An Assessment of the National Institute of Standards and Technology Manufacturing Engineering Laboratory: Fiscal Year 2010

Panel on Manufacturing Engineering; National Research Council

ISBN
978-0-309-16161-9

40 pages
8 1/2 x 11
PAPERBACK (2010)

AN ASSESSMENT OF THE NATIONAL INSTITUTE OF STANDARDS AND TECHNOLOGY MANUFACTURING ENGINEERING LABORATORY

FISCAL YEAR 2010

Panel on Manufacturing Engineering

Laboratory Assessments Board

Division on Engineering and Physical Sciences

NATIONAL RESEARCH COUNCIL
OF THE NATIONAL ACADEMIES

THE NATIONAL ACADEMIES PRESS
Washington, D.C.
www.nap.edu

THE NATIONAL ACADEMIES PRESS 500 Fifth Street, N.W. Washington, DC 20001

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This study was supported by Contract No. SB134106Z011, TO#8, between the National Academy of Sciences and the National Institute of Standards and Technology, an agency of the U.S. Department of Commerce. Any opinions, findings, conclusions, or recommendations expressed in this publication are those of the authors and do not necessarily reflect the views of the agency that provided support for the project.

International Standard Book Number-13: 978-0-309-16161-9
International Standard Book Number-10: 0-309-16161-4

Copies of this report are available from

Laboratory Assessments Board
Division on Engineering and Physical Sciences
National Research Council
500 Fifth Street, N.W.
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Printed in the United States of America

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

Montgomery Alger, Air Products and Chemicals, Inc.,
Dianne Chong, The Boeing Company,
Harry Cook, University of Illinois (emeritus), and
David Markle, Consultant, Saratoga, California.

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 Alton D. Slay, Warrenton, Virginia. Appointed by the National Research Council, he was responsible for making certain that an independent examination of this report was carried out in accordance with institutional procedures and that all review comments were carefully considered. Responsibility for the final content of this report rests entirely with the authoring panel and the institution.

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Summary

The mission of the Manufacturing Engineering Laboratory (MEL) of the National Institute of Standards and Technology (NIST) is to promote innovation and the competitiveness of U.S. manufacturing through measurement science, measurement services, and critical technical contributions to standards. This mission is consistent with the NIST mission. The MEL is organized into five divisions: Intelligent Systems, Manufacturing Metrology, Manufacturing Systems Integration, Precision Engineering, and Fabrication Technology (not assessed because it provides instrument and fabrication support for NIST researchers).

The MEL total staffing for fiscal year (FY) 2009 was 183 (171 full-time permanent staff and 12 other staff), and its estimated annual budget for FY 2010 is $48.7 million ($35.5 million from NIST appropriations, $7.1 million from other agencies and external research and development, and $4.8 million from calibration service fees and reimbursables; the total excludes shops). The MEL also has 99 guest researchers. For FY 2006 through FY 2009, MEL total staffing has been 201, 198, 188, and 183, respectively, and for FY 2007 through FY 2010 (estimated), MEL total funding has been $51.0 million, $50.1 million, $49.7 million, and $48.7 million, respectively.

The Intelligent Systems Division has 31 NIST (full-time permanent) staff and 14 guest researchers (full-time-equivalent). Its FY 2010 estimated funding is about $8.9 million, with about 38 percent coming from extramural sources, and it has 3 programs containing 12 projects. The Manufacturing Metrology Division has 33 NIST staff, 7 guest researchers, and 2 postdoctoral researchers. Its FY 2010 estimated funding is about $9.9 million, with about 17 percent coming from extramural sources (including reimbursable services). It has 3 programs containing 20 projects. The Manufacturing Systems Integration Division has 26 NIST staff, 1 part-time permanent worker, 34 NIST associates, and 1 postdoctoral researcher. Its FY 2010 estimated funding is about $9.5 million, with about 7 percent coming from extramural sources, and it has 2 programs containing 10 projects. The Precision Engineering Division has 35 NIST staff, 22 guest researchers, and 1 postdoctoral researcher. Its FY 2010 estimated funding is about $12.7 million, with about 23 percent coming from extramural sources, and it has 3 programs containing 19 projects.

A panel of experts appointed by the National Research Council (NRC) has assessed the four divisions. Panel members visited these divisions and reviewed their activities. The scope of the assessment included the following three criteria: (1) the technical merit of the current MEL programs relative to current state-of-the-art programs worldwide; (2) the adequacy of the MEL budget, facilities, equipment, and human resources, as they affect the quality of MEL's technical programs; and (3) the degree to which MEL programs in measurement science, standards, and services achieve their stated objectives and desired impact.

In this report, the summary assessment of the MEL is given, followed by a summary assessment for each division. Chapters 1 through 6 present a description of the assessment process, detailed assessments of the divisions, and overall report conclusions.

SUMMARY ASSESSMENT OF THE LABORATORY

The Manufacturing Engineering Laboratory continues to excel in measurement science, measurement services, and technical contributions to standards. The MEL is achieving its mission, making crucial contributions to innovation and to the competitiveness of U.S. manufacturing. From a national perspective, MEL activities such as standards development and calibration services are providing baselines for many sectors of the economy. On an international level, the MEL is enabling industries to relate standards used in the United States to those used in other countries; this capability is necessary and critical for the participation of U.S. industries in international commerce. Research by MEL staff is on the forefront of measurement sciences, enabling industry to develop and deliver products of ever-higher quality and complexity to world markets and enabling future innovative manufacturing industries and processes. It is essential that the MEL maintain the integrated level of effort required for success in this broad spectrum of activities.

Across the MEL, project management and portfolio management strategies have continuously improved. The portfolio of projects is increasingly customer-focused (taking into account present and future customers) and well distributed technically in terms of high and low risk and short- and long-term payoff. Although this achievement is noteworthy, the MEL will need to address looming challenges in measurement science, measurement services, and standards in areas such as transformable, high-precision factories that operate beyond the current state of the art in accuracy and quality[1] and new manufacturing processes and products with decreasing dimensional scale and integrated biotechnology.[2] To address these challenges will require more coupling of critical project selection with technical staff and equipment development than the MEL currently has done.

Measurement science, measurement services, and standards that are well beyond the current state of the art are required to ensure the future competitiveness of U.S. industry in sustainable, high-value-added manufacturing with transformable factories that produce with high precision using manufacturing processes and products with ever-decreasing dimensional scale. This is also true for information technology (IT) for manufacturing, including knowledge bases and “smart” products and factories, and for biotechnology for manufacturing, including biological product components and biologically derived process components. Closer coupling into the MEL of other technology areas of NIST (IT and materials, for example) and closer coupling into the MEL of external expertise (in the application of biological processes and materials in manufacturing, for example) are necessary for addressing these areas and preparing for the future. The technical expertise of the MEL staff, its equipment, and its relationships with other laboratories must evolve quickly to meet the future needs of industry in areas such as these.

The MEL is having a significant impact on today’s manufacturing industries, ranging from traditional production industries to optics industries to semiconductor

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[1] Francesco Jovane, Engelbert Westkämper, and David Williams, *The ManuFuture Road: Towards Competitive and Sustainable High-Adding-Value Manufacturing*. Berlin: Springer-Verlag 2009.

[2] National Research Council, *Visionary Manufacturing Challenges for 2020.* Washington, D.C.: National Academy Press, 1998.

industries, and it is making significant enabling contributions to future U.S. manufacturing industries. Examples are numerous, including the following:

- An industrial Ethernet network performance test tool that allows vendors and users to validate network performance before deployment;
- NIST SP 800-53, *Recommended Security Controls for Federal Information Systems,* and NIST SP 800-82, *Guide to Industrial Control Systems Security;*
- Standard for the Exchange of Product model data (STEP);
- Online testing services that enable software vendors to validate the conformance of their products to standards;
- Standards for wireless sensors;
- Techniques for using deoxyribonucleic acid (DNA) molecules as an intrinsic small-force standard;
- Improvement of mass metrology and calibration by tying the current air-based kilogram definition to the vacuum-based alternative definition;
- Development of an atomic force microscope (AFM) for line roughness measurements crucial for 22 nm lithography; and
- Atomically sharp tip nano-writing to be used in developing standards for dimensions on the order of a few atoms that are traceable to NIST.

The MEL is recognized as the world leader in many of these areas.

The MEL has excellent research facilities and equipment. In general, its equipment is state of the art or beyond, well maintained, and operated by knowledgeable experts. However, its equipment will age quickly, constraining the ability of the laboratory to respond to changing technology. Significant upgrades in metrology equipment will be required in the near future to update existing systems and put in place next-generation systems that are more reliable and that cost less. However, the Advanced Measurement Laboratory (AML)[3] has provided best-in-the-world facilities for equipment that in many cases is the most advanced available. The MEL also will benefit from the construction of a new robot test facility, which will be an important national resource for this rapidly developing industry. However, other countries also are making major investments in such facilities. The MEL successfully leverages many of its programs through partnerships, primarily with federal agencies but also with key industries. The budget available for capital acquisitions seems to be inadequate for such a capital-intensive laboratory.

MEL staff are doing high-quality, innovative work. While progress has been made in hiring permanent scientific and engineering staff in key areas, the MEL remains significantly underfunded for personnel, with stagnant budgets exacerbated by increasing costs. Current staffing is highly senior, and a lack of new positions makes bringing in junior people difficult. Such issues continue to result in stop-gap reliance on guest researchers. Postdoctoral salaries are inadequate for engineering fields, making it difficult to attract the best candidates in critical technical areas—candidates who are potential

[3] The AML is a NIST facility that is used by multiple NIST operating units. Within the MEL, the Precision Engineering Division and the Manufacturing Metrology Division have laboratories in the AML.

future permanent staff. Several MEL staff have been in acting positions for a long time, a situation likely to affect career paths and threaten overall staff retention and development and hence the technical capability and competence of the laboratory. In response to such issues, NIST should critically assess its commitment to and support of manufacturing, in line with President Obama's placement of manufacturing as a top national priority and its importance in job creation and increased competitiveness in U.S. industry.

SUMMARY ASSESSMENTS OF FOUR DIVISIONS

Intelligent Systems Division

The Intelligent Systems Division (ISD) develops the measurements and standards infrastructure needed for the application of intelligent systems. It has well-established core competencies in standards, performance evaluation, measurement, interoperability, safety, and security. The ISD is serving as a catalyst in promoting collaboration between industries, with a focus on standards and testbeds, and it has established new standards for the security of industrial control systems. The ISD's technical capabilities are among the best in the world in STEP-NC (Standard for the Exchange of Product model data: Numeric Control; standard for programming machine tools) and OMAC (Open Modular Architecture Controller) for real-time data models, machine compensation, machining tool path optimization, Ethernet/Internet Protocol (IP) performance testing, and other applications. The division has established industrial controls and networks standards for federal government and industrial users. NIST SP 800-53 was established for security controls for federal information systems, and NIST SP 800-82 was established as a guide to industrial control systems security. These allow the federal agencies and the private sector to determine the proper security controls for their IT systems as well as to secure their industrial control systems effectively while addressing their unique requirements. The ISD is recognized as a world leader in the performance evaluation of complex, intelligent systems.

The work of ISD staff is sound and state of the art; yet, the work is small in a field of rapidly evolving technology and would benefit from the closer integration into the MEL of other NIST IT resources. The ISD has brought its strengths in measurement, performance evaluation, standards, and interoperability to bear on important related areas such as the security and safety of industrial control systems. Strengthened global benchmarking and self-assessment activities by the division should be performed to identify gaps and drive future project selection. The ISD could have broader impact through consortium development, further leveraging industry involvement and investment to accelerate the dissemination of developed standards. The ISD has excellent research facilities and equipment; however, many other places around the world (e.g., Germany, Japan, Korea, Singapore, Europe) are making major investments in the intelligent systems area, and ISD facilities and activities are no longer unique and unrivaled.

Manufacturing Metrology Division

The Manufacturing Metrology Division (MMD) programs cover mechanical metrology, metrology for advanced optics, and measurements and standards for science-based manufacturing needed to promote innovation and international trade by U.S. industry. The MMD is supporting standards from cradle to grave and rebirth, including the development of new standards, the calibration of artifacts to the current standards, and new concepts that may become the fundamental foundation on which next-generation standards are built. The MMD is making measurements that could not be done before by improving existing technologies and developing new approaches. It also is enhancing current capabilities through automation to improve accuracy and to reduce uncertainty, costs, and turnaround time. The programs compare very favorably with peer activities at the national standards institutions of other countries such as England and Germany. MMD staff members are key participants in standards committees for such areas as mass metrology and wireless sensors, and they actively disseminate the results to a wide audience.

The research portfolio of the MMD is well distributed, from mature to emerging technologies and from low-risk projects such as automating calibration capabilities, to high-risk projects such as utilizing DNA molecules to serve as an intrinsic small-force standard. The MMD staff is engaged in high-quality, innovative work. The division is increasingly customer-driven and has improved its process for selecting new projects and focus areas. Much of its metrology infrastructure is aging and will need to be updated in the near future.

Manufacturing Systems Integration Division

The Manufacturing Systems Integration Division (MSID) is responsible for working with industry to develop and apply software interoperability and standards for both product innovation and life-cycle management. The MSID is also charged with developing the metrics and standards for the manufacturing information and knowledge essential to meet today's highly integrated, distributed, and complex supply-chain environment. The division is building on its strengths and taking a longer-term approach in which the knowledge representation of manufacturing processes and products is expected to be an enabler for new manufacturing capabilities. MSID's efforts follow the successful deployment of STEP standards for the distribution of engineering knowledge for machine parts. According to industry customers, the results of MSID's research and development (R&D) are highly useful in paving the way for efficient, low-cost, high-volume manufacturing for the particular segment of manufacturing being looked at, and they are likely to be equally useful across many domains of manufacturing and even the full business enterprise. However, the R&D has been more focused on traditional industries such as the automotive industry than on the semiconductor and pharmaceuticals manufacturing industries.

Unfortunately, largely owing to human resource limitations, only a few selected areas can be worked on at the current time; nonetheless, the MSID has made impressive strides in those areas on which it is focused. In order to prove the viability of the knowledge representation, models of different aspects of manufacturing are created and tested (e.g., the supply chain, shipping, processing, etc.), and these are discussed with potential customers (manufacturers, suppliers of equipment and materials, transportation companies, etc.) at well-attended workshops. Simulation of various aspects of manufacturing are carried out and compared to real manufacturing output to determine whether the assumptions and rules are justifiable and whether the model output is accurate, timely, and worthwhile.

Precision Engineering Division

The Precision Engineering Division (PED) conducts R&D in precision-engineered length-metrology-intensive systems in both measuring and production machines, aiming for both high-accuracy measurement results and first-principles analysis of measurement systems. The division maintains many activities and services, many or possibly most of which are among the best in the field. With a relatively small level of funding, the PED successfully performs a critical role for the nation, carrying on in the ever-changing and challenging legacy of NIST.

The PED provides the foundation for dimensional measurements ranging over 12 orders of magnitude (from kilometers to nanometers). Thus the work of this division is crucial to the current and future competitiveness of U.S. industry and in the development of standards traceable to NIST. The PED staff is enthusiastic about its work, dedicated and knowledgeable.

The PED divides its work into four groups, basically by length scale: nanometer (nm) to micrometer (μm), micrometer to millimeter (mm), millimeter to meter (m), and greater than 1 m. These groups have primary responsibilities within these scales but interact strongly and provide expertise throughout the PED.

The PED provides NIST a remarkable and cost-effective interface with the outside world. Its impact is clearly evident. This is seen, for example, from the following: (1) continuous requests for its services from industry and government that far exceed the capacity of the PED to meet, (2) interest in technical work presented at meetings, (3) demonstrated collaborations with a variety of industrial concerns, (4) citations garnered by publications, and (5) the acquisition of equipment either donated or purchased at bargain prices.

Since the previous assessment by an NRC panel in 2008, the PED has made major strides in several areas. It is maximizing the advantages of the new Advanced Measurement Laboratory. By reducing artifacts such as vibration and temperature variations, the AML environment has enabled the limiting capabilities of machines to be assessed directly and routinely, avoiding the need to compensate for the environment. In helium-ion microscopy, the PED is operating as a beta site for advanced equipment. It is also moving into highly relevant new areas, such as metrology that is essential for fuel cells, the development of atomic-scale metrologies traceable to the meter, and new methods for detecting defects for next-generation integrated-circuits technology. The application of the PED's coordinate measuring machines (CMMs) such as the Moore M48 provides unique capabilities for performing accurate measurements on difficult objects—for example, assisting the U.S. Army by making measurements of local damage on body armor impacted by projectiles to an accuracy of 0.1 mm. Overlay metrology, as done in the PED, is recognized as state of the art.

The PED laboratories are spacious, with good infrastructure. They are well lit and have stable air temperature and low ambient vibration resulting from isolated floor pads. In general, the division's equipment is state of the art or beyond, well maintained, and operated by knowledgeable experts. The minimal acquisition of capital equipment threatens future PED infrastructure and technical capabilities. Nevertheless, the PED is clearly the place to go for the best in manufacturing metrology.

RECOMMENDATIONS

The recommendations of the panel based on its assessment of the Manufacturing Engineering Laboratory and its divisions are as follows:

- Across the MEL, project management and portfolio management strategies have continuously improved; however, more coupling of critical project selection with technical staff and equipment development should be pursued.
- Closer MEL coupling with other technology areas of NIST (information technology and materials, for example) and with external expertise (in the application of biological processes and materials in manufacturing, for example) should be pursued.
- The MEL's research facilities and equipment will age quickly, and significant upgrades in metrology equipment will be required in the near future to update existing systems and put in place next-generation systems.
- The MEL should review the budget available for capital acquisitions, which seems to be inadequate for such a capital-intensive laboratory.
- The MEL is adversely affected by issues such as the significant underfunding for personnel, the difficulty of bringing in junior staff, the inadequacy of postdoctoral salaries, and the fact that several staff members have remained in acting positions for a long time. To address such issues, NIST should critically assess its commitment to and support of manufacturing, in line with the President's placement of manufacturing as a top national priority and its importance in job creation and increased competitiveness in U.S. industry.
- For the Intelligent Systems Division, there is a need for strengthened global benchmarking and self-assessment activities.
- The ISD is leveraging its program development through partnerships with other agencies. NIST and the MEL should provide incentives and not disincentives for such partnership activities through their budgeting processes, overhead rates, merit policies, and so on. The partnerships with industry are more limited, and they should grow. The ISD could make broader impacts through consortium development.
- The ISD is limited by staffing constraints, flat budgets, and attrition, which may be impeding the development of and recognition of leadership by ISD staff in the world technical community, and this should be addressed.
- The Manufacturing Metrology Division should continue to develop the process for selecting new projects and focus areas and ensure its transparency.

- The MMD workload has increased as new capabilities have been added. More funds for personnel should be provided.
- The MMD should continue to enhance its current capabilities through automation to improve accuracy, reduce costs, broaden operational ranges, reduce uncertainty, and reduce turnaround time.
- Much of the MMD metrology infrastructure is aging and will need to be updated or repaired in the near future. Funds will be necessary to update these systems, develop models of next-generation metrology systems that are more reliable and lower in cost, and then develop these next-generation systems.
- The Manufacturing Systems Integration Division should better articulate its successes to a wider audience of researchers and practitioners.
- Staffing in the MSID is highly senior. It is difficult to bring in junior staff, and attracting postdoctoral researchers remains a problem because of salary, permanence, and other issues. Other means of obtaining resources should be considered: for example, interns and people from industry working on-site.
- The Precision Engineering Division should continue participation in regional and international round robins as a key benchmarking exercise.
- The budget available for PED capital acquisitions is inadequate for such a capital-intensive division and should be increased.
- The PED should pursue stronger interfaces with other areas of NIST: for example, the Center for Nanoscale Science and Technology and the Physics Laboratory.
- The PED management needs to develop and implement a critical-skills staffing plan independent of future budget developments so that its critical expertise within NIST is maintained.

1

The Charge to the Panel and the Assessment Process

At the request of the National Institute of Standards and Technology, the National Research Council has, since 1959, annually assembled panels of experts from academia, industry, medicine, and other scientific and engineering environments to assess the quality and effectiveness of the NIST measurements and standards laboratories, of which there are now nine,[4] as well as the adequacy of the laboratories' resources. In 2010, NIST requested that five of its laboratories be assessed: the Building and Fire Research Laboratory, the Manufacturing Engineering Laboratory, the Materials Science and Engineering Laboratory, the NIST Center for Neutron Research, and the Physics Laboratory. A separate panel of experts assessed each of these; the findings of the respective panels are summarized in separate reports. This report summarizes the findings of the Panel on Manufacturing Engineering.

For the fiscal year (FY) 2010 assessment, NIST requested that the panel consider the following criteria as part of its assessment:

1. The technical merit of the current laboratory programs relative to current state-of-the-art programs worldwide;
2. The adequacy of the laboratory budget, facilities, equipment, and human resources, as they affect the quality of the laboratory's technical programs; and
3. The degree to which laboratory programs in measurement science, standards, and services achieve their stated objectives and desired impact.

The panel adopted the following additional assessment criteria to make the broad factors more explicit. These criteria were only suggested to guide the assessment process and did not need to be individually addressed.

1. Technical Quality and Merit Assessment Criteria
   - *Relative Technical Caliber:*
     —How does the technical quality of the laboratory programs compare to current state-of-the-art programs worldwide?
     —Does the laboratory work product consistently demonstrate evidence of high technical quality (including but not limited to papers in high-impact technical publications, invited talks to major scientific and industry conferences and workshops, and external awards and recognition)?

[4] The nine NIST laboratories are the Building and Fire Research Laboratory, the Center for Nanoscale Science and Technology, the Chemical Science and Technology Laboratory, the Electronics and Electrical Engineering Laboratory, the Information Technology Laboratory, the Manufacturing Engineering Laboratory, the Materials Science and Engineering Laboratory, the NIST Center for Neutron Research, and the Physics Laboratory.

- *Distinctness:*
  - —Do the projects reflect mission focus?
  - —Is the value proposition distinctive and in keeping with NIST's role and strategy?
- *Relevance:*
  - —Is there a clear tie between projects and NIST and MEL strategic priority areas?
  - —Do the projects reflect a broad understanding of comparable work being done elsewhere (in other government laboratories, universities, and industry)?
  - —Are there demonstrable links between NIST researchers and the external community?
- *Balance:*
  - —Does the laboratory adequately balance anticipatory, longer-term research and activities that respond to immediate customer needs?

2. Adequacy of Budget, Facilities, Equipment, and Human Resources Assessment Criteria
   - *Available Tools:*
     - —Is the state of the equipment and facilities adequate to meet project objectives and customer needs?
   - *Critical Mass:*
     - —Are the available scientific and technical competencies adequate to achieve success?
     - —Is available funding adequate to achieve success?
   - *Agility:*
     - —Is the laboratory sustaining the technical competencies and capacity to respond quickly to critical issues as they arise?
3. Achievement of Stated Objectives Assessment Criteria
   - *Technical Planning:*
     - —Are appropriate milestones identified? Do they appear feasible?
     - —Are obstacles and challenges defined (technical, resources)?
     - —Are the roles of the investigators clear, and are the individual project tasks and objectives clearly linked to those of other projects within a given strategic priority area?
   - *Dissemination:*
     - —Is the laboratory regularly implementing sound and effective techniques and practices for delivering products and services?
     - —Are the results of the laboratory projects readily available to stakeholders?
   - *Impact:*
     - —How well do the laboratory programs in measurement science, standards, and services achieve their stated objectives and desired impact?
     - —Will the laboratory products have a consequential, long-term impact?

- *Level of effort:*
  —Are research projects scaled appropriately to meet the technical problems being addressed?
- *Responsiveness:*
  —Are the research projects moving at a pace and in a direction that is well matched to current and emerging stakeholder needs?

4. Other Considerations
   - *Collaboration and crosscutting within a given laboratory*
   - *Project-level technical planning*

The context of this technical assessment is the mission of NIST, which is to promote U.S. innovation and industrial competitiveness by advancing measurement science, standards, and technology in ways that enhance economic security and improve the quality of life. The NIST laboratories conduct research to anticipate future metrology and standards needs, to enable new scientific and technological advances, and to improve and refine existing measurement methods and services.

In order to accomplish the assessment, the NRC assembled a panel of 15 volunteers, whose expertise matches that of the work performed by the MEL staff.[5] The panel members were also assigned to four subgroups (division review teams), whose expertise matched that of the work performed in the four divisions reviewed in the MEL: (1) Intelligent Systems, (2) Manufacturing Metrology, (3) Manufacturing Systems Integration, and (4) Precision Engineering.

The panel met at the NIST facilities in Gaithersburg, Maryland, on March 8-10, 2010. After the full panel had met for a session of welcoming remarks from the NIST Director's representative and an overview presentation on the MEL by MEL management, the panel divided into its four review teams, and each team (led by a team leader chosen from within the panel) then visited with the staff of its respective MEL division for about a day. During these visits, the review team members attended presentations, tours, demonstrations, and interactive sessions with the MEL staff. Subsequently, the entire panel assembled for about a day-and-a-half meeting, during which it interacted with MEL and NIST management and also met in a closed session to deliberate on its findings and to define the contents of this assessment report.

The approach of the panel to the assessment relied on the experience, technical knowledge, and expertise of its members, whose backgrounds were carefully matched to the technical areas of MEL activities. The panel reviewed selected examples of the technological research covered by the MEL; because of time constraints, it was not possible to review the MEL programs and projects exhaustively. The MEL selected the examples reviewed by the panel. The panel's goal was to identify and report salient examples of accomplishments and opportunities for further improvement with respect to the following: the technical merit of the MEL work, its perceived relevance to NIST's own definition of its mission in support of national priorities, and specific elements of the MEL's resource infrastructure that are intended to support the technical work. These examples are intended collectively to portray an overall impression of the laboratory,

[5] See http://www.nist.gov/mel/ for more information on MEL programs. Accessed May 1, 2010.

while preserving useful suggestions specific to projects and programs that the panel examined. The assessment is currently scheduled to be repeated biennially, which will allow, over time, exposure to the broad spectrum of MEL activity. While the panel applied a largely qualitative rather than a quantitative approach to the assessment, it is possible that future assessments will be informed by further consideration of various analytical methods that can be applied.

The comments in this report are not intended to address each program within the MEL exhaustively. Instead, this report identifies key issues. Given the necessarily nonexhaustive nature of the review process, the omission of any particular MEL program or project should not be interpreted as a negative reflection on the omitted program or project.

2

Intelligent Systems Division

The Intelligent Systems Division's stated goal is to develop the measurements and standards infrastructure needed for the application of intelligent systems. The ISD has well-established core competencies in the areas of standards, performance evaluation, measurement, interoperability, safety, and security. It plays an important role in promoting the science, technologies, and tools related to manufacturing engineering. Standards and services are very important to U.S. innovation and industrial competitiveness, especially in the current global economic environment in which many countries are making serious investments in intelligent manufacturing technologies.

The ISD is serving as a catalyst in promoting collaboration between industries, with a focus on establishing standards and testbeds in the areas of computerized numerical control (CNC), dimensional inspection equipment interoperability, manufacturing robotics and automation, and autonomous-vehicle and materials-handling systems. In the areas of safety and security, the ISD has established new standards for the security of industrial control systems. The ISD's technical capabilities are among the best in STEP-NC and OMAC for real-time data models, machine compensation, machining tool path optimization, Ethernet/IP performance testing, and others.

The ISD currently has 31 NIST staff and 14 guest researchers. Its FY 2010 estimated funding is about $8.9 million, with about 38 percent coming from extramural sources.

TECHNICAL MERIT RELATIVE TO STATE OF THE ART

The ISD promotes the development of measurement science and interoperability standards to enhance manufacturing robotics and automation equipment and the underlying industrial control systems. The division's recent efforts have focused on areas such as requirements and performance standards (defining, specifying, measuring, and evaluating robot and automation system performance and capabilities; proposing and facilitating repeatable, objective, and quantitative test methods and their associated environments, artifacts, and data); interoperability standards (requirements, interface definitions, data modeling, conformance assessment tools, facilitating the bringing together of industry stakeholders); and infrastructural technology to help build next-generation unmanned systems. The ISD operational environment includes strong interest and investment by federal agencies in robotics/intelligent systems, especially in the areas of defense and homeland security.

The ISD serves U.S. manufacturing by developing solutions for measurements, interoperability, and safety and security for intelligent robots, automation, and control systems. There is a renewed U.S. interest in manufacturing, robotic and automation systems at different levels. The ISD's short- and long-range plans are well in line with those of NIST. For example, NIST's proposed Innovations for 21st Century U.S. Manufacturing initiative points out the need to—

> Provide the measurement tools and capabilities necessary to develop and apply robotic technologies that are "smarter," more flexible, and better able to operate safely and effectively in less structured environments, to facilitate mass customization in manufacturing processes.[6]

The ISD is recognized as a world leader in the performance evaluation of complex, intelligent systems. The division is also recognized for its work in the development of interoperability standards for manufacturing automation systems, and its Intelligent Manufacturing Interoperability Standards Program has been in operation for some time. The motto for this program is "Smarter Data for Smarter Manufacturing." The newest activity in this framework is the Quality Information Interoperability project, in which the effort is focused on the seamless integration of quality requirements from design through planning, production, analysis, and reporting.

The ISD has been successfully leveraging the development of its manufacturing program through partnerships, primarily with Department of Defense (DOD) agencies, the Department of Homeland Security (DHS), and the Department of Transportation (DOT). Nearly 40 percent of ISD resources come from such partnerships. This is a strong indicator of the external recognition of ISD activities and expertise.

ADEQUACY OF INFRASTRUCTURE

The ISD has excellent research facilities and equipment, some of which is loaned by partners. It also will benefit from the new NIST robot test facility whose construction is expected to begin in the fall of 2010. The facility will be an important national resource for this rapidly developing industry. However, many other places around the world (e.g., Japan, Korea, Singapore, Europe) are making major investments in this area, and ISD facilities and activities are no longer unique and unrivaled.

The staffing resources are limited, constraining the ability of the ISD to respond with agility to changing technology needs. Strong world leadership is likely to be difficult to maintain when many management positions within the division are "acting" positions.

ACHIEVEMENT OF OBJECTIVES AND IMPACT

The ISD continues to develop its strategic technologies and testbeds in the areas of interoperability standards for quality information, next-generation manufacturing robotics for safety and security, and performance measurement of autonomous-vehicle systems, among other areas. It has had significant impact on the establishment of standards in these areas. One of its major impacts has been to establish industrial controls and networks standards for federal government and industrial users. NIST SP 800-53 was established for security controls for federal information systems, and NIST SP 800-82 was established as a guide to industrial control systems security. These allow federal agencies, as well as the private sector if it so desires, to determine the proper security controls for their IT systems as well as to secure their industrial control systems

[6] Additional information on this proposed NIST program initiative can be found at http://www.nist.gov/public_affairs/factsheet/comp_manuf2011.cfm. Accessed August 16, 2010.

effectively while addressing their unique requirements. SP 800-53 has been downloaded more than 1.25 million times since its initial release in 2009. In the area of robot safety, the ISD has developed a technical specification as input for the next revision of the International Organization for Standardization (ISO) robot safety standard (ISO 10218: *Robots for Industrial Environments—Safety Requirements*) to allow human-robot collaboration. The ISD is also contributing technical expertise to a new standard (ISO 13482: *Robots and Robotic Devices—Safety Requirements—Non-medical Personal Care Robot*) for nonmedical and personal-care robots and robotic devices. In the area of autonomous systems, the ISD has developed sensor performance metrics, standards, and infrastructure technology to support the use of semiautonomous and autonomous manipulators and vehicles, and control architecture.

In the area of quality information interoperability, the ISD and the International Association of Coordinate Measuring Machine Manufacturers demonstrated I++DME interoperability (I++DME is a nonproprietary language for communicating with a CMM) for different CMM manufacturers and enabled I++DME-compliant products in production facilities worldwide. In addition, the ISD has developed a new version of the Dimensional Measuring Interface Standard (DMIS) to support manufacturing industries' needs in integrating measurement systems with design and quality-assurance systems.

In the area of intelligent manufacturing, industrial control systems, and network standards, the ISD has developed an Industrial Ethernet Network Performance (IENetP) Test Tool that is an open-source test tool for industry: it allows vendors to determine device network performance during development and allows users to validate device network performance before deployment. Version V1.0.1 was released in 2009, and there had been more than 375 downloads as of February 1, 2010. The ISD has developed Mobility Open Architecture Simulation and Tools (MOAST), which is an implementation of the 4D/RCS reference model architecture for unmanned vehicle systems. It continues to develop STEP-NC, which defines a feature-based view of operations and includes solid-model descriptions, material, tooling, and tolerances. STEP-NC is part of the ISO 10303 suite of standards for the exchange of product and process data: specifically, Application Protocol 238 (AP-238). AP-238 is intended to replace the 50-year-old "G-code" format for numerically controlled machine tools that specified primitive tool motions.

CONCLUSIONS

Following are the conclusions of the panel based on its assessment of the Intelligent Systems Division:

- The caliber of the work in the ISD is sound and state of the art. Many projects have had high impact, including the industrial Ethernet test tool, security/safety standards of industrial control systems, the DMIS for CMMs, and performance testing of robots.
- There is a need in the division for strengthened global benchmarking and self-assessment activities. Such benchmarking can identify gaps and drive future project selection.

- It is commendable that nearly half of the ISD activities are not strictly in discrete-parts manufacturing. This is evidence that the ISD can bring its strengths in measurement, performance evaluation, standards, and interoperability to bear on important related areas such as the security and safety of industrial control systems, autonomous systems, and others.
- The ISD is leveraging its program development through partnerships, primarily with DOD agencies and the DOT. It is important that NIST and the MEL provide incentives, and not disincentives, for such partnership activities through their budgeting processes, overhead rates, merit policies, and other means. The division's partnerships with industry are more limited compared to those with government agencies, and they should grow. The ISD could make broader impacts through consortium development, further leveraging industry involvement and investment to accelerate the dissemination of the developed standards.
- The ISD is limited by staffing constraints, flat budgets, and attrition. This may be impeding the development and recognition of leadership by ISD staff in the world technical community.

3

Manufacturing Metrology Division

The mission of the Manufacturing Metrology Division is to fulfill the measurements and standards needs of U.S. discrete-parts manufacturers in mechanical metrology and advanced manufacturing technology. This mission is accomplished under the rubric of four focus areas: (1) research and development in realizing and disseminating the International System of Units (SI) mechanical units; (2) the development of methods, models, sensors, and data to improve metrology, machines, and processes; (3) the provision of services in mechanical metrology, optics metrology, machine metrology, process metrology, and sensor integration; and (4) leading in the development of national and international standards.

The research portfolio of the MMD is well distributed from low- to high-risk projects. Low-risk projects such as automating calibration capabilities in sound or mass have resulted in improved processes (e.g., lower uncertainty, larger dynamic range, reduced costs) while reducing the reliance on manual labor to execute these calibrations, enabling more efficient use of personnel and the ability to address customer needs better. High-risk projects—such as utilizing DNA molecules to serve as an intrinsic small-force standard, or the newly purchased laser lithography tool for fast diffractive-optics manufacture—are positioning NIST to continue its global leadership in nanotechnology and nanomanufacturing. The result of this research portfolio is a team and facilities that are well suited to target the four focus areas of the division. The MMD executes its mechanical metrology mission through two major efforts: (1) either by improving currently known processes or by developing completely new approaches, it makes measurements that could not be done before; and (2) it enhances current capabilities by means of automation to improve accuracy, reduce costs, broaden operational ranges, reduce uncertainty, and reduce turnaround time.

The MMD currently has 33 NIST staff, 7 guest researchers, and 2 postdoctoral researchers. Its FY 2010 estimated funding is about $9.9 million, with about 17 percent coming from extramural sources (including reimbursable services).

TECHNICAL MERIT RELATIVE TO STATE OF THE ART

NIST is well known for the high quality of its work in manufacturing metrology, and it continues to build this reputation from a variety of perspectives. The measurements executed in the MMD are of high quality and are often the de facto standard to which the National Measurement Institutes (NMIs) of other nations are held. Furthermore, the MMD team continues to develop new means of making measurements to address the ever-increasing demand for improved tests. For example, the work in the redefinition of the kilogram places NIST in the leadership position for next-generation mass definitions. The kilogram redefinition will be enabled through the establishment of the first “mise-en-pratique” (practical method for realization) and the dissemination of a new kilogram definition and a dissemination system that directly ties the current air-based kilogram definition to the vacuum-based alternative definition using stable artifacts with wear-resistant and chemical inertness characteristics that are maintained in controlled environments. Such work is critical in linking definitions employed in the United States to those used in other countries. Such links are necessary to ensure that U.S. industries can effectively compete in the global market.

Of particular note is the unique and highly innovative approach toward establishing SI traceability for small-force measurement. Atomic and single-molecule forces will be evaluated as potential intrinsic standards and references. New techniques using DNA molecules to serve as an intrinsic small-force standard and atomic force microscope microcantilevers and plastic deformation (nano-indentation) tests are being investigated to support nanomechanical investigators who are using atomic force microscopy to probe the physical characteristics of matter at the nanoscale. If successful, the results of this effort will place NIST ahead of other NMIs on measuring and calibrating extremely low forces.

The work by the MMD in science-based manufacturing is important in obtaining fundamental knowledge of manufacturing and metrology processes that, from a mechanistic perspective, will enable advances in processes and their control that are critical to moving current and next-generation manufacturing capabilities in the United States forward. However, this program cannot, and should not, address all fundamental issues in process modeling. It needs to be focused on measurement science and the needs of measurement services and standards.

In emerging areas such as wireless sensors, NIST researchers are acknowledged leaders in the development of standards. They developed a testbed for using and demonstrating wireless sensors (temperature and vibration). A sensor network on the shop floor was implemented as a validation platform for sensor and networking standards in factory environments. Given the likely widespread impact of this technology, it is critical that this leadership role be maintained with appropriate investment.

ADEQUACY OF INFRASTRUCTURE

The facilities and equipment of the MMD are very good, with state-of-the-art equipment found in each of the programs. For example, the large-mass calibration equipment is globally unparalleled. Other examples include optics (flat and spherical surface metrology equipment) and nanostructured-optics fabrication facilities. New equipment such as the laser lithography tool (with expected delivery in late 2010), a metal-based additive manufacturing system (still in the procurement process), and the newly automated calibration (mass and microphone) facilities will help the division to meet its objectives. The staff is extremely well suited to meet the objectives of the division and has demonstrated this capability with a very productive and successful recent history. There is no doubt that the staff will be able to continue its mission in a successful manner. Furthermore, it is hoped that the newly automated systems will enable the staff to spend more time conducting research.

ACHIEVEMENT OF OBJECTIVES AND IMPACT

The MMD continues to do a very good job of developing standards, providing calibration services, and establishing traceability. It remains at the state of the art in force measurement, optics metrology, machine-tool metrology, and acoustics metrology. The division has significant impact on the nation and the world through its broad spectrum of standards work, from defining new standards, to supporting current standards, to providing new fundamental definitions for next-generation standards. For example, MMD personnel are actively involved in the development of new standards (e.g., five-axis coordinated motion standards and Institute for Electrical and Electronics Engineers [IEEE] and ISO standards for wireless sensors). With respect to supporting current standards, services for the calibration of geometry (e.g., flatness, sphericity), mass, force, acceleration, and acoustical properties are state of the art and second to none. The MMD is developing new techniques to address next-generation standards such as a low-power precision magnetic levitation system. This system provides a link between present mass calibrations that are done at atmospheric pressure and the next-generation alternative calibrations that will be executed in vacuum. Systems such as this will enable the United States to lead in mass metrology and calibration well into the 21st century.

CONCLUSIONS

Following are the conclusions of the panel based on its assessment of the Manufacturing Metrology Division:

- The staff of the MMD are doing high-quality, innovative work and are to be commended for their outstanding efforts.
- The research portfolio of the MMD is well distributed, from mature to emerging technologies, and from low-risk to high-risk projects.
- The MMD is supporting standards from cradle to grave and rebirth, including the development of new standards, the calibration of artifacts to the current standards, and new concepts on which next-generation standards are developed.
- The MMD's measurement services are invaluable to the U.S. economy and for national security. From a national perspective, the division's calibration services provide a baseline for many sectors of the economy. From an international perspective, global commerce relies on the ability to relate standards used in the United States to those used in other countries.
- The MMD is customer-driven and clearly understands the importance of its work with respect to manufacturing, engineering, and science.
- The MMD has improved the process for selecting new projects and focus areas. It should continue to develop this process and ensure its transparency.
- The workload has increased as new capabilities are added to the MMD, but funding for personnel has remained relatively flat. More funds for personnel are necessary to enable the MMD to continue to expand its critical functions.

- The MMD should continue to enhance its current capabilities by means of automation in order to improve accuracy, reduce costs, broaden operational ranges, reduce uncertainty, and reduce turnaround time. This change would also have the effect of freeing personnel from routine calibration tasks, enabling them to spend more time on advanced research efforts.
- Much of the MMD metrology infrastructure is aging and will need to be updated or repaired in the near future. Funds will be necessary to update these systems, develop models of next-generation metrology systems that are more reliable and lower in cost, and then develop these next-generation systems.

4

Manufacturing Systems Integration Division

Two main focus areas within the Manufacturing Systems Integration Division are that of sustainable and life-cycle information-based manufacturing and that of supply-chain integration; both are appropriately aligned with the needs of U.S. industries. All the projects within these two programs are aligned with the MEL mission.

The Sustainable and Lifecycle Information-based Manufacturing (SLIM) Program has three primary objectives:

1. *Providing key standards requirements and best practices for sustainable manufacturing.* This objective includes analyzing and defining the relevant standards for areas ranging from carbon-footprint determination, to energy-resource management, to hazardous-material management. The program is also developing a scheme for computing the carbon footprint of a manufactured product—a critical mathematical "score" that can help resolve concerns such as the issue of reusable versus disposable products. NIST is looking to ensure that new standards mesh with current practices, so researchers are working to harmonize their "green" information standards with existing software standards for manufacturing product data, such as ISO 10303, popularly known as STEP.
2. *Providing a framework for environmental manufacturing models by determining key attributes and developing information models necessary for sustainable manufacturing.*
3. *Developing protocols for testing and simulating the application of "green" standards.*

In the Supply Chain Integration Program, the MSID has selected to focus on and address a set of key industrial "pain points" for maximum impact:

1. *Improving the information flow across the supply chain;*
2. *Gathering and disseminating best practices in sustainable manufacturing;* and
3. *Identifying meaningful sustainability metrics that lead to improvements.*

The supply/value chain sustainability question spans a very broad spectrum, from the mining of raw resources, through product manufacture and use, finally to product disposal. The focus is on supplier discovery and long-range logistics. Both of these issues involve significant integration problems. The Supply Chain Integration Program's technical focus is on the development and testing of standards needed to address those problems, collaborating with organizations such as the Open Applications Group, Inc., which develops domain standards, and with organizations such as the Object Management Group (OMG) and the World Wide Web Consortium (W3C) that develop knowledge representation standards.

The division currently has 26 full-time permanent NIST staff, 1 part-time permanent worker, 34 NIST associates, and 1 postdoctoral researcher. Its FY 2010 estimated funding is about $9.5 million, with about 7 percent coming from extramural sources.

TECHNICAL MERIT RELATIVE TO STATE OF THE ART

The MSID continues to undertake and execute programs of high technical merit and strong relevance and effectiveness with respect to U.S. competitive manufacturing. The division’s efforts in the SLIM Program, OMG, W3C, and STEP standards already worked out for engineering and manufacturing have been exemplary. In the SLIM Program, high-quality work is being performed related to heavy metal industries (e.g., aerospace, automotive).

MSID staff have elevated the status of product life-cycle management (PLM) from being merely an engineering concern to an enterprise-wide business concern, with emphasis on information integration and collaboration with partners. Achieving, ensuring, and maintaining global interoperability constitute too large a task for all but the biggest corporations. In addition, NIST is tasked to help address the interoperability problem at the global level. Working with industry, the MSID is helping to devise sustainable solutions for this multifaceted and global challenge in supply-chain requirements and the business aspects of PLM.

The MSID continues to bridge ISO 10303 application protocols to these modeling-language standards. A notable standardization achievement is the Simulation Interoperability Standard Organization’s Core Manufacturing Simulation Data specification standardization. The MSID has also continued to enhance online testing services that enable design-engineering, supply-chain, and e-business software vendors to validate the conformance of their products to emerging or existing standards. It has also provided tools to the standardization community to ensure rigorous quality for the standards themselves.

Work with the DHS shows the universality of the nature of informatics; the concepts being studied will be a bridge to the future in manufacturing. The systematic approach to informatics has applicability well beyond the domain of manufacturing, and this expertise as applied to the DHS is a special asset to NIST.

The development of a framework for an integrated tool set based on the widely used TOGAF (The Open Group Architecture Forum) is a solid beginning for defining the requirements of Enterprise interoperability and ensures completeness of the tool set.

ADEQUACY OF INFRASTRUCTURE

Given the MSID’s information-centric paradigm, the advanced manufacturing systems and networking testbed and the simulation laboratories’ equipment and facilities are adequate to meet projects’ objectives. Given the limited resources of the MSID, the scale of specific projects and the work planning are appropriate.

The actual-dollar annual budget has remained relatively constant over the past 5 years, at roughly $10 million in a time of generally increasing cost in all areas. This has a number of negative impacts in the context of MSID’s achieving its goals; due to insufficient expertise in other areas, the efforts in manufacturing remain limited in scope. For example, the budget and number of staff members are lower in 2010 than they were in 2008.

ACHIEVEMENT OF OBJECTIVES AND IMPACT

With its limited resources, the MSID has had to scope its focus carefully, and it has addressed the requirements and gaps in the standards. This work has been exemplary and should be extended deeper into the enterprise and to other areas such as the semiconductor and pharmaceuticals manufacturing industries through the resourcing of sufficient staffing. As a result of MSID's highly qualified staff, it is the acknowledged leader in the development of STEP standards and internationally recognized as a leader in influencing global standards bodies and other multinational organizations. MSID staff are active in standards committees for ISO STEP standards and are active in disseminating information by participating in meetings and conferences. They are motivated and capable and are providing high-quality work and expertise. The work being done by the MSID on the standards such as STEP is but one of the areas that are of high value and much interest to the U.S. industries. In addition, the MSID has had a very strong impact on interoperability and standards modularization and harmonization. The standards that have been developed by the MSID are already in use by U.S. manufacturing industries as well as by the Honda Motor Company, Ltd., and have been adopted by vendors.

CONCLUSIONS

Following are the conclusions of the panel based on its assessment of the Manufacturing Systems Integration Division:

- Through workshops and other external activities, the MSID has significant impact in areas in which it is active: customer requirements, standards, regulations, and others. As a result of its highly qualified staff, the MSID is internationally recognized as a leader in influencing standards bodies and other multinational organizations (including OMG, W3C, the Automotive Industry Action Group, and STEP).
- The MSID informatics effort is an essential and integrated effort across many domains and many issues, ranging from interoperability to "green" issues to supply-chain issues, from semiconductors to pharmaceuticals to aircraft. If this effort is disrupted, the chances of success in meeting goals become minimal.
- MSID technical leadership in treating modeling as an inherent and inseparable part of the manufacturing and even enterprise processes is commendable. And given the systematic approach to modeling informatics developed over the years and the expertise within the division, the MSID has a unique opportunity to influence not only other segments of the manufacturing domain, but it can also impact health care, security, and other complex activities.

- The MSID has clearly met its goals and objectives as evidenced by a reading of the division's progress reports. Nonetheless, it should articulate these successes better to a wider audience of researchers and practitioners.
- Current MSID staffing is highly senior, and the consequent lack of new positions makes bringing in junior people difficult. Attracting postdoctoral researchers remains a problem because of salary, permanence, and other issues. All of these considerations will impact the influx of new ideas, as will the reduced budget compared to that of previous years. Perhaps other means of obtaining resources can be considered—for example, having interns, having people from industry working on-site, and other possibilities.

5

Precision Engineering Division

The Precision Engineering Division delivers to industry important length-related measurements, standards, and technology services that directly support the products and processes of U.S. manufacturing. These standards are measured by a whole array of instrumentation ranging from atomic force microscopes to conventional and frameless coordinate measuring machines using contact, particle beam, and optical measuring probes, machines, and systems. Features of interest range in size from 1 kilometer (calibrated telecommunication cables) to meters (laser trackers) to nanometers (critical-dimension [CD] metrology instruments and nanoparticle dimensional metrology).

Modeling capabilities and methods are being developed together with experimental measurement technologies, and these are used jointly to address next-generation problems. For example, the code for modeling AFM data is now widely used in the industry. A new version, Java Monte-Carlo Simulator for Secondary Electrons (JMONSEL), of the widely used NIST code MONSEL is being developed for three-dimensional scanning electron microscopy (SEM). Consistent with NIST policy, codes are made freely available to the technical community.

The PED currently has 35 NIST staff, 22 guest researchers (full-time-equivalent), and 1 postdoctoral researcher. Its FY 2010 estimated funding is about $12.7 million, with about 23 percent coming from extramural sources.

TECHNICAL MERIT RELATIVE TO STATE OF THE ART

Essentially all of the PED's programs reviewed for this assessment push the state of the art in their areas. These programs are well connected to NIST objectives and to the needs of the industrial and scientific communities. The PED's leaders are internationally recognized within their fields, and they provide excellent technical leadership within their areas of expertise. The PED recognizes that one of its primary roles is to maintain metrology standards. Toward this end, the division has developed a nanowriting capability using an atomically sharp tip (whose shape can be determined and modified accordingly), which will generate badly needed standards for dimensions on the order of a few atoms that are traceable to NIST. This capability will be critically important at the 22 nm node and beyond in integrated-circuit (IC) technology. Regarding metrology, the PED is developing a calibrated atomic force microscope (C-AFM) that is already returning line roughness measurements that will also be crucial for 22 nm lithography and beyond. Also important for metrology, the PED is developing step-height standards for calibrating AFMs. Its helium-ion microscopy is state of the art and gives the PED new capabilities in dimensional analysis.

The 65 m laser-tracker test-range distance metrology project represents an important project that currently only NIST can do. The objective is to allow measurements made in air to be referenced to the standard meter to within parts in 10^7 by accurately measuring, then compensating for, pressure and temperature variations. This is done by a creative use of frequency combs to transfer the standard meter to the laser wavelength through Global Positioning System (GPS) timing, then to use the laser wavelength as the secondary standard for the actual measurement. The project has already achieved a capability of 5 parts in 10^7.

ADEQUACY OF INFRASTRUCTURE

The move to the Advanced Measurement Laboratory has provided best-in-the-world facilities for equipment that in many cases is the most advanced available anywhere. The quality of the AML facilities has translated into instrument performance that routinely provides fundamental limits independent of environmental effects.

Equipment availability in the PED is good, but the acquisition of equipment appears to be limited and overly reliant on fortuitous connections between PED personnel and outside organizations. The PED has been very creative in benefiting from these connections in that collaborators and customers have made equipment available at good prices. One example is the Moore M48 CMM that was brought in from the Sandia National Laboratories. The PED is an equipment-intensive division, yet it does not appear to have a regular program for the acquisition of critical equipment needed to maintain its technical capabilities.

ACHIEVEMENT OF OBJECTIVES AND IMPACT

Dimensional metrology is advancing well, with existing capabilities being driven to new levels and new capabilities coming online. The JMONSEL modeling code for SEM imaging is a case in point, anticipating the needs for future IC technology, in which devices will be using the third dimension. A further example of anticipating future needs in IC technology is the C-AFM project, with the objective of providing accurate measurements of linewidths, pitch, and sidewall roughness, all of which will become critical at the 22 nm node and beyond.

Division members continue to receive awards and recognition—for example, the Nano-50 Award for Scatterfield Microscopy, the Department of Commerce Gold Medal for Leadership in International Standards, and two Department of Commerce Silver Awards: one for the development of optical methods in overlay and the other for the NIST microfeature CMM probe. Two members were elected fellows of SPIE. One paper (on removing tip-shape from scanning probe microscope images) by PED staff has been cited 187 times at last count, which is an unusually large number in a fast-moving field where publications in conference proceedings are more common, and many of these have a short lifetime.

In addition to the Department of Commerce, the PED provides services to the National Aeronautics and Space Administration; the Bureau of Alcohol, Tobacco, and Firearms; the Federal Bureau of Investigation; the Department of Energy; the Bethesda Naval Medical Center; and other government entities such as the U.S. Army.

One concern is the reliance of the PED on contractors rather than on permanent staff. The PED is to be commended for its creativity in making budgets stretch, but that is not likely to be a long-term solution. One of the major advantages of NIST relative to other organizations is institutional memory—that is, the continuity provided by experts who have become very good at operating the specialized equipment that allows NIST to fulfill its role. Excessive reliance on contractors negates this advantage.

Over the past decade, PED staff have played an active role in the development of American Society of Mechanical Engineers (ASME) standards as well ISO standards. ISO standards are widely used, although U.S. standards are technically superior. The MEL leads an international task force to improve the rigor of the ISO CMM standard and also chairs the effort to harmonize the U.S. and ISO CMM standards. Unifying U.S. and ISO CMM standards reduces barriers to trade by enabling internationally based supply chains, clarifying contractual requirements, and eliminating redundant procedures and training. PED contributions have included the following:

- ASME B89.7.3.1-2001: *Guidelines for Decision Rules: Considering Measurement Uncertainty in Determining Conformance to Specifications*
- ASME B89.7.3.3-2002: *Guidelines for Assessing the Reliability of Dimensional Measurement Uncertainty Statements*
- ASME B89.4.22-2004: *Methods for Performance Evaluation of Articulated Arm Coordinate Measuring Machines*
- ASME B89.7.4.1-2005 (technical report): *Measurement Uncertainty and Conformance Testing: Risk Analysis*
- ASME B89.7.5-2006: *Metrological Traceability of Dimensional Measurements to the SI Unit of Length*
- ASME B89.4.19-2006: *Performance Evaluation of Laser-Based Spherical Coordinate Measurement Systems*
- ASME B89.7.3.2-2007: (technical report): *Guidelines for the Evaluation of Dimensional Measurement Uncertainty*
- ASME B89.4.10360.2-2008: *Acceptance Test and Reverification Test for Coordinate Measuring Machines (CMMs), Part 2: CMMs Used for Measuring Linear Dimensions*

An MEL report[7] (published in 2007) was cited heavily in the National Research Council report on ballistic imaging.[8]

CONCLUSIONS

Following are the conclusions of the panel based on its assessment of the Precision Engineering Division:

- The PED research staff is knowledgeable, enthusiastic about what they are doing, and committed to excellence. They strive to maintain relevance by

[7] T.V. Vorburger, J.H. Yen, B. Bachrach, T.B. Renegar, J.J. Filliben, L. Ma, H.-G. Rhee, A. Zheng, J.-F. Song, M. Riley, C.D. Foreman, and S.M. Ballou, *Surface Topography Analysis for a Feasibility Assessment of a National Ballistics Imaging Database,* NISTIR 7362, Gaithersburg, Maryland: National Institute of Standards and Technology, May 2007.

[8] National Research Council, *Ballistic Imaging,* edited by Daniel L. Clark, John E. Ralph, Eugene S. Meieran, and Carol V. Petrie, Washington, D.C.: The National Academies Press, 2008.

remaining in contact with key industrial constituencies, such as SEMATECH, and focus on topical areas and projects that are likely to become important in the future.
- The PED staff do well working with what they have. Laboratory facilities are very good, with available equipment generally being state of the art, often unique. Even though they may be decades old, facilities are maintained in top condition and are operated by experts. Consistent with the general NIST philosophy, this institutional expertise is a national resource.
- The PED interface with the outside world is outstanding. Its staff participates in relevant meetings, which not only aids their goals of disseminating information to industry but also keeps PED personnel updated and attuned to customer needs.
- PED impact is clearly significant. This is evidenced in many ways—for example, by the large number of ongoing collaborations with companies. The number of requests for services far exceeds the capacity of the division to meet them. Other measures include the number of citations for PED staff publications, and the division's ability to acquire equipment, either donated or purchased at bargain prices. The PED is to be commended for handling the many demands on its time by appropriate triaging—for example, routing routine requests for gage-block metrology to commercial vendors.
- The PED's coordinate-measurement and uncertainty expertise is unique and not likely to be duplicated anywhere else. This expertise was critical in its recent work contributing to the U.S. Army's resolution of an issue involving large, body-armor contracts.
- The PED appreciates that one of its roles is to maintain metrology. Its state-of-the-art atomically sharp tip nanowriting capability will, among other applications, be used to generate badly needed standards for dimensions on the order of a few atoms that are traceable to NIST.
- Some semiconductor CD metrology work is not state of the art owing to the approaches being used. However, this can probably be justified as investigating ways of taking metrology in new directions. The acquisition of relevant equipment in 2010 will eliminate this concern.
- The PED works toward positioning itself to the future. In particular, it concentrates on projects that are expected to be important in the near-term future. These include nanometrology, improving optical resolution, better sensors, and establishing metrology standards for fuel cell catalysts. At the same time it has dropped projects best handled elsewhere, such as sieve standards and civil engineering metrology now done more conveniently by GPS.
- The planned equipment allotment from the American Recovery and Reinvestment Act of 2009 (Public Law 111-5) is a welcome development.
- The PED should continue its participation in regional and international round robins as a key benchmarking exercise.
- The budget available for capital acquisitions is inadequate for such a capital-intensive division.

- The PED could benefit from stronger interfaces with other areas of NIST. The panel heard little concerning the natural interfaces that should occur—for example, between the PED and NIST's Center for Nanoscale Science and Technology and Physics Laboratory.
- PED management needs to develop and implement a critical-skills staffing plan independent of future budget developments so that its critical expertise within NIST is maintained. At present there is too much dependence on guest workers, which appears to be as a direct consequence of flat long-term funding.

6

Overall Conclusions

The Manufacturing Engineering Laboratory has excellent staff and exceptional facilities. Its work is essential in supporting the NIST mission of promoting U.S. innovation and industrial competitiveness by advancing measurement science, standards, and technology. The MEL is having a significant impact on today's manufacturing industries, ranging from traditional production industries to optics industries to semiconductor industries. The MEL is making significant enabling contributions to future U.S. manufacturing industries and jobs. A few examples include the following:

- Redefinition of the kilogram, across-the-board potential impact, from megascale to nanoscale industries;
- Piconewton measurement using biological molecules (DNA) as intrinsic force standards, bridging "bio" and "nano," opening new frontiers in materials and micro-/nano-devices;
- Measurement technology development for larger, next-generation silicon wafers;
- Safety and security of industrial control systems (1.25 million downloads of the standard);
- Portable ability to measure to 100 micrometers over 65 meters, NIST-traceable to the standard meter, enabling quality and precision in large products, structures, and so on; and
- Work in model-based enterprises in manufacturing that has been shown to be equally applicable to security operations.

A significant number of projects at NIST are necessarily related to the integration and interoperability needed for effective commerce. Therefore, there is a requirement to maintain deep expertise in the applications of technologies and to maintain permeable interactions among disciplines. This deep expertise exists only at NIST, is not easily replicable, and is difficult to develop elsewhere; yet, it is crucial to the future of manufacturing.

Across the MEL, portfolio and portfolio management strategies have been continuously and significantly improved, resulting in a portfolio of projects that is customer-focused (taking into account present and future customers) and well distributed in terms of high and low risk and short- and long-term payoff. This needs to continue, with even better articulation of project focus, to achieve desired external impacts. Institute-level management needs to ensure that morale and knowledge-management issues receive due consideration (retirements, the use of "acting" managers, budget reductions, growth inequities, improvement of scientific methods, the role of external funding, etc.). Acting positions and added responsibilities without commensurate compensation may be adversely affecting the career paths of line managers, resulting in losses of key personnel and stagnation in promotions and opportunities for promotions.

Postdoctoral researcher salaries are inadequate for engineering fields, making it difficult to attract the best candidates, many of whom are potential future permanent staff. The budget available for capital acquisitions seems to be inadequate for such a capital-intensive laboratory.

The future competitiveness of U.S. industry in sustainable, high-value-added manufacturing with high precision and using manufacturing processes and products with ever-decreasing dimensional scale will be in doubt without measurement science, measurement services, and standards that are well beyond the current state of the art. This is also true for biotechnology in manufacturing, including biological product components and biologically derived process components, as well as for information technology in manufacturing, including knowledge bases and “smart” products and factories. The equipment in the MEL and the technical expertise of its staff will need to evolve quickly to meet future needs in these areas. Furthermore, the breadth of the challenges to be faced will require closer coupling into the MEL of other technology areas of NIST, such as information technology and materials, and closer coupling into the MEL of external laboratories’ technological expertise, such as biological processes and materials in manufacturing.