panel meetings can be found at the National Academies of Sciences, Engineering, and Medicine website at http://www8.nationalacademies.org/cp/ for each respective panel.

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. *Project 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;
2. *Methodology and approach.* 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;
3. *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; and
4. *Scientific 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.

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, the ARLTAB examined its extensive and detailed notes from the many ARLTAB panel and individual interactions with ARL during 2015. 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 the Academies' 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 omission of mention of any 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 of 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 S&T campaign 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

This chapter discusses the biennial assessment process used by ARLTAB and its five panels. Chapters 2 through 7 provide detailed assessments of each of the ARL S&T campaigns reviewed in 2015. Chapter 8 presents findings common across multiple S&T campaigns. The appendixes provide the ARL's

S&T campaigns and their mapping to the technical areas reviewed in 2015, biographical information on the ARLTAB members, the assessment criteria used by ARLTAB and its panels, and a list of acronyms found in the report.

2

Materials Research

INTRODUCTION

The Panel on Materials Science and Engineering at the Army Research Laboratory (ARL) conducted its review of ARL's programs in biological and bioinspired materials, energy and power materials, and engineered photonics materials at Adelphi, Maryland, on June 10-12, 2015. This chapter provides an evaluation of that work, recognizing that it represents only a portion of ARL's Materials Research campaign.

ARL's Materials Research spans the spectrum of technology maturity and addresses Army applications, working from the state of the art to the art of the possible—25 years into the future—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 sciences is one of ARL's primary core technical competencies. The materials sciences work supports the mission of ARL, as the U.S. Army's corporate laboratory, to provide innovative science, technology, and analyses to enable a full spectrum of operations.

BIOLOGICAL AND BIOINSPIRED MATERIALS

The scientific quality of the work in this area is on par with that of leading federal, university, and industry laboratories, reflects a broad understanding of the underlying science and research being conducted elsewhere, and is recognized as a component of the broader national effort in biomaterials research through its government (e.g., the U.S. Army Edgewood Chemical Biological Center and the U.S. Army Natick Soldier Systems Center) and university (e.g., Institute for Collaborative Biotechnology at the University of California, Santa Barbara) partnerships and collaborations.

This research area has grown substantially over the last 2 years. The knowledgeable leadership direct principally competent, early-career scientists. Relative to the importance of this research, the person-power in this area is considered suboptimal.

The laboratories are generally well equipped to perform the types of studies and analyses required for the biological research. The biological characterization and imaging tools are good, with recent additions of next-generation sequencing and protein synthesis and medium-scale bioreactors with real-time metabolism analysis capabilities. A peptide sequencer would provide important missing capabilities and would help to accelerate research.

Among the excellent research activities of this group, particular promise is shown by the stabilization of proteins against thermal and chemical extremes, using new chemistries and methods to derive antibody-like reagents that improve on antibody properties (specifically, biomolecular recognition and binding characteristics).

Accomplishments and Advances

Biomaterials for Hazardous Materials Detection

The development of synthetic bioreceptors as alternatives to antibodies is being pursued to allow biosensing outside the laboratory and in conditions more representative of those found in the field (e.g., high temperature). Overall, this project, conducted by a relatively new group of researchers, is equivalent to the best work performed elsewhere. The work supports a variety of missions, including water and food defense, individual soldier protection, and collective protection. The concept is to mimic antibody binding with small peptides. An approach screens large libraries of enhancing affinity, selectivity, and other desired features (e.g., serum stability) via an iterative process. The group is exploring a number of different strategies to perform this screening, which is a significant strength of its approach.

To create high-affinity and robust biosensors, independently binding peptides are chemically conjugated using click chemistry to identify bi- or greater ligands. The use of cyclic peptides in place of linear peptides is also being explored as a means to higher-affinity molecules. It is impressive that this technology has allowed rapid (less than 1 week) identification of binding peptides. The group's demonstration of binding to aluminum alloys provides a practical example of its capabilities. Overall, this very productive group is doing cutting-edge work that complements work ongoing in extramural laboratories.

Given the alternative strategies for achieving similar outcomes (e.g., single-chain thermostable antibodies), more specific performance criteria or target product profiles will be needed for further development of some of these areas.

Biohybrid Materials for Sensing

Bio-nano-hybrid systems are being investigated for their potential applications for in vivo physiological monitoring, nanomedicine, traumatic brain injury (TBI) dosimetry, and other photonics-based sensing. The intent of this research is to understand the interactions taking place at the biomediated, nanocrystalline, photonic or nanophotonic biomaterials interface, and to develop new designs for tailored light or matter interactions that can be applied to Army needs. The examples presented use proteins to stabilize nanoclusters and control photonic materials properties. Protein-nanocrystalline structures have been embedded with neurons to detect primary blast-induced neurotrauma, a potential means to investigate mild TBI. The protein-stabilized nanoclusters (P-NCs) were synthesized in situ in neuronal and nontumorigenic cells—the first demonstration of in situ nanocluster growth in nontumorigenic cell lines.

This project provides a good example of grassroots-driven collaboration with outside laboratories. It is very good fundamental research with potential applications to sensors (ligand recognition) and to cell targeting for drug discovery and development. The research is characterized by good integration of modeling and experimental work across bio-molecular- to cellular-length scales. However, more fundamental work is needed to determine the location of nanoclusters, to determine whether protein(s) stabilize the nanoclusters, and to validate in vitro expressions under high pressure.

The effort to utilize P-NCs for monitoring pressure in TBI appears to yield distinct spectral peak intensity changes. Without concurrent modeling efforts it is not certain whether these intensity differences can be due solely to changes in nanocrystal clusters in proteins or can also be due to other effects. It is therefore unclear whether this research would be better directed toward sensors for TBI or other extreme conditions.

A smaller project is focused on the development of a real-time handheld detector for synthetic cannabinoids based on use of a cannabinoid receptor as a transduction element for detection of contraband material. This is an attractive approach, given the diversity of targets (generated by the illegal synthetic drug community) that can be detected using the functional receptors that trigger downstream cognitive effects. Further investment in this project is expected to depend on performance parameters that are yet to be determined, including the limits of detection, the dose response across a useful operational range, and the signal to noise performance in the presence of interference.

Bioinspired and Biomimetic Materials for Protection

This effort addresses a number of related topics intended to improve the performance of polymers in areas relevant to the Army mission, as well as the use of polymers in studies of TBI. ARL's biobased polymer program has been used to produce transitioned biorubber toughening agents, reactive diluents, monomers for polyamides, biobased bisphenol A analogues, and multiphenolic monomers. One program was directed toward developing high-performance biobased polymers for Army applications. The goal of the program is to utilize renewable lignin-based resources to create molecules for the production of high-performance polymers. Successes to date include synthesis of monomers of diepoxy and demonstration of polymers with very high glass transition temperatures. The associated challenges include development of scalable chemistries and structure-property-toxicity capabilities that would allow for transition of the technology to industrial partners.

Another project focused on improving the properties of polymers by incorporating reversible cross-links to enhance toughness. The goal of a third project is to develop high-temperature adhesives that are inspired by the extraordinary properties of spider silk and muscle titin, specifically by incorporating reversible cross-links whose breakage can allow the unfolding of polymer domains. While inspired by natural polymers that derive their mechanical properties from hydrogen bonding, this project focuses on the use of reversible metal bonds as high-temperature tougheners. The emphasis in both projects on developing a mechanistic understanding is a strength, because so much of the other work on these topics is empirical. The emphasis on high-temperature performance differs from the focus in most other laboratories that work on these topics. It is unclear, however, whether simple insertion of metallic elements will achieve the strength and toughness levels of the natural polymers, but new insights are likely, and the coordination with modeling is laudable.

A small project presented in this area addresses the extremely important problem of TBI. The experimental setup devised is fairly simple: A small (2 g) explosive charge is detonated close to a tank that contains neuron cells. This approach to load cells is novel compared to other TBI studies using cell cultures and may yield new insights. Although this is an exciting project, it needs to be part of a much larger and broader program studying TBI; it could be connected to efforts taking place at other Department of Defense (DOD) laboratories. This project needs to also consider more interpretable dynamic loading of neuron cells. Test configuration could allow simulation of pressure waves so that any observed changes in the neuron cells can be related to a known pressure history.

Bioconversion, Biosourced Energy

This is an appropriately focused long-term effort to address Army-specific needs for dealing with food and water wastes. It connects well with other Army entities and is appropriately resourced in terms of both equipment and competent personnel.

A positive characteristic of the program is its university outreach and collaborations, intended to draw in expertise and technologies. These relationships may be leveraged or enhanced through the developing ARL open campus initiative. A more formal connection with the Army Medical Command, particularly in the areas of wastes and health, will be important.

To achieve the programs' goals, it may be worthwhile to put more emphasis on high-throughput approaches to empirically screening large numbers of communities; this could allow more rapid identification of desired bacterial communities. It might also prove useful to examine lessons that may be learned from the limitations of previously fielded systems.

Opportunities and Challenges

Because biology is a growth area, ARL has an opportunity to identify and recruit a critical mass of biologists, including microbiologists and polymer/organic chemists, looking well into the future to create an integrated community of researchers. The process of recruiting and retaining talent could encourage better articulation of the expectations and career paths that lead from postdoctoral researchers who are contractors to scientists who are government employees, and to develop an effective mentorship program emphasizing professional development and job satisfaction.

ARL needs to reexamine its polymer-related work to assure the closest possible relations between the researchers at its Adelphi and Aberdeen locations.

ENERGY AND POWER MATERIALS

Accomplishments and Advances

The quality of the research projects, the staff, and the facilities is comparable to high-quality research laboratories elsewhere in industrial and academic environments. Where there are gaps in the technical skills or methods needed for a project, the ARL staff demonstrate mature experience and judgment in seeking out high-quality collaboration with other non-ARL researchers within and beyond the Army research enterprise.

The early-career researchers are strong and have excellent skills, which likely reflect good mentorship by senior personnel. Importantly, the research staff are enthusiastic and throughout the review demonstrated a clear focus on Army needs, an appreciation for the importance of moving basic research to technology to impact, and skill in selecting research methods and tools involving experiment, theory, and simulation.

The portfolio of research projects reviewed included an appropriate balance of high-risk, long-term-impact projects along with mid-term and short-term projects. There was a broad, deep coverage of different devices, different fuels, and different applications covering a wide range of size and time scales.

There are continuing improvements in research quality, staff hiring in both postdoctoral and permanent positions, and collaborative activity. As part of these improvements, ARL has expanded its modeling capabilities. The current in-house capability for carrying out high-level simulation and modeling activities is of high quality and moving in the right direction.

Advanced Energy Storage: Advanced Battery Chemistry

Though the advanced battery effort at ARL is small relative to similarly focused programs at other federal laboratories (e.g., Department of Energy laboratories), it is internationally recognized for its high scientific quality and long history of productivity and innovation.

The research includes significant elements of experimental and computational numerical modeling work. The laboratory equipment for experimental work is excellent, spanning an impressive range of capabilities from materials synthesis and characterization, to electrode and cell fabrication. Computational efforts in the battery area are good but appear to be relatively recent. They could possibly benefit from additional resources and emphasis.

The team has excellent qualifications that are well matched to their research challenges. In addition, program participants have an excellent understanding of research conducted elsewhere and are well aware of critical research issues and advances from around the world. The ARL team has formed a local Center for Batteries in Extreme Environments, which provides a good model for interaction of ARL staff with non-ARL scientists.

The projects in this area also are synergistic with one another. The team thinks hard about transition pathways to scale-up, manufacture, and commercialization and seems well positioned to make decisions and negotiate arrangements to transition ideas to the field.

The team has begun generating a database of properties on electrolytes, including interfacial reactivity. A pathway may exist for organizing these data in a manner similar to that being pursued for other battery materials in the materials genome initiative. Productive work may come from the team's interactions with that initiative focused on electrolytes, possibly including the effect of additives on interfacial reactivity.

Advanced Energy Storage: Structural Batteries Using Additive Manufacturing

The researchers are successfully developing techniques for fabricating multifunctional battery materials using additive manufacturing (AM). The lattice structures constructed using AM have favorable mechanical properties and controllable surface area per unit volume, which permits tailoring and optimization of electrochemical performance. With respect to weight reduction for batteries and capacitors, the AM method has clear advantages over earlier methods. The measured elastic properties and electrical performances of the fabricated materials agree well with the finite-element modeling performed as part of the project.

The techniques and materials are promising, and the scientific quality of the project is comparable to quality at leading research institutions. A more comprehensive modeling and simulation component addressing chemistry and physics, in addition to mechanics, might be desirable for understanding effects such as the influence of porosity on performance of gels. The project has a good balance of theory and experimentation. It would be good for the team to consider the previous work on nanotrusses done at the Naval Research Laboratory to see if there is anything in this work that might be applicable. To help design for sufficient mechanical durability and reliability of materials, it might be worthwhile to investigate the strength and failure properties of the fabricated materials as well as their elastic moduli. It may also be desirable to consider the practical issues associated with scaling up the laboratory AM process to full-size batteries. This project has significant potential for innovative discovery.

Alkaline Fuel Cells: Optimizing Structure and Chemistry of Ion-Containing Polymers for Charge Transport

This project focuses on the development of alkaline fuel cells. Conventional approaches rely on a liquid KOH electrolyte as a means of OH^- exchange. This electrolyte is problematic because it is a liquid and can be poisoned with CO_2 owing to the formation of K_2CO_3. The goal of this project is to circumvent these problems using a polymer electrolyte. In particular, a mixture of dicyclopentadiene and CO is used to create a bicontinuous microstructure intended to maintain high OH^- conductivity and strong mechanical properties. The OH^- conductivities achieved were the best reported, though the mechanical behavior was not adequate. By increasing polymer molecular weight and cross-linking, strength and toughness were increased nearly twofold, but this is still far less than competing materials. It is unclear whether this mechanical behavior would be acceptable. The researchers were able to enhance material behavior by optimizing microstructure, which was in turn achieved by increasing the connectivity of the hydrophilic domains.

This research is Army-relevant, reflects a correct understanding of the literature, makes use of state-of-the-art facilities, and is of high quality, comparable to similar university and industrial efforts. However, the scope of the effort requires expansion if the work is to have a substantial impact within this community. Additionally, being more engaged with this community—e.g., the multiuniversity research initiative at the Colorado School of Mines—would help this work proceed by enhancing critical decision making—for example, in materials selection. This project would be strengthened significantly by the addition of a modeling component. There are many existing methods and codes that could be helpful; for example, the group at the National Renewable Energy Laboratory is modeling this sort of system.

The publication record of the researchers is prolific: Seven papers have been published, one is under review, and four more are in preparation.

Alternative Energy Photovoltaics

This project utilizes quantum dot nanomaterials for photovoltaic conversion and focuses on enhanced light absorption and minimizing reflective losses. This nanomaterial approach eliminates the need for a traditional tracking system and, if successful, would significantly impact a number of Army applications requiring flexible and efficient power.

The researchers have established productive collaborations with the communities at the University of Texas, the State University of New York, Microlink Devices, and the University of Michigan—all characterized by a good mix of experiment, theory, and simulation. The researchers demonstrate a broad understanding of the related science as exemplified by their efforts to modify the wetting layer thickness to increase electronic capture; they have achieved photovoltaic (PV) efficiency 6 percent above the record for GaN.

Alternative Energy: Highly Mismatched Alloys

This project develops material to split water by using sunlight as the energy source. This research is high risk but potentially offers a very high payoff. The idea, based on results appearing in the literature, is to replace some N with Sb in GaN to form GaN_xSb_{1-x}. It was predicted that by adding Sb, the bandgap could be lowered to about 2.2 eV, producing an efficient light absorber. These alloys, highly mismatched in size or electronegativity, have never before been synthesized. The group has significant experience with Group V alloys and apparently a unique synthesis capability.

The experimental results shown verify the bandgap crossing model (developed at Lawrence Berkeley National Laboratory [LBNL]) up to $x = 0.22$. Materials produced remain crystalline. It appears that very small amounts of Sb lower the bandgap significantly. The principal investigator did not understand why the model predicted such behavior. An understanding of the controlling physics needs to be developed.

Attempts could be made to fabricate a device, though this necessitates doping these materials. Doping can now be done for GaN, but it is not clear what effect the Sb will have on this process.

Good collaborations with LBNL and with the University of Strathclyde and the University of Nottingham (both in the United Kingdom) are ongoing. Only theory is done at LBNL. There is also significant competition from the National Renewable Energy Laboratory and the University of North Carolina; these groups are focused on different materials. This project could be aided by more modeling. There have been five publications by this group in the last year.

Alkaline Fuel Cells

The principal objective of this research is to create anion exchange membrane/proton exchange membrane stacks, eliminating the need to transport water throughout the cell and potentially reducing the mass and footprint of the device. The principal investigators have pulled together an excellent team, including a group at Georgia Institute of Technology.

The principal investigators were aware of many of the relevant issues for successfully constructing such a cell, including issues regarding delamination. This work has a robust modeling component. Overall, this research is innovative and promising.

Alloy Type Anodes for Lithium-Ion Batteries

Lithium (Li)-ion battery performance and weight reduction may be improved by using silicon (Si) anodes to increase the capacity for Li storage. This project addresses an important practical difficulty with Si anodes, which is their tendency to experience mechanical failure after a small number of electrical discharge and recharge cycles. The principal investigator has performed careful in situ measurements of this effect using an atomic force microscopy technique. The implementation of these experimental techniques is the main achievement of the work so far. The principal investigator is also working on coatings for anodes to reduce cracking, with encouraging results. The project also supports collaborations with the University of Utah to use molecular dynamics (MD) simulations to study the electrical and mechanical processes involved. MD seems to be a very promising method for understanding the fundamental aspects of the cracking problem. In particular, analysis might help to reveal why thin coatings apparently reduce damage in spite of the very large linear strains to which the coatings are subjected. The project would benefit from a closer working relationship between the experimental and computational team members.

Beta(photo)voltaics

The project is intended to develop a long-lived (25-year goal) power source using beta and alpha energy conversion in wide bandgap (WBG) semiconductor materials and phosphors. The approach uses a beta emitter (tritium) to produce electricity. Current designs do not produce enough power to be useful for the Army, and so the isotope power source is coupled with a Li-ion battery to take care of power demands during higher current demands such as during signal generation. The isotope power source is used as a trickle charger for the Li-ion battery. Electrochemical capacitors were used, but there was high leakage current.

This project started as an engineering problem. Isotope power sources have been used for years in weapons applications. Since the Army has access to isotope materials, it made sense to utilize this approach for power production. To test the concept, an isotope power source was fabricated that generated 100 μW.

The innovative concept applies to the investigation of three-dimensional (3D) interaction space in WBG materials and phosphors to increase energy conversion and efficiency. The project is well thought out, and it has a high probability of success. The principal investigator is performing mechanical cross-section simulations to aid in design, so the mix of theory, experimentation, and computation is sufficient. The qualifications of the researcher and the facilities appear to be compatible with this research challenge. If successful, this could open a myriad of small power source applications for the Army.

Carbon Formation During Catalytic Oxidation of Hydrocarbon and JP-8 Fuel

The use of logistics fuel for compact, heat-driven electric power generation is compromised because sulfur impurities poison the catalytic activity of microcombustors. In this project, a materials-by-design approach is being used to identify promising combustion catalysts, which are investigated with experimental and computational methods. In situ spectroscopy is incorporated with short contact-time reactors to identify surface species during catalytic combustion of prototype fuel, while simultaneously monitoring poisoning. These data, used in conjunction with a microscopic reaction diffusion model of surface events during combustion, clarify the effect of sulfur. It has been recognized that sulfur enhances carbon formation on platinum (Pt) but not on rhodium (Rh). The project promises to accelerate microcombustor catalytic design through reactive flow modeling. This is good scientific work linked with sound engineering methods for scale-up and extension to logistic fuels.

Critical Solvation Issues in Lithium-Ion Batteries

This poster describes part of the excellent battery program that focuses on Li salt solvation in organic carbonate and water solvents. The objective is to better understand fundamental electrolyte interface properties. The work showed preferential solvation of Li by ethylene carbonate (EC) in EC/dimethyl carbonate mixtures, which is relevant to solid-electrolyte interphase formation at carbon anodes. New water-in-salt electrolytes having less than 20 weight percent water in Li bis-trifluoromethanesulfonimide were prepared, and early-stage results are quite promising. This is an example of an emerging class of electrolytes called deep eutectics. Water in this electrolyte is thought to have very different properties from conventional water because such a large fraction of these water molecules are contained in solvation shells. Understanding of interface passivation could help in electrolyte material choice. The work is led by an energetic PI and is synergistic with the overall thrust of the ARL battery effort. Its high scientific quality is demonstrated through publication in quality journals.

High-Voltage Li-Ion Electrodes and Electrolytes

This project involves work on olivine $LiMPO_4$-type cathodes, where M is Co, Mn, and Ni substituting for the usual Fe. These three metals have more positive redox potentials, so batteries using these materials have higher voltages. $LiCoPO_4$ has a high potential but usually exhibits significant capacity fade upon cycling. The ARL team found that mixing some Fe with the Co results in much less capacity fade, with minimal loss of overall capacity. A mechanistic understanding of the diminished capacity fade is being pursued. The work is of high quality and fits well with the significant worldwide effort to identify new battery cathodes to enable higher energy density batteries.

Isomeric Materials Research

This project addresses the use of nuclear transitions for energy-on-demand. The concept is to convert a long-lived, excited nuclear state to a short-lived ground state by excitation by photons or neutrons. The main scientific content is nuclear physics, in contrast to the mainstream atom/electron/photon-centered work in the ARL materials campaign. The work requires investigation of level diagrams for candidate nuclei. Because of the complexity of the few-body problem for large nuclei, the nuclei cannot be modeled to sufficient accuracy but have to be measured. The investigators combine information from the literature with their measurements. The conversion concept has been demonstrated for a silver isotope. The work is of high technical quality and is published in the appropriate journals. This is a long-term, high-risk approach with regard to practical applications, with many questions to be answered, including how to produce the long-lived excited state in sufficient quantities, but it is worth pursuing. If successful, impact could be high.

Lattice Conductivity of Dense Ta-Doped $Li_7La_3Zr_2O_{12}$

LLZO is a candidate for a solid electrolyte in Li batteries. The goal of this study is to enhance Li conductivity via doping Ta for Zr. Using this approach, the investigators were able to reproduce a similar study by Goodenough and suggested that other enhanced results in the literature were likely due to other defects. This is a very good addition to the literature, where reproducibility of key results is often lacking. Furthermore, this work had a strong density functional theory component that was performed at the Naval Research Laboratory (NRL). The work would be outstanding if there were researchers within ARL who could complement the efforts of NRL.

Mathematical Modeling and Lifetime Extension of Thermal Batteries

Thin-film thermal batteries could provide improved reliability and performance over present designs in munitions. This project is successfully developing a comprehensive analysis tool that models the thermal energy balance, gas generation, and electrical performance of thin-film thermal batteries. So far, it is mainly the thermal problem that has been addressed. The ARL thermal model has been integrated into Sandia National Laboratories' Sierra finite element code. The method that ARL is developing could be combined with a mathematical optimization tool, providing a direct and systematic way to improve battery design. There was no mention of validation of the model, suggesting that this is not a central focus. The principal investigator did not seem to understand the model being used. Therefore, in addition to adding the multi-physics capabilities that are planned, it would be desirable to obtain experimental data that would be needed to validate the submodels (e.g., thermal, gas transport, electrical, chemical) as the code grows in size and complexity.

Pyroelectric Materials for Energy Applications

Led by a competent postdoctoral researcher, this project draws on a 2006 paper[1] reporting a giant electrocaloric effect in perovskite oxide PZT (metallic oxide based piezoelectric material) to propose and prototype a device to convert heat/infrared photons to electrical energy. The concept is to run a heat engine loop between the low polarization branch of the polarization versus field (P-E) hysteresis loop at high temperature and the high polarization branch at low temperature. There is much room for optimization by choice of materials and by controlling the quality of the thin film, with leakage current being of particular concern. The collaboration with the University of California at Berkeley will help with the latter. The long-term application will be the remote supply of energy by an infrared laser and could be used, for example, to recharge drones in flight. The work is of high technical quality, and the project leader communicates well with the broader community. As the work progresses, more modeling could be integrated into the project.

Understanding C-C Bond Breakage on Plasmonic Nanostructures

This proof-of-concept project is directed toward developing catalyst structures for breaking the C-C bonds associated with high energy density logistic fuels (e.g., ethanol) using light-harvesting nanoscale arrays formed by localized surface plasmon resonance. This is a unique fabrication approach based on a good concept for photo-reformation of logistic fuel. The project represents a high-risk endeavor. The first steps toward forming such structures have been made with use of the Specialty Electronic Materials and Sensors Cleanroom facility. Initial work includes modeling the plasmonic aspects of the structure. Additional modeling worked is planned to take account of the immersed, reactive, electrochemical environment. Experimental characterization of the photo-induced reactions is planned, using well-established electrochemical and surface science methods. Desorption mass spectroscopy electrophotometry has been reported by others and may be considered for this project. At this point, there are no experimental data on the structure, and the current understanding of the reaction mechanism is speculative. It would be helpful at this point to create a device and test it out. It is not yet clear whether this fabrication method can be implemented at large scale.

[1] A.S. Mischenko, Q. Zhang, J.F. Scott, R.W. Whatmore, and N.D. Mathur, Giant electrocaloric effect in thin-film PbZr0.95Ti0.05O3, *Science* 311:1270, 2006.

Grain-Boundary Engineering of Ion-Conducting Ceramics

This project examines two approaches to reducing ion transfer resistance at grain boundaries in the fast lithium-ion-conducting ceramic $Li_{3x}La_{2/3-x}TiO_3$, $x = 0.11$. Previous work showed that this solid-state electrolyte material had good conductivity. The idea is to change grain boundary (GB) properties to improve GB conductivity. Grain boundary modification was achieved by simple lithium-ion exchange from solution, and by silica coating the starting particles with SiO_2 using magnetron sputtering. Both approaches provided modest increases in conductance, both at GBs and in the bulk. A study on variations in bulk ionic conductivity with thermally induced changes in crystal structure was also pursued. The mechanism by which surface coatings change GB conductance is not fully understood; more structural characterization work—for example, by transmission electron microscopy (TEM)—is planned to help address this point. It was also found that different processing conditions could change crystal structure and conductivity. The principal investigator, a postdoctoral researcher with ceramics experience relevant to Li battery technology, needs to learn more about the battery aspects of the work to become fully integrated into the overall effort. Still, this is excellent work for a relatively new employee. The work is of high quality and contributes to a growing body of knowledge regarding use of ceramic materials to replace liquid or polymer electrolytes in Li batteries.

Opportunities and Challenges

Questions remain as to whether ARL was mobilizing aggressively enough to capitalize on both internal advances and external advances made by the broader community—for example, whether the recent world-leading results on enhancement in quantum well infrared photodetector (QWIP) efficiencies are being translated into capability demonstrators for manufacturers and customers. Similarly, ARL may not be working to leverage external advances in silicon photonics, especially with regard to heterogeneous materials. However, in both cases, these concerns were partially allayed by discussions with staff and management regarding the status of some programs related to these technologies. For the QWIP work, for example, ARL has hired an external business consultant and is working with NASA and others on technology transfer for the QWIP breakthroughs. Nonetheless, there remains more opportunity for ARL to capitalize on its internal and external advances.

The enormous potential impact of the photonics work could have been presented more vigorously and compellingly. One way of doing so could be to augment an individual photonics presentation with an explicit description of the broader potential impact if it succeeds. Army goals were noted, but they often comprised immediate technical targets as opposed to what the ultimate impact could be for a more comprehensive field of science or for broader Army applications.

The presentation on structural batteries using additive manufacturing has significant potential associated with its innovative approach. The project combines novel fabrication methods with insight into selection of compatible multifunctional elements that combine structural components with energy storage components. Experimental work is carried out concurrent with modeling studies that guide system design choices. The external collaborations are facilitated by a flexible methodology that provides easy incorporation of next-generation subcomponent materials as they are developed. However, the effort needs to grow across a wider range of projects, with a focus on identifying appropriate modeling methods and on closing the experiment–theory–simulation loop. Increased interaction with the significant computational resources of ARL could help bridge the gap until additional capacity is available within the Materials Research campaign. At present, first-principles computational modeling is growing, mainly through collaboration with recognized experts elsewhere, guided by very capable but limited-in-number experienced internal research staff.

In comparison to the expansion in first-principles modeling, engineering models are underutilized, perhaps because in-house expertise in this facet of modeling is limited. Engineering models are typically developed at the outset from a simple set of input parameters or components that, together with the model, predict system behavior. These components are improved as empirical knowledge of the system's behavior increases. Routine methods are now available to identify the most sensitive components for which improved fundamental knowledge is needed, to provide uncertainty quantification, and to guide system-level optimization during scale-up or scale-down beyond experimental regimes. The combination of an appropriate engineering modeling effort with the intuitive understanding of experimentalists is a highly effective engineering approach and needs to be targeted as a growth area.

In some energy and power applications, such as Li-ion batteries and fuel cells, there is a broad, vigorous, fast-moving, worldwide research effort directed toward identifying fundamental scientific issues and developing novel materials and entire systems. Accordingly, the narrowly focused ARL projects need to pick the right niche in order to have impact. The knowledge necessary to define the goals of such projects depends critically on tracking research advances elsewhere. Because postdoctoral and other early-career permanent staff researchers benefit from exposure to research activities beyond ARL, it is critically important to promote and expand active mentoring by senior staff.

ENGINEERED PHOTONICS MATERIALS

The quality of the work in photonics materials is comparable to that found at most research universities. This is an impressive accomplishment in light of the inherently wide scope of the technical program, which is essential to addressing diverse current and future Army needs. The quality of the work presented reflects a high level of technical competence and professionalism on the part of the researchers and management.

The portfolio of the engineered photonics materials group shows a good balance of high-risk, longer-term work with nearer-term customer-driven solutions or incremental, critical technology refinement. This well-balanced portfolio is supported by a strong materials capability in staff expertise and laboratory or clean room infrastructure. Investments are impressive for computational modeling and simulation that ARL has successfully implemented to complement its strengths and core competencies in materials synthesis and characterization, as well as device work. All of these facilities and capabilities are being leveraged into compelling device and application-driven work, especially in ultraviolet (UV) materials, infrared (IR) devices, and the device physics in both areas. In addition to technical diversity, there is workforce diversity.

Accomplishments and Advances

Alternative Energy: Photovoltaics

This project involves work to improve performance of low-concentration photovoltaic cells targeting robust, lightweight power for soldiers in theater. The technical focus is developing solutions using III-V quantum-dot materials to extend performance into the longer wave regions of the solar spectrum, and to improve efficiency by minimizing recombination.

Solar PV is one of the important pathways to reducing the weight of power solutions in theater. The experimental work showed solid progress, reflecting the strong competence of the team, which evinced expertise that includes epitaxy and sophisticated quantum dot engineering, polyethylene terephthalate (PET) moth eye surfaces, and intentionally induced morphological features on III-V layers for enhanced photon capture. There appeared to be extensive collaborations with researchers outside ARL.

The wetting layer state-engineering designs might benefit from more direct experimental verification of their efficacy in reducing recombination in the dots. There was a lack of clarity on the trade-offs between the high concentration (30 to 100 times what is typically seen when realizing the benefits of advanced materials) and the low concentration (less than 4 times what is typically required in nontracking applications). More clarity is needed on the system-level incremental cost of multijunction cells with significantly higher efficiencies relative to single-junction material solutions such as GaAs, which is still very high ($40,000 per square meter), or the quantum dot approach pursued in this work. Additional questions include comparisons with spectral splitting, which was examined in the DARPA-sponsored very-high-efficiency solar cell program.

Biophotonics

Progress was reported on protein-wrapped fluorescent metal nanoparticles, motivated by their potential use as neuronal pressure sensors. The long-term goal is to develop a fundamental mechanistic understanding of mild traumatic brain injury onset and development.

The fundamental work on the biomediated synthesis of atomic nanoclusters was compelling, and the fact that the proteins retain their native functionality after synthesis has tremendous potential. For example, the resulting nanoparticles may be noncytotoxic, and it may be possible to direct them to specific locations within a cell. These nanoparticle building blocks are anticipated to provide unique opportunities based on their interesting optical and physical properties. An example given was fluorescence change with pressure seen for one protein but not a different protein, an indication that interesting protein science may be enabled by this system.

There is some concern regarding the specific proposed application for these particles for understanding shock waves in tissue. The fluorescence changes with pressure were small (20 percent over 400 MPa for one system and about 6 percent over 600 kPa for a different system). In real tissue, these small changes over less than 1 ms, from a single or a few particles, will be very hard to observe. What is needed is a deeper physical analysis of the full system, including the signal-to-noise ratio in realistic shock wave and illumination conditions, and what is anticipated at a single neuron level. Also needed is a comparison with other potential techniques, such as Forster resonance energy transfer and plasmonic particles, in the context of nanoscale pressure sensors.

This ambitious work offers strong opportunities for discovery; it is a high-risk early-stage effort in ARL's expanding biophotonics effort.

Modeling and Analysis of Ultraviolet-Light-Emitting-Diode Materials

The objective of this project is to use many-body theory to model lifetime in III-nitride structures, including free carrier and exciton effects, polarization fields, and density-dependent screening of Coulomb interaction and polarization fields. This is one of the projects indicative of ARL's investments in more comprehensive modeling to support its strong core materials capabilities and competencies.

This a very challenging problem, and the principal investigator is making good progress in describing radiative lifetime, including many-body effects such as phase-phase filling, screening, and quasi-particle renormalization. However, nonradiative processes were not described at the same level of theory. Semiempirical, nonradiative models using activation energy were shown not to fit experimental data well, but improved fits were achieved with a combination of a fixed temperature-independent component plus an activation-energy component.

The development of first-principles-based and self-consistent predictive capabilities to describe carrier lifetime in III-nitride structures, including both radiative and nonradiative processes, is not easy. However, the principal investigator presented a scientific strategy to make progress toward addressing this challenge. The strategy calls for alloy fluctuations, a many-band description of the electronic wave function, the use of nonparabolic bands, and the inclusion of nonradiative recombination processes. This is a project of high technical merit and of potentially high impact in support of the Army's mission.

Ultraviolet Avalanche Photodetector Research

This work entailed the compelling development of models and experimental devices and materials to evaluate the efficacy of novel solutions for improved single-photonic avalanche detectors in the UV as replacements for photomultiplier tubes.

The principal concept is to use GaN and AlGaN epitaxial layers to address the reduction in quantum efficiencies that stems from the use of semitransparent metal electrodes on current SiC devices. Self-assembled monolayer structures were introduced to either isolate the SiC to a multiplication layer or to just use the AlGaN as a transparent contact layer to keep the SiC away from surface so as to avoid surface recombination.

This work is promising and has high-quality external partnerships. It has mainly involved epitaxy development and Si diffusion studies, and the transitioning of these to device results in avalanche operation is awaited.

Short-Wavelength Infrared Device Modeling and Optimization

This project is directed at the development of a comprehensive model that combines the finite-difference, time-domain electromagnetics of nanostructured surfaces with finite-element modeling, drift-diffusion transport to understand and optimize device designs and material structures. The model is comprehensive in that it included material, electronic, optical, and especially nanostructured geometric properties that strongly impact the electromagnetics. The integrated software suite allowed analysis of very complicated multipixel arrays, and the principal investigator showed how more simplistic models would not properly capture major performance factors. One example was that the performance of nanostructured cones could be estimated reasonably well with effective medium models at longer wavelength, but at shorter wavelengths complex scattering among the cones dominated the performance. The model was shown to be useful in assessing pixel cross talk in arrays, as well as heterostructure design and junction location for optimization of collection efficiency while minimizing generation-recombination (GR) dark current.

This is an excellent project directed toward an important topic in terms of the needs of both the Army and the broader technical community.

Diode-Pumped Tm/Ho Composite Fiber 2.1 μm Single-Mode Laser

The goal of this research is to provide a simpler and more compact 2.1 μm thulium (Tm)/holmium (Ho) source capable of achieving 100 W power in eye-safe lasers for situation awareness, monitoring, and tracking illumination and, perhaps, frequency conversion to directional IR countermeasures.

Early work has been conducted on an innovative concept to make a dual-core fiber laser that would support thulium lasing at 1,950 nm in a multimode core that would, in turn, pump a Ho single-mode core at 2.1 μm. This design is intended to achieve two excitations in the Tm with a single optical pump in the 800 nm range. This is an interesting concept, but it is too early to expect definitive evaluation of the potential.

This effort may now be positioned to benefit from a stronger modeling component to resolve the impact of saturation on spatial mode competition and laser performance. Suitable baseline modeling capabilities are readily available in the literature, and in conjunction with a more deliberate experimental plan, the modeling may be useful for isolating critical performance trade-offs.

The principal investigator is engaged in a valuable external partnership with strong competence in these fiber materials.

Thermal Property Engineering: Exploiting the Properties of Ceramic

This project consists of preliminary work on improving mid-IR lasers by increasing the effective thermal conductivity of the gain media, using nanoscale composite MgO (high thermal conductivity) with Er:Y_2O_3 (the gain media). This work addresses many scientific and engineering challenges, including the achievable effective thermal conductivity of the composite, which may be limited by phonon scattering, and the achievable volume fraction of gain media needed to be competitive with current solutions.

This work has high potential, and it may benefit from some early modeling to determine the property bounds and trade-offs. The team could also be more vigilant in reaching out to others, including the Air Force Research Laboratory, to evaluate similar work.

Photoacoustic Spectroscopy for Hazard Detection

This project involves work on an elegant and simple device approach for detecting trace elements. While many optical detection techniques are available, these are usually large and contain many precision optical elements. The detection technique proposed is small, robust, and potentially inexpensive, if applications supporting high-volume laser production are realized.

Engaging more broadly with the outside community would be beneficial, including with vendors of existing optical sensors and comparative testing on species of current interest, perhaps in the context of ARL's open campus initiative. In addition to offering a potential for more pervasive use, this will better ensure that this transitions into a product useful to the Army.

Understanding Inkjet Printed Standards for Optical Measurements

This work involves a system based on the well-tested use of inkjet printing. Although ARL has used only a single print head, the researchers have been able to print on many materials (e.g., rubber, metal, and wood) with contaminants included. The system can be used to understand how the samples age, and the flexibility of patterning and reproducibility of the technique were shown to be useful in capturing the unexpected impact of real-life variations of species on surfaces in the field. This is important work that continues to be funded by customers.

Single-Beam Femtosecond Multiplex CARS

This work illustrates the outstanding evolution of research aimed at using a collinear approach to coherent anti-Stokes Raman spectroscopy (CARS) for trace gas detection. These studies focused initially on pulse characterization but transitioned to the examination of mathematical methods and algorithms for extracting the desired spectral signal from broadband background spectra. The principal investigator was able to demonstrate strong signal-to-noise ratio improvements that substantially enhance the efficacy of the CARS approach.

Photon Trap for Infrared Detection

This project involved the expanded modeling and experiments on the microresonator enhancement presented two years earlier. The work showed that very small variations in microresonator dimensional control had strong impact on both the peak efficiencies and the bandwidth of the enhancement. The results were encouraging, indicating that design regimes existed where very high efficiency could be supported over a band that was easily large enough for many Army applications.

This important advance may not be receiving sufficient resources to move quickly to highly optimized commercial technology. Also, ARL's studies of the dynamic behavior of materials are likely to be advanced by improvements in infrared detection at modest elevated temperatures.

Ultrafast Spectroscopic Noninvasive Probe of Vertical Carrier Transport in Heterostructure Devices

This work involved pump-probe studies of ultrafast carrier dynamics and charge transport in heterostructures, with the ability to interrogate charge-generated terahertz field profiles in materials prepared for device structures. This research represents a valuable investment in advanced characterization, and the quality of both the topics and investigators is excellent. In addition to being of immediate value to materials and device researchers, the projects are conducive to quality papers and conference presentations of broad interest to the technical community.

Tunable Solid-State Quantum Memory Using Rare-Earth-Ion-Doped Crystal, Nd^{3+}:GaN

This project involved high-risk, early work aimed at using GaN as a host material for the neodymium ion (Nd^{3+}) in quantum memory research. The objective of this project is to perform photon echo experiments to provide an estimate of the memory storage time and capacity in cryogenically cooled Nd^{3+}:GaN crystals. The plan is to ultimately fabricate GaN polar heterostructures from which to design a quantum memory device with multimode capacity. Although this project is in its early stages, this work makes strategic use of ARL's strong GaN materials and molecular beam epitaxy (MBE) growth capabilities to gain a competitive position in a field that is drawing worldwide attention. Moreover, the ARL team has a strong track record of published contributions in this field.

Opportunities and Challenges

The consistent development and extension of modeling to broader sets of problems and applications is an opportunity area. One prototype project is short-wavelength IR device modeling and optimization. This research illustrates ARL's expanded efforts to provide critical modeling support in areas where there is high investment in underlying materials and device technologies.

The important software tool set coming from this research is not only essential for designers, but it may also provide critically sensitive parameters that could be used in process control for commercial partners and suppliers of imaging solutions to the Army, which necessitates engaging with the manufacturers. The project's principal investigator has started this engagement.

OVERALL QUALITY OF THE WORK

Overall, the researchers and the management are of high caliber. Most of the projects presented are excellent and have a pervasive potential impact. The scientific soundness and the use of fundamental sciences are outstanding. 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.

ARL is making progress in its quest to become a premier research institution in the area of materials science. Several 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. 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.

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 open campus initiative can enhance collaborations.

Advances in biomaterials are essential for the application of biology to detection and sensing. The fledgling field of bioinspired and biomimetic materials will be an important source of inspiration and insight for the future materials scientist. This relatively immature ARL thrust is growing rapidly and shows tremendous potential. Because biology is a growth area, ARL has an opportunity to identify and recruit a critical mass of microbiologists and polymer/organic chemists and needs to be looking well into the future to create an integrated community of researchers.

Developing and improving energy storage devices and batteries will be essential if the future warfighter is to gain an advantage from the increasing availability of relevant technology. The same advances will also find applications across a wide nonmilitary spectrum. ARL's research in this crucial arena is broad, covering different devices, fuels, and applications across a wide range of time and size scales. ARL needs to move aggressively to capitalize on internal and external advances in the energy and power arena. For example, the world-leading results on enhancement in QWIP efficiencies need to be translated into capability demonstrators for manufacturers and customers. ARL needs to work more aggressively to leverage external advances in silicon photonics, especially with regard to heterogeneous materials.

Engineered photonic materials are necessary for sensors, energy generation, and improvements to device performance—all essential to the future warfighter. The portfolio of the engineered photonics materials group shows a good balance of high-risk, longer-term work with nearer-term, customer-driven solutions or incremental but critical technology refinement. ARL needs to continue on its course to broaden modeling in support of a larger number of problems and applications. As a prototype for this expansion, ARL needs to look to its short-wavelength IR device modeling and optimization. The software tool set coming from this research is essential for designers, and it may also provide critically sensitive parameters for potential use in process control for commercial partners and suppliers of imaging solutions to the Army, which necessitates engaging with the manufacturers.

3

Sciences for Lethality and Protection

INTRODUCTION

The Panel on Ballistics Science and Engineering at the Army Research Laboratory conducted its review of ARL's programs on Battlefield Injury Mechanisms, Directed Energy, and Armor and Adaptive Protection on June 23-25, 2015.

ARL's research into lethality and protection sciences during 2015 ranges from basic research that improves our fundamental understanding of scientific phenomena to technology generation that supports battlefield injury mechanisms, directed energy programs, and ballistics and blast programs that address weapon–target interactions and armor and adaptive protection developments. ARL's human response, directed energy, and armor and adaptive protection mission scope work is performed within the Weapons and Materials Research Directorate (WMRD), the Survivability and Lethality Analysis Directorate (SLAD), the Human Research and Engineering Directorate (HRED), and the Sensors and Electron Devices Directorate (SEDD). 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 advanced weapon systems.

BATTLEFIELD INJURY MECHANISMS

Understanding the mechanism of ballistic injury is essential to the mission of ARL, specifically for protecting the warfighter against traumatic brain injury and extremity fracture injuries. All of the presentations related to injury mechanisms supported ARL's recognition of the importance of this issue. The biggest challenge is bridging the science/engineering gap between the materials science—intensity of soldier protective devices and the biomedical aspects of injury mechanisms, or, more precisely, quantifying the level of mechanical insult leading to significant injury. The program, as presented, is a start to bridging this gap. However, increased commitment of resources will be required for it to become state of the art, where it will have to be if it is to enable the protective devices relevant to the threats of the next 25 years. The program presented is a good starting point, but it needs to aspire to create state-of-the-art models of medical injury. This will require improved coordination with the technical leadership of the field. Understanding the mechanisms of injury to the degree needed to give effective protection is key to improved protective designs. Meeting this challenge is essential to the mission of ARL, and the areas of traumatic brain injury (TBI) and musculoskeletal injury will continue to be the main areas of concern, along with an increasingly sophisticated understanding of how mechanical insult impacts neural function. All models need experimental validation, and all experimental programs would benefit from increased use of statistical data evaluation and statistical experimental design.

Computational mechanics work on battlefield injury mechanisms and human response to threats and on protective equipment, including the mechanics of fibers and fiber composites, are being combined with experimental efforts to characterize, validate, and verify the computational results. This combination of efforts is laudable.

The program in human responses to threats is performed mostly by junior staff, who are pursuing research objectives focused on short- to medium-term objectives. While the staff are capable, the research is generally not state of the art. Studies were described that focused on the assessment of neuronal response injury using a blast tube injury model with cells grown in monolayer on a flexible membrane. The flexible membrane is also subjected to defined strains in order to model the induction of cell injury. Primary end points include cell viability, calcium signaling, and cell morphology. Long-term goals are to develop a mechanistic understanding of neuronal responses in 2D and 3D culture systems in response to well-defined strain fields. Extension of these studies to assess damage to brain tissue, whole organs, and/or tissue-engineered models of the regional damage would be worthwhile. The results of clinical functional magnetic resonance imaging (fMRI) studies of TBI might help to target specific regions of the brain for in-depth analysis. Overall, given the current state of neurosciences and the advances in optogenetics and other techniques, the biological studies described were relatively rudimentary. It is unclear whether on-site senior investigators with expertise in neuroscience participated in this program of study. Collaboration seems to be taking place with one postdoctoral fellow's former senior Ph.D. advisor, but further outreach is needed, including with neuroscience investigators in academia, to augment the military's broader TBI research portfolio.

A second set of studies focused on the assessment of neuronal responses to injury using a microexplosion model involving cells grown in monolayer submerged in an aquarium-based environment. Primary end points include cell viability, calcium signaling, and cell morphology. Future plans are to study neuronal responses in 2D and 3D culture systems placed within a gel-contained model of a human skull. The quality of the biological studies is rudimentary. The investigations do not appear to include the use of a model system in which the stress fields imposed on the cells have been fully characterized. A gel-containing human skull is an interesting model system, but it will require careful correlation of the estimated in vivo force microenvironment with the in vitro system created in their model system.

A third set of investigations focused on assessing the impact of anthropomorphic variability on the mechanisms of human injury, identifying sites of maximum vulnerability, and determining options for designing improved protective garments and equipment. Clinical computerized tomography (CT) data sets are acquired of soldiers killed in action (KIAs) in order to refine existing computational models of human injury and protection. Collaborative efforts have been pursued with the University of Maryland Shock Trauma Center and other programs. The quality of the scientific studies is high and utilizes an appropriate mix of theory, computation, and experimentation applying state-of-the-art laboratory equipment and numerical models. Extension of these studies to CT and MRI data sets of personnel who are injured in the field but not KIA would be worthwhile. The work designed to predict lumbar burst strength is a start but does not represent the thinking of current investigators in the field. It is necessary that the researchers develop communication channels with research leaders to increase the sophistication and applicability of the approach. While the pig skull work was a reasonable approach, it is unclear if the pig skull is relevant to the critical human skull issues that need to be understood.

The computational efforts in the human biomechanics area are somewhat behind the state of the art in computational mechanics of soft tissue. Specific details include the use of linear tetrahedral elements instead of hexahedral elements for soft tissue response, and there was a lack of viscoelastic properties for material response at high strain rates and high pressures. Further, there was only limited inclusion of the effects of statistical variance into necessary parameters of the computational problem to assess these effects. Such information is essential when computationally modeling humans and humanlike responses. The computational team needs to increase the sophistication of the models appropriate for the problem and needs to interact more extensively with subject-matter experts in human and soft tissue material response in the Army research community and the wider research community.

Overall, the biological programs appear connected programmatically, but they seem isolated from a scientific perspective. There appears to be little synergy or communication between the individual researchers. This lack of synergy is particularly significant to the junior staff, who could benefit greatly from strong mentoring by the appropriate technical communities. They need to become familiar with the current state of the art in their research areas and move quickly to achieve that state. They could also benefit from increased management support to help them learn how to overcome the administrative barriers associated with purchasing supplies and equipment.

To bring the current program to state of the art will require increased coordination of ARL technical personnel with the relevant biomedical communities and the hiring of scientists experienced in the computational modeling and experimental exploration of the effects of mechanical trauma on people, especially in the cases of injuries to the brain and extremities. Current personnel would benefit from experienced mentorship and connections to the field as practiced in university and other government laboratories. The equipment was reported to be consistent with beginning stages of the work and commensurate with the early-career status of the researchers and the brief time (1-2 years) that the program has been in operation. There is little evidence in these projects of the longer-range vision of ARL. The work presented continues to concern itself with current or near-term Army needs.

The research to better characterize the properties of materials relevant to protective systems is sophisticated and mature and is providing the data needed to understand the mechanical performance of protective devices. The project on the ballistic response of knitted materials is a small, well-executed modeling effort that is very relevant and important to ARL needs. While the work is not particularly novel, the results are unique and will be useful for the future design of protective equipment. The study of fiber mechanical properties under very high strain rates is impressive and is likely to provide data needed to better model soft and hard armor design and performance. Nonetheless, the scope of both the experimental and computational programs need to be broadened.

ARL reported a new internal program to study the chemistry and processing of the next generation of protective fibers. This program is supported by newly installed facilities, and it will focus on the modification of existing polymers with additives designed to increase overall performance (nanocomposites) and gel spinning of polyethylene. These represent a reasonable start, but there are other areas of both chemistry (next-generation Kevlar, self-healing materials) and processing (nanofiber production, melt spinning precursors) that need to be assessed as potentially attractive research areas for ARL. The understanding and improvement of polymeric components in protective systems is core to the ARL mission. As with the new programs in biology, mentorship and interaction with area leaders is necessary to ensure that the program is state of the art and aimed at producing materials to satisfy current and future (2040) Army needs.

Overall, ARL is to be commended for initiating programs that link the biology of injury to the materials and constructs designed to protect the warfighter. It is difficult to move into new areas and quickly develop state-of-the-art programs—and to assume leadership. The programs reviewed generally demonstrated technical skill in the chosen areas but often were not state of the art, and they seemed out of touch with the relevant scientific communities. There is an obvious challenge in moving quickly from beginner to leader, but this also provides great opportunity to assess the relevant science and engineering and devise programs to leapfrog to the next level of understanding. The program in battlefield mechanisms, human response, and human protective equipment is conducted by a strong cadre of scientists, and a credible program is under way.

Summary of Accomplishments

Battlefield injuries are an important area of research for ARL, because a better understanding of the mechanisms of injury is vital to improving protective measures. This is especially true for protection of the head, where there is considerable uncertainty about allowable levels of shock, which greatly affects protective options. The research projects presented were appropriate to the problem, and the staff is competent. The projects are short to medium term, which is reasonable for the early stages of a new program. As would be expected in a new research area, there are challenges to be overcome.

Challenges and Opportunities

Current projects are not the state of the art. Work at the cutting edge is difficult to maintain in a small program that does not have the option afforded to larger programs of pursuing multiple approaches simultaneously. Nevertheless, a greater effort could be made to assess the current research in the field and move closer to that cutting edge.

The program seems isolated both within ARL and from the larger outside scientific community. The burdens of being a small, new program in a new discipline within a large organization are many. There are fewer opportunities for constructive discussions and feedback, less chance for synergistic collaboration, and poorer awareness of current developments relevant to their own work. There are administrative burdens associated with procuring materials and supplies that are unfamiliar to the procurement branches of the laboratory. The cumulative effect of fighting through these issues will take a toll on the researchers' time and is a distraction from the pressing needs of maintaining a competitive research program. Management could consider assigning a single administrative contact person, who would become familiar with the unusual needs of the program and, perhaps, act as an advocate for the program within the administrative channels. A long-term vision needs to be developed. The beginnings of this thinking were presented, but they are not yet sufficiently developed to be useful. Such a long-term vision could express a philosophy that helps guide resource allocation and program direction.

DIRECTED ENERGY

The ARL S&T campaign plans 2015-2035 and technical strategy documents[1,2] categorize directed energy (DE) as a focused area under the much broader category of electronic warfare (EW), in accordance with the Army's definitions. The ARL posture designations for both radio frequency (RF)-DE and laser-DE are *collaborate* rather than *lead*. The subsuming of DE under EW and a collaborate-only posture indicate that ARL has downgraded the priority of DE within its technology portfolio from its previous robust effort. The consequence of this status change was evident in the current programs presented: They appear to be a small collection of seemingly unrelated projects. In addition, the current program, with the exception of the project in solid-state laser sources for tactical applications, seems to be concluding soon. Noticeably absent from almost all presentations was any thought of how the operational needs that the current systems were designed to meet would be satisfied in the 2035 time frame highlighted by the ARL director.

In view of the currently fragmented DE program, ARL needs to take a strategic look at the DE area to determine its ongoing priority and refocus ARL's effort with a view to the 2035 time frame. This strategic review needs to include consideration of future capabilities that the Army will need that DE might fill, and what DE capabilities might be fielded by our adversaries for which the Army will need countermeasures. A focused ARL DE program would benefit from a systems-level study addressing future Army missions in which DE could play a role and in which DE effectiveness and alternatives to DE are traded off. In this study, ARL could expand and diversify the laser program to seek avenues for integrating the technology with platforms of importance to the Army. Additional missions for DE could include illuminators; multispectral sensing, identification, tracking, targeting, and damage assessment; electronic protection/countermeasures for enhanced Army platform survivability against optical and IR guided weapons; and nonlethal weapons. Such a broadly based study is the necessary first step in planning a robust and relevant DE program to address the Army's future requirements. ARL has a

[1] U.S. Army Research Laboratory, *Army Research Laboratory S&T Campaign Plans 2015-2035*, Adelphi, Md., September 2014.

[2] U.S. Army Research Laboratory, *Army Research Laboratory Technical Strategy 2015-2035,* Adelphi, Md., April 2014.

significant capability in solid-state laser development—an obvious focus area for the future. In most cases the six projects reviewed met or exceeded the evaluation criteria, which included the following: Does the technology maturation employ appropriate laboratory equipment and/or numerical models? Is the research team properly qualified? Do the facilities and laboratory equipment seem to be state of the art?[3] Are the programs crafted to employ the appropriate mix of theory, computation, and experimentation? Specific concerns about individual projects related to these criteria are included in the following evaluations.

A highlight of the overall program in DE is the project on adaptive and scalable high-power, phase-locked fiber laser arrays. This work is a notable achievement, is recognized as such by the technical community, and appears to be ready for the next step, transition to the field.

The Department of Defense (DOD) recently articulated an electromagnetic (EM) maneuver warfare initiative. While ARL researchers did not reference this initiative, if all the services were to develop joint and independent programs as part of this effort, that could give ARL an opportunity to reexamine its role and strategic opportunities in EM maneuver warfare.

RF-Enabled Detection Location and IED Neutralization Evaluation

The scientific quality of RF-Enabled Detection Location and IED Neutralization Evaluation (REDLINE) research is comparable to that at leading federal, university, and industrial laboratories, both nationally and internationally. This is a first-class effort with full understanding of, and direct access to, operational needs and with a clear systems approach to reducing technical risks and delivering a successful experimental prototype.

The research program reflects a broad understanding of the underlying science and of research conducted elsewhere. The experimental confirmation of a complex propagation, detection, identification, and predetonation process is impressive.

This project is ready to begin the next step, deployment in the field. There is still an applied research effort needed to investigate detection, identification, and predetonation of increasingly advanced, emerging threats. The poster presenters mentioned the potential for mounting the capability on unmanned aerial vehicles. This seems to be a good idea, especially if ARL seeks to investigate the evolving improvised explosive device (IED) threat beyond the near term.

Hostile Fire Detection

In general, the scientific quality of the research is as good as that achieved at leading federal, university, and industrial laboratories, both nationally and internationally. The investigators used standard codes and modeling techniques. Although not strikingly novel, the work was credible and demonstrated useful integration of known techniques. The investigators also appeared to have access to intelligence about specific threats that may not be widely known.

The research program reflects a broad understanding of the underlying science and research conducted elsewhere. The researchers have addressed the major issues associated with detection and geolocation of threats such as rocket-propelled grenades and small arms. There was an appropriate level of modeling and predictive work to address near-term deployment but not longer-term strategic innovation. The prototype work that has been exercised in limited deployment responds to a near-term problem. Advanced (2035 horizon) modeling, diagnostic, sensor development, and test capabilities were not brought up.

[3] Note that the panel did not visit any laboratories during this year's review, so the assessment of the state of the art of the equipment is based solely on the presentations and briefings.

Operational data from full field deployments would drive next-generation innovation and improvement in identification and geolocation signature analysis for targeting support. This would produce results that could ultimately be transitioned to the field in a continuous upgrade process.

Adaptive Techniques for Advanced Radar Tracking and Optimization

The scientific quality of the research is basically sound in the context of unclassified university research, but it is not up to the standard of leading federal, university, and industrial laboratories working in this area. There appeared to be little or no awareness of existing, similar work in advanced radar development other than some unclassified university research. Reaching out to a major radar program, perhaps one of the Army's programs, might have revealed similar, prior work and identified what is and is not already in existence.

As for appropriate laboratory equipment and numerical models, there appear to be adequate computing resources but no association with radar R&D facilities or laboratories to ensure a practical base of experiment and experience. It is also not clear whether the signal interference modeling is relevant to existing radar clutter, interference, or jamming environments. Such interference can depend on the design characteristics of the radar under consideration, so general approaches may not be directly relevant.

There could be projects that, with improved direction, access, and resources, produce results that can be transitioned ultimately to the field. Possible collaboration with the Navy's extensive efforts in sonar tracking and optimization may be fruitful. The freshly conceived algorithms and use of greater computing power might provide useful insights to radar R&D facilities and developers. Some algorithms may be interesting for specific interference waveforms as spectral crowding increases.

Solid-State Lasers

The scientific quality of the research is comparable to that achieved by leading federal, university, and industrial laboratories. This research is aimed at identifying candidate materials, methodologies, and techniques for scaling solid-state lasers to mission-significant powers within the constraints of space, weight, and power (SWaP). Although many laboratories are doing similar work, ARL is concentrating its effort in eye-safer spectral regions that are of critical importance for the Army. The research program reflects a broad understanding of the underlying science and of research conducted elsewhere. ARL's work is known and respected by laser scientists at other institutions.

Programs crafted to employ more modeling would provide an enhanced mix of theory, computation, and experimentation. Given the objective of this project, the researchers need the capability for simulating, even crudely, an entire system from wall plug to target. This is the only way an analysis of alternative materials and architectures can be performed. Such an analysis would permit more informed choices for R&D paths to follow.

Adaptive and Scalable High-Power, Phase-Locked Fiber Laser Arrays

This research program is devoted to developing high-power (tens of kilowatts) fiber lasers by coherently combining lower power systems. The researchers have successfully combined seven lasers, each of which can continuously produce as much as 1.5 kW. A novel method has been developed for coherently combining the multiple beams. This is the critical element of any high-power fiber system. Feedback from a diffractive element located at the output aperture provides an optical signal that serves to phase lock the laser array. Another strength of this method is the modest bandwidth requirement for the feedback system (only 15 kHz), which is very attractive from the perspective of developing a reliable weapons system. Coherently combining the individual laser beams occurs at approximately 10 m from the output aperture, which is well into the far field. Beam quality is also actively monitored in the far field so as to optimize the efficacy of the phase-locking process.

The impact of this ARL laser system appears to be significant. In follow-on work, the Defense Advanced Research Projects Agency and the Lincoln Laboratory of the Massachusetts Institute of Technology have scaled this system so as to combine as many as 21 lasers. Although it is not clear at this point whether the ARL system will ultimately be incorporated into a real weapons system, it is evident that the system architecture has influenced other work. Low-power versions of the ARL design are, for example, being developed for civilian use. Another impressive aspect of this program is that it has resulted in six patents.

The high-power fiber laser system is the result of a decade of work at ARL. This program demonstrates the value to DOD of investing in novel research over a prolonged time. A further accomplishment is the understanding of the physics of intense optical fields propagating in a fiber. One practical outcome of this understanding was the finding that fiber core diameters as large as 20 μm could be used while maintaining beam quality.

Nonlinear Propagation and Target Effects of Ultra-Short-Pulse Lasers

This basic research project examined nonlinear propagation in the atmosphere of an ultra-short-pulse (1 psec) laser beam in a self-generated, ionized channel. The researchers observed that the ionized channel through which the beam propagated was much more stable at a pulse repetition frequency (prf) near 1,000 Hz than at a frequency of 50 Hz. The causal physics was conjectured to be that the channel remained steady at the higher prf owing to the lack of thermal dissipation of energy of the nitrogen and oxygen plasma that formed the channel.

Also reported was that the beam, when incident on solid surfaces, created ripples in the surface of the material over the area covered by the beam. This phenomenon was previously reported by others for metals and semiconductors but was demonstrated for the first time on polymers by the ARL team.

The researcher showed a strong knowledge of the experimental laser techniques and knowledge of previous literature. It was not made clear, though, why the experimenter followed the path he did. The quality of the work appears to be high and the facilities used at ARL were adequate for investigating this phenomenon. It was not clear, however, if computational modeling was performed to substantiate the proposed model. The experimenter did not have a clear idea of where this work was headed and how the Army might benefit from it.

Summary of Accomplishments

The REDLINE team has developed a kill chain concept for the detection, geolocation, identification, and triggering of IEDs. Model predictions and prototype experiments verified the performance of the harmonics-based approach, and the program has advanced to early system prototype testing.

Investigators working in the hostile fire detection area have developed diagnostic, modeling, and prototype hardware capability of detecting and geolocating hostile fire for enhanced soldier survivability. The work addresses three major areas in disrupting the lethality chain: threat signature characterization and identification; analysis of intervening and interfering material; and sensor systems response.

Significant field testing has enabled the development of a large, well-understood archive of unique multispectral data that was used to construct databases for rapid threat identification. ARL's work expands and improves the database of medium wavelength infrared (MWIR) and ultraviolet (UV) threat information. The analytical tools available to model EM propagation through both the atmosphere and various types of obscurants employed fundamental, well-understood concepts. The analytical tool for modeling intervening media and obscurants is a unique capability that was developed with academic collaborations and was empirically validated. The models have been integrated with various types of sensor payloads and packaged into the prototype hardware. The work has produced a patent on optical gunfire rocket and explosive flash detection that has been embedded in the electro-optical (EO)/IR sensor hardware. The investigators have taken the work from innovation to field prototype.

In the program developing adaptive techniques for advanced radar tracking and optimization, the concept involves a radar pre-look at the spectral signal environment prior to each dwell and uses algorithms to select quieter frequency gaps to form appropriate waveforms that minimize received interference while retaining required waveform resolution.

This experimental work on adaptive and scalable high-power phase-locked fiber laser arrays was outstanding; the experimenters clearly understood the issue and why it was being pursued, and they described well the problems that had to be overcome to produce the results of this beam combining experiment. Given the available laser power, the results were impressive and are headed in the right direction for producing a high-quality ($M^2 \sim 1$) combined beam from 6 to 8 fiber lasers that are all phase-controlled using an innovative optical feedback technique. Effective use of laboratory equipment was demonstrated. Whether or not this work can combine a sufficient number of fiber lasers to produce a 100 kW class laser is not clear.

Challenges and Opportunities

Limited test results of the REDLINE team confirm theoretical predictions of range, detection, and identification. However, an ROC curve (probability of detection versus probability of false alarm) based on test results and model predictions is not yet complete. Similar test data are needed for the likelihood of killing an identified target. Such a comprehensive characterization is needed, especially in a cluttered urban environment, as part of the program to verify that the system is operationally viable. This information will be required if the range of the system, say, by utilizing an unmanned aerial vehicle, is to be considered.

Also, the REDLINE team indicated an upcoming transition to 6.3-6.4 development. However, there is still 6.2 R&D to be performed, including characterizing emerging trigger threats and other countermeasures and design modifications to accommodate those evolving threats. Because the IED threat is expected to continue, a critical need exists for a continuing research program to address the projected and potential advances of the threat in the coming decades.

No strategic plan was presented for further development and maturation of the models for hostile fire detection, for advanced sensor capabilities, or for continuing experimental evaluation of future threats. To be effective, contributors and researchers need to become involved with established radar S&T and R&D groups—for example, such groups within the Army—to gain feedback on the viability and value of the approach compared to earlier work. The qualifications of the research team in the area of adaptive techniques may not be up to the research challenge, given the team's lack of access to operational radars and ongoing radar developments. There does not seem to be a core radar group within which this work is performed, so it is unclear why the work is under way in this particular research campaign. This may be a strategic question for ARL relative to the Army technical infrastructure. (The Naval Research Laboratory has had a robust radar research program for years.) The facilities and laboratory equipment may not be state of the art compared to the signal processing laboratories of advanced radar programs. Indeed, there appears to be no radar test site, data collection capabilities, or other laboratories associated with this work. The program is not crafted to employ the appropriate mix of theory, computation, and experimentation nor was there a connection to any existing or new radar and radar R&D facilities.

ARMOR AND ADAPTIVE PROTECTION

ARL has a strong record of achievement in the basic and applied sciences and the engineering of penetration and protection. The ongoing work described in the review showed how ARL is building on this tradition of excellence to provide the knowledge basis for future Army needs. This is a core competency that underlies Army capabilities.

The presentation on penetration, armor, and adaptive protection provided an impressive overview of ongoing research aimed at meeting shorter- and longer-term issues. The shift of focus from the goal of addressing short-term Army needs to the goal of carrying out research that will maintain world leadership in this area for future Army needs was evident.

The depth of knowledge of the staff and the evidence of interaction between staff members were impressive. They were also aware of and knowledgeable about projects other than their own. It is important that ARL ensure a steady supply of new staff into this critical area and that newcomers can benefit from the experience of senior researchers.

There was significant evidence of teamwork and integration among the projects in, for example, adaptive protection. There were examples of linkage of experiments and computational modeling to provide physical insight into problems, to aid in new designs, and to explore new concepts. The combination of modeling and experiments is essential in many cases, but there are circumstances in which it is appropriate to focus on a single mode of inquiry: experiments carried out as discovery science; modeling to develop an understanding of scenarios that are impossible or prohibitively expensive to investigate experimentally; development of new modeling approaches and techniques that promise to enhance predictive capabilities of ballistic phenomena; and development of new experimental methods that promise to provide a better understanding of the physical mechanisms underlying ballistic phenomena. ARL described a ceramic armor concept that was made possible by a previously developed experimental technique aimed at enhancing a basic measurement capability.

The staff apparently have freedom to pursue new ideas that can lead to breakthroughs that might otherwise be found more slowly, if at all. An example was the armor concept, a serendipitous discovery developed nearly to completion before being fully funded.

Developing a predictive capability for damage and fracture in metals, ceramics, and polymers underlies the efficient development of new material systems for protection and for penetration. At present, there is no framework that has penetration capability. However, experimental, theoretical, and computational advances being worked on in other countries are making such a capability seem possible in the not-too-distant future. A systematic approach based on understanding the key physical processes is needed because of the wide range of material systems that are becoming available. There are so many possibilities that a trial error-and-correction approach would be too expensive. It is important that ARL develop a leadership capability in this area. That requires the ability to identify damage and failure mechanisms in material systems of interest, the theoretical expertise to model these failure mechanisms, and the computational ability to simulate armor concepts and designs for the range of conditions encountered in the field. It is unlikely that a detailed quantitative capability will be developed. A more realistic expectation is a predictive capability that ranks the response of proposed armor systems to various threats and provides scaling relations that can be confidently used to transfer laboratory-scale tests to field condition response. Success in this area requires hiring and developing a critical mass of staff and having the needed experimental and computational capabilities.

Modeling

As pointed out above, ARL uses both experiments and modeling to develop new armor concepts and designs. ARL's use of modeling is maturing and is becoming better integrated into armor development and design. The researchers presented evidence that ARL was using numerical simulations to explore armor concepts more expediently than could be done through experiments. There were also examples of modeling being used to provide physical insight into experimentally observed phenomena, and there were examples of concepts and designs being examined that could not be tested experimentally with current capabilities.

Numerical simulation represents a key capability for ARL in the armor and adaptive protection area. ARL staff are customers for and collaborators with developers of advanced computational tools. Much of this activity involves codes developed at Department of Energy (DOE) National Nuclear Security Administration laboratories (Lawrence Livermore National Laboratory [LLNL] and Sandia National Laboratories [SNL]). These tools include ALE3D (LLNL), ALEGRA (SNL), and CTH (SNL). Some usage of multiphysics Sierra codes (SNL) was also reported. These are probably the appropriate tools for ARL's problem set (impact, high rate, energetic materials, and electromagnetics), because they scale well on parallel platforms and are the most advanced tools available. There was some use of commercial codes (e.g., LS-DYNA) as well, which allows ARL to exploit developments in, for example, crashworthiness analysis as it relates to the automobile industry.

ARL's relationship with the ALEGRA and CTH development teams at SNL has allowed it to drive the code development to address its own needs. ALEGRA is an arbitrary Lagrangian-Eulerian code with electromagnetics capabilities that is well-suited to a specific subset of ARL's problems. ARL staff are trained in use of the code, and this seems to have improved the sophistication of the analyses conducted. ARL is a significant user of CTH (SNL Eulerian shock physics code) for armor and adaptive penetration applications; in fact it is perhaps the largest DOD user as measured by central processing unit hours. This is ARL's workhorse code for impact problems. ALE3D is utilized for these problems as well. ARL staff members develop constitutive models to describe material behavior for all of these codes, which speaks to the level of sophistication of ARL modeling.

There was some evidence of the use of multiple codes to address different physics in a single problem. Use of the codes in this way will likely increase in the future, although coupling of codes is a challenging endeavor that will make the development of general frameworks for the coupling of codes increasingly useful.

ARL researchers indicated that their overall framework for multiscale modeling is also intended for armor and adaptive protection problems. The multiscale modeling work will likely become increasingly important for modeling complicated material behavior.

There was evidence that the researchers' computational work was limited by the available classified computing capability. ARL indicated that a 100,000 (node or core) machine was available for unclassified work but only a 15k (node or core) machine existed for classified work. For 3D magnetohydrodynamic calculations with ALEGRA, thousands of cores are required for several days—a significant portion of the computing power available at ARL. ARL therefore does much work of this type in a 2D axisymmetric configuration. Although this is less computationally expensive and is useful for many problems, it limits ARL's capability to explore oblique impact conditions and other scenarios that are not axisymmetric. Also, as ARL works to develop their its parametric studies and its verification, validation, and quantification of margins and uncertainties (V&V/QMU), many more simulations will be required, further straining the available computing power. ARL needs or will soon need more powerful classified computational platforms in order to accomplish its mission. A challenge in justifying more powerful classified machines is that ARL's relatively small classified user community places high demands on the machines at some times and lower demands at others, potentially leaving significant portions of a large computing cluster idle. A potential solution to this is to utilize designs that allow sections of a large computing cluster to swing between unclassified and classified mode. In this manner, the allocation of resources can more effectively address the needs for the two types of computing resources.

Developing predictive models for damage and fracture for armor and adaptive protection applications is an important research direction, and in these circumstances the material response is not likely to be entirely deterministic. Therefore, the scientific and evidentiary value of this research effort will be greatly enhanced by adopting a ubiquitous statistical perspective. Understanding the nature of the assumptions and approximations underlying predicted or anticipated behavior and how these can be updated as data/knowledge is gained will improve ARL's ability to develop technologies to adapt and survive in extreme and hostile environments. Furthermore, statistical scatter in experimental data could be an indication of subscale behavior with implications for modeling, so its impact on predictions needs to be explored through sensitivity studies and uncertainty quantification methods.

Experimental Aspects

ARL's work in armor and adaptive protection is also supported by experimental work. ARL utilizes its in-house capabilities for ballistics testing, which appears to be fairly well developed. Nonetheless, ARL needs to develop a wish list for experimental capabilities as well as a timetable for obtaining them for future needs.

ARL is also utilizing unique national facilities such as the Dynamic Compression Sector at the Advanced Photon Source at Argonne National Laboratory and the proton radiography (pRad) capability at the Los Alamos National Laboratory (LANL). Utilizing advanced facilities in this manner will advance ARL's science base and leverage these important national capabilities.

There were also instances in which ARL identified important technical developments and brought them to ARL. For example, it is developing a flash tomography capability and a capability to utilize photon Doppler velocimetry (PDV) in its work. It is important that ARL continue to find important technological developments and bring them to ARL when appropriate. In the case of PDV, ARL would benefit from engagement with the wider PDV community (e.g., the PDV workshop) and, if possible, seek out a short course that would train staff in the use of the PDV. ARL will also need to figure out how to exploit PDV effectively in its work.

The panel encourages continued development of the relationship with the additive manufacturing group at ARL and with experts around the country. Additive manufacturing has the potential to enable new armor concepts but could at the same time lead to new threats from adversaries.

There was significant discussion of the use of energetics to solve armor and adaptive protection problems, but there was little discussion of the science of energetics. The armor and adaptive protection group needs to engage more with the energetics group at ARL as well as with outside experts. For example, there are several concepts that rely on modification of explosive sensitivity that may be beyond current ARL capabilities. Technologies being developed in this area have the potential to enable significant advances in armor capabilities. Furthermore, state-of-the-art tools for modeling energetic materials are being developed elsewhere at ARL that may be applicable to armor and adaptive protection problems. The science of energetics in the context of armor and adaptive protection may be significantly different from that science in the context of warheads, so the ARL group working on armor and adaptive protection may benefit from a workshop on energetic materials for reactive armor. They might also encourage the Army Research Office to establish a Multidisciplinary University Research Initiative in this area.

Summary of Accomplishments

ARL has a strong record of achievement in the basic and applied sciences and the engineering of penetration and protection. Its presentation of experimental and modeling results and progress in penetration, armor, and adaptive protection provided an impressive summary of ongoing research aimed at meeting short- and longer-term mission needs.

There was significant evidence of teamwork and integration among the projects, in, for example, adaptive protection. Examples of the connection between experimentation and computational modeling that gave physical insight into problems were especially noteworthy, such work is likely to aid in developing new designs and exploring new concepts.

The benchmarking of simulations with experiments and the emphasis on bringing advanced technology (particularly in the x ray region) to bear on diagnostics were impressive.

Challenges and Opportunities

One challenge for those working in applied classified areas of armor R&D is to figure out ways to interact with outside experts. Ways to do this include participating in appropriate forums (classified meetings, interlaboratory workshops, international exchanges); identifying canonical unclassified problems and cases that can serve as conduits for collaborations with universities and other outside experts; and conference participation, which is very important even for those who cannot present because their work is classified. Conference attendance by those working in classified areas helps them remain up-to-date in their fields.

Rigorous procedures for the validation of model-based predictions that are consistent with current state-of-the-art methods use experimental data and the propagation of uncertainty as well as the characterization of associated modeling errors. This requirement is exacerbated by the complex multiscale and multiphysics interactions relevant to many predictive efforts that are under way at ARL in the armor and adaptive protection areas.

As ARL works to develop its use of parametric studies and V&V/QMU, many more classified simulations will be required, further straining the available classified computing power. ARL needs to elucidate a strategic plan for more powerful classified computational platforms in order to accomplish its short-term and current mission needs and to support future mission needs and deliverables. It also needs to continue development of its relationships and projects examining the utilization of additive manufacturing (AM) to address current and future Army needs. There is an opportunity for the ARL additive manufacturing group to interact and collaborate with experts around the country at DOD facilities and federal agencies and in academia and industry. Additive manufacturing has the potential to enable new armor and protection as well as new weapon concepts; AM could also lead to new threats from adversaries, which means new challenges to our warfighters. There is a need as well for procedures to qualify and certify AM materials to meet Army needs. AM has become a realm where new ideas are being developed and where the future Army is being enabled, so that ARL must become involved in AM work, and ARL needs to develop a strategic plan in this area. ARL's modeling programs must embrace the importance of variations, errors, and margins for establishing thresholds and statistics that support the development of predictive capability and design capability.

The presentations on damage and failure modeling demonstrated that modeling of damage evolution, fracture, and failure is a critical prerequisite for developing predictive and design capabilities in penetration mechanics. It is critical that ARL establish a focus in this area as soon as possible.

OVERALL QUALITY OF THE WORK

ARL's research on lethality and protection ranges from basic research that improves its basic understanding of scientific phenomena to the generation of technology that supports (1) battlefield injury mechanisms, human response to threats, and human protective equipment; (2) directed energy programs; and (3) ballistics and blast programs that address weapon–target interactions and armor and adaptive protection developments.

Its research on battlefield injury mechanisms is important for ARL because a better understanding of these mechanisms is vital to improving protective equipment. This is especially true for protection of the head, where there is considerable uncertainty about allowable levels of shock, which greatly affects protective options. The most impressive accomplishment of the battlefield mechanisms–human response–human protective equipment program is that a highly competent cadre of scientists is at work and a credible program is under way. A long-term vision for the battlefield injury mechanisms projects could serve as philosophy that helps allocate resources and set program direction. Almost all the topics presented in this subsection—battlefield mechanisms, human response, and human protective equipment—had a combination of computational and experimental approaches. The real-time interplay of experiment and computation is needed.

ARL's campaign plans categorize directed energy (DE) as a focused area under the much broader category of electronic warfare (EW), in accordance with the Army's definitions. The ARL posture designations for both radio frequency-DE and laser-DE are to *collaborate* rather than *lead*. The subsuming of DE under EW and a collaborate-only posture indicate that ARL has downgraded the priority of DE within its technology portfolio from its previous robust effort. The consequence of this status change was evident in the current programs presented: They appear to be a small collection of seemingly unrelated projects. ARL needs to take a strategic look at the area of DE to determine its ongoing priority and focus the effort accordingly, with a view to the 2035 time frame; the strategic review needs to include consideration of future capabilities that the Army will need that DE might fill, and what DE capabilities might be fielded by our adversaries for which the Army will need countermeasures. A focused ARL DE program would benefit from a systems-level study addressing future Army missions in which DE could play a role and in which DE effectiveness and alternatives to DE are traded off. A highlight of the overall program in DE is the project on adaptive and scalable high-power-phase-locked fiber laser arrays. This work is a notable achievement, is recognized as such by the technical community, and appears to be ready for the next step in transition toward field deployment.

ARL has a strong record of achievement in the basic and applied sciences and engineering of penetration and protection. The research and development described in the armor and adaptive protection area showed how ARL is building on its tradition of excellence to provide the knowledge basis for current and future Army needs in protecting our warfighters. This remains a core competency that underlies Army capabilities across the entire DOD, and it needs to be preserved and nurtured. There was significant evidence of teamwork and integration among the projects in, for example, adaptive protection. Examples of the link of experiments and computational modeling to provide physical insight into problems were especially noteworthy, with potential to aid in developing new designs and exploring new concepts. Benchmarking simulations with experiments and the emphasis on bringing advanced technology (particularly in the x ray region) to bear on diagnostics were impressive. Developing a predictive capability for damage and fracture in metals, ceramics, and polymers underlies the efficient development of new material systems for protection and for developing approaches to needed penetration capabilities. At present, there is no framework that has this capability. However, experimental, theoretical, and computational advances being developed in other countries are making such a capability seem possible in the not-too-distant future. A systematic approach based on understanding the key physical processes is needed because of the wide range of material systems that are becoming available. Material modeling for these systems would beneficially include reliable modeling of the effects of temperature and pressure—two effects that are mostly underrepresented in much of the computational and experimental effort.

4

Information Sciences

INTRODUCTION

The Panel on Information Sciences at the Army Research Laboratory is charged with reviewing Army Research Laboratory (ARL) research in the broad areas of computational sciences, information sciences, and atmospheric sciences. A 2-year cycle of review has been adopted for this purpose with the focus in 2015 on reviewing activities in Computational Sciences and on that portion of the Information Sciences portfolio related to work in system intelligence and intelligent systems (SIIS) and in sensing. Research in information sciences related to networks and communications, cyber, and human information and information interaction will be reviewed in 2016.

The panel conducted its review of the ARL Information Sciences campaign on June 17-19, 2015. ARL research in information sciences is focused on developing and enhancing intelligent systems for the analysis of information and knowledge. Included in this approach are technological advances that support information acquisition, reasoning with such information, and activities, including collaborative communications, that support decision making. An important aspect of this work is information assurance and analysis of trust. The overall research effort falls within the broad categories of sensing and effecting, SIIS, human and information interaction, networks and communications, and cybersecurity. The first two of these broad areas were reviewed in 2015.

SYSTEM INTELLIGENCE AND INTELLIGENT SYSTEMS

Research projects in SIIS were presented in three thematic areas: information understanding, information fusion, and computational intelligence. Collectively the work addresses technical challenges in the use of sensors, communication, and computing to provide the soldier with new levels of tactical intelligence and the automated support needed for missions. Areas of specific endeavor include language translation, information extraction, semantic analysis, understanding of human trust networks, fusion of conflicting information, integration of video and text analytics, anomaly detection, reasoning under uncertainty, robotic control and path planning, and models of cognition and tactical decision making.

Accomplishments

The research portfolio contains an appropriate mix of theory, computation, and experiments and is clearly of value for the support of Army missions. The research projects were generally, but not uniformly, of a good quality. The strongest work has been published in elite conferences and archive literature, and additional opportunities exist to disseminate other work at respected venues. It was difficult to identify a unified theme or common basis for the multiple projects, and the principal challenge for each of the three areas of research is to fuse the collection of projects into a coherent whole.

Information Understanding

Research in this theme focuses on the development of critical methods and techniques for transforming data so as to provide useful information to the soldier. The work represented solid but incremental advancement in several interesting and potentially important areas such as language translation, information extraction, semantic analysis, and understanding of human trust networks. Some of the projects appear to have potential for short-term applications in the field. The research staff ranges from experienced researchers with doctoral degrees to students pursuing master's degrees or internships. Laboratory resources appeared to be adequate to support the research agenda.

The work on temporal information extraction focuses on methods for extracting temporal relationships from text for constructing knowledge networks. The proposed approach is technically solid and particularly well grounded in the available literature. Temporal relations are an important area for future work by search engine companies, and the long-term applications to the Army are clear. This work has been published in a top conference—Association for Computational Linguistics (ACL)—an indication that it is first-rate quality work. The impact of the work is already evident in that other researchers at ARL are making use of this work.

Ongoing research on influence in social networks is closely related to activities in the network science Collaborative Technology Alliance (CTA) and pertains to identifying mechanisms for trust formation in human networks. The effort has emphasized identifying main factors, but the work has not addressed this issue in the context of networks. Most results to date are based on an analysis of data from the online microfinancing company Kiva and other lenders and are related to microfinancing and corruption perception indexes. The opportunities for extending this work to intelligent systems research for the Army were not readily apparent. The project would benefit from additional awareness and understanding of the literature in the area of online trust.

Also stemming from work related to the network science CTA is research related to agent-based semantic analysis in information retrieval. This research focuses on how to manage information dissemination across constrained channels based on the trade-off between size and accuracy. Rather than posing the task as a constrained optimization problem, the proposed approach implements a fuzzy logic model in order to include model uncertainty or fluidity in the attributes. The work requires a clearer articulation of what additional insights into operational questions are available from the proposed methodology. Further, to establish the advantages of the approach, it would be helpful to compare results against those obtained through more traditional optimization techniques. If such optimization techniques have inherent limitations or are not applicable in this particular problem setting, statement of the problem could better articulate those techniques.

An example of a 6.2 (applied) level research program addressing a real-world need is the project whose objective is to perform language translation in an automated fashion with a goal of enhancing translation capabilities for low-resource languages. The approach involves the construction of a language model based on entropy minimization that selects those sentences that need to be translated by humans in order to construct a best overall training corpus. The novelty of the work centers on methods for constructing the language model.

Information Fusion

Research in this area pertains to the fusion of data from disparate sources to produce timely, actionable information for the soldier. The research has advanced the state of the art in several interesting and potentially important areas such as fusion of conflicting information, integration of video and text analytics, and anomaly detection. The quality of the research was generally good, ranging from archival quality results publishable in top journals to preliminary but promising work. In some instances there was an apparent lack of full awareness of critical literature and alternative approaches. The researchers engaged in the projects were well qualified and possessed a range of experience. While laboratory resources appeared to be adequate to support the research agenda, there were not enough experienced staff to fully develop the ideas.

Research on estimating credibility by fusing subject opinions was of good technical quality and was disseminated in a reputable conference. This research focused on fusing multiple inconsistent and potentially conflicting information sources. The work treated inputs as propositions with truth-values and used subjective logic in a manner that took into account prior experience with the sources. It was well grounded in statistical machine learning approaches, but it could benefit from consideration of prior work in the human computation literature.

A project that seeks to develop an observer model for helping soldiers determine salient targets draws upon recent advances in image processing and neuroscience. The approach is to train a saliency model on the basis of experiments with experienced soldiers and then adapt that model for automated training of less experienced soldiers. The work emphasizes anomaly detection in saliency models. It is well grounded in previously published work and could be advanced by research considering information from a network of devices.

In a related vein, research is also being conducted into integrating complementary or contradictory information into a fuzzy model in order to determine the value of the information. The underlying idea is to take multidimensional values of information metrics and to project them onto a single dimension. This kind of dimensionality reduction facilitates subsequent sequence-based analyses. It is not clear that such analyses could be performed without unnecessary loss of information. This work would benefit from considering the results of previous research in indexing, feature reduction, and information theory.

Several research efforts in the thematic area of information fusion were in the early stages of investigation. An effort dealing with intelligent information management in the battle environment focused on bandwidth management during distribution of information to end users. The approach is based on linear scoring functions with weights established by the users. Its effectiveness is based on questionable assumptions about human capability, and the investigators might want to consider alternative approaches in the literature that deal with learning user preference and modeling utility in humans.

Another early research effort that could potentially have important impact is based on a hypothesis that learning from video and text could benefit from being done together when video includes or is associated with text. The improvement in the quality of the results comes with the cost of implementing joint learning methods, a much harder problem to solve. The next appropriate steps would include a literature review that examines relevant advances in optical character recognition, video retrieval, and object recognition in videos.

Computational Intelligence

Research in computational intelligence examines the development of intelligence in systems to support highly automated or autonomous operations in support of Army missions. The research efforts have yielded significant advances in several interesting and potentially important areas such as reasoning under uncertainty, robotic control and path planning, and models of cognition and tactical decision making. Researchers engaged in the effort are well qualified, but the team comprises a disproportionate number of early-career researchers. Some of the research efforts lack the staff that would be needed to fully develop the ideas. In particular, projects related to information for robot navigation and message delivery and those requiring expertise in psychology would all benefit from strategic recruitment in targeted areas of expertise.

A research project focused on improvement of visual classification for navigation purposes uses an approach of implementing partially supervised discovery and labeling the navigation domain. The research aims to reduce the effort associated with human labeling of terrain and objects in images for the purpose of supervised learning of objects in images. Over-segmenting the image and then using clustering techniques on the resulting segments accomplish this goal. Human labeling based on the clusters is much faster but less accurate. However, this loss of accuracy does not significantly degrade robot navigation when using the new visual system. This research is expected to have an important impact and has yielded promising initial results.

Another promising research project uses a semantic vector space for reasoning in the presence of uncertainties. This work seeks to take advantage of two different types of semantic models with a goal of augmenting a curated knowledge base by reasoning through analogies based on statistical representations. Both the ideas and the proposed methodology contain novel elements, but the work is still in an early phase. A number of complexities have to be resolved, including those arising from multiple meanings for words. The work is well grounded in the literature, and the researchers are aware of related efforts in the research community. With continued support and application to meaningful problems, it has the potential for publication in top journals.

Investigations into the concept of robust distributed communication relays for minimizing message latency in a vulnerable and uncertain operating environment are also ongoing, albeit at a preliminary stage. The research is focused on resource-constrained, dynamic environments, where it may be advantageous to use kinetic or nonelectronic means to augment electronic information distribution. The formulation results in a very hard computational problem based on vehicle routing. The approach to handling the computational difficulty derives from an integrated heuristic/high-power computing (HPC) methodology and is being tested in a simulation environment. While the pertinent literature has been explored and cited, additional benefits in computational efficiency may be gained by using recent work on probabilistic spanning trees.

Another example of an early research project investigates strategies employed by humans in situations similar to those experienced by soldiers facing trade-offs between short-term and long-term actions. Initial results in two-player games, which have been obtained using computer agents, demonstrate that there is no dominant strategy. The underlying hypothesis for the work is that these games will provide an environment for investigating how humans move between strategy, tactics, and actions. Although at a preliminary stage, the work addresses an important problem. It is critical to place this research in the context of the literature on human cognition, training, game theory, and computation intelligence in games. Another effort at modeling human cognition was based on varying the volume and velocity of data presented to shooters who have to make a choice of targets. This allows investigation of the effects of data attributes (in classic big data terms) on human ability to make decisions. This topic appeared to be narrow research toward a master’s degree, and its future is unclear.

Ongoing work at a more advanced level looks at the use of an information-gain metric to design paths for autonomous mobile robot movement. Entropy minimization concepts are used to develop optimal routes for mobile ground robots. This work has evolved to an advanced demonstration level; there is a good plan for future work that would make use of recent advances in combinatorial optimization methods and that would include constraints on power and available onboard computational bandwidth.

The concept of episodic memory consolidation and revision, or robotic dreams, was used to identify precursors to events such as the deployment of an improvised explosive device. The research is premised on the hypothesis that this computationally demanding problem is intractable in a real-time computation environment but is more amenable to large-scale background processing using otherwise idle computing resources. While this problem is of significant importance, it was unclear what level of computational efficiency was added through the episodic memory consolidation approach vis-à-vis simply devoting additional computational resources to the problem directly. It was not readily apparent how the approach is distinct from traditional work-stealing methods for background processing during low computational loads.

Challenges and Opportunities

The most significant challenge facing the SIIS program is the development of a coherent and unifying thrust for the research program. Overall, there was little evidence that the whole would be greater than the sum of the parts that were reviewed. The portfolio of research is broad, with many lightly staffed projects. A challenge lies in a better integration of the work to pursue fewer, but more significant and more ambitious projects. Such prioritization is important to focus the limited staff on strategically selected projects so as to more fully develop the ideas. It is possible that the above impression is due to the selection of the topics presented to the panel. ARL leadership noted that projects had been selected to provide a broad sample of the research portfolio rather than to explore its depth. If there are elements that more coherently unify the research projects, then it is important to highlight such integration, not just in the top-level overviews but also in the project descriptions themselves.

Intelligent systems research is increasingly dependent on harnessing vast quantities of data, and the fields of scalable machine learning and big data analytics are advancing rapidly. A number of important techniques and tools have been developed to address these emerging challenges, many in the open source community. Some of the projects reviewed in this report would benefit from understanding and using these new tools. Such an approach is being practiced in research related to cybersecurity and other areas that were not reviewed in 2015.

Some of the reviewed projects were particularly strong because they combined pertinent approaches—for example, the combination of statistical/machine learning [ML] methods with linguistic rules—to address research challenges. Beyond such innovative and opportunistic approaches, some impactful research projects demonstrated clear integration with other activities and research at the ARL and other external entities. Other opportunities for such integration exist and could be more broadly embraced.

New advances in automation have changed the roles of humans and machines in intelligent systems to a degree that humans and machines need to collaborate in task activities. Therefore, the human systems perspective has to be fully integrated into any development to ensure usability and robustness of the results. The ARL presentations did not include the work on human interactions, making it difficult to assess the impact of some of the systems intelligence research.

SENSING AND EFFECTING

Research projects in sensing and effecting covered thematic areas of non–imaging sensors, image understanding, sensor and data fusion, and radar signal processing. There was a strong focus in the area of acoustic sensors that collectively examined new materials applications alongside the development and implementation of better signal processing capabilities. Cross-modal face recognition was an important thrust in the image understanding research. The use of long-wave infrared polarimetry to facilitate discrimination of manmade and nonmanmade objects was another thrust in this research. The sensor and data fusion focus was largely on approaches for dynamically adapting information to situational changes and appears to comprise engineering advances as opposed to exploring fundamental science. Research in radar signal processing was both relevant and of good technical quality, and it focused on signal processing in congested and cluttered environments.

Accomplishments

The research portfolio contains a mix of projects in areas that are well aligned in support of future Army missions. The research was generally of a good quality but not uniformly so. The research projects emphasized applications as opposed to the foundational science. Some of the work is being published in top venues, but researchers could be given additional guidance and encouragement to present their work at leading conferences and then pursue publication in top archival journals. In general, the research staff were well qualified and demonstrated a good understanding of the important challenges in their work. The long-term research vision provides a natural framework for integrating the individual efforts. However, the connection between these individual activities and this overall framework was not clear. Finally, the time horizon for some of the projects can be shortened (to 3-7 years) to demonstrate proof of concept; the pace of technology advances in the field dictates this necessity.

Non–Imaging Sensors

Research in this domain is primarily on the application of acoustic sensors for Army-relevant tasks, including identifying helicopters through acoustic signatures, to localizing gunfire, and to long-range detection of vehicles or weapons. The Army has a long history of using such sensors, but new technologies and new signal processing techniques could extend the range and the precision of these sensors, reduce complexity, and minimize power requirements.

Research related to the application of new materials in the design of windscreens for acoustic sensors has yielded positive outcomes. Acoustic sensors covering a range of frequencies, from infrasound to ultrasound, were explored in this study. Ongoing efforts are evaluating a range of porous materials and are characterizing their efficacy relative to baseline materials used in traditional microphones (e.g., foam). The work is based on results from partners at the University of Mississippi. The results have been presented at good conferences but have not been submitted for publication in archival journals; internal technical reports document the progress of this work. ARL needs to consider the submission of this work for publication in an archival journal. There is an opportunity to use foundational theoretical knowledge to guide in the selection of optimal materials for this application.

In research related to enhancing the effectiveness of acoustic sensors, the work on identification of helicopters through the use of innovative signal processing techniques has yielded promising results. The signal-processing algorithm takes advantage of the relatively invariant blade speed to determine the Doppler shift and to calculate appropriate motion compensation, which is then used to auto-focus. Papers describing the approach have been published in recognized journals.

Research in this domain is also exploring sensors alternative to the more traditional microphone arrays. In particular, a research project is directed at investigating the use of microelectromechanical systems (MEMS)-based, three-dimensional acoustic particle velocity sensors. A commercially available sensor was adopted for this work, and the ARL research is focused on developing signal-processing techniques better than those provided by the vendor for applications that include localization for small-arms fire and triangulation of continuous waves. These devices have significant potential for reducing complexity, weight, and power requirements. Their robustness in field applications continues to be an area for research and development. Findings of this research have been presented at recognized conferences and documented in internal technical reports.

Image Understanding

The image understanding research program was generally of high quality. The work is being published in high-quality journals and shows a comprehensive understanding of research conducted elsewhere and how the ARL research fits into the broader research landscape. The cross-modal face recognition work represents an excellent example of an appropriate applied research topic for ARL given the mission need for such an approach. The researchers were able to articulate the unique Army needs in these problems and were addressing them.

The research on polarization shows strong potential, and continued collaborations with camera producers would enhance capability. Researchers demonstrated an outstanding ability to summarize the significance and impact of the work. Additionally, the collaboration in this project related to sensor algorithms for polarization imagery was considered to be a positive outcome of the ARL open campus initiative.

The image understanding work was applied research rather than fundamental. Appropriate laboratory facilities were available to carry out this research. The work was judged to be relevant to Army needs and could ultimately be transmitted to the field. In particular, the manmade object discrimination work recently resulted in a patent, and a transition path is under way.

Sensor and Data Fusion

The research efforts in this area tended to be more incremental engineering advancements as opposed to addressing fundamental questions. As an example, design concepts for dynamically adapting information to the situational changes in the utility of data attributes (e.g., accuracy, latency, reliability, data rate) could be a fundamental topic for investigation; instead, it was treated as a human factors problem rather than as a broader concept for automated management of data prioritization. Given the engineering development focus of much of the work, the researchers did not present current state of the art in sufficient depth, and they appeared to lack access to the field data that would have allowed them to do so.

Research related to detection of vehicles, personnel, or targets is key to Army operations and requires the use of multiple sensor arrays. The fusing of information from many sensors observing similar objects (dependent data) is key to developing better inference. The research focuses on developing a means to fuse correlated information.

The work on dynamic belief fusion applies a sound and seemingly straightforward approach. It integrates the outputs of different object detectors by assigning ambiguity levels derived from previous performance to each detector. An approach of dynamically allocating probabilities based on prior performance has been developed that demonstrates the improvement in detection accuracy over conventional fusion methods.

Another area of research is aimed at developing and enhancing tools to reduce the time between data gathering and making decisions. While important from a practical perspective, the research effort is simply an extension of a fuzzy logic–based tool to assess value of information (VoI) through the use of additional membership functions. The work is in an early stage, and the fundamental technical advances of the approach are not readily apparent.

Across the entire research endeavor, access to actual field data would further enrich the research effort and would help to distinguish the work from that in the outside research community. In the area of dynamically adapting information to situational changes, for example, research in the commercial applications arena focuses on certain performance objectives that do not meet the requirements in the military context. It is important to build in recognition of ease of disruption and cost of errors (e.g., of human life) as explicit considerations in the performance objectives, and field data become a critical component in evaluating such criteria.

The laboratories and infrastructure support were appropriate to support the research; the access to the E/H-Field laboratory is particularly beneficial to ongoing research. The researchers were academically well prepared to undertake the work.

Radar Signal Processing

The research reviewed in this domain was of good technical quality and showed promising results. The research problems were well defined, the methodology was explained at an appropriate level, and the results were well organized. Detecting moving personnel under tree cover on the basis of frequency-modulated continuous-wave (FM/CW) radar is an important challenge. A full-wave approach, realized through the use of a parallel 3D finite-difference time-domain algorithm, is deployed for this purpose. Likewise, the ability to detect targets obscured by artifacts in ultra-wideband imagery is also relevant and important from an Army perspective. Mission requirements dictate effective performance in the presence of uncontrolled radio frequency (RF) transmitters, and RF interference notch-filtering techniques are widely used in such applications. An alternative approach based on sparse representation and recovery of signal was proposed that does not have the shortcomings of notch-filtering techniques.

The work related to nonlinear radar methods is also timely. It focuses on the use of nonlinear harmonic radar to achieve greater sensitivity across a narrow frequency band. These approaches have been in the literature for a few years, and early applications in the field represent an important next step. Based on these experiments, a 3-7 year time horizon for transitioning to full-scale developments in this area is a real possibility.

HPC facilities at the ARL are a key enabler for this work, especially in applications to detect moving personnel under cover. In a similar vein, the significant use of radio equipment indicates adequate infrastructure to support the research effort.

Two of the projects employed computer simulations to generate input data that were used to demonstrate improved receiver processing techniques. While adequate for purposes of showing proof of concept, the use of real data would also significantly benefit further studies. Simulated data might lack some of the complexities in real data and could lead to false validation of the proposed methodology. ARL might be able to get such data from other DOD laboratories or from the industry. If necessary, simple experimental set-ups could be built to collect such data.

Challenges and Opportunities

The overall technical quality of the research in this area was good, albeit with a greater focus on technology development than on foundational research. Overall, researchers are aware of relevant work in their domain of interest, but this was not always the case. The research problems are important to the Army and are unlikely to be pursued in academic institutions or other government research laboratories.

From an engineering standpoint, the researchers seemed knowledgeable about identifying and adapting or creating new signal processing techniques to the target domain and good at doing this. From a foundational standpoint, however, it was less clear how well the algorithms or ideas would transfer to other domains, or how knowledge would be gained to better understand the underlying physics of the domains

In the area of image understanding, an increased emphasis on developing rich data sets and the quantitative improvement of performance for larger data sets—especially data sets that include mission-relevant variability—would enhance the impact of the program. In particular, a better understanding of how easily an adversary could defeat cross-modal recognition efficacy is of interest. The research emphasis could be expanded to embrace the fundamental science in order to better understand the physics that drive cross-modal features and the information-theoretic fundamental performance bounds. This would enhance the overall quality of the research and produce results with longer-term impact. Additionally, ARL could better connect with and provide intellectual leadership to the broader facial recognition community by creating and curating open, standardized data sets as well as challenge problems for researchers to explore.

In the area of sensor and data fusion, dynamic automatic control of data attributes with operator support represents an important emerging area of research. This is especially true given the explosion in sensor technology and limitations in both communications bandwidth and human–computer interaction. A new opportunity would be to expand the focus to automatic data control rather than limiting control to the operator interface as the only basis for stimulating data control actions. While industry wishes to develop cryptographically solid authentication and authorization, the needs of the Army are more complex. While the authorization to manage parameters of a system resides with a few individuals, provisions have to exist for others to take over or at least prevent unauthorized access by others. One possible area for research is to design systems with redundancy, so that if one sensor net or dashboard is subverted, it would be immediately detected. Similarly, based on knowledge of the system, the ability to identify system behavior as illogical and possibly compromised would be hugely beneficial in such field operations.

The radar signal processing work could benefit if the engineers working in this area had graduate-level training. There have been significant advances and new tools in the radar signal processing area, and familiarity with these would elevate the research. It would also help to improve the success rate for presentations at leading conferences and publications in top journals. Access to advanced technical knowledge online or by other means can be explored. The work related to nonlinear radar shows promise for immediate transfer to a range of battlefield applications. Finding ways to transitioning this technology as rapidly as possible would be extremely helpful in meeting critical needs in Army operations.

Wireless (and other) communications is a critical part of Army operations today, and its importance keeps increasing. It would be beneficial for ARL to build some capability in this area, at least to support other activities in the laboratory. Lack of this communications technology skills set will increasingly become a disadvantage

OVERALL QUALITY OF THE WORK

The research portfolio in SIIS includes a growing component focused on enabling technologies, the underlying science, and novel applications to intelligent and autonomous systems. In all cases the intelligent systems issues under study showed clear relevance to the future missions of the Army. The projects were generally of good technical quality. Importantly, especially among the junior researchers, there was a good awareness of external research and connections to professional organizations and outside research communities; these are important for maintaining and growing the technical quality of the research. The research results are appearing in respected conference proceedings and archival journals. ARL has continued to demonstrate its responsiveness to the general comments and recommendations of the *2013-2014 Assessment of the Army Research Laboratory* by the National Research Council is increasing the number of Ph.D. scientists on its research staff in key areas.

The opportunity for strong technical contributions and for differentiating the work from research conducted elsewhere, as well as enhancing the value proposition for the Army, lies in a mission-oriented thrust to the research. A number of projects in the research portfolio have just such a mission focus and the associated constraints (e.g., limits on the volume of prior information or on available network bandwidth), and these serve as a clear driver of the technical direction of the work. Other projects would similarly benefit by a focus on those areas where the special needs of the Army are not addressed in the basic research agenda being pursued outside of ARL, including the development of technology products related to this research.

The research thrust in sensing and effecting includes projects that address emergent needs of the Army. New theoretical advances and resulting tools have led to a rapid evolution of technology in this domain, and the 3- to 7-year horizons for ongoing research projects at ARL are quite reasonable. The research was generally of high quality, with a focus that is unlikely to be pursued by researchers at universities or at other federal or industrial research laboratories. As an example, recognition of ease of disruption and cost of errors (e.g., human life) needs special attention; field data become critical to the solution of this problem. The researchers generally demonstrated a good understanding of the problems being considered, were able to provide an appropriate statement of the research problem, and pursued appropriate methodologies. They demonstrated awareness of the state of the art and of the related research pursued elsewhere. The facilities required to support the research, including both instrumentation and the computational tools, were adequate.

5

Computational Sciences

INTRODUCTION

The Panel on Information Science at the Army Research Laboratory (ARL) conducted its review of ARL's advanced computing architectures, computing sciences, data-intensive sciences, and predictive simulation sciences at Aberdeen, Maryland, on June 15-16, 2015. This chapter evaluates that work, recognizing that it represents only a portion of ARL's Computational Sciences campaign.

The Computational Sciences review looked at four distinct areas of research: computing sciences, predictive simulation sciences, data intensive sciences, and advanced computing architectures. Ongoing work in each of these areas is assessed in the next sections of this chapter.

ADVANCED COMPUTING ARCHITECTURES

Alongside a focused research effort in tactical high-performance computing (HPC), researchers have moved to explore new and interesting computer architectures, including neuro-synaptic computing, the epiphany many-core chip, and quantum networking. The research staff in these areas of work exhibited high quality research skills and is well organized and positioned to succeed.

Within Computational Sciences, big data/analytics and HPC are treated separately. Given that important applications will increasingly combine high-performance analytics and high-performance computing, it is important to assess the impact of integrated computing on architecture and operating environments. Architectures will move to datacentric designs where compute is moved to data throughout the systems environment. This will be true in the data center and at the tactical edge. Analytics on very large dynamically changing graphs will be critical to gaining insights from big data. While the computation in scientific computing can be statically scheduled, computing on graphs is data-dependent. The operating environment therefore needs to change to schedule dynamic computations; this capability is also required for resilience in the battlefield.

Accomplishments

Work in tactical HPC has identified key aspects of the solution space and is exploring important issues related to establishing the utility of those aspects. A particularly interesting observation by ARL researchers is that the tactical HPC space is potentially richer than the commercial space, owing to differences such as communication reliability and potential deployment of field resources. The commercial space currently consists of handheld devices and cloud-computing resources deployed in data centers. The tactical HPC space includes handheld devices, field-deployed tactical (potentially mobile) resources, strategic resources close to the battlefield environment, and cloud-computing resources located in military data centers. ARL has developed models that will guide offloading decisions in these complex computing environments. An interesting question for ARL to explore is the commercial applicability of the intermediate resources to issues such as smart highways.

An example of tactical HPC is the project in multiobjective geometric optimization, a tool to safely guide soldiers to strategic viewing points in the presence of adversaries at known locations. The computational effort (ray tracing) to determine, in real time, a safe path in a 3D modeled megacity, avoiding detection by one or more known enemies, is significant and beyond the capabilities of current and emerging handheld devices. Input from the handheld device (tablet) to the remote HPC system and receipt of output back to the tablet do not place excessive demands on the energy-limited tablet. Researchers have explored a variety of solutions on a set of HPC platforms, with varying performance. This is a high-priority Army application, but security and resilience have yet to be considered.

The work on computation ferrying is exploring an important aspect of realizing ARL's vision of tactical HPC. It considers the tasks that could be computed on handheld devices or on mobile tactical HPC resources. The project has developed a simulation environment in which to study the behavioral properties of the system to determine the specific scenario parameters for when it is necessary and reasonable to use offload tasks from the handheld devices. Initial results have demonstrated that offloading proves most useful for intermediate task sizes, which achieve a balance between communication cost and improved computation speed. Overall, this direction will motivate an end-to-end solution for battlefield computing.

In addition to establishing modeling and simulation capabilities to guide offload decisions, ARL has explored critical issues related to programmability and performance of edge (handheld) devices. The work with open computing language (OpenCL) programs demonstrates that devices can achieve significant computational efficiency, particularly in terms of power and performance. This work can serve as the basis for parameterizing the models and simulations that will guide offload decisions. A possible direction for future work on handheld devices is to develop an understanding of the trade-off between performance per watt (i.e., power efficiency) and the amount of power available in handheld devices (i.e., battery lifetime of those devices).

The project in dynamic binary translation (DBT), which demonstrated the fastest cycle-accurate emulator design in the 2014 MEMOCODE[1] contest, falls in the areas of power-performance and heterogeneous computing. The research group developed a DBT to allow fast cross-architecture execution of binary codes. This would, for example, allow legacy binary code developed on a now obsolete architecture, e.g., i8080, for which the source code is not available, to be run efficiently on another current architecture, e.g., a low-power ARM.[2] DBT is a well-mined area with results in the literature dating back to the 1990s. What sets this work apart is that this DBT outperformed all other MEMOCODE entries by a factor of seven, with close to 1.1 cycle efficiency.

Challenges and Opportunities

In advanced computing architectures, the Computational Sciences campaign specifically identified the goal of leadership in areas that include heterogeneous computing; many-core integrated architectures; tactical HPC; power, performance, and portability; quantum computing; neurosynaptic computing; and software-defined networking (SDN). "Leadership" is a posture in which ARL maintains considerable in-house expertise, has a substantive infrastructure, and devotes significant investment based on unique Army needs. If one adds to this objective a leadership role in the research community, then the above list is extremely ambitious. It would be sensible for ARL to define a more limited list of areas in which it will achieve this leadership.

[1] MEMOCODE is the Association for Computing Machinery (ACM)-Institute of Electrical and Electronics Engineers (IEEE) International Conference on Formal Methods and Models for System Design.

[2] ARM is a family of instruction set architectures for computer processors developed by British company ARM Holdings, based on a reduced instruction set computing (RISC) architecture.

ARL is developing in-house expertise with potential to establish a worldwide leadership role in neurosynaptic computing and has plans to establish substantive infrastructure by investment in the area. Additionally, it is investing in quantum networking as a specific focus within the topic of quantum computing.

There is significant research effort worldwide in heterogeneous computing, many-core integrated architectures, and power, performance, and portability. Most of this work is taking place within data centers, with some researchers exploring deployment in the field. ARL has a clear opportunity for broader community leadership and significant impact on the Army's capability if research in these areas is focused on tactical HPC. As part of this work, ARL could investigate advanced techniques for security and resilience in the battlefield infrastructure. The battlefield environment implies much higher costs for usability and reliability than does a commercial environment. The investigation here could look at the rescheduling of work dynamically as parts of the infrastructure go offline and come back online.

The majority of the posters presented as part of advanced computing architectures can be brought under this umbrella. While the posters mostly represented good work, many were missing the driving application or scenario, and they tended to be incomplete. The two posters related to SDN (software-defined networking) were missing a critical piece—the dynamic reconfiguration of the network has to be driven by the requirements of the workload, which need to be specified in declarative language or detected automatically. The ARL researchers are to be commended for their participation in the GENI (global environment for network innovations) community and for the quality of the infrastructure that they have built.

The two key challenges for tactical HPC are (1) the selection of high-priority Army applications and scenarios to drive the research and (2) the inclusion of security and resilience of the infrastructure as an explicit research goal. The latter challenge may necessitate new hiring and/or the forging of external partnerships.

Broader community leadership in quantum networking is also possible, but a more in-depth review of this thrust needs to be considered. The research is being done in the context of a larger Center for Distributed Quantum Information that has the specific objective to study the essential elements for implementing and exploiting a resilient network of quantum devices. The level of resources allocated needs to be reassessed if the goal is to build leadership in this area.

ARL researchers are pursuing interesting and important research in the area of advanced computing architectures. However, the work frequently is not appearing in tier one conferences and publications—e.g., International Symposium on Computer Architecture; IEEE's Micro's Programming Language Design and Implementation (PLDI), Architectural Support for Programming Languages and Operating Systems (ASPLOS), and SC (formerly Supercomputing); and the International Conference for High Performance Computing, Networking, Storage and Analysis, which are the most important publication venues for research in the area. The key issue for achieving such publication successes for ARL is learning how to package research results for those venues. ARL researchers can only learn this skill by attending those conferences and participating in their organization, such as program committees.

COMPUTING SCIENCES

Computing sciences aims to develop the understanding, tools, techniques, and methodologies to fully exploit emerging computing architectures. This is accomplished through the realization of efficient task parallel algorithms and the use of advanced memory hierarchies. These efforts are expected to greatly reduce the time required to restate algorithms in parallel form and to correct implementation faults and bugs. The research areas of focus can be broadly categorized as programming languages, computational environments, and software integration. More specifically, research in programming languages seeks to improve performance, portability, and productivity of methods for Army-specific applications. Software integration aims to reduce the cost of entry for developers of scientific software and for scientists, engineers, and other users, allowing them to effectively use evolving computing environments. The evolution of the computing infrastructure is creating new challenges, ranging from energy-aware software development to software for massively parallel and distributed systems. The research in software integration is focused on addressing these challenges and developing an approach for software design that is predicated on the principle of systematic software reuse.

Accomplishments

The ARL computing sciences group has established a strategic focus in quantum computing; parallel processing environments for large, heterogeneous parallel systems; and tools to simplify application development for HPC environments. Establishing a coherent and sustaining strategy in these areas was a major accomplishment. The group has also grown its work in exploratory research while still providing support for issues of immediate importance to the Army's mission. The group has established an approach to keeping its computing infrastructure up to date with the latest hardware and software systems and tools, effectively upgrading the HPC system infrastructure every 2 years (staggered replacement of two HPC systems, each on a 4-year replacement cycle). While this turnover in equipment can be a challenge for application developers, the group is working to provide tools to simplify application development and help the developer optimize performance on the more advanced systems.

Research in quantum computing and software environment optimization is especially noteworthy and recognized as being leadership work that advances the basic science in important areas of computing technology. The focus within quantum computing is hardware abstraction at the function level (referring to a network of devices rather than an individual device) versus the Qbit, or device, level. This work has the potential to advance the knowledge and technology for future quantum computing systems.

Similarly, the focus on software environment optimization for hierarchical many-core and heterogeneous processing environments is on tools and algorithms to support code development and optimization of emerging HPC system structures. This work will be important for the efficient and effective use of HPC systems under development for ARL applications.

Two projects stood out as incorporating outside-the-box concepts and resulting in high-quality basic research that integrated theory, computation, and experimentation. These projects were focused on the development of threaded message-passing interface (MPI) for reduced instruction set computing (RISC)-array multicore processors and on HPC scaled quantum hardware description language (QHDL)-based modeling of entanglement dynamics in Jaynes-Cummings circuits in open system evolution. The first of these provides ARL a solid foundation to pursue innovative solutions to the challenging problem of power-efficient parallel programming. The second is one of the few efforts in quantum networking, and the development of hardware abstraction language will have strong value in future systems. Another project, dealing with an auto-tuning benchmark for HPC accelerators, represents valuable tactical research versus long-range basic science. This research supports initial performance optimization of existing applications and benchmark codes on emerging HPC systems. Auto-tuning in this work is a higher level tuning (as contrasted with a widely practiced industry approach of using libraries).

Work related to communication-avoiding approaches for Lanczoz eigensolvers demonstrated a good understanding of the interaction of mathematics and HPC. The approach is in the process of being submitted to Sandia National Laboratories for inclusion in production codes (Anasazi) to realize the benefits of scaling; the potential for such deployment is a sign of high quality and immediate scientific relevance and impact. A project dealing with hierarchical multiscale computational framework was technically strong but not considered as representing basic research. This work could be transitioned to a production code.

Challenges and Opportunities

The major challenges facing the computing sciences group include scaling applications across large parallel heterogeneous systems, developing tools and frameworks that work on multiple parallel system architectures, and improving software performance and developer productivity in the face of all evolving system architectures and capabilities. System designers have to create more exotic system architectures to increase system capability and performance, since processor clock speed has been flat for many years. Also, new and emerging applications target the processing of very large data sets or cover a large problem space (e.g., time and structure size), putting pressure on system designers to consider system architectures optimized for datacentric computing (large data/computation ratio). The complexity of system architectures and the need to handle large data sets have significantly increased the challenge of giving application developers effective and efficient software environments, frameworks, and languages. However, ARL's computing sciences group has the opportunity to create the tools needed to optimize performance and scale for mission-critical applications and user environments. Increasing the capability of the Army is dependent on the computing sciences group's development of technologies to continue scaling of capacity and performance of the Army's computing infrastructure and emerging applications.

Research related to domain-specific languages is an appropriate focus given the promise of improvements in productivity. Work is ongoing to create a new language (e.g., Liszt) for domain-specific parallel programming. The analysis of results did not include comparison with other graphics processing unit (GPU) languages, and the metric used to evaluate productivity (e.g., lines of code) was not sufficient. It was not clear if this work holds promise of transitioning to an ARL customer or to any outside agencies, given the lack of control of GPU architectures. It was also unclear whether work on datacentric, extreme-scale computing provides a viable, sustainable, or unique capability over existing task-oriented parallelism frameworks. Related work on adaptive fast multipole methods using task-oriented parallelism suffered from a lack of supporting performance data and insufficient analysis and articulation of scaling properties. Work related to the implementation of a Bayesian quantum game builds an experimental, computational, and theoretical framework for using quantum statistics to model aspects of cognition. While the approach is conceptually promising, a more detailed presentation and references to related work would be beneficial.

DATA-INTENSIVE SCIENCES

The goal of the data-intensive sciences research portfolio is to understand and exploit the fundamental aspects of large-scale, multidimensional data analytics. There are currently three areas of focus in data-intensive sciences research: the science of large data, computational mathematics for data analytics, and real-time data access and analytics. The first two of these research areas were part of the current review.

Accomplishments

Current accomplishments in this research portfolio include new model order reduction methods for partial differential equations (PDEs), cognitively steered exploration of solutions to PDEs at different resolution, efficient summarization and visualization of high-dimensional data sets, and concise characterization of spall damage in materials. ARL has a goal of leading research in the areas of explosive mechanisms and high strain rate and fracture. A new research effort has been prepared in computation of game strategies exploiting symbolic representation and in using a new neuromorphic computational architecture.

It is encouraging to see the focus in these important areas. The initial set of projects appears to be promising and is beginning to show good progress. Specifically, the work on developing a high-performance, sparse, nonnegative, least square solver advances the state of the art and leverages ARL's expertise in numerical analysis and HPC. Similarly, the work on neuromorphic computing represents a fresh and original approach.

The work related to model order reduction methods for large-scale simulation data is part of a larger collaboration with the Stanford University group on model order reduction. ARL is pioneering the parallelization of hyperreduction methods to bring greater computational efficiency in the simulation of PDE codes. The approach being implemented is novel and important. The researchers are well informed on the state-of-the-art approaches in this field, and appropriate equipment and numerical models have been selected. The availability of world-class HPC resources is a strong driver, and the collaboration with the Stanford University group is impressive. The work contains the appropriate mix of theory and computation. Additional work in deriving error estimates and bounds for the hyperreduction results would strengthen the impact of this work.

The new thrust in programming approaches for neuromorphic cognitive computing represents a novel and intriguing research program. The principal investigator has the appropriate background for this work and has demonstrated a good understanding of the fundamental research questions. The use of hand-coded basis functions is appropriate for the initial stages of investigation, but other alternatives could be considered that have a basis in coding theory—for example, the use of low-density parity check codes. This research thrust is at a preliminary stage, and it is too early to decide whether an accelerated resource track would result in a high-impact transfer.

A research effort related to large-scale network experimental data reduction has led to acceleration of processing time for measured network packet traces. The approach uses a standard relational database with a combination of custom query processing that includes map-reduce and data summarization and compression. Providing several new visualizations of network operation augments the approach. The work is of high value and is adequately funded. One possible extension of the work would be to advance the state of the art for visualization through the use of nonlinear manifold learning techniques and unsupervised explanation of system regimes to reveal anomalous phenomena.

The research portfolio includes a focus on large multiscale material modeling with a special emphasis on identification of damage modes. Molecular dynamics simulations have been used in conjunction with a sectioning data reduction approach to develop a new and elegantly simple hydrostatic criterion for spallation of crystalline materials. The new criterion was then used to visualize the stress state from the data set obtained for an impact simulation. The research provides a new characterization of spallation. Furthermore, the approach, using molecular scale simulation coupled with novel data characterization, is broadly applicable in related problems.

The work of the visual simulation laboratory is focused on the use of a visualization-based framework to allow users to steer a multiresolution PDE simulation. The principal contribution of this work is in the computational steering of a parallel algorithm, but it was not clear whether the innovation was in the parallelization approach or in the visual framework in which the simulation was performed.

Challenges and Opportunities

Currently there is no research roadmap that identifies specified projects and goals linking research efforts to the stated goals—the science of large data, computational mathematics for data analytics, and real-time data access and analytics. The portfolio of research is primarily focused in computational simulations on HPC platforms. The portfolio could be broadened considerably given ARL's varied and demanding real-world data intensive applications that go well beyond computational simulations. Some examples are big data analytics in the context of social networks, geographic information systems, and situation awareness (e.g., in the context of cybersecurity). There is an opportunity to take a leadership role in developing scalable numerical optimization methods and multiscale and linear algebra methods for state-of-the-art machine learning that are suitable across a wide range of architectures, including large HPC systems, tactical HPC, and mobile systems. Existing expertise and strengths in the areas of numerical analysis, scientific computing, and parallel computing need to be leveraged in this context.

The data sets of interest for Army applications are characterized by their complexity and high dimensionality, and computing constraints often dictate computations that are approximate or statistical in nature. The data-intensive sciences research could be strengthened by incorporating more rigorous problem formulations that take such constraints into account and that lead to results with theoretically grounded error bounds. The research would contribute to ARL focus on verification and validation in computational science and would also enhance visibility through improved quality of publications. Given that many applications will combine big data, HPC, and high-performance analytics, there is a tremendous opportunity for datacentric computing to impact the design of HPC systems and their operating environments.

ARL is a Department of Defense (DOD)-wide supplier of supercomputing capacity and networking. The state of the art has today shifted to an emphasis on data-rich computations. In many sciences, large, widely accessible databases—for example, protein databases and large language corpora—have played a fundamental role as engines for progress. Military-focused computations can benefit today from such an approach. For example, huge data sets comprising network data, textual interactions, and even audio logs are generated and archived by large training exercises. The collection, curation, and dissemination of such large military-focused data sets could be vital to the ARL research mission as well as future engineering and technology efforts throughout the DOD. This is a natural evolution for ARL. Serving these data could be over the same communication networks that ARL currently maintains. The data could be housed in the same supercomputer centers that ARL operates for the DOD. Ultimately, such a service would be far more valuable than just providing raw compute cycles.

It is important for ARL researchers to anticipate new technologies and how they could impact its research agenda. One example of a technological trend to monitor is the emerging disruptive revolution in memory technology. Akin to the effect that cheap high-volume, solid-state drives (SSDs) have had on the supercomputing landscape, a larger disruption is expected with the high-speed, large-volume nonvolatile memories that will be available in the near future. How this will affect architectures and especially algorithms and software design is unknown today. ARL could take a leadership role in understanding the impact in general and especially with regard to Army applications.

Similarly, ARL research could also consider a focus on the missing elements of a computational architecture that could provide battlefield information dominance architecture (IDA). ARL is contributing strongly to this goal in the front end, via advanced sensing and networking. For the middle layers of an IDA, where data are reduced, fused, correlated, analyzed, and reduced to actionable information, there is evidence that ARL is building leading capabilities and advancing the state of the art. However, it would be desirable for ARL to devote more attention to looking at the back end of the IDA, where information is delivered to the individual warfighter. An information chain is limited by its weakest link. Beyond human factors research, research into the optimal adaptation of new and emergent technologies required for architecting the back end is required. As an example, low-latency, high-fidelity virtual reality (VR) devices and rendering engines made possible by advances in computing and organic light-emitting diode (OLED) displays will reset fundamental user interface (UI) assumptions in a far more profound way than did two-dimensional (2D) graphical user interfaces (GUIs), mobile or touch. The implications of these devices for the back end of the IDA are equally profound. An opportunity exists for ARL to take a leadership role in understanding how advanced displays, visualization techniques, and algorithms can be used, beyond the current applications to training, to reach an integral part of the future battlefield.

PREDICTIVE SIMULATION SCIENCES

The research program in predictive simulation sciences reflects an appropriately broad understanding of the underlying science and of comparable R&D activities at other institutions and agencies. Many of the research projects include collaborations with academia, federal laboratories, and industrial partners, and a few already have transition plans in place to deploy the results of the research in appropriate national security settings. Most of the publications cited are of recent vintage, and many have academic or industrial collaborators. A review of the work shows a few gaps in broad understanding, largely explained by the nature of the work, which requires expertise in both computational sciences and in the application domain. This underscores the importance of collaborations in the work.

Numerical models are generally relevant to the work proposed. Many of the projects are currently compute-bound and are now exploring ways to more effectively utilize additional computational capabilities available via GPUs or other exascale technologies. Close collaboration with leading universities and federal laboratories actively working on exascale computational technologies needs to be encouraged in ARL's Computational Sciences efforts to ensure that state-of-the-art developments in these fields can be transferred to ARL's Computational Sciences R&D projects in a timely manner.

The research qualifications of the ARL staff are relevant to the technical challenges inherent in the R&D work. There are some indications that the cultural changes necessary to effect a transition to a campaign-based strategy for R&D initiatives are still in progress, but no substantial expertise gaps were observed in the predictive simulation sciences presentations and poster discussions.

The R&D efforts presented incorporated appropriate levels of theory, computation, and experiment. Experiment could use existing validation data to ensure that simulations are predictive, but some of the research utilized real-world laboratory results to steer or refine computational science predictions. For example, the meso- and microscale weather project utilized airborne weather sensors to improve microscale models in near real time. Additional effort in integrating theory, computation, and experiment via formal validation and verification (V&V) techniques would be a welcome addition to many of these projects.

Some exceptionally promising projects found in the Computational Sciences campaign R&D portfolio are listed separately below. Most projects showed evolutionary progress, but there are projects that may provide revolutionary benefits to the ARL mission.

Future outside-the-box, close collaborations between predictive simulation science R&D projects and information sciences efforts have the potential to create novel hybrid technologies from the fusion of these two technology arenas. Large-scale computational simulation and large-scale data analytics seem an especially appropriate fusion for ARL R&D investigations.

Accomplishments

Multiscale material modeling is a potentially game-changing computational technology for predictive simulation in the mechanical sciences. The work on multiscale simulations based on scale-bridging combines several important threads of cutting-edge research into a useful software product that has the potential to provide higher fidelity deterministic and nondeterministic forward simulations in fluid and solid mechanics. These multiscale simulations are essential for assessing vulnerability, lethality, and effectiveness of weapons and protection systems, and the current effort demonstrates the project's utility in theory and also in practical application to software commonly used by the DOD (e.g., Lawrence Livermore National Laboratory's ALE3D production software tool,[3] used for high-explosive weapons and target simulations). In addition to this research being of high value for predictive forward analysis, its multiscale sampling subsystem can lead to vastly improved performance for inverse analyses and quantification of margins of uncertainty (QMU) estimations. The latter, in particular, are often computationally expensive for application to large-scale problems. The principal technical challenges for this work lie in the availability of HPC resources, because the smaller scale simulation components can consume prodigious numbers of computational cycles. The research group has worked to overcome this

[3] ALE3D is a 2D and 3D multiphysics numerical simulation software tool using arbitrary Lagrangian-Eulerian (ALE) techniques.

challenge by deploying an optimal sampling scheme to reduce computational burdens on the smaller scale simulation components and by utilizing software broker components to aid in the load-balancing required for optimal use of HPC resources.

An important focus of the ARL research related to developing predictive capabilities for use on low-power computer platforms representative of what would be available to Army personnel in the field. Research on synchronous time-driven simulation for HPC accelerators focused on the simulation of large ensembles of random events for tactical cybersecurity applications. The research approach was to simulate the continuous real-world setting by utilizing a finite-state approximation that would converge to the continuous case as time step size decreased. Synchronization of events is problematic, with longer time intervals and smaller time step size, causing computational costs to increase significantly. The focus is to seek statistical convergence for the larger time steps. Validation of results on larger and more realistic data sets would be warranted.

In the area of materials modeling, research on scalable algorithms for simulating dislocations in microstructured crystals focuses on fusion of discrete dislocation theory coupled with continuum finite-element approximation, toward the capture of inelastic effects in polycrystalline and heterogeneous material structures. The research is promising and has broad applicability for material and structural failure simulations. Each element of this algorithmic fusion has strengths and limitations, but the coupling of these two techniques promises to remedy the weaknesses of each while preserving their considerable strengths. One of the most difficult technical challenges for this work is the effective load balancing of HPC resources. In computational physics, localization phenomena are not handled effectively through static load-balancing techniques, and the research could benefit from consideration of new developments in adaptive parallel load-balancing techniques. Because a similar challenge arises when transitioning from current computing architectures to emerging pervasively threaded hardware such as GPUs, due attention to research and development efforts in academia and other federal research institutions efforts is warranted.

The research on computational drug discovery focuses on developing efficient techniques for discovering which readily available molecules may be suitable for synthesizing drugs for use against pathogens that an adversary might deploy as biological weapons. This effort leverages a variety of university collaborators and is helped by access to ARL HPC resources such as the Excalibur supercomputer. The broad impact of the success of this research is significant for national security and in public health settings. Considerations relevant to technical limitations of this work include whether currently available libraries contain potential drug candidates, whether the identified compounds are optimal in effectiveness, and whether limiting the scope of these searches to small compounds is the best path for drug discovery.

Challenges and Opportunities

Predictive simulation sciences are increasingly important in DOD R&D venues. A broader understanding of the strengths and weaknesses of modeling and simulation techniques and of their impact on Army R&D practices is essential to help steer ARL research activities toward full realization of future simulation trends.

A challenge that cuts across the predictive simulation sciences portfolio is the lack of cutting-edge R&D efforts in validation, verification, and uncertainty quantification. V&V are indeed essential for all simulation applications, and failure to attend to these basic measures puts all of ARL's computational effort at risk of being of little value in the decision-making process. It is therefore important to raise V&V and related research in QMU as an important intellectual thrust in the ARL campaigns.

Many of the presentations and posters referred to an interest in utilizing emerging hybrid (i.e., thread-scalable with distributed memory, commonly termed MPI+X) computational architectures. The researchers at ARL who work in these intellectual venues can learn much by leveraging the considerable ongoing R&D efforts in advanced programming models for exascale computing that are occurring in leading universities and federal laboratories. In addition to these promising HPC developments, many of the computing-at-the-tactical-edge projects could also benefit from closely following these ongoing R&D efforts. One promising side benefit of exascale HPC research is the development of lower-power petascale and terascale resources that would be appropriate for this class of tactical computing.

The use of computational fluid dynamics (CFD) tools for the aerodynamic analysis and prediction of flight behavior of Army ballistic weapons parallels similar work in academic, industry, and federal laboratory settings. The coupled aerostructural simulation tools provide useful preliminary analyses at low Mach numbers. A serious limitation of the ongoing work is the assumption of rigid-body response for the projectile. While such an assumption would greatly simplify the computation, its validity has to be questioned for slender projectiles. Furthermore, while the assumption of rigid-body dynamics would hold for conventional artillery projectiles, finned structures are often sufficiently flexible and would impugn the accuracy of the predictions. Additional effort needs to be directed at extending the methodology for larger scale problems, higher resolution analyses, and optimizing the computational codes to take full advantage of emerging computational architectures.

OVERALL QUALITY OF THE WORK

There has been a significant improvement in quality of the research over the past 3 years, as indicated by the methodology pursued, the quality of the personnel assembled, and the infrastructure capabilities that have been developed over this period. The majority of the research presented (in both scheduled presentations and in the posters) was of comparable quality to that conducted in leading research universities or in federal and industrial laboratories. There were some projects where researchers clearly demonstrated a deeper knowledge of existing theory, of prior research in the field, and of state-of-the-art technology in relevant areas. Other projects provided a clear problem statement, including the articulation of a specific strategic direction for the research. It would be important to mentor researchers so that these best practices are embraced more broadly across all research groups. In each R&D effort, due emphasis was given to publication in relevant journals or proceedings, including (but not limited to) the open literature. Collaborations with university researchers via the ARL open campus initiative would provide opportunities for ARL staff to gain experience in the professional value of a continuous publication record.

Over the next decade, big data, complex analytics, and modeling and simulation will all come together in critical ARL applications and environments. This is evident from the materials provided by ARL in the area of computing sciences, data-intensive sciences, and predictive simulation sciences. Many of these applications will execute in a battlefield environment, where security and resilience will be of paramount importance.

To gain transformational improvements in power, performance, and resilience, the entire stack—hardware, software, and applications—needs to be codesigned. ARL has a tremendous opportunity to be a leader, especially in battlefield environments. To accomplish this, ARL would benefit from tasking an enhanced team of technical leaders to ensure that the subareas are increasingly engaged in real codesign.

The computational science campaign is an inherently interdisciplinary enterprise, providing enabling technologies that cut across all of the ARL R&D campaigns. The capabilities of the Computational Sciences campaign support virtually the entire spectrum of ARL R&D efforts. A broad swath of the projects could benefit from a better understanding of the theoretical and mathematical foundation that governs these problems. An increased contact and collaboration with researchers strong in theory—for example, from mathematics and computer science as well as the foundational science domains—would help achieve this. In particular, adding more computer scientists to the computational sciences research effort would encourage a more rigorous approach and would help advance the research agenda.

The projects reviewed comprised a mix of long-range basic science research and short-range research addressing tactical challenges and opportunities. The short-range research work is important, given the many challenges faced by the Army in its fields of engagement; ARL is developing innovative solutions to these high-priority tactical problems. It is also critically important that ARL continue to bring greater emphasis in its research portfolio to long-range strategic research in advancing fundamental knowledge in the underlying science. Strong relationships with key external entities have proven to be valuable across the breadth and depth of ARL research activities. This is an important positive development for ARL, and engagement with additional leading research institutions would further strengthen the awareness and capabilities of ARL researchers in important strategic areas.

6

Sciences for Maneuver

INTRODUCTION

The Panel on Mechanical Science and Engineering at the Army Research Laboratory conducted its review of ARL's vehicle intelligence (VI) programs—human–machine interaction, intelligence and control, and perception—at Adelphi, Maryland, on July 8-10, 2015. This chapter evaluates that work, recognizing that it represents only a portion of ARL's overall Sciences for Maneuver campaign.

HUMAN–MACHINE INTERACTION

The human–machine interaction (HMI) research at ARL reviewed by ARLTAB in 2015 was of top quality. The researchers presented studies with rigorous design, evaluation, and analysis, and all used appropriate metrics in their evaluations. They have a thorough understanding of related research and have built collaborations with others at ARL across campaigns and have connected with the right faculty and laboratories in academia through the Robotics Collaborative Technology Alliance (RCTA). The research team has benefitted from an expansion in the postdoctoral program and early-career hiring, which has grown the capabilities and collaborations of the team.

Each individual project defines its own appropriate algorithmic or experimental metrics, but the researchers did not uniformly communicate the higher-level success criteria—that is, what makes their project successful in the context of the larger HMI effort. Such metrics need to be defined at a programmatic level and also be communicated well to the research team; some researchers could not identify the larger goals of the program.

The science in the HMI program is technically sound, and the work is published in top journals, including *Human Factors*. The work needs to have broad exposure, which is achieved through presentations at conferences and meetings. The utility of the work appears to be recognized within ARL—for example, elements from the tactile feedback project will be incorporated into the next warrior experiment.

The use of soldiers in experiments is commended. The move toward more realistic warfighting vignettes and more real-life simulations that instantiate threats and hostile elements would help to establish the value of a technology in achieving a desired capability.

Some researchers were embedded directly with the soldiers for a few weeks, and their experiences directly led to the formulation of research topics. This type of exchange is of great value for the research program. Also, some researchers are permanently stationed at U.S. Army installations, where they have regular contact with active-duty soldiers and are able to recruit soldiers as participants in research.

The research presented will be shifting from one-person/one-robot studies to multiperson/multirobot scenarios. This shift in focus is appropriate as the Army moves to the use of more complex teaming architectures. This new direction will bring a need for additional research in trust and in HMI, raising questions about how one verifies software and validates systems to build confidence in the joint human–machine system, considering complex, emergent behaviors. This use case also highlights the importance of providing the right information at the right time to the humans and to the robots, identified as a thrust of the HMI program.

Human–Robot Trust

In recognition of the changing role of people in a human–robot system, this topic investigates the relationship between trust and the design of vehicle autonomy. The goal is to look at design factors proactively in simulation concurrently with technology development, rather than retroactively; the design of human–robot interaction during early system development is important in order to create a robot system that will be used effectively and as intended. This project is commendable in that it is conducting evaluations and experimentation concurrently based on the applied robotics for installation and base operations system development at the U.S. Army Tank Automotive Research, Development and Engineering Center (TARDEC). The simulation models are based on real data from the system under development at TARDEC.

The milestones are clearly defined, appropriate, and feasible. This 6.2-funded work (early applied research) may lead to shorter-term application than the 6.1-funded work (basic research) described for most of the other HMI projects, though both may have longer-term implications. Trying to visualize what will be available in the way of automated vehicles in the longer term is challenging. This work seems to be a good stepping-stone to future interactions of humans with autonomous vehicles. Additionally, the close interaction with TARDEC on this project shows that the research is targeting a current Army need.

The researchers turned up more than 300 definitions of the simple-sounding word *trust*, a fundamental variable when working with people. They explained convincingly that trust is a critical factor to be considered when studying the interactions between humans and autonomous vehicles.

A three-factor model for trust, developed for the RCTA, served as the foundation of the researcher's Ph.D. thesis on human–robot trust. The effort takes an analytic and empirical approach, deconstructing the factors involved in trust, into three categories: human, environmental, and robotic. One known factor that influences trust is system reliability. The effects of many other factors, including stress, workload, personality, trust propensity, and coping style, are still unknown. Quantifying this space is the basis and motivation for the project.

The equipment and tools that are being used are appropriate for this early investigation. The team is in collaboration with TARDEC as well as collaboration across ARL directorates, using the Control of Autonomous Robotic Vehicle Experiments (CARVE) and the Robotic Interactive Visualization Toolbox (RIVET) simulation tools. The trust theory was developed through the RCTA. The autonomous vehicle is under development by TARDEC, and current work uses computer-based simulation. The simulation is low fidelity—a reasonable first step for an early investigation. The simulation is based on data from the real system at TARDEC, and the simulation is updated as the actual system is developed further. Improvements in the simulation's impact could be achieved with some affordable upgrades to the current desktop solution: for example, with wrap-around hardware.

There is some question about the effect of perception of risk on the experimental results, given the use of a simulated environment instead of a real one. Prior research in HMI has shown that the perception of risk, or lack thereof, influences the behavior of participants in studies with human subjects.

The work has been published in top journals, including *Human Factors*. Broad exposure of ARL's work is necessary and is achieved through presentations at conferences and meetings.

The findings on how different people trust an autonomous system illustrate the complexity of the challenges faced by the new technologies. The project also demonstrates the effectiveness of the RCTA mechanism for conducting Army-relevant research in academic environments and the pathways that are created to hire researchers into ARL.

Multimodal Displays for Human–Robot Interaction

The motivation for the project is well-founded: Indeed, a soldier's visual modality is overloaded. Additionally, constraints on auditory communication may pose a threat to soldier security and mission success. This project investigates the use of other modalities for communication with the soldier, including tactile and gesture. The project goal is to identify interaction modes (single or in combination) that are most effective for soldier-robot communication. The focus is on achieving external validity by synthesizing and translating theory-based predictions, meta-analysis, and experiments to determine whether results generalize to the field.

The project is commendable in that it conducted experiments with real soldiers in a realistic environment and context. The principal investigator is an outstanding practical researcher, and the effort is a clear success. The work was disseminated well at conferences and meetings; journal publications would be very valuable to the research community.

The experiments conducted would have been improved if they had explicitly included in the scenarios a robot as a critical element to provide meaningful information to the soldier, rather than focusing on the communication medium itself. Additionally, the information passed to the tactile belt could have been provided as easily from a human as from a robot, and so other scenarios involving human–human communication using the tactile belt could be performed.

The comparison of text messages, which remain on the screen, versus one-time tactile input, is questionable. It would be reasonable to allow the soldier to re-trigger the signal, which would provide a better comparison of the two methods in terms of the length of time for which the information is available.

Understanding how the technology supports the soldier in abnormal conditions is important, because there may be trade-offs in task performance and situation awareness. Additional insight into the effect of the tactile vest on the soldier's behavior is expected if disruptive scenarios are incorporated into the experiments.

Overall, the project has developed a piece of technology that has the potential to improve soldier performance, particularly in terms of safely passing information in combat situations.

Human-Autonomy Sensor Fusion for Rapid Object Detection

The project conducts research on models of fusion between computer vision and neurophysiological responses. Recognition systems do not integrate humans explicitly; this project looks at an alternative architecture in which humans are peers to share the information with autonomous systems. The approach fuses human neurophysiological response to enable rapid real-time target detection. The objective of the work is to evaluate the hypothesis that joint human–autonomous system target recognition surpasses the target recognition capability of the autonomous system alone.

The project defined appropriate algorithmic and experimental metrics. The larger milestones and success criteria were less clear, although the project is part of a larger project with 40 researchers.

The project addresses challenging technical issues; neural classifiers are not yet fully understood. The push-button response (part of the human target recognition component) lags behind computer vision, and the neurophysiological recognition lag depends on human conditions. The goal is to produce overall better accuracy and efficiency with a human sensor and to demonstrate a path forward to relevant target tracking and engagement scenarios.

At this preliminary point, the results support the hypothesis that the human component improves object detection, but it is unclear whether the improvements are significant from a practical standpoint. While the research is young and the delta improvement is small in terms of making progress to a fielded, capable system, the payoff could be significant. One manuscript has been submitted for a journal publication and another was accepted and presented at the International Conference on Intelligent Robots and Systems 2015 conference. This project is currently limited to object detection, but it could be expanded to explore similar approaches for object classification.

INTELLIGENCE AND CONTROL

The intelligence and control (I&C) research theme is focused on enabling the teaming of autonomous systems with soldiers. The overarching goal is to develop an intelligent autonomous system of robots that can perform effectively in an uncertain environment by optimally using limited resources. The topics investigated in this research area are aimed at generating the technologies needed to meet the challenges posed by future military operations that could occur in military-relevant missions and in military-relevant environments. To meet the goals of the research theme, six research programs have been initiated:

- *Control* focuses on the low-level processes and closely couples sensing and action (actuation) of individual elements of the vehicle;
- *Planning and guidance* focus on the mid-level, vehicle-centric layer of the control architecture, with immediate path-planning objectives;
- *Abstract reasoning* focuses on the cognitive element of the architecture, with a special emphasis on human–robot teaming occurring at this level of the architecture;
- *Teaming and coordination* focus on the interaction of multiple homogeneous or heterogeneous entities to achieve a specified goal, including coordination and communication;
- *Behaviors* focus on actions of a vehicle built from a hierarchy of elemental tasks and capabilities to achieve one or more specified goals; and
- *Learning and adaptation* focus on employing key cognitive features of an intelligent vehicle to enable control of its actions and/or behavior to successfully achieve goals in dynamic and/or unrecognizable scenarios and environments.

Projects in the teaming and coordination and learning and adaptation project areas were not presented for review.

The focus of the I&C theme is developing software and algorithms that enable the vehicle to approach a higher level of cognition, enabling the teaming of autonomous systems and soldiers. The I&C theme has tight couplings with the RCTA program and the Micro Autonomous Systems Technologies (MAST) Collaborative Technology Alliance program, with some specific ARL focuses. The higher level cognition that the I&C theme focuses on is aimed at enabling autonomous assets to work in environments of relevance to the military—caves, subterranean spaces, jungles, undercanopies, megacities, and urban environments. Specific I&C research topics are targeted to leveraging state-of-the-art approaches and expanding them to address the uniqueness of the military environment and missions. To identify specific research projects that address the theme, the Army needs, which emphasize high-level capabilities, are deconstructed into specific project areas. The following projects were presented for review.

Abstract Reasoning: Spatial Reasoning in Uncertain Conditions

The focus of this research was on determining how to characterize information collected from field data represented as the collection of uncertain (or incomplete) information. The primary issues this research is trying to resolve are how to build an initial knowledge base and how to expand it autonomously when needed. The state of the art in this domain has been achieved by Microsoft (Bing), Google (Knowledge Graph), and IBM (Watson). The primary limitation of current approaches is that they are trying to extract all information prior to deployment (versus at query time). Overall, the principal investigator (PI) demonstrated broad understanding of the field and possesses the skills necessary to perform this research. The PI employs adequate tools and methods for this research and has several papers published, including in well-respected venues such as the Association for the Advancement of Artificial Intelligence.

Opportunities

This is an analytical study that is still a work in progress. It was not completely linked to specific military-relevant applications and did not involve any real-world experiments. Issues that might impact the success of the work include how to determine whether outcomes are reliable and correct; how to get algorithms and operations to run on the robot processor (along with the other processing components); and understanding key elements of the development path necessary to get to that point. Only limited results were presented. Estimates of the algorithm accuracy were not provided; more effort is required to provide evidence of feasibility. Experiments would also be helpful. Growing the PI's team might help in addressing these challenges.

Planning and Guidance: Autonomous Mobile Robot Exploration with an Information-Gain Metric

This research applied an information-based approach to the mobile robot exploration problem, based on probabilistic and entropy concepts. Effective robot exploration is important for intelligence, surveillance, and reconnaissance efforts. It was shown that the developed algorithm could be used to more effectively detect improvised explosive devices (IEDs). Probabilities or weighted probabilities could also be used to reflect prior information. As such, the problem being addressed is particularly relevant to the mission of enhancing the warfighter's capabilities via intelligent robotic teams. The algorithm presented was compared to a baseline (non-information based) algorithm. The PI was well aware of the state of the art in this domain and is well qualified to pursue these important issues. The PI's collaborative efforts, which led to a number of publications, are excellent.

Opportunities

While the information-based entropy algorithm was shown to outperform the baseline (greedy) algorithm, work needs to focus on describing the pros and cons of each algorithm, comparing the algorithms presented to other algorithms considered in the literature, examining the effect of local topology on the algorithm's temporal and spatial performance, examining the effect of a priori probabilities and weightings on algorithm performance, its reflection of real-world concerns (e.g., uncertain communications, terminal hazards), and extending the work to include multiple robots.

Behaviors: Scene Consistent Visual Saliency

This research dealt with how to better define visual saliency in a dynamic environment. The project was first envisioned because ARL researchers were examining images from a moving robot and realized that present definitions of saliency did not give consistent metrics for saliency—for any given feature—as the moving camera passed a feature and dynamically changed its field of view. The goal was to define visual saliency in a manner that was independent of the view in a general way. As a step toward this, the research considered images obtained from a fixed camera as it panned, tilted, and zoomed to give different views. This was the first step toward defining a more general definition for a camera with a moving base. The approach began with a bottom-up method of determining saliency, in which one looks for whatever jumps out of the background. Later, this approach was merged with the top-down approach of looking for specific objects. Using a consistency metric, it was realized that consistency for the saliency of a given feature in the surroundings can be obtained only if various images (from different views) are merged into a composite mosaic that casts the set of pixels as a unified field of view. From this concept came a consistent definition of saliency of the visual image. The project is well thought out and has demonstrated that the new definition of saliency can give consistent answers for saliency over a range of camera angles and zoom parameters. The scientific quality of the work is excellent, and the researchers are qualified to do the work. The researchers understand the positioning of this work with respect to other work in the field and have published in appropriate journals and conference proceedings.

Opportunities

The approach represents a first step in addressing a larger problem. It does not work well when the focus is changing, so additional improvements in methodology are needed. This work could also be improved by use of a depth parameter via the stereoscopic effect (once the base is allowed to move). Researchers could then better understand how the work connects with other human–machine interaction work in ARL. The researchers need to identify how the work addresses an important need—that is, why is it necessary to measure saliency consistently and how good does saliency consistency need to be for images to be useful for the Army mission? An additional opportunity could include integrating eye-tracking devices to try to determine what a solider thinks is salient, inferring what the solider is trying to convey based on eye-gaze, and providing that information to the robot or informing the robot planning algorithms.

Control: Autonomous Self-Righting for a Generic Robot with Dynamic Maneuvers

In this research, the problem of self-righting a fallen robot was examined. This situation occurred when the robot fell despite all that had been done to prevent toppling, so the problem is an important one. A potential energy method was used to address the problem. The method is based on an approximation approach that was shown to be potentially useful for robot design, minimizing the number of states from which acceptable recovery is not feasible. The PI has provided metrics and validations to evaluate the accuracy of the approximation. The associated publications of the PI are also good, and a related patent has been filed.

Opportunities

The work could examine how well the energy approach taken by ARL works in practice and a more precise (albeit computationally more burdensome) measure of acceptable recovery (e.g., a measure that includes spatial/temporal constraints). Although the focus is on righting the robot from a static overturned position, a better understanding of the dynamics would come from a more general examination of a broader set of related issues, including stabilizing and destabilizing factors before overturn and the ability to right itself while falling and rolling before coming to rest.

Behaviors: Autonomous Navigation Analysis

This project had the objective of evaluating the performance of three different Army robots navigating from a fixed starting point to a number of predetermined global positioning system way points in an outdoor environment. The evaluation was at the system level—that is, the overall performance of the robots, including their sensors, controllers, and traction/power train systems, were included. The project was designed to expand on research that had been conducted indoors by Microsoft and apply it to the more Army-relevant situation occurring outdoors, in unfamiliar surroundings and with various obstacles that cause significant difficulties for the robots. The experiment was conducted at the Aberdeen Proving Ground facility, and the errors, difficulties, time, and success rates of the robots were evaluated. Further experiments are planned over the next year to enrich the comparison of system performances. The referenced work done by Microsoft was an appropriate starting point. The researchers were qualified to perform this research and they conducted the research as a team and used state-of-the-art facilities to conduct their analyses.

Opportunities

This project was not a sophisticated research effort, but it was a good start in evaluating the performance of a system. Future work could focus on developing methods to predict system-level failures and understanding what causes them. It could conduct more detailed experimentation and analysis to better grasp the effect of the various system components on the robot's performance.

Abstract Reasoning: Robotic Dream—Episodic Memory Consolidation and Revision

This research focused on the development of a memory system that allowed a robot to retain knowledge from previous experiences. There was some uncertainty about how long this particular project has been pursued. It was listed as a 2004-2020 effort, but it was unclear whether the project was ending or continuing through 2020. There was mention of a path forward, including transition to CTA partners, although this was not defined. It would be helpful if the objectives included more metrics-oriented information and were more clearly set forth.

Storing and processing only exciting events and precursors is an elegant and logical contribution, and there is also a process to code the events into a set of simple low-memory symbols. Memory access time savings also seem intuitive, and they are dramatic.

One PI indicated that no similar research was being done elsewhere, but this was belied by the numerous references cited in a recent journal paper of the PI, which had a sufficient scholarly section of related research. The PIs could continue to strive to publish work in mainstream journals in the field, such as those of the Association for Computing Machinery or the Institute of Electrical and Electronics Engineers.

Opportunities

Since this research has been in existence for a while, there needs to be a stronger linkage, at this point, to military-relevant scenarios.

Overall Intelligence and Control Accomplishments

The I&C team is developing and supporting a suite of forward-looking technologies, algorithms, tools, collaborations—all of which are important for the warfighter effort. ARL has brought together a number of different viewpoints and different skills from different disciplines to start thinking about these problems and tackling them in innovative ways. Collaboration with universities and other agencies and industry has been active and of high value, and ARL has invested in the research through the people it has hired. In general, PIs recognize related research and methods and leverage them to push forward improvements to address the uniqueness of military-relevant problems. While unifying demonstrations, milestones, objectives, and capabilities could better motivate the specifics being developed and elucidate how they will be integrated, the developments being pursued are for the most part essential.

Overall I&C Challenges and Opportunities

The I&C team needs to move on to the next step—bringing the different research projects together synergistically to successfully address broader problems faced by the Army. The I&C team has a good start on this but needs to formalize the process for integrating and knitting together the various research pieces necessary to transition to the next step. Developing quantitative milestones for gauging progress and performance would help in this endeavor. By using milestones, research projects can be redirected where appropriate to better achieve the overall mission goals. It would also be good to see the process whereby desired future capabilities or goals are broken down into a sequence of achievable (realistic) short-term capabilities and goals.

There also needs to be a focus on the big picture: an understanding of where ARL is going and how the projects fit into the bigger picture. To quantify general progress and application-specific performance, more specific connections to the literature could be made in the course of baselining or benchmarking. All projects could make sure to reference the related literature (baselines, metrics, or benchmarks) and understand how they fit and compare. Through mentoring, guidance, and appropriate milestones, quicker progress might also be made toward integrating projects and more effectively contributing to solutions to important problems. Mentoring can come from both internal and external experts. ARL's open campus concept can be used to bring in external experts.

Challenges to I&C research focus on determining (1) how to deal with trade-offs in order to determine which research to continue; (2) how to effectively integrate outcomes from the individual projects and develop a methodology for this integration; (3) how to share the overarching systems perspective and relay that vision to the research projects; (4) how to identify and validate the process of getting from high-level capability or needs to research tasks (and evaluation or benchmarking of whether they comply with needs); (5) how to appropriately delineate between basic and early applied work; (6) how to balance and integrate top-down and bottom-up-driven processes; (7) how to compare the research against the standard baseline data sets (when available) and how to identify standard metrics for validating whether the research has achieved the stated goals of the proposed work; and (8) how to transition the research from work on simplified problems that facilitate analysis to actual scenarios that are germane to the Army's unique problems and characteristics.

PERCEPTION

The ARL aspires to be the nation's premier laboratory for land forces. The perception group at ARL has made significant headway toward achievement of this goal. It has succeeded in establishing relationships with top university laboratories, has attracted some outstanding personnel, especially new Ph.D.'s, and is undertaking interesting and relevant work on a par with academic departments. The ARL perception group is well aware of the current trends in the research community through participation in top, highly competitive conferences in the field. ARL's open campus policy appears to be making a positive difference in the quality of the work.

The perception group did not articulate clearly the context within which it works and did not clearly differentiate its approach from the approaches in other areas. Research work on robotics perception needs to be linked to the power needed for the robot or the materials of which the robot is constructed. A systems approach is needed here. Therefore, based on the material presented, the following were inferred:

- The perception group, for the purposes of this evaluation, works in the context of three scenarios:
  — Microautonomous systems and technology (MAST), where soldiers use microrobots to explore;
  — Robotics collaborative technology alliance (RCTA), where soldiers use robot/human teams to penetrate the built environment; and
  — Applied robotics for installations and base operations, where robots perform functions on bases, relieving the warfighters of these functions.
- Most of the perception group's efforts are basic research in one of the three scenarios. The goal of each is as follows: Within the next 5 years, perform relevant basic science; 5 to 10 years from now, inspire concrete modules for the three integrated scenarios; and 10 to 15 years from now, apply these modules to support integrated experiments, which will subsequently enter the Army Research, Development and Engineering Center as processes to be matured by 2040.

The perception research was assessed according to its achievement of the above-inferred goals.

Autonomous Squad Member

This project attempts to detect changes in the tactical situation by observing the motion of individual soldiers. It is an interesting and important problem as the Army integrates robots into small unit operations. It was not made clear whether there is a roadmap from the broad concept to achievable steps in that direction. Is it going to be practically feasible to deploy a robot with sufficient capabilities in the next 10-15 years? Will the robot participate beyond being a team member? In 2040, a robot may have unique capabilities—will it then be a more active participant in activities?

Data-Driven Learning and Semantic Perception

The core of this work is using video analysis to categorize the actions a human is performing using machine learning with a hierarchy of action templates. This is good, focused work using state-of-the-art methods. Like similar methods, there are still questions about its broader applicability. It would be informative to learn how this work might relate to or affect other projects in the group.

Efficient Discovery and Labeling of Environments for Visual Classification and Autonomous Navigation

This project is also using machine learning methods to examine video data. In this case, the intent is to segment the scene into regions such as trafficable areas, vegetation, buildings, and sky. This is a good combination of theory and practical application and has great potential. The work could become a framework for developing and testing other new ideas and scenarios.

Dynamic Belief Fusion

Dempster-Shafer theory is a well-known framework for reasoning about uncertain events when, because the categories might overlap, the sum of probabilities need not add up to one. The method introduced here updates Dempster-Shafer for object detection. The results indicate that the new method outperforms existing methods, but the theoretical basis has not yet been fully explored.

Immersive Display of Robot Lidar Imagery

ARL has its own design for a lidar that has excellent performance, generating 256 × 128 pixel depth images. This project takes that three-dimensional (3D) data and displays it on an Oculus Rift head-mounted display for visualization. The project is building the tools needed to enable future research efforts.

Real-Time Optical Flow

The basis of optical flow—measuring the apparent motion of a scene as the observer or the object moves—has been established for many decades. Typical optical flow techniques break down with large changes in illumination (e.g., the sun going behind a cloud) or with cluttered scenes (e.g., trees blowing in the wind). The work shown here demonstrates a new approach, which is much less sensitive to the absolute brightness of the scene and is capable of differentiating the optical flow from humans moving in the scene from the flow caused by vegetation. While the parts of the algorithm are not novel, the combination of these subunits shows promise.

Overall Perception Accomplishments

The perception group presented a broad spectrum of projects, including understanding group behavior, perception for mapping and navigation, and basic research on dimensional reduction and clustering. Many of these projects are of high quality and are informed by the goals and needs of today's Army. The projects are well defined, and the researchers are aware of the state-of-the-art of computer vision. The group actively participates in important international conferences, which guarantees their awareness of the current and relevant activities in computer vision. Most of the work focuses on specific scenarios relevant to the Army. While it may not be as broad or groundbreaking as the best university research, the work is appropriate to the ARL context.

Through the MAST and RCTA collaborations, the perception group has access to many of the best computer vision researchers in the country, including those at University of Illinois; University of California, Berkeley; University of Southern California; John Hopkins University; and Carnegie Mellon University. Although these collaborative projects at the universities were not within the scope of this review, it seemed clear that they are a good chance to enhance the visibility and quality of the science at ARL. These collaborations need to be exploited to continue to strengthen the group.

The facilities, equipment, and approaches are well-targeted at the group's goals. The laboratories appear to have created a good computing and experimental environment, and the test site at Fort Indian Town Gap provide realistic scenarios for testing against the three scenarios.

The researchers seemed to work smoothly together, with encouragement from their management to cross organizational boundaries both within ARL and with other national laboratories. At the same time, it was not apparent what mechanisms exist to encourage sharing information; a regular seminar series might be a good addition.

While the quality of the work overall is very good, there was no single project that stood out as especially promising and ready for accelerated deployment. The closest is the work on weakly supervised segmentation for mobility. This project is significant for several reasons: an interesting vision/science result was published at a major conference; it is an integrated end-to-end project that demonstrates the value of the research; and it is an external collaboration with a university. These are all indicators of the project's scientific value and intrinsic contributions. The more projects that exhibit those characteristics, the stronger the perception effort will be.

It would have been helpful to present, in a concise form, a list of publications, awards, and other data that would help to convey the recognized accomplishments of the group.

Overall Perception Challenges and Opportunities

Perception is a rapidly evolving area. The tool sets, the approaches, and the benchmarks on performance change yearly (sometimes monthly). It is also an area in which it is highly competitive to hire, placing a premium on providing the best resources, colleagues, and opportunities to attract the best people.

The ARL has done a very good job of building a strong perception group and giving them the opportunity to perform very credible single-investigator basic research. To move to the next level, ARL needs to think about a few audacious challenges that go beyond the extant state of the art—so-called grand challenges. These challenges would provide an exciting context for the group and would provide a point of focus for collaborative efforts. This is not to say that the work might not continue to be basic research. Semantic labeling of scenes, for example, would contribute both to the various integrated scenarios and to the international perception community.

More domain-specific challenges for teams, such as off-road mobility, would speak to the broader ARL mission. There are many other possibilities, but it is important for the perception group to aspire to one or more audacious projects that speak to Army needs.

Another opportunity would be to pursue some common platform/sandbox concepts that could be built upon. For example, the project related to weakly supervised segmentation deployed on a robot could be driven in a wide variety of directions. Its current application for driving is already interesting, but perhaps that could be expanded to become a platform for testing other segmentation methods (e.g., motion-based segmentation) and human body tracking for teaming. Again, this would become a point of cohesion for the group.

Most of the work presented focused on relatively traditional RGB vision.[1] However, there is no reason to limit the activities to vision. It may be relevant to consider multispectral sensing, range sensing, and contact sensors, such as temperature, force, and pressure.

OVERALL QUALITY OF THE WORK

In each of the three pillars of the Vehicle Intelligence (VI) program—intelligence and control, perception, and human–machine interaction—the research quality was generally high. Research results are published in high-quality journals. Collaboration with other government agencies, industry, and universities continues to yield positive benefit. Internal personnel advancement, including hiring new, well-qualified Ph.D. researchers, strengthens the capability of the Sciences for Maneuver VI research and development program.

[1]RGB is an additive color model in which red, green, and blue light are mixed in various ways to reproduce a broad array of colors.

Each of the three pillars of the VI program has demonstrated significant progress in advancing its research and development objectives to support the warfighter in increasingly complex environments. The research and development activities in each pillar were consistent with its defined objectives. Opportunities in multiperson/multirobot scenario simulation, teaming of autonomous systems with soldiers in uncertain environments, multispectral sensing, range sensing, contact sensing, and immersive display of robot lidar imagery may allow ARL to take the lead in this research and offer greater benefit to the soldier.

The I&C pillar employs innovative approaches in developing and supporting advanced technologies, algorithms, and tools in support of the warfighter effort. There are high-value collaborations with top universities, industry, and other government agencies. This pillar invests in advancing the effectiveness and efficiency of its research personnel.

The perception pillar benefits from high-quality collaborations with top universities that enable successful hiring of outstanding personnel at the Ph.D. level. Current trends and research vectors were observed. Research personnel participate in highly competitive technical conferences and publish in top research journals.

The human–machine interaction pillar's research and development program is of high quality, based on rigorous design and appropriate metrics. It benefits from a substantial increase in external and internal collaborations. Through early retirements and expansion of the postdoctoral program, qualified Ph.D. personnel have been hired.

The VI research and development program is correctly constituted and resourced with workforce and facilities. In general, the VI team demonstrates good awareness of the scope and direction of research and development in each of the pillars. Cognizance of related activities in industry, government, and international research and development enable meaningful goal setting and tactical adjustments in specific program advancements.

Within VI research and development programs, research quality is generally of high quality. Based on rigorous design, useful evaluation and analysis, appropriate metrics, thorough understanding of related research, workforce interaction at critical open conferences, and publishing VI investigations in top journals, VI is well positioned to maintain and improve the quality of its research products.

Recently hired researchers within VI appear to be well qualified to conduct leading research and development in VI. These new additions to the VI workforce have been educated and trained by leading faculty in the three pillars at top-ranked U.S. academic institutions. At ARL new personnel are exposed to effective mentoring. The VI principal investigators are well prepared and energetic.

VI collaborations with U.S. industry, government, and academe appear to be extensive, very effective, and enabling in advancing the VI research and development mission. These collaborations are important components driving VI awareness, leading to the establishment of meaningful goal setting and tactical program adjustments. Similarly, the collaborations feed the energy of the VI principal investigators.

Inclusion of U.S. soldiers in VI field experiments is commendable. Usage of more realistic vignettes and real-life simulations in experiments would be very beneficial. In particular, the use of realistic warfighting vignettes, where researchers are in the field with soldiers, provides opportunities to test and evaluate research hypotheses more thoroughly, including the revelation of previous unknowns.

Within VI the emerging shift from one-person/one-robot studies to multiperson/multirobot studies merits sustained attention. This shift exposes VI to more complex teaming architectures, concomitant realistic field environment, and potential improvement of the validity and applicability of the research results.

Some strategic goals and tactical milestones for VI research and development programs could be made more apparent. To help quantify general progress and application-specific performance, more efforts need to be made in terms of baselining and benchmarking. A process whereby desired capabilities and goals are broken down into a sequence of achievable (realistic) short-term capabilities and goals would be beneficial. Unifying demonstrations, milestones, objectives, and capabilities could help to better motivate the specifics being developed and how they will be integrated.

Application of more systems integration principles across research projects and pillars would strengthen the overall impact of VI research products. Similarly, connectivity between individual principal investigators could be improved.

The VI program is well positioned to maintain and improve the quality of its research products. To move to the next level, VI needs to undertake carefully chosen, audacious, grand challenges that go beyond the extant state of the art. Resulting activity and research products would provide leadership in research and development. This would yield inherent advantages in framing VI problems to achieve solutions that benefit the Army.

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Human Sciences

INTRODUCTION

The Panel on Human Factors Sciences at the Army Research Laboratory conducted its review of selected research and development (R&D) projects of the ARL Human Sciences Campaign and the Assessment and Analysis Campaign at the Aberdeen Proving Ground, Maryland, on July 14-16, 2015. The Human Sciences project areas reviewed were these:

- *Humans in Multiagent Systems.* These efforts aim to achieve critical technological breakthroughs needed for future Army multiagent, mixed-agent teams to effectively merge human and agent capabilities for collaborative decision making and enhanced team performance in dynamic, complex environments. The challenges for human sciences R&D are soldier workload, situation awareness, trust, influence, and cultural cognition.
- *Real World Behavior.* The objectives of the R&D in this area are to enable the collection, analysis, and interpretation of human behavioral data within dynamic, complex, natural environments. ARL conducts R&D in two areas (1) real-world complexity in human science experimentation and (2) assessing human behavior in the real world. A key focus of this work is the development of novel technology and methodologies and to collect and analyze these data in real world conditions.
- *Toward Human Variability.* The goals of this R&D are to enable high-resolution, moment-to-moment predictions of an individual soldier's internal and external behavior and performance and the ways in which soldiers interact dynamically in mixed-agent team and social settings in both training and operational environments. Human variability R&D is conducted in two areas: (1) multifaceted soldier characterization to develop a comprehensive understanding of the factors influencing human variability and (2) brain structure function coupling to create a multiscale understanding of the relationship between the brain's physical structure, its dynamic neurophysiological functioning, and human behavior.

The Panel on Human Factors Science also reviewed a component of the Assessment and Analysis Campaign portfolio on assessing mission capabilities of systems. The goal of this area, more or less, is engineering and acquisition decision support for current and future army human systems. Efforts are conducted in two areas, the first of which is human factors, which focuses on integrated human factors engineering (HFE) and system engineering (SE) assessments and analytic techniques to predict human, system, and mission capabilities early in the acquisition cycle. In this first area, HFE applications and tools are developed and refined to lower acquisition costs and improve design. The second area, soldier survivability, is concerned with analysis and engineering to increase the survivability of platforms and soldiers operating in combat environments.

Since the Board's 2014 assessment, ARL has restructured its portfolio of ongoing and planned research and development to align with its S&T campaign plans for 2015-2035. These plans direct strategic shifts in emphasis that could transform the current program of work motivating new directions for future research. This transformation is in its early stages, and, as might be expected, the fit of some ongoing work into the key campaign initiatives (KCI) in the S&T campaign plans for 2015-2035 is a bit uneasy.

The increased emphasis on understanding and managing real-world complexity within the KCIs is an important and notable development. Increasingly, complex sociotechnical systems that encompass interactions among multiple agents whose behavior is governed by intangible variables (e.g., emotion and culture) will pose many tough challenges for the "Army after next." Research in this area will likely promote increased interdisciplinary collaboration with other campaign areas. Conceptual and theoretical breakthroughs from the growing adaptive complex systems engineering literature need to be leveraged to support this work.

In general, gains were evident in publication rates and in the establishment of collaborations and partnerships with relevant peers inside and outside ARL. The ARL human sciences work environments are exceptional in terms of their unique and advanced technological capabilities to support research. ARL has continued to successfully attract clever postdoctoral researchers from a diverse set of universities and disciplines.

Overall, ARL has been proactively responsive to prior concerns and recommendations from ARLTAB to good effect. For example, the materials provided in advance of the review meeting were generally more informative, presentations were more uniform, and statistical analysis has become more rigorous. Additionally, the efforts of ARL leadership to overcome constraints on conference participation by scientists and engineers are laudable. Overall, these are outstanding accomplishments and mark a visible advance over prior years.

ARL's vision for 2015-2040 is compelling and raises expectations for an innovative program of research designed to be responsive to the needs of the Army after next. Unfortunately, this is not yet fully evident in the portfolio currently being assessed. Certainly, the reorganization of the portfolio into KCIs is promising in this regard, and it may take some time to transform and mature the program of work and its representation to consistently align with new critical paths. At present, however, some of the groupings appear forcibly merged, with the conceptual linkages between them unclear (e.g., how does the human–robotic interaction work relate to the social cultural work?). The relevant and high-value niches for human sciences research and development within the KCIs with respect to what others have done, are doing, and where ARL could best contribute is in serious need of clarification by elaboration. ARL needs to consider surveying the external communities in academia, industry, and other government agencies to establish strategic baselines for investments in these areas.

A general challenge, noted in past assessments by the ARLTAB, persists with respect to the critical need for access to military-relevant subjects in the work. Many of the real-world research questions that ARL is dealing with urgently require more effort with respect to subject populations and the representation of mission contexts. A number of studies presented drew upon ARL researchers as subjects to a worrisome degree. As another example, researchers at the soldier performance and equipment advanced research (SPEAR) facility waited eight months to acquire and run a limited number of soldiers as subjects. ARL needs to find a workable solution to this problem that threatens to compromise the credibility and impact of important research addressing vital Army needs.

On a positive note, statistical analysis at ARL has become increasingly rigorous; however, other analytical tools (e.g., mathematical modeling [optimization] and data mining) need further consideration in the program of work.

Several questions arose with respect to gaps in the disciplinary composition of the ARL human sciences workforce. Important core competencies such as systems and simulation engineering are absent; hiring is needed to grow these competency areas. There was also an expressed challenge and concern about the scant number of technicians needed to support the increasingly high-tech research and development within the human sciences campaign.

HUMANS IN MULTIAGENT SYSTEMS

Accomplishments

ARL human sciences work in multiagent systems addresses sociotechnical network operations, focusing on distributed collaboration and decision making in complex operational environments; sociocultural competency skills needed to support, inform, and influence operations in complex environments; human–robot trust; teaming of humans and intelligent systems; and human control of multiple robots. ARL appears primed to make important contributions to this paradigm and demonstrated a sound awareness of the key trends driving the research challenges in this area (i.e., the rise of the networked organization, increasing autonomy, and the need for cultural competency in military operations). The work in the area of human–robotic interactions and trust builds on the extant baseline of substantive theoretical and empirical work dealing with trust in automation. The conceptual organization of data-to-decisions at social cognitive, information, and communication layers allows for effective linkages and human–system integration with other multiagent systems activities. Hence ARL is applying a well-integrated systems approach to the study of purposeful social systems, addressing not only structure but also the role and function of sociotechnical Army systems involving people, information, and technology. The research staff, including postdoctoral researchers and interns with recent experience, appears competent. However, from a staffing perspective, this is an area that would benefit from growing interdisciplinary collaborations as the portfolio matures. Similarly, the modeling and simulation capability to support this work is good, but an expanded toolkit will be needed to enable substantive advances in the future.

Challenges and Opportunities

The potentially valuable work in this area faces inherent challenges, but overall there does not appear to be a coherent vision for how the research holds together and cumulatively builds to push the state of the art. This may be the result of a forced merger of ongoing activities into the new campaign organization, which is still somewhat immature.

The problem area as scoped is very broad-ranging, including human–technology interactions to human–human interaction (sociocultural interactions), and it is not clear how all of the pieces fit together. For example, the distinction between the human–robot interaction (HRI) research and sociocultural research is an important one, because these groups have different pre-theoretical ideas and histories, concepts, analogies, and terminology and very different subject matter and methodologies. Although there are connections that could be made between these areas, they are generally distinct subdisciplines, and the connection between them needs to be made clear in the present organization.

The emerging work on joint operations of robots and humans is an important area of work with a large body of extant research that needs to be strategically considered as ARL evolves its niche in this area. There are many directions to be considered, including multiple HRI configurations (i.e., multiple humans with multiple robots), threats to security or integrity of robots as potentially compromised agents, and the possibility of coadaptation and coagency, where either the human or agent can take control. The progress at ARL has been unidirectional (i.e., human to robots) and needs to progress to encompass bidirectional communication—that is, humans trusting robots and robots trusting humans.

Good use is made of modeling and simulation (M&S) in this area, although there is room for some improvement by expanding the toolkit of available techniques. For example, there are instances in which a statistical or event-driven simulation is used instead of physics-based M&S. M&S has emerged as a discipline in itself, as opposed to only an enabling technology, with several universities now offering degree programs. As such, ARL needs to consider recruiting more simulationists onto its research staff.

The emphasis on experimental work by the human factors group is commendable, but good mathematical and computational models of the robots, the interacting humans, and the feedback could save a lot of trial and error, provide insight, allow testing of different control regimes and feedback strategies, quantify sensitivity, help with identifying worst-case scenarios and sources of instability, and provide guidance to the design of experiments. There are modeling opportunities, especially of human operators, of robots, and of human collaborators from the "'viewpoint" of the robot. The development of such models can aid understanding about how humans and robots interact by using inexpensive simulations and sensitivity studies. These studies need to be done before undertaking costly experimentation with humans and physical machines.

The challenges of HRI are inherently interdisciplinary, and drawing upon multiple contributing competencies is necessary to have successful, relevant outcomes. For example, the investigators in this area have, for the most part, backgrounds in psychology, and they could benefit from the knowledge, alternative frameworks, and approaches of experts in robot navigation, control, and modeling and simulation. Multidisciplinary approaches can interrogate issues from multiple perspectives, promote the integration of insights, and facilitate the connection of ideas in novel ways. Over the years, ARL has apparently supported a body of work on robotic control and navigation and already has many experts on staff, including mathematicians, electrical engineers, mechanical engineers, and physicists. There now appears to be a great opportunity for joint development of models and algorithms supporting this work. The description of research in multiagent systems appeared to focus on the human factors aspects of the systems and did not describe collaborative interactions with robotics researchers. Such collaborations are essential for a full understanding of the robotics features of such systems.

There is a wealth of available knowledge to be leveraged on how robots identify where they are, map their environments, plan their movement in autonomous or semiautonomous settings, use beacons and milestones, identify obstacles and hazards, fulfill commands, navigate, and follow trajectories. There is an opportunity to use this knowledge in the design of joint human–machine action. Missing out on this wealth of knowledge means that the algorithms developed by the human sciences campaign may miss out on a variety of behaviors and constraints that are well studied and well-modeled by individuals with mathematical, mechanical, electrical engineering, and computer science training.

Another area where ARL research on joint robot–human action can benefit is the significant body of work on hard fusion. Also of increasing significance is the emerging field of soft and hard fusion. Soft and hard fusion appears to be a major opportunity for developing a framework for HRI scene interpretation, because it admits a large suite of heterogeneous inputs, including heat sensors and tweets. There are numerous individuals across ARL with relevant expertise in this area, but there was scant evidence of any collaboration with these individuals.

ARL identified a focus on sociotechnical systems, including data to decisions, decision support systems, human dynamics of cybersecurity, and network team performance. Although ARL identified human dynamics of cybersecurity as a component of ARL's focus on sociotechnical systems within its Human Sciences campaign, ARL's Human Sciences campaign did not present anything that was germane to cyber research. Given that there exist many opportunities for adversaries to compromise robots or influence people, this would seem a critical area for human sciences research. This work may already be ongoing under a different ARL campaign, but it is important to support proactive collaboration and engagement of the human sciences in this area.

The research on understanding sociocultural influences suffered from some serious methodological design flaws and weaknesses in analysis that completely undercut its potential usefulness and impact. Chief among the problems was the studies' reliance on a subject population that was not representative of the target population. More specifically, subjects were uniformly Christian, white males who did not remotely reflect the religious, ethnic, racial, or gender demographics of the Army personnel targeted by the study, making it difficult and misleading to draw any credible conclusions from the findings of this study. The serious problematic design of this study suggests a need for preapproval quality vetting of proposed research designs at ARL.

REAL-WORLD BEHAVIOR

Accomplishments

The collection and analysis of human behavioral data within dynamic, complex, natural environments is an ambitious and challenging undertaking. Not surprisingly, the accomplishments in this area are only somewhat incremental given the immature state of the art and the groundbreaking challenges to develop needed enabling technology and methodology. Continued strategic investment to push advances in this area would yield significant payoffs for the Army and potential spinoffs of benefit to other government and private sector research and development.

Both the environment for auditory research (EAR) facility and the SPEAR obstacle course are outstanding, world-class facilities that have been brought in to this key campaign initiative. The research team using these facilities is well focused and has effective leadership. Ongoing hardware updates to the EAR facility will ensure that it is state of the art and easy to use for advanced studies of auditory perception. Since the ARLTAB's 2013-2014 review, the research at the EAR facility has become more general and more relevant to the real world. Specifically, studies appear better designed, are less controlled than traditional psychoacoustic work, and address questions that can impact situations beyond the specific conditions tested. These advances could beneficially be pushed even further to raise the ante on research outcomes to an even higher level of importance and excellence. The collaboration with the neuroscience group to jointly measure behavior and neural signals, using electroencephalogram (EEG) technology, is laudable.

The research presented in this area appears focused on mission-relevant problems and contexts and draws on measures from multiple domains (e.g., biomechanics, cognition, and neurosciences), consistent with the goal of addressing real-world complexity. For example,

- The research using electrocortical activity to distinguish between uphill and level walking is apparently the first study to demonstrate that cortical activity changes while the human walks over different terrains. However, given the limited statistical power of the EEG signal to distinguish the terrain condition (level or incline), it would be necessary to consider more sophisticated analytics (e.g., source analyses for EEG studies) or other methods (e.g., signal enhancement methods that can reduce artifacts from electrode movement) to provide feed-forward control signals for exoskeletons. Regardless of outcome, this type of work is a good example of the foundational research needed to support the development of highly mobile sensing systems that could be useful in the field. Advanced measures for evaluating signal quality need to be developed, and the translational neuroscience (TN) group needs to ensure that it is aware of and understands the lessons learned from prior work in this area.
- The work on stretchable conductive elastomers for soldier biosensing was impressive and, if successful, could have applications well outside the military realm. This is also important foundational work, showing encouraging progress, to enable EEG measurement under real-world conditions where soldiers are moving, sweating, and otherwise burdened.
- The effort showing the effects of marching, rucksack load, and heart rate on shooting performance in the field is an applied study with considerable generality, because it is designed to understand the effect of work and fatigue on human performance. The study makes excellent use of the SPEAR facility and is very relevant to real-world Army combat, where soldiers may carry heavy rucksacks for extended periods of time.
- The research dealing with temporal and semantic coherence of sounds has implications for the presentation of multisensory data for training—for example, the possible effect of latency in presentation of initiating event and audio and visual stimuli generated in response to the event.

- The research on a novel measure of driver and vehicle interaction and research on eye movement correlates of behavioral performance in a simulated guard duty task showed interesting use of validating measures other than EEG. The novel driver–vehicle interaction metric and eye-tracking measurement used appeared less complex with respect to the collection and interpretation of data than the EEG measures that seem to dominate ARL's real-world research paradigm.

Challenges and Opportunities

Measuring and understanding behavior in the real world is an audacious objective given the limits to the current understanding of nonlinear causal propagation and emergence in complex real-world systems and environments. True multidisciplinary projects are generally rare but are essential in order for this area to mature to yield meaningful and valuable outcomes.

Research in the real world requires giving up experimental control for the most part. It requires ecologically valid contexts and tasks and the means to capture and analyze the nonlinear causal interactions of multiple variables that may contribute to variance in performance and behavior. For example, it is not appropriate for real-world studies of auditory localization to assume fixed head and sounds unnaturally short that are turning on or off simultaneously. Expertise in ecological psychology and complex sociotechnical systems engineering is needed and could provide useful insights and research strategies under this initiative.

It may be possible to conduct some tightly controlled studies as a tool for assessing whether a new technique is feasible and then progress to a study in a more ecologically valid setting. Indeed, there may be a continuum of increasing complexity within which it may be possible to effectively derive valid causal assumptions. Therefore, based on findings, the driving–vehicle interaction work might be repeated for validation in more capable simulators before moving out to data collection in real-world driving in the field. Developing a methodology for moving research between the laboratory and real-world settings would be a major step forward and a significant contribution to establishing a methodological advance for real-world research.

The project on systems-based metrics of team states using communications data is somewhat ambitious, envisioning the collection of massive amounts of data on hundreds of individuals on a 24/7 basis on brigade-level mission command training exercises. Big data analytics will then be applied in an effort to explore the extent to which group efficacy is a function of variables such as shared understanding of command intent. The hope is that the data collection will be unobtrusive and that it will permit intervention before an existing or potential problem. The analysis of this massive volume of heterogeneous team communication data appears daunting and might benefit by collaboration with information technology or computer sciences subject-matter expertise resident elsewhere in ARL.

TOWARD HUMAN VARIABILITY

Accomplishments

Understanding and predicting human variability is an important and timely topic of investigation. Current systems are calibrated to the average performance of the average person in challenging circumstances; optimized adaptive systems might enable better use of human capacity when situations and states permit. Advances in this area reflect the availability of increasingly sophisticated behavioral and brain measures and the development of new analytic and statistical methods that may enable adaptive systems in operational settings.

The human variability research at ARL addresses the variability in performance between different individuals and the variability within one individual at different times and particularly in different states.

Two components of this research initiative were presented: (1) cognitive neuroscience research and development with a focus on real-world measurement designed to illuminate the connection between brain states and behavior and their potential implications for brain–computer interfaces and (2) a proposed initiative to understand and predict variations in performance with measures of human behavior and physiological state over long periods, using relatively unobtrusive immersive measures interspersed with laboratory-based tests and measures.

Overall, the work in this area seems to be of exceptional quality. The majority of the research efforts used EEG (or in some cases fMRI) indexes of brain responses associated with visual or auditory processing or with motor responses. Several of the newer projects used either EEG sensor data or fMRI activity to identify patterns of coactive brain circuits that are characteristic during different stages of sensory, motor, or cognitive tasks. Novel work was presented aimed at advancing the state of the art of dynamic analysis of brain signals to identify active brain circuits and show how activity within these brain circuits differs within individuals and between individuals across the time course of responses in typical operator-relevant tasks. The research infrastructure in EEG, eye movements, and (through university collaboration) fMRI is superb and well suited to address the target issues.

This group has recruited an exceptionally strong set of researchers, including well-qualified postdoctoral and early-career scientists representing different technical backgrounds, with some gender and ethnic diversity. A number of the presentations featured early-career scientists. Overall, the presentations indicated good mentorship of these early-career researchers.

The quality, productivity, and scope of coverage in journal publications and presentations continue to be exceptional. The recent peer-reviewed publication record indicated between 5 and 10 journal articles per year since 2012, including 6 to date in 2015, with 10 additional articles submitted. The focuses of publications are well distributed over the scope of the initiative and are directed at cutting-edge issues in human variability. For example, a number are focused on EEG and/or survey methods (e.g., the Big Five inventory) and a number evaluate intra-individual gender measures. The majority of the verbal and poster presentations for current and completed work were focused on brain states and behavior in a variety of operational situations.

An informal network of shared resources and shared knowledge is developing that transcends organizational boundaries. In particular, there appear to be considerable cohesiveness and teamwork that extend across ARL laboratories. The level of awareness and cooperation across the laboratories is impressive, the resources needed to advance the work are available, and the collective expertise can rival that in top academic institutions, where a more insular attitude is commonplace. Cohesiveness can be a powerful tool, and ARL deserves kudos for maintaining this excellent environment.

Challenges and Opportunities

Many of the projects presented appeared to be at formative stages at both empirical and theoretical levels, and the range of problems being worked on seemed somewhat vague, diverse, and unconnected. However, the implicit focus was clarified somewhat during small group discussions with the research staff, who described the focus as the identification of potential brain–behavior signatures for brain–computer interface translation.

The development of practical adaptive systems based on assessment of operator state is an important research objective and would benefit from a focused set of research priorities using a well-defined set of high-value operator tasks and operational contexts. The current effort appears devoted to testing and gaining expertise with various biometric measurements (e.g., field testing of EEG and multimodal sensors). However, the diverse array of biosensors and the extent of potential behavioral components require some winnowing of possibilities. In addition to high-fidelity brain measurements examined in the laboratory, a range of other measures such as multiple cue or cue fusion approaches needs to be considered, with the goal of identifying potentially lower fidelity neurocognitive measures of brain state. Fused cue approaches use multiple data modalities (e.g., heart rate measures, eye movement behaviors, simple EEG indicators, and other behavioral indexes) to achieve possible benefits of cue integration in the classification of human states (e.g., attention, vigilance state, fatigue). This could, in turn, be foundational to the notion of precision performance, whereby inputs, decisions, and scheduling demands can be tailored to the individual, including the mental state of the individual.

One caution is that the ARL studies on individual differences focus almost entirely on developing neurophysiological measures, with little or no incorporation of more traditional behavioral and psychological measurements. As a counterexample, ARL's reported research has shown that a relationship exists between the spatial abilities of operators and their performance on robotic tasks. This finding illustrates how much information on individual differences might be missed if the focus is entirely on biological sensors. Advice on the selection of appropriate psychological measurements depends on the parameters of a particular targeted behavior (e.g., precision), but their incorporation could be given a careful and more complete consideration in the overall research strategy.

The planned new initiative in unobtrusive immersive measurement of behavior is potentially an enormous problem domain. The findings and best practices from other related major data projects need to be leveraged to identify the research niche with the highest potential return on investment for ARL. As an example, there is a program of the U.S. Department of Transportation designed in part to characterize state precursors of traffic events. Other potential opportunities for leverage include advances in detecting and correlating attention or fatigue states with human performance in smart-home projects or monitoring system efforts associated with medical issues or adaptive support for aging populations.

One of the core challenges faced by this work—as in other initiatives addressed earlier—is the availability of suitably representative human subject populations for research testing. These might include civilian populations where those are appropriate or selected access to military personnel, where data need to be representative of the populations to which the research is expected to be applied. Suitably representative populations are especially important for credible research on interindividual variation.

Another core challenge is the need to engage appropriate information systems and computational resources where needed. The scope of data that could be collected in the immersive measurement for understanding and predicting individual variation in performance has the potential to be massive. The measurements planned in the immersive workplace (possibly including recording facial expression, direction of gaze, all keystrokes in work projects, and some simple physiological measures of heart rate) suggested the generation of large amounts of data. While preliminary and pilot testing of such data in smaller units may be feasible without special arrangements, the large data demands of ongoing immersive projects of this kind are likely to require specialized data management plans and adapting existing algorithms or developing new algorithms for data mining and data analysis. This would necessitate engagement of more expertise in information systems and computational resources. While the information systems and computational resources were not part of the research program under review, it was indicated that arrangements were under way for broader collaboration with other ARL researchers and staff with expertise and resources in this area.

The cognitive neuroscience group has recruited a number of early-career researchers and collaborators from academia. Although there was evidence for strong mentoring of these individuals, the expansion of the group, combined with the fact that key individuals are moving up into administration, suggests a need to develop expanded procedures for mentorship and for the identification of a set of mentors.

For the planned research into characterizing and predicting human variability, a series of workshops is being planned to discuss relevant research topics to enable program development. This is laudable, and a beneficial expansion of this effort (perhaps under ARL's open campus initiative) could include short-term visitors from academia or industry to broaden intellectual engagement around planned initiatives such as that for large-scale immersive measurement and individual variability.

Research on individual variability is one of the most difficult problems in the field of psychology, and there is much motivation to understand the phenomenon. High-quality and high-impact research in this area, focused on measurement, estimation, and prediction, could position the group for a broadly recognized leadership role. Unique high-impact studies of individual differences and intraindividual variability as it relates to stress, fatigue, and other psychophysiological states in targeted operational environments could also provide significant benefits, beyond those envisioned by ARL, to external university or industry research efforts that generally do not have direct access to these operational contexts.

ASSESSING MISSION CAPABILITY OF SYSTEMS

Accomplishments

The work in this area is comprised of human-centered engineering and decision support methods, models, and tools supported under ARL's Assessment and Analysis campaign. Most of the projects that were presented in this area are responding to important and specific Army customer needs, such as the efforts dealing with human modeling, field assistance in science and technology, human behaviors negatively affect engineering solutions, and fire suppressant effectiveness. Soldier surveys conducted by ARL to identify and characterize problems with equipment and systems used in the field yield valuable feedback that can, if effectively acted on, save lives, promote mission effectiveness, and potentially provide long-term cost savings to the Army.

Progress and advances are evident in the integration of human factors and systems engineering tools. A prime example of this is in the integration of SysML activity diagrams as input to Improved Performance Research Integration Tool (IMPRINT) models. The facilities, tools, and test equipment used in this area (e.g., the renovated obstacle course) appear fully up to date and are exceptional.

Commendable efforts are under way at ARL to advance assessment science by developing new models, tools, and metrics to support the acquisition and fielding of effective human systems responsive to emerging missions and threats. For example, improving the integration of human factors and systems engineering tools in the soldier decision framework model is a significant step forward. Advances in technology, system and mission environments, and changes in soldier roles and the nature of the work they do require attendant and anticipatory advances in assessment science, methods, and tools.

Challenges and Opportunities

The Army continues to be a DOD leader for human systems integration as an integral part of DOD systems acquisition and engineering. As such, it is an important challenge and responsibility for ARL to push the science of human systems evaluation, not just to be the evaluators of record. ARL needs to lead the envisioning and development of new methods and models that are militarily relevant to future technologies, missions, and threats and that will support the acquisition and fielding of effective human systems. As an example, ARL leverage of advances in cognitive engineering can support diagnosis and assessment of complex human systems, human technology interfaces, training programs, and work redesign with methods and tools (e.g., cognitive task analysis) that can identify the mental demands (e.g., workload) and cognitive skills (e.g., situation awareness, decision making, and planning) needed to complete a task or accomplish a mission.

Another major challenge is to improve the timeliness of human systems assessment and analysis to ensure that it is not cast aside, to the detriment of soldier and mission effectiveness, in the rush for rapid fielding due to war. The process of evaluating new systems in wartime has to allow a rapid response while not ignoring the human science factors. The problem is how to best tailor human systems processes to support wartime (rapid fielding) versus peacetime system acquisition. Enhanced use of modeling of system and mission environments needs to be considered for its potential to accelerate these processes.

ARL needs to be in the feedback loop, both sending and receiving on human systems integration (HSI) issues from system conceptualization, acquisition, and design, through fielding to prevent future problems and failures with the process and to ensure long-term improvements. For example, problems identified prior to deployment that were rectified need to be tracked to determine their impact in the field. Similarly, problems in the field that were identified might warrant changes in process to assure they are captured in the future. Field data on adherence to usage recommendations or human systems effectiveness of equipment need to be systematically fed back to modifications or redesign. This would enable continual improvement of the ARL assessment and analysis processes and their impact on future Army systems. An additional benefit would be a documented audit trail that could support validation of the cost-benefits of the process for use in future baselines.

ARL could use customer-funded projects to motivate human sciences S&T research ideas and directions and to provide pilot data. Because research is fundamental to ARL, even customer-funded projects could push the research agenda. A continual focus on using contract work to provide pilot data would enhance research and identify meaningful data or problems. If the linkage between ARL human sciences research and HSI applications were more transparent, it could facilitate investment by external operational customers in the work. For example, ARL researchers indicated strong desires to connect research-based findings with field-based operational effectiveness and customer-responsive work.

Researchers making connections with military personnel in the field to gain soldier perspective has the potential to be transformative. It can inform ARL research, motivate scientists and engineers, and lead to rapid and/or dramatic changes that can have significant impact on soldiers. Programs that enable ARL investigators to collect field data have been cut, thereby reducing and/or eliminating experiences and data that are extremely valuable to the HSI effort. Assuring these opportunities for research and assessment in the field continue and expand is a key priority. In a similar vein, the Army provides a course whereby new employees are introduced to Army systems and procedures. There would be value in making this real-world sensitization standard procedure available for all ARL civilian scientists and engineers.

OVERALL 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. In general, 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. ARL has done an excellent job by hiring highly skilled postdoctoral researchers, who are being groomed to become next-generation researchers. The increased exposure of ARL in publications and conferences is commendable. This will further improve S&T quality, encourage interactions with researchers who study the same issues elsewhere, provide ARL personnel with invaluable networking, and prompt researchers from other agencies and from universities to offer their expertise to ARL. The ARL facilities are, for the most part, superb. Collaboration with the broader scientific community is generally good and would be amplified by effectively networking with and capitalizing on the great academic programs that many of these postdoctoral researchers have been drawn from.

While there has been good progress at growing ARL basic science, more needs to be done. Unique contributions to science in the portfolio presented are not always evident. The key exception is the initiative on individual variability, which has effectively demonstrated the potential to make important contributions to the science of brain state measurement and individual differences. Overall, the ARL neuroscience laboratory, with its emphasis on high-quality R&D and peer-reviewed publications on par with distinguished university peers, is an exemplar on which to grow and sustain basic science across the human sciences KCIs.

The new emphasis on advancing assessment science in the human factors area of assessing mission capability of systems is commendable; it needs to be brought into balance with the assessment-for-hire field assistance in this KCI, to position ARL to effectively support the Army after next. The relationships built through good customer-driven work can be leveraged to gain support for the science and technology needed to advance this capability.

ARL may already possess the in-house expertise to effectively deal with many of the complex challenges anticipated to confront the Army after next; it is important to assure that beneficial synergies that exist across the KCIs are systematically leveraged. Three areas in human sciences might benefit from broader ARL exposure, engagement, and collaborations: Big data analysis, autonomous or semiautonomous systems, and EEG-based studies in real-time (or near-real-time) systems.

Linking on-site research to field-based applications work and developing a unique set of capabilities relevant to Army needs, military operations specialties, and contexts potentially represents a unique strength and feature of the ARL human sciences. More work needs to be done here. 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 to best impact the Army after next. The KCIs are promising in this regard; it may take some time to transform the current program of work and its representation to consistently align with this new core competency structure that links expertise across ARL directorates.

Taken individually, each area of the human sciences campaign (humans in multiagent systems and real-world behavior and human variability) can be cast as a grand challenge, because it is complex, multidisciplinary, and involves many unknowns, requiring multilevel focuses on theory, data, modeling, and engineering to meet stated and implicit goals and objectives. For example, research on individual variability is one of the most difficult problems in the field of psychology; the planned new initiative on unobtrusive immersive measurement of behavior is potentially an enormous problem domain; and measuring and understanding behavior in the real world is an audacious objective given the limits to our current understanding of nonlinear causal propagation and emergence in complex, real-world systems and environments. These grand challenges are further complicated by the interdependence and overlap of these areas of the campaign. A coherent strategy and vision, not yet evident, are critically needed for how ongoing and planned research holds together, capitalizes on useful existing theoretical and empirical baselines, and cumulatively builds to achieve goals and objectives over the near, medium, and long terms.

8

Crosscutting Conclusions and Recommendations and Exceptional Accomplishments

ARL's mission—to discover, innovate, and transition science and technology to ensure dominant strategic land power—demands an institutional culture that values and rewards foresight and farsighted vision while meeting the Army's current scientific and technological needs.

As technology marches on at an unprecedented pace, the relentless pursuit of innovation by means of an integrated multidisciplinary system approach is becoming increasingly important. Through an interconnected, holistic perspective and integrated systems approach, project synergies and spillover benefits can be optimally harvested. A concerted effort to understand future needs and to craft the research portfolio relevant to the Army of the future is the ultimate challenge as well as an opportunity for ARL.

The competitive institutional stature of the ARL vis-à-vis other research organizations in the United States and abroad hinges on crafting and executing a robust and focused research portfolio. The success of ARL researchers, in turn, is directly linked with their continued professional development in the workplace. Nurturing the research staff, tenured and early-career, requires a continuing effort.

In this uncertain funding environment and the fast-moving global technological landscape, productivity is another essential element of institutional success. The ability to shorten the research cycle from science to technology to useful product is essential to the institution's competitiveness and sustainability.

Additional opportunities will be presented by having the ability to effectively utilize technologies, commercial or otherwise, that are deemed critical to the well-being of the soldiers, eschewing the not-invented-here syndrome. A systematic, structured effort to leverage innovations from outside sources, by either complementary in-house projects or by collaborating with well-selected research partners, will enhance the overall productivity.

During the 2015 reviews, collaboration efforts were well demonstrated across ARL Science and Technology (S&T) campaigns and externally. Most of the projects were engaged in upward collaborative efforts to various degrees; this is commendable. The success of ARL's leadership in recruiting energetic, early-career talent was evident. However, a heightened excellence can be achieved by working toward a higher level of portfolio focus, project synergy, and overall productivity.

In the act of constant innovation, ARL can continue building toward a best-in-class, forward-looking culture. To this end, researchers need to be relentlessly asking the questions, What is the impact? How can we make an impact? What comes next?

ARL's open campus initiative is poised to facilitate cultivation of a constantly innovative environment. The initiative also serves as a conduit for garnering the benefits of open innovation in search of the delicate balance between importing and exporting knowledge to sustain a competitive edge.

This chapter highlights crosscutting conclusions and recommendations. At the end of this chapter exceptional accomplishments are identified that correspond to each of the ARL S&T campaigns areas reviewed in 2015.

RESEARCH PORTFOLIO, NICHE AREAS, AND STAFF DEVELOPMENT

During the 2015 assessments, which are summarized in this interim report, the ARL campaign areas did not uniformly present adequate information to permit confident understanding of the overall portfolio of ARL research or the rationale for sampling of the projects selected for review, nor did they clearly present a rationale for a limited set of niche areas selected and pursued to drive a robust research portfolio that addresses the significant relevant scientific and technical challenges. The metrics for evaluating the success of projects within the context of ARL's strategic plans, the technical strategies for starting and terminating projects, and the approach to mentoring the research staff were also not clearly described. (This information will be needed when ARLTAB prepares its final report summarizing the 2015-2016 assessment.)

Judged by the limited sample of projects reviewed, the research portfolios in the various campaign thrusts at the ARL comprise projects that reflect a broad scope of activities in the given areas of research. While there may be value in each project at an individual level, significant impact can only be realized through better integration and the development of a coherent and unifying thrust for the research program. Without such a focus, and against the backdrop of constraints on materiel resources and a limited workforce, it is impractical to expect ARL to establish leadership in any chosen area of research endeavor. It is, therefore, important to identify niche areas where ARL aspires to assert research prominence and distinction, and to focus effort and resources in a manner that achieves the desired impact. ARL research would benefit by focusing on critical needs that are addressed at greater depth.

Such a rationale would include identification of how ARL expects to lead in a limited set of areas while watching and leveraging in others; how the chosen research focuses would enable ARL to be perceived by customers, peers, competitors, potential recruits, and its own scientists and engineers as an unparalleled provider of value in each of the niches in which it executes its program. Defining the rationale for leadership in a research niche could include such considerations as anticipated Army needs for such technological superiority and the feasibility of accomplishing them, cutting-edge facilities, ability to be agile and proactive in response to domain dynamics, acknowledged competency by peers and competitors, likelihood of effective transfer and transition; and capability for effective leverage and collaboration.

ARL has to strike a balance between farsighted high-risk, high-reward research and the programs necessary to meet more immediate Army needs. ARL's open campus initiative provides an opportunity to explore strategies to promote and nourish a farsighted scientific culture balanced against the more pragmatic Army needs. Regardless of the strategy employed in this exploration, key questions need to be addressed. Principal among these is the development of productivity metrics different from those used to assess short-term productivity such as number of citations. From these metrics ARL will be able to develop appropriate expectations for research productivity. As a means to this end, ARL management might take a historical look at discoveries and technologies that produced impacts 25 years later and in retrospect determine how these developments might have been identified and evaluated.

An effective research portfolio will evince not only selection of projects for inclusion, but also appropriate termination of projects. Sustained progress in the S&T campaigns requires ongoing assessment and prioritization of ARL's strategy goals tied to the specific objectives and evolving needs to support the campaigns. A strategic approach to phasing out projects will assure that ARL remains focused on campaign needs and that technical programs and projects remain focused on meeting both near-term mission needs and long-term investment goals. An effective strategic approach also facilitates reallocation of personnel and other resources personnel in support of new topics and objectives.

Exit criteria might include such considerations as (1) technical feasibility has been proven or determined unlikely, (2) work has been adequately addressed by others, (3) the Army requirement has been met, (4) higher strategic priorities demand reallocation of resources, (5) lack of technical progress, (6) shift in scientific and technical paradigm, and (7) determination that the expected benefit to the Army no longer exists.

The recruitment and development of competent scientific and technical staff are essential to the successful performance of the research portfolio. Recognition of success and recognition for success go hand in hand. Associated with metrics for program and project success is a formalized reward system for staff. The reward system may include such components as monetary and nonmonetary awards, internal recognition, external peer review, research freedom, and laboratory-wide recognition of stature (for example, fellowships).

Beyond rewards, staff development includes enhancement of the individual's professional knowledge, skills, abilities, and career growth. The increasing influx of new research personnel into ARL provides an opportunity to continue the advancement of high-quality research. A significant portion of these new hires is being educated and trained at leading U.S. universities in areas of interest and importance to the mission of the Army. The research culture at several of these universities is different from that at ARL. Recognizing this cultural difference and taking action to accelerate the careers of new research hires within the ARL culture require a formal mentoring process that is effective and efficient in transforming successful researchers from one culture (academia) to a different culture (ARL).

Mentoring is more than obtaining a favorable return on investment. Effective mentoring impacts the whole person, reflecting the mentee's strengths and needs, both internal and external to ARL. The impacted mentee is then able to provide ARL with more than high-quality research—namely, an enriched culture that becomes self-sustaining and more productive.

Recommendation 1. For each campaign ARL should provide to the review panels during the 2016 review a description of its research portfolio that describes each program and project in the portfolio. This description should include information on the project conception and initiation, project planning and scope, project performance and control, and project life cycle and should identify the percentage of each researcher's time allocated to the project, facilities and equipment required to support the work, and the inception date and anticipated completion milestone or termination date of the project. By referring to the portfolio description, ARL should provide to the review panels for each campaign answers to the following questions:

(1) What sampling strategy has ARL applied to the selections of projects to present for review? In what ways do the selected projects provide a representative sample of the portfolio?
(2) What projects represent the limited niche areas in which ARL proposes to work, in which of these areas does ARL propose to lead, and what is the rationale for its niche and leadership choices?
(3) What metrics has ARL identified to define the success of a project, and which exit criteria has ARL identified to help decide when to terminate a project?
(4) What rewards has ARL established to promote accomplishments by staff?
(5) What is ARL's approach to recruitment and development of its staff, including the approach to mentoring?

INTEGRATION OF RESEARCH AND SYSTEMS ENGINEERING

During the 2015 reviews, which are summarized in this interim report, the ARL campaign areas did not uniformly present adequate information to permit confident understanding of how projects are integrated within and across campaigns and of the systems engineering whereby projects are conceptualized and planned from initial planning (considering the relevant theory base and the work of others) through application of results (considering potential for transition to development).

The distribution of projects reviewed showed a common mission goal but unique research and development challenges that reside within different campaign thrusts. This speaks to the increasingly multidisciplinary nature of contemporary research challenges. While it may be possible to develop a solution in isolation that meets the functional needs of a campaign thrust, such a solution may be suboptimal at best; in the worst case, such a solution may seriously compromise the ability to meet the functional requirements defined in another campaign thrust. Adopting a systematic and formal approach for collaborating in a multidisciplinary research and development environment can circumvent some of these issues.

The problems faced by the Army of the future are extremely complex and will require options for solutions that are complex and multidisciplinary in conception. Success by the campaigns depends on effective leveraging of ARL's disciplinary competencies. Despite best intentions, however, interdisciplinary collaborations often flounder within research laboratories in the face of inadequate vision, skills, incentives, resources, or action plans. Deliberate inclusion of interdisciplinary interactions in the early stages of problem formulation can yield unexpected results and may result in solutions that have a greater impact.

To optimize the progress of their research, to set a path forward for each project, and to perform tests, analyses, and experiments that produce meaningful results, researchers need to consistently analyze data and contemplate the theories that are behind the observed physical phenomena, test data, and modeling systems. A key consideration in data collection and analysis is face validity—the extent to which a test, experiment, model, or analysis measures and examines what it is purported to measure and examine. A salient example of inadequate face validity is the selection of nonmilitary human subjects for study in human science experiments purported to yield results and conclusions generalizable to the military population. It is suggested that ARL survey communities in academia, industry, and other government agencies establish strategic baselines for investments in interdisciplinary areas.

ARL might consider treating its evolving interdisciplinary research and development as a challenge problem in organizational change and might consider assigning proactive responsibility to individuals with the expertise and mandate to develop and facilitate an ARL-centric approach that leverages ARL disciplinary strengths for each campaign area.

Recommendation 2. For each campaign ARL should provide to the review panels during the 2016 review answers to the following questions:

- **(1) How does each specific project presented fit within the overall framework of ARL's research portfolio, and how are projects and programs integrated within and across campaigns so that their work is performed in cognizance of related work and their findings feed into one another and into common goals?**
- **(2) How are systems engineering principles and processes applied across the life cycle of projects?**
- **(3) How is face validity addressed across the design of experiments, modeling, tests, and analyses?**
- **(4) What approaches are planned to secure military-relevant subjects for human sciences tests, experiments, and field studies?**

FACILITIES AND EQUIPMENT

In addition to human capital, facilities and equipment constitute a critical pillar of the ARL infrastructure. ARL possesses an extensive suite of state-of-the-art facilities supporting all of its campaigns. These facilities support high-quality work at ARL; they also represent a key attractant for recruitment and for candidates to participate in ARL's open campus initiative. While some of the facilities are new, others are aging and warrant ongoing analysis of needs for maintenance. Some of the facilities are seriously underutilized.

ARL's vision of Army needs and of ARL's goals through 2035 requires facilities and capital equipment upgrades and acquisition investments tied to technical campaign goals, for both computational and experimental needs. The vision would take into account the long timeline for acquisition, upgrades and refurbishment, construction, decommissioning, and dismantlement.

During the 2015 reviews that are summarized in this interim report, the ARL campaign areas did not present adequate information to permit confident understanding of ARL's plans for maintaining, expanding, or contracting current facilities; determining the need for new facilities; staffing the facilities; and securing funding to support these plans.

Recommendation 3. ARL should work to complete formulation of 5-, 10-, 15-, and 20-year strategic plans linked to the technical goals for staffing, facilities, and capital equipment, and should present the plans to the panels during the 2016 reviews. The plan should include a 2-3 year short-term tactical plan for access to necessary computing resources.

ARL RESPONSES TO RECOMMENDATIONS

The ARLTAB's recommendations are proffered with the understanding that the Board is not an oversight body and with the confidence that ARL will consider the value of the recommendations and the feasibility of pursuing their implementation. However, it is always helpful during the assessment to learn the ways in which ARL has addressed the recommendations of the previous review.

Recommendation 4. ARL should present to the panels during the 2016 reviews responses to the recommendations contained in this interim report.

EXCEPTIONAL ACCOMPLISHMENTS

The following are the exceptional accomplishments for each campaign area.

Materials Research

The biological and bioinspired materials group has an excellent track record that includes the stabilization of proteins against thermal and chemical extremes using new chemistries and methods to derive antibody-like reagents that improve upon antibody properties (specifically bimolecular recognition and binding characteristics).

The research on structural batteries using additive manufacturing combines novel fabrication methods with insight selection of compatible multifunctional elements that combine structural components with energy storage components. Experimental work is carried out concurrent with modeling studies that guide system design choices. The external collaborations are facilitated by a flexible methodology that provides easy incorporation of next-generation subcomponent materials as they are developed.

ARL has an opportunity to move aggressively to capitalize on internal and external advances in the energy and power arena. For example, the world-leading results on enhancement in quantum-well infrared photodetector (QWIP) efficiencies could be translated into capability demonstrators for manufacturers and customers.

In the area of engineered photonics materials, facilities and capabilities are being leveraged into compelling device- and application-driven work, especially in the ultraviolet (UV) materials, infrared (IR) devices, and the device physics in each of these areas.

Sciences for Lethality and Protection

The most impressive accomplishments of the battlefield injury mechanisms program are that it has been implemented, a strong cadre of scientists is working on it, and a credible program is under way. Almost all the battlefield injury mechanisms research topics presented had a combination of computational and experimental approaches whose interplay will be fundamental to the success of this research.

In the directed energy area the ability imparted through the RF-enabled detection, location, and IED neutralization evaluation (REDLINE) technology applied to a convoy to sweep and destroy IEDs without interfering with operations and civilian communications is a game-changer. The progress in applying an old idea, harmonics detection, to solve this problem is impressive. The investigators have done an exceptional job of transitioning the hostile fire detection technology to an operational prototype. Patents to protect intellectual property rights provide the potential of monetizing the innovation, e.g., for acquisition by police forces. This level of transition is probably more appropriate for 6.3-6.4 R&D.

In the armor and adaptive protection area, the research and development described showed how ARL is building on its tradition of excellence to provide the knowledge basis for current and future Army needs in protecting our warfighters. This remains a core competency that underlies Army capabilities across the entire DOD.

Information Sciences

Of the reviewed projects, the work on using a distributional semantic vector space with a knowledge base for reasoning in uncertain conditions represents a strong contribution. The research features a combination of statistical and machine learning (ML) methods with semantic rules for reasoning in an uncertain environment. This work draws upon the use of semantic models with a goal of augmenting a curated knowledge base by reasoning through analogies based on statistical representations. Both the ideas and the proposed methodology contain novel elements. The work is well grounded in the literature, and the researchers are aware of related efforts in the research community.

The opportunity for strong technical contributions and for differentiation from research conducted elsewhere, as well as the value proposition for the Army, lies in a mission-oriented focus to the research. In several projects this focus and constraints, such as limits on prior information or on available bandwidth, were a clear driver for the research. The work on autonomous mobile robot exploration with an information-gain metric stood out in this regard. This project featured a functional prototype of a robot capable of autonomous exploration. This work has opportunity for near-term application, and yet it is set in an information theoretic framework that is rich enough to support the development of more sophisticated and capable algorithms applicable to potential missions.

Computational Sciences

Research efforts in areas of quantum computing and software environment optimization are leadership-quality work that advances the basic science in important areas of computing technology. The development of a threaded message-passing interface for reduced instruction set, computing array multicore processors has yielded innovative solutions to the challenging problem of power-efficient parallel programming. The work on high-performance computing scaled quantum hardware description language is representative of one of the few efforts in the area of quantum networking; it is likely to have a strong influence on the development of future systems.

Multiscale material modeling is a potential game-changing computational technology for predictive simulation in the mechanical sciences. These multiscale simulations are essential for assessing vulnerability, lethality, and effectiveness of weapons and protections systems, and the current effort demonstrates the project's utility in theory and also in practical application to software commonly used (e.g., Lawrence Livermore National Laboratory's ALE3D production software tool,[1] used for high-explosive weapons and target simulations).This research is of high value for predictive forward analysis, and components of this work have application to enhancing the performance of inverse analyses and QMU estimations.

Sciences for Maneuver

In the human–machine interaction (HMI) area, the science is technically sound, and the work is published in top journals, including *Human Factors*. The utility of the work appears to be recognized within ARL—for example, elements from the tactile feedback project will be incorporated into the next warrior experiment. The use of soldiers in experiments is commended. The move toward more realistic warfighting vignettes and more real-life simulations, which instantiate threats and hostile elements, would help establish the value of a technology in achieving a desired capability. The research presented will be shifting from one-person/one-robot studies to multiperson/multirobot scenarios. This shift in research focus is appropriate as the Army moves toward use of more complex teaming architectures. This use case also highlights the importance of providing the right information at the right time to the humans and to the robots, identified as a thrust of the HMI program.

The intelligence and control (I&C) work employs innovative approaches in developing and supporting advanced technologies, algorithms, and tools in support of the warfighter effort. This area invests in advancing the effectiveness and efficiency of its research personnel. The focus of the I&C theme is on developing software and algorithms that enable vehicles to approach a higher level of cognition, enabling teaming of autonomous systems and soldiers. The higher level cognition that the I&C theme focuses on is aimed at enabling autonomous assets to work in the environments of relevance to the military.

In the perception area, the work on weakly supervised segmentation for mobility is significant for several reasons: an interesting vision/science result was published at a major conference; it is an integrated end-to-end project that demonstrates the value of the research; and it involves an external collaboration with a university.

Human Sciences

In the human variability research, the initiative on individual variability, with its emphasis on high-quality R&D and peer-reviewed publications is making important contributions to the science of brain state measurement and individual differences. The recent peer-reviewed publication record indicated 5-10 journal articles per year since 2012, including 6 to date in 2015, with 10 additional articles submitted. The focuses of publications are well distributed over the scope of the initiative and are directed at cutting-edge issues in human variability.

Appendixes

A

Army Research Laboratory Organization and Science and Technology Campaign Framework

Figure A.1 is an organization chart for the Army Research Laboratory (ARL), Figure A.2 is ARL's science and technology (S&T) campaign framework, and Table A.1 maps the ARL organizational chart to the campaign areas reviewed in 2015.

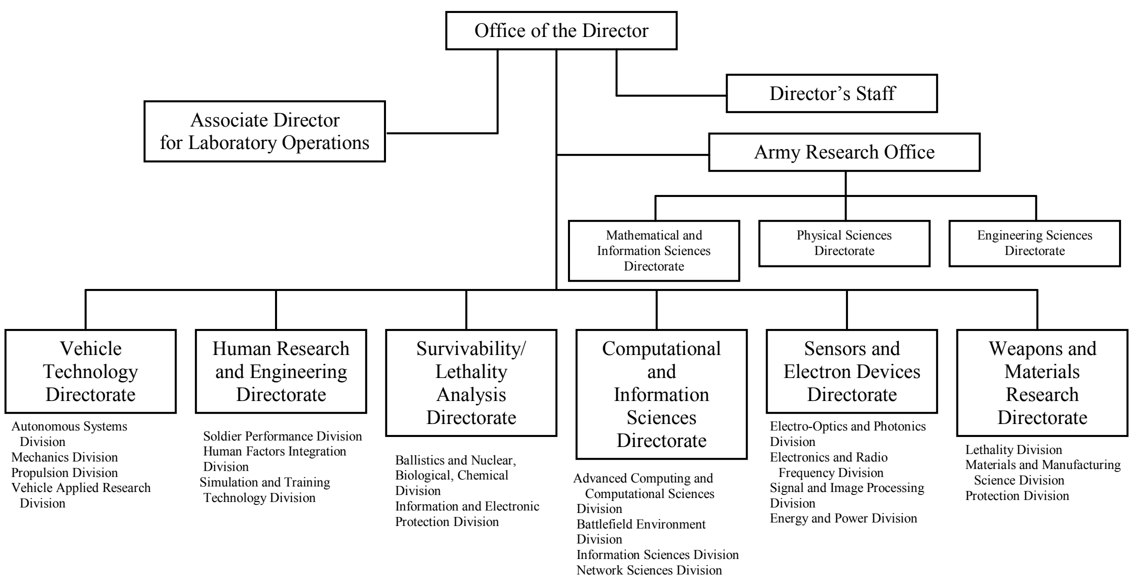

FIGURE A.1 Army Research Laboratory organization chart.

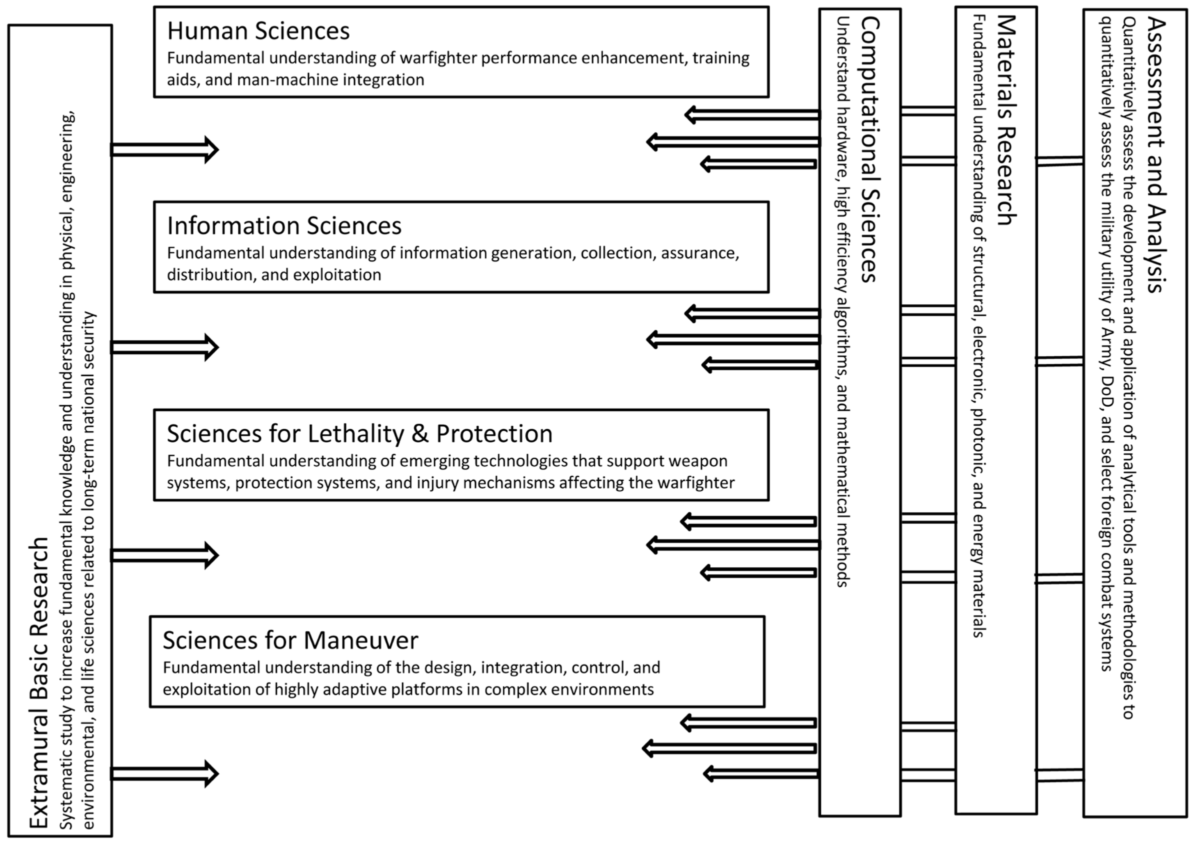

FIGURE A.2 ARL's S&T campaign framework: Extramural Basic Research, Computational Sciences, Materials Research, and Assessment and Analysis, ARL's four crosscutting campaigns act in concert with its four focused campaigns, Human Sciences, Information Sciences, Sciences for Lethality and Protection, and Sciences for Maneuver, leading to knowledge products and technologies.

TABLE A.1 Mapping of the ARL Organization Chart to the S&T Campaign Areas Reviewed in 2015

Campaign	2015 Topic	ARL Directorate Involved
Materials Research	Biological and bioinspired materials Energy and power materials Engineered photonics materials	SEDD, WMRD
Sciences for Lethality and Protection	Battlefield injury mechanisms Directed energy Weapon-target interactions	WMRD, SLAD, SEDD, CISD
Information Sciences	Sensing and effecting System intelligence and intelligent systems	CISD, SEDD
Computational Sciences	Advanced computing architectures Computing sciences Data-intensive sciences Predictive simulation sciences	CISD, SLAD
Sciences for Maneuver	Human–machine interaction Intelligence and control Perception	VTD, HRED, SEDD, CISD
Human Sciences	Humans in multi-agent systems Human variability Real-world behavior	HRED, SLAD
Assessment and Analysis	Assessing mission capability of systems	SLAD, HRED

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; and WMRD, Weapons and Materials Research Directorate.

B

Biographical Sketches of Army Research Laboratory Technical Assessment Board Members and Staff

JENNIE S. HWANG, *Chair,* NAE, is the chief executive officer of H-Technologies Group and board trustee and distinguished adjunct professor at Case Western Reserve. 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.

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 and Europe and along the Pacific Rim focused on contemporary issues in complex sociotechnical systems. He is a fellow of the Human Factors and Ergonomics Society and the International Ergonomics Association.

MARK EBERHART is a professor in the Department of Chemistry and Geochemistry at the Colorado School of Mines, where he directs the Molecular Theory Group (MTG). At the MTG, knowledge of bonding is obtained through detailed topological analyses of the spatial distribution of electrons in molecules and solids. Many subtle aspects of the distribution become obvious when viewed from a topological perspective. The accompanying topological formalism gives well-defined, unambiguous, meaningful, and consistent definitions to previously indeterminate quantities such as atomic bonds and basins. His work is based primarily on first principles computations, which provide the electron charge densities, and on topological analysis software developed at the MTG. He is also exploring the topological and geometric origins of the stability of amorphous metallic alloys. In addition to its work on condensed-phase systems, his group has active research programs exploring the relationships between charge density and the chemical properties of molecular systems, both organic and inorganic. Dr. Eberhart holds a B.S. in chemistry and applied mathematics from the University of Colorado, an M.S. in physical biochemistry from the University of Colorado, and a Ph.D. in materials science and engineering from the Massachusetts Institute of Technology.

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 has directed a research team working on investigations of the dynamic 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 mechanical response of materials. These constitutive and damage models are utilized in engineering computer codes to support large-scale finite element modeling simulations of structures ranging from national defense (DOE, DOD, DARPA), industry (GM, Ford, Chrysler, and Bettis), foreign object damage, and manufacturing. He is a Life Member of Clare Hall, University of Cambridge, in the U.K., where he was on sabbatical in the summer of 1998. He co-chaired the Physical Metallurgy Gordon Conference in 2000. He is a fellow of the American Physical Society (APS), a fellow of ASM International (ASM), and a fellow of the Minerals, Metals, and Materials Society (TMS). He also serves on the International Scientific Advisory Board of the European DYMAT Association. In 2010 he served as the president of the Minerals, Metals, and Materials Society. Starting in 2012 he became the chair of the Acta Materialia board of governors, which oversees the publication of the journals *Acta Materialia*, *Scripta Materialia*, and *Acta Biomaterialia*. He has authored or coauthored over 410 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-Mont.). 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 American Institute of Aeronautics and Astronautics (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, 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, nonlinear 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. He is an elected fellow of the AIAA, the AHS, and the NTA for personal engineering achievements, engineering education, management, and advancing cultural diversity.

Staff

EVA LABRE is the administrative coordinator for the Laboratory Assessments Board (LAB) in the Division on Engineering and Physical Sciences (DEPS) at the National Academies of Sciences, Engineering, and Medicine. 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. In February 2014 she was promoted and has recently taken on more responsibilities related to financial aspects of the work of the LAB. Ms. Labre previously held administrative positions at the Academies on the staff of the Committee on International Organizations and Programs in the Office of International Affairs and on the staff of the Research Associateship Program in the 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 LAB, the Army Research Laboratory Technical Assessment Board (ARLTAB), and the Committee on the National Institute of Standards and Technology Technical Programs, all within DEPS at the Academies. Since 1994, he has been a senior staff officer at the Academies, 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 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 the Academies projects on air traffic control automation, musculoskeletal disorders and the workplace, and the changing nature of work. Prior to joining the Academies, 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 LAB in DEPS at the Academies. Since 1999, he has been directing projects in the areas of defense science and technology, including those carried out by numerous study committees of the LAB, the ARLTAB, the Naval Studies Board, and the National Materials and Manufacturing Board. Prior to joining the Academies, 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 was administrative assistant at the LAB in DEPS at the Academies, where from March to December 2014 she assisted in the management of the administrative aspects of panel formation, panel meetings, report publication and dissemination, and program development. In addition, she was responsible for travel expense accounting. Prior to joining the LAB, Ms. Shelton 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 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/or numerical models?
- Are the qualifications or 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 Board will also consider 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:

Project Goals and Plans

- Are the objectives clearly stated and are tasks well defined to achieve objectives?
- Are milestones defined? Are they appropriate? Do they appear feasible?
- Are obstacles and challenges defined (technical, resources, time)?
- Assuming success, what difference will it make to the science base, the end-user, or in a mission area context?
- Does the project plan identify dependencies (i.e., successes depend on success of other activities within the project or on the success of projects developed outside ARL)?
- Does the project represent an area where application of ARL strengths is appropriate?
- What stopping rules, if any, are being or should be applied?

Methodology and Approach

- Are the methods (e.g., laboratory experiment, modeling/simulation, field test, analysis) appropriate to the problems? Do these methods integrate?
- Are the hypotheses appropriately framed within the literature and theoretical context?

- Is there an alternative approach that facilitates the progress of the project?
- Is there a clearly identified and appropriate process for performing required analyses, prototypes, models, simulations, tests, etc.?
- Is the data collection and analysis methodology appropriate?
- Are conclusions supported by the results?
- Are proposed ideas for further study reasonable?
- Do the trade-offs between risk and potential gain appear reasonable?
- If the project demands technological or technical innovation, is that occurring?

Capabilities and Resources

- If staff or equipment are not adequate, how might the project be triaged (which technical thrust should be emphasized, which sacrificed?) to best move toward its stated objectives?
- Recruiting new talent into ARL.

Scientific Community

- Presentations and colloquia.
- Participation in professional activities (society officers, conference committees, journal editors).
- Papers in quality refereed journals and conference proceedings (and their citation index).
- Educational outreach (serving on graduate committees, teaching/lecturing, invited talks, mentoring students).
- Fellowships and awards (external and internal).
- Participation on review panels (ARO, NSF, MURI, …).
- Patents and intellectual property (IP) and examples of how the patent or IP is used.
- Involvement in building an ARL-wide cross-directorate community.
- Public recognition, e.g., in the press and elsewhere, for ARL research.
- Collaborations (lead, partner, support).

D

Acronyms

2D	two-dimensional
3D	three-dimensional
ACM	Association for Computing Machinery
ARL	Army Research Laboratory
ARLTAB	Army Research Laboratory Technical Assessment Board
ARO	Army Research Office
CISD	Computational and Information Sciences Directorate
CRA	Collaborative Research Alliance
CTA	Collaborative Technology Alliance
DARPA	Defense Advanced Research Projects Agency
DE	directed energy
DOD	Department of Defense
DOE	Department of Energy
EAR	environment for auditory research
EEG	electroencephalogram
fMRI	functional magnetic resonance imaging
FY	fiscal year
GPU	graphics processing unit
GUI	graphical user interface
HPC	high-performance computing
HRED	Human Research and Engineering Directorate
HRI	human–robot interaction
HSI	human–system integration
IED	improvised explosive device
IEEE	Institute of Electrical and Electronics Engineers
IMPRINT	Improved Performance Research Integration Tool
IR	infrared
ITA	International Technology Alliance
JP-8	jet propellant 8 (fuel)
KCI	key campaign initiative

Li-ion	lithium ion
M&S	modeling and simulation
MAST	micro-autonomous systems and technology
MEMS	microelectromechanical system
MURI	Multidisciplinary University Research Initiative
NASA	National Aeronautics and Space Administration
NSF	National Science Foundation
PDV	photon Doppler velocimetry
PLDI	programming language design and implementation
QMU	quantification of the margin of uncertainty
QWIP	quantum-well infrared photodetector
R&D	research and development
RF	radio frequency
S&T	science and technology
SEDD	Sensors and Electron Devices Directorate
SLAD	Survivability/Lethality Analysis Directorate
SPEAR	soldier performance and equipment advanced research
SWaP	space, weight, and power
TARDEC	Tank Automotive Research, Development, and Engineering Center
TBI	traumatic brain injury
TEM	transmission electron microscopy
TN	translational neuroscience
UV	ultraviolet
V&V	validation and verification
VTD	Vehicle Technology Directorate
WMRD	Weapons and Materials Research Directorate