An Assessment of the National Institute of Standards and Technology Manufacturing Engineering Laboratory: Fiscal Year 2008

Panel on Manufacturing Engineering, National Research Council

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

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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:

Harry E. Cook, University of Illinois,
Max G. Lagally, University of Wisconsin,
Elsa Reichmanis, Georgia Institute of Technology,
Larry Thompson, Henly, Texas, and
Masayoshi Tomizuka, University of California, Berkeley.

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 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 aligned with 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 our quality of life.

The MEL is organized in five divisions: Intelligent Systems, Manufacturing Metrology, Manufacturing Systems Integration, Precision Engineering, and Fabrication Technology. A panel of experts appointed by the National Research Council (NRC) assessed the first four divisions. Panel members visited these divisions and reviewed their activities.[1]

As requested by the Director of NIST, the scope of the assessment included the following criteria: (1) the technical merit of the current laboratory programs relative to the current state of the art worldwide; (2) the adequacy of the laboratory facilities, equipment, and human resources, as they affect the quality of the laboratory technical programs; and (3) the degree to which the laboratory programs in measurement science and standards achieve their stated objectives and desired impact. In addition to these three criteria, the panel was asked by the Director of NIST to assess the projects within the laboratory conducted under the America COMPETES Act of 2007, which supports the President's American Competitiveness Initiative (ACI).[2]

In the sections below, the summary assessment of the MEL is given, followed by a summary assessment of each division. The chapters after the Summary then present the charge to the panel and a description of the assessment process, detailed assessments of the individual divisions, the progress of the programs funded under the America COMPETES Act of 2007, and overall report conclusions.

SUMMARY ASSESSMENT OF THE LABORATORY

The panel's summary assessment of the Manufacturing Engineering Laboratory is as follows:

- The MEL is achieving its mission and helping NIST achieve its core mission through the development of needed technologies, tools, and standards in areas that are key to successful U.S. innovation and industrial competitiveness.
- The MEL staff is highly capable, nationally and internationally respected, and well motivated; the staff possesses a strong positive outlook and is passionate about the work of the laboratory.
- All four of the MEL divisions assessed have one or more projects whose technical work is among the best in the field. Examples include but are not limited to the Helium-Ion Microscopy project in the Precision Engineering Division (PED), the

[1] The fifth division of the MEL—the Fabrication Technology Division (FTD)—was not assessed because it is a support organization providing fabrication and technical support services to all NIST staff. FTD assists NIST staff in the design and development of instruments and measurement devices needed to maintain the national and international standards of measurement and measurement services.

[2] See Domestic Policy Council, Office of Science and Technology Policy, 2006, *American Competitiveness Initiative,* Washington, D.C. "America COMPETES Act" is the short title for the America Creating Opportunities to Meaningfully Promote Excellence in Technology, Education, and Science Act of 2007 (Public Law 110-69).

Mass and Force Metrology projects in the Manufacturing Metrology Division (MMD), the Automation Interoperability project in the Intelligent Systems Division (ISD), and the Supply Chain Integration project in the Manufacturing Systems Integration Division (MSID).

- The MEL has excellent facilities and testbeds in many areas. It has maintained its equipment capabilities through innovative partnerships with equipment suppliers and other outside entities. Maintaining this level may require additional investment.
- There is a need to reexamine program priorities through strategic planning at both the laboratory and division levels in order to achieve improved balance between attention to top-down program directives of national significance that cut across multiple disciplines and attention to innovative bottom-up ideas from individual researchers.
- The continued achievement of technical objectives and the maintenance of core competencies will require taking action with respect to personnel succession planning, more aggressive hiring of young permanent staff, and addressing shrinking sources of personnel in key areas such as core manufacturing technologies, metrology, and optics. A lack of resources threatens the development of needed technologies and tools and the ability to hire more postdoctoral associates. Moreover, making use of guest workers who do not have the possibility of permanent employment does not address the succession planning issue.
- It is too early to assess the progress of programs in the MEL that are funded through the President's American Competitiveness Initiative and the America COMPETES Act of 2007. The support that these initiatives promise is providing for important Supply Chain Integration and Bio-Imaging programs. Future expanded MEL involvement in such initiatives is encouraged, and should take into account the fact that manufacturing includes broader areas of supply chain, life cycle, and service. To have greater impact on the core mission of NIST, the very definition of "manufacturing" should be expanded to cover the broader areas of service, enterprise productivity, and products for areas such as health care, farming automation, and intelligent transportation systems.

Overall, the four individual divisions are performing to the best of their ability, given available resources. In many areas in all four divisions, the capabilities and the work being performed are among the best in the field. However, reduced funding and other factors such as difficulty in hiring permanent staff are limiting (and are likely to increasingly limit) the degree to which MEL programs can achieve their objectives and are threatening the future impact of these programs.

SUMMARY ASSESSMENTS OF FOUR DIVISIONS

Intelligent Systems Division

The Intelligent Systems Division develops intelligent systems technologies, tools, and standards that have major impacts on the successful progress of U.S. innovation and industrial competitiveness. It has established strong leadership in the areas of intelligent systems measurement, interoperability, safety, and security.

Measurement has been one of the ISD's major strengths, and the division has maintained its excellent reputation and technology leadership in this area. In the area of interoperability, the focus has been on establishing standards and testbeds in the areas of computer numerical control (CNC), dimensional inspection equipment interoperability, and autonomous-vehicle and materials-handling systems, with the ISD serving as a catalyst in promoting collaboration among industries. In the area of safety and security, the ISD has made important contributions in establishing NIST SP 800-53, *Recommended Security Controls for Federal Information Systems,* and NIST SP 800-82, *Guide to Industrial Control Systems Security*. The ISD has technical capabilities in its core programs that are among the best. These programs include micro- and nanomanufacturing measurement and positioning systems, Standard for the Exchange of Product Model Data: Numerical Control (STEP NC)[3] and Open Modular Architecture Controller (OMAC) for real-time data models, machine compensation, machining tool path optimization, and Ethernet/Internet Protocol (IP) performance test tools.

While ISD facilities are generally very good, the human resources available to achieve important goals are inadequate. The prognosis for hiring successor personnel appears to be problematic in key areas, potentially threatening future core competency in the ISD's critical skills. Finally, the ISD has opportunities to expand its capabilities and impact in diversified, value-added industries, covering broader areas of manufacturing relevance including the areas of service, enterprise productivity, health care, farming automation, and intelligent transportation systems.

Manufacturing Metrology Division

The Manufacturing Metrology Division programs compare very favorably with peer activities at the national standards institutions of other countries. For example, the Mass and Force Metrology projects are at the forefront in their domain. Even where investments in programs at other laboratories, such as the Physikalisch-Technische Bundesanstalt (PTB) in Germany, are higher, the MMD staff has the ability to maintain competitive programs. This is reflected in the results of a worldwide round-robin study conducted in the mass area. Also, in emerging areas such as wireless sensors, NIST researchers are acknowledged leaders in the development of standards. Given the likely widespread impact of wireless sensors technology, it is critical that this leadership role be maintained with appropriate investment.

MMD staff members are active in standards committees for such areas as mass metrology and wireless sensors. They are active in the dissemination of results to a wide audience through the organization of and participation in meetings and conferences. An example is the upcoming International Academy for Production Engineering (CIRP) symposium in the machining area that is to be held at NIST.

The MMD staff reviewed by the panel are extremely capable and well motivated, and they have a strong positive outlook. These facts, coupled with excellent facilities and equipment, have yielded high-quality work. However, a number of concerns may impede the continued excellent performance of the MMD. For example, more staff members are needed in critical areas such as optics. The hiring of trained replacements for soon-to-retire senior staff members and the recruiting and retaining of young engineers and scientists are needed. The use of postdoctoral associates is an excellent vehicle for bringing in and training new young talent; however, making use of the availability of guest workers who do not have the possibility of permanent employment is unlikely to address longer-term strategic personnel issues.

[3] STEP NC is a standard developed by the International Organization for Standardization (ISO) to bring computer-aided design/computer-aided manufacturing (CAD/CAM) data into CNC.

Manufacturing Systems Integration Division

The Manufacturing Systems Integration Division has an excellent international reputation and excellent technical expertise in electronic information exchange, rich semantic structures, and systems integration. The MSID has appropriately focused its scope on three major programs: Supply Chain Integration, Sustainable and Lifecycle Information-based Manufacturing, and Simulation-based Interoperability Standards and Testing. For each of these programs, the outputs from the MSID include rigorously defined standards and protocols, realistic pilot programs, and software and interoperability testing services.

The scope of the MSID's programs is in line with its budget, and it has produced high-quality research with concrete results. In general, the MSID is doing excellent technical work that is at the state of the art. The groups in the division that are researching and influencing interoperability standards are performing technical work that ranks among the best. This has been demonstrated, for example, with interoperability standards, the development and testing of standards, simulation, and the assisting of vendors in the implementation of the new functionality. Improved dissemination of the excellent work done in the MSID group on semantic interoperability could have significant impact far beyond the Supply Chain Integration project. Core personnel are working very well as a team, providing overall strong leadership.

However, the effective MSID budget has been severely reduced over recent years, resulting in a shift from permanent personnel to guest researchers; furthermore, there appears to be a lack of successor personnel in key positions. These changes are reducing the division's agility, effectiveness, ability to achieve stated objectives, and national impact.

Precision Engineering Division

The Precision Engineering Division is providing the foundation of dimensional measurement that is crucial to the U.S. industrial and scientific communities. The move to the division's current facilities, which are the best of their kind, with their stringent environmental control, has resulted in a dramatic improvement in metrology capabilities. The PED has maintained equipment capabilities that are among the best through innovative partnerships with equipment suppliers and other outside entities. The PED's efforts in helium-ion microscopy, atom-based metrology, nanoparticles for biosystems, and whole wafer/photomask capability are forward-looking. The PED has had major impact both nationally and internationally by delivering new standard reference materials, calibration services, and documentation.

The PED research staff reviewed by the panel are knowledgeable, dedicated, and enthusiastic about their work. The PED has made significant improvements over the past 3 years in meeting the needs of the semiconductor industry. Future opportunities exist for the division to seek feedback from U.S. industry, to increase the visibility of the PED within the national technical community, and to promote traceability and standards development. Benchmarking is performed currently for other national standards institutions, but this activity could be expanded to industry in order to capture significant cutting-edge capabilities not available at other national standards institutions.

The PED needs more favorable cost structures to support the delivery of calibration and measurement services; these include, for example, the use of machine charges, consumables charges, service center charges, and activity-based cost accounting. Strategic planning is likely to be crucial in the following areas: capital equipment; human resources, including the succession of personnel; technical focus areas (roadmaps); and investment and disinvestment in calibration and measurement services.

The Charge to the Panel and the Assessment Process

At the request of the National Institute of Standards and Technology, the National Academies, through its 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 2008, 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. Each of these was assessed by a separate panel of experts; 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) 2008 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 the current state of the art worldwide;
2. The adequacy of the laboratory facilities, equipment, and human resources, as they affect the quality of the laboratory technical programs; and
3. The degree to which the laboratory programs in measurement science and standards achieve their stated objectives and desired impact.

In addition, because NIST has begun to receive increases in funding through the President's ACI and the America COMPETES Act of 2007, the Director of NIST also requested that the assessment panels specifically examine and review the progress of all of the FY 2007-funded initiatives relevant to their respective laboratories and comment on these program growth areas explicitly in their reports.

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.

To accomplish the assessment, the NRC appointed a panel of 21 volunteers whose expertise matched that of the work performed by the Manufacturing Engineering Laboratory staff. Each panel member was also assigned to one of four review teams whose members' expertise matched that of the work performed by the staff in the four MEL divisions being assessed: Intelligent Systems, Manufacturing Metrology, Manufacturing Systems Integration, and Precision Engineering.[5]

The panel met at the NIST facilities in Gaithersburg, Maryland, on March 26-28, 2008. After the full panel met for a session of overview presentations by the MEL management and staff on March 26, the panel divided into its four review teams, each of which then visited its respective division for a little over a full day (on March 26-27). During

[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.

[5] See http://www.mel.nist.gov/ for more information on MEL programs. Accessed August 12, 2008.

these visits, the review team members attended presentations, tours, demonstrations, and interactive sessions with the MEL staff. Immediately following the review team meetings, the full panel assembled for a meeting on March 27-28 during which it attended interactive sessions with the laboratory managers and also met in a closed session to deliberate 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 within which the MEL activities are conducted. The panel reviewed selected examples of the standards and measurements activities and the technological research presented by the MEL. It was not possible to review the MEL programs and projects exhaustively. The examples reviewed by the panel were selected by the MEL. 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 impact with respect to achieving its own definition of its objectives, and specific elements of the MEL's resource infrastructure that are intended to support the technical work. These highlighted examples for each MEL division are intended collectively to portray an overall impression of the laboratory, while preserving useful suggestions specific to projects and programs that the panel considered to be of special note within the set of those examined. The assessment is currently scheduled to be repeated biennially. 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 and focuses on representative programs and projects relevant to those 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.

The report's Summary first highlighted issues that apply broadly to several or all of the divisions or to the laboratory as a whole. Then, after this chapter on the charge to and approach taken by the panel, individual chapters present observations specific to the respective laboratory divisions. Comments on the progress of the programs funded under the America COMPETES Act are followed by overall conclusions.

Intelligent Systems Division

The Intelligent Systems Division has established strong leadership in the areas of measurement, interoperability, safety, and security. It plays a vital role in promoting manufacturing-engineering-related science, technologies, and tools, and its standards and services are crucial to U.S. innovation and industrial competitiveness. The ISD has maintained its excellent reputation and technology leadership in measurement. It is serving as a catalyst in promoting collaboration between industries, with a focus on establishing standards and testbeds in the areas of CNC, dimensional inspection equipment interoperability, 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 micro- and nanomanufacturing positioning systems, STEP NC and OMAC for real-time data models, machine compensation, machining tool path optimization, and Ethernet/IP performance testing.

TECHNICAL MERIT RELATIVE TO STATE OF THE ART

The ISD programs are well aligned with NIST's core roles and strategy, focusing on measurements, standards, and technology development for the benefit of industry and commerce. The division has done an excellent job of identifying the major needs and opportunities of U.S. industry. However, given restrictions in budget and personnel, it has been unable to pursue these opportunities fully.

The caliber of the work of the ISD programs assessed is at the state of the art. The division's collaboration with top universities, industry, and military agencies demonstrates the reputation and competence of the ISD products and services. The dimensional inspection equipment interoperability effort is the leader in cooperation with multinational companies. The division has made significant efforts at reaching out to industrial partners, educating them with respect to the benefits of standardization as a means to achieve cost reduction and interoperability. There is a healthy level of technical publications, invited talks, external awards, and participation in national and international committees by ISD staff.

Measurement has been one of the ISD's major strengths, which has been maintaining its technical leadership reputation. The following observations pertain to the area of measurement science for manufacturing robotics and automation:

- Six-dimensional dynamic sensing represents the state-of-the-art technology for sensor calibration.
- In the area of micro-, meso-, and nanomanufacturing and positioning (measurement and manipulation), the ISD has demonstrated significant improvement in the accuracy of measurements. The division could conduct a benchmarking workshop. Such a workshop could invite experts from the international community to evaluate how the competitive science and technologies from other research laboratories, institutions, and industry in the related areas can further enhance the standards efforts at NIST.
- The ISD has significantly facilitated the establishment of the following industrial robot safety standards: ANSI [American National Standards Institute] B56.5: *Safety Standard for Guided Industrial Vehicles and Automated Functions of Manned Industrial Vehicles* and ISO [International Organization for Standardization] 10218-1:2006: *Robots for industrial environments—Safety requirements—Part 1: Robot,* which have been deployed by industry users.

- The ISD's efforts in establishing consortia and competitions in robotics and sensor technologies for localization, detection, navigation, and materials handling constitute a commendable approach for leveraging diversified, global resources.

Interoperability work in the ISD has focused on establishing standards and testbeds in the areas of CNC and dimensional inspection equipment. The ISD has been serving as a catalyst in promoting industrial collaboration. In the area of automation interoperability standards:

- The ISD has done an excellent job in bringing together competitors and partners and aligning them to a common standard. Demonstrations have been effectively used to facilitate compliance.
- STEP NC and OMAC for real-time data models, machine compensation, and machining tool path optimization have been ongoing efforts at the ISD, which has established ISO 10103 AP238: *STEP NC—Standard for the Exchange of Product Model Data—Numerical Control* and I++DME interoperability testing protocols. The ISD should consider working with industry associations and societies (such as the Association for Manufacturing Technology and the Society of Manufacturing Engineers and others) to establish user groups or working groups for further dissemination. Further, the ISD can move on to next-level challenges in enterprise-level data modeling and standards efforts.
- Safety and security work has focused on industrial controls and networks standards for federal government and industrial users. NIST SP 800-53 was established as *Recommended Security Controls for Federal Information Systems*. NIST SP 800-82 was established as *Guide to Industrial Control Systems Security* in the areas of intelligent manufacturing industrial control systems and network standards.
- Ethernet/IP performance test tools in partnership with the Open DeviceNet Vendor Association are a good way to promote standards in industry. This is a good area for the ISD to lead and in which to facilitate a national and international effort in establishing standards and guidelines.
- The ISD might explore other opportunities in industrial wireless networks and diagnostics-related standards.

ADEQUACY OF INFRASTRUCTURE

The ISD has been successfully leveraging its program development through partnerships with industry and government. It has excellent research facilities and equipment, some of which are loaned by industry. The resources are limited (especially in terms of personnel), constraining the ability to respond with agility to changing technology needs. ISD researchers appear to be engaged in a number of collaborative projects for promoting cross-disciplinary activities. However, these diversified activities impede the impact of the ISD owing to the high workload of its staff as well as the lack of committed resources. The ISD has staff members approaching retirement; there have been several recent retirements, with only one new permanent technical staff member hired in the past 3 years. There should be a robust and stable succession plan to guarantee core competency in the ISD's recognized critical expertise.

ACHIEVEMENT OF OBJECTIVES AND IMPACT

Regarding the degree to which ISD programs have achieved their stated objectives and desired impact:

- The ISD has made major achievements in terms of its program objectives. It has had visible and important impacts on the establishment of standards for government and industry user groups in measurement science for robotic safety, machine tools interoperability, autonomous guided vehicles, and materials-handling systems.
- The RoboCup Rescue competition[6] has made visible impacts on the global robotics research community. Other programs could use this leveraging model for future collaboration and partnerships with the international research community. The ISD could also further develop partnerships with the National Science Foundation, the Department of Defense, the National Aeronautics and Space Administration (NASA), and others to leverage their Research Experience for Undergraduates, Research Experience for Teachers funding to encourage more K-12 teachers and undergraduate students to participate in its future activities.
- Participation in consortia and external committees (e.g., automatic guided vehicle manufacturers' consortium, OMAC, and others) shows an overarching effort to benefit industry.

CONCLUSIONS

The conclusions of the panel based on its assessment of the Intelligent Systems Division are as follows:

- The division programs are well aligned with NIST's core roles and strategy, and the division has done an excellent job of identifying the major needs of and opportunities with respect to U.S. industry. The division has shown increased emphasis on the concerns of U.S. industry about risk, cost, and compatibility of manufacturing technology.
- The caliber of the work in the division is at the state of the art. The ISD has excellent research facilities and equipment. Measurement is a major area of strength in which it maintains a position of world leadership. Its dimensional inspection equipment interoperability effort, for example, is the leader in cooperation with multinational companies.
- The division has a healthy level of technical publications, invited talks, external awards, and participation in national and international committees. It reaches out to industrial partners regarding the benefits of standardization as a means for cost reduction and product improvement.
- Limited resources are constraining the agility with which the division can respond to changing technology needs. The division has staff members approaching retirement and needs a robust and stable succession plan to guarantee its future core competency.
- Current efforts within the division are well aligned with opportunities in embedded machine and device intelligence, machine health prognostics and management

[6] See http://www.isd.mel.nist.gov/PerMIS_2007/proceedings/Papers/PerMIS07.Final_Balakirsky.pdf. Accessed August 15, 2008.

standards, and the detection and prevention of product counterfeits, as well as virtual engineering simulation standards and tools.

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. The division aims to conduct metrology research, provide calibration services, develop standards, establish traceability, and produce high-quality scientific and technical output. It conducts research and development in realizing and disseminating the Systeme International (SI) mechanical units; develops methods, models, sensors, and data to improve metrology, machines, and processes; provides services in mechanical metrology, optics metrology, machine metrology, process metrology, and sensor integration; and leads in the development of national and international standards. The division currently has 35 full-time staff, 1 NRC postdoctoral researcher, and 14 guest researchers. Its yearly funding for 2007 was about $10 million, with about 20 percent of this total coming from extramural sources.

The staff of the MMD reviewed by the panel is extremely capable and well motivated and has a strong, positive outlook. These facts, coupled with excellent facilities and equipment, have yielded high-quality work. However, a number of concerns may impede the continued excellent performance of the MMD. For example, more permanent staff members are needed in critical areas such as optics. Trained replacements are needed for soon-to-retire senior staff members. Succession planning should be executed so that gaps can be identified and young engineers and scientists recruited. The use of postdoctoral associates and the funding of graduate students are excellent vehicles for bringing new young talent into the division and properly training them. However, making use of the availability of guest workers who do not have the possibility of permanent employment does not address the succession planning issue.

TECHNICAL MERIT RELATIVE TO STATE OF THE ART

The MEL is well known for the high quality of its work in manufacturing metrology, and industry seems pleased with NIST's calibrations and leadership. The MMD staff is extremely positive and motivated; many staff members have worked at NIST for many years and seem proud of their work. In some areas, especially optics metrology, the group is smaller than its reputation would suggest; the number of important projects that it has warrants a larger staff. The wireless sensors work is an exciting emerging area with high potential for growth. The MEL should position itself well to be a leader in setting global standards in this important area. The work in improving mass metrology and small-force measurement technology is extremely advanced and should prove to be very productive and useful to industry. There is considerable scope for outstanding publications in high-impact journals in this area. The new projects in optics involving the testing of the phase-transfer function of an interferometer and the use of nanostructured optics for the testing of mandrels for x-ray telescope mirrors and the measurement of the radius of curvature of large, precision, spherical surfaces in the radius-of-curvature range of $10 \text{ m} < R < 1,000 \text{ m}$ are important and should be valuable for the optics industry. The work on measurement methods for machine dynamics and machining process modeling is well done and leverages NIST's historic expertise in measurements and machining. This is long-term research; significant findings will require the provision of long-term support. Given the high-risk nature of this work, it is doubtful that significant fundamental results will be generated in a year or two. If this project is pursued, it should be supported for a longer duration regardless of initial results.

The MMD programs compare very favorably with peer activities at the other National Metrology Institutes (NMIs). For example, the Mass and Force Metrology projects are at the forefront in their domain. Even where investments in programs at other laboratories—for example, PTB in Germany—are higher, the MMD staff is confident of its ability to maintain competitive programs. This is reflected in the results of a worldwide round-robin measurement comparison conducted in the mass and force areas. Also, in emerging areas such as wireless sensors, MMD researchers are acknowledged leaders in development of standards. 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 assessed. For example, the large-mass calibration equipment is unparalleled. Other examples include optics (flat and spherical-surface metrology equipment) and the NIST nano-optics fabrication facilities. The staff is highly motivated and appears to approach its assigned tasks with enthusiasm. The facilities and equipment appropriately support the MMD core mission and the carrying out of its various projects to completion.

Some weaknesses exist with respect to personnel matters and succession planning. For example, a mechanism to hire replacements in anticipation of retirements appears to be lacking, a source of concern to staff. Furthermore, there are too few staff members in some key areas such as optics, given the facilities and importance of this area. The reliance on guest researchers to carry out core activities is a cause of concern. Among other things, there is a loss of knowledge and experience when there is insufficient overlap with succeeding guest researchers. More postdoctoral associates are needed.

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 top of the field in force measurement, optics metrology, machine tool metrology, and acoustics metrology. The MMD staff are active in standards committees in such areas as mass metrology. Their work on wireless sensors standards committees has resulted in establishing standards for wireless data communication among sensors. They are active in the dissemination of results to a wide audience through the organization of and participation in meetings and conferences. An example is the upcoming CIRP symposium in the machining area that is to be held at NIST.

Several drivers for U.S. manufacturing have influenced the content of the MMD programs. Through frequent interactions and collaborations, the division ensures that MMD measurements and standards activities address the needs and priorities of its customers. The division also produces high-quality work on optics metrology and small-force measurement technology. It is, however, not clear how research projects are chosen. It is suggested that studies such as those by the NRC on grand challenges for manufacturing be considered in the interest of fostering more high-risk, high-payoff work.

The division evinced multiple instances of good interlaboratory collaboration. Most notable among these is one between the Mass Metrology Project and the Argonne National Laboratory. The project identified a unique, diamond-like carbon coating developed at Argonne as a highly effective protective layer for new mass artifacts being developed for future mass dissemination purposes and has exploited this well. The coating originally was developed as a low-friction coating at Argonne. The impact of this collaboration is likely to be high for both participants.

While the publication output is high, the staff should be encouraged to publish more in peer-reviewed journals with high impact factors. This would also be a plus in attracting high-quality postdoctoral associates. A study and mapping of customer needs with MMD capabilities would be very useful for highlighting the accomplishments of the program in the service of industry, federal, and state organizations.

CONCLUSIONS

The conclusions of the panel based on its assessment of the Manufacturing Metrology Division are as follows:

- The MMD is at the top of the field in force measurement, optics metrology, machine tool metrology, and acoustics metrology. It has very good facilities and equipment that have yielded high-quality work. Its programs compare very favorably with peer activities at the other NMIs.
- The MMD ensures that its measurements and standards activities address the needs and priorities of its customers. Examples include the division's work in wireless sensors standards, in improving mass metrology and small-force measurement technology, and in the measurement of the radius of curvature of large, precision, spherical surfaces.
- The MMD continues to do a very good job of developing standards, providing calibration services, and establishing traceability. The MMD staff is active in standards committees and in the dissemination of results to a wide audience through its organization of and participation in meetings and conferences.
- Permanent staff members are needed in critical areas such as optics. Succession planning should be used to identify gaps and to recruit young engineers and scientists. The reliance on guest workers who do not have the possibility of future employment should be reduced in favor of postdoctoral associates and graduate students.
- While the publication output is high, the staff should be encouraged to publish more in peer-reviewed journals with high impact factors.
- A study and mapping of customer needs with MMD capabilities would be very useful for highlighting the accomplishments of the program in the service of industry, federal, and state organizations.

Manufacturing Systems Integration Division

The Manufacturing Systems Integration Division develops and applies interoperability standards and measurements for software used in manufacturing systems integration. The MSID has expertise in electronic information exchange, semantic structures, and systems integration that is comparable to that of the top 10 institutions in these areas. The MSID has identified supply chain integration, sustainable and lifecycle information-based manufacturing, and simulation-based manufacturing interoperability standards and testing as focus areas in addressing the ever-increasing complexity of manufacturing and supply chain processes. All division projects are aligned with one of these programs. The results from each project in the MSID include rigorously defined standards and protocols, realistic pilot programs, and software and interoperability testing services.

The goal of the Supply Chain Integration Program is to demonstrate an infrastructure for the testing and integration of automated systems that exchange data and information (including semantics) throughout the supply chain. This program has demonstrated significant maturity during the past 3 years. One important impact of the program is the deployment of a number of syntax- and quality-based testing and validation tools. Another is significant advances in techniques for the sharing of semantic information between supply chain partners. Many of these tools and techniques have broad applicability within manufacturing and in other disciplines.

The Sustainable and Lifecycle Information-based Manufacturing Program works on extending product and process data standards to the broader spectrum of information needed to sustain products over their life cycle. This program has produced a number of key results in the past few years, including transitioning STEP to integrate with Object Management Group (OMG) and World Wide Web Consortium (W3C) standards and migrating STEP for wider implementation. Continued work in this area is vital to the efficient allocation of both manufacturing capacity and valuable materials as well as to the protection of the environment.

The Simulation-based Manufacturing Interoperability Standards and Testing Program is particularly topical, as standards in simulation are in their infancy. It is a good strategy for the MSID to invest in this area, as it is critical to industry. As the complexity of manufacturing systems continues to increase, it becomes exponentially more complex to design and operate these systems without multiple integrated software tools, including in many cases both simulations and manufacturing automation systems. Collaboration with the Department of Homeland Security (DHS) should pave the way to expanding this work into the management of manufacturing and supply chain disaster recovery.

The MSID has increasingly focused its programs, which are in line with the MEL mission. Because funding and human resources have remained static or declined, it has been necessary for this division to remain lean and yet agile. Its technical work is generally excellent. Most of its projects are outstanding and have delivered significant standards, pilots, and testing programs that have benefited the targeted user communities.

TECHNICAL MERIT RELATIVE TO STATE OF THE ART

The three focus areas (supply chain integration, sustainable and lifecycle information-based manufacturing, and simulation-based manufacturing interoperability standards and testing) are appropriately aligned with the needs of American industry. In addition, the projects within each focus area are in line with the MEL mission and reflect a broad understanding of comparable work being done elsewhere (in other government laboratories, at universities, and in industry). Links have been established with key members of the international community to achieve the division's goals.

In the supply chain integration area, high-quality work is being performed on logic and semantics in the basic Automated Methods for Integrating Systems (AMIS) concept and applied AMIS-related projects. This is a difficult problem of utmost importance to improving supply chain operational efficiency. The MSID has developed a very innovative approach in the modeling of logic-based semantics. Furthermore, the Naming and Design Rules and Quality of Design services are very important to facilitating and accelerating supply chain integration. These services in fact address problems encountered in areas beyond manufacturing and could form the basis of broadly applicable leading-edge capabilities.

In the sustainable and lifecycle information-based manufacturing area, the MSID has had a very strong impact in STEP development. It has continued the development and testing of STEP modular development environment and modular application protocols; in particular, work relating to AP203 E2: *Configuration Controlled 3D Design of Mechanical Parts and Assemblies* is to be commended. This new (E2) version of AP203 was modularized and updated to include several module sets for new applications. Recent MSID efforts include transitioning STEP to integrate with OMG and W3C standards and migrating STEP for wider implementation.

In the simulation-based manufacturing interoperability standards and testing area, work is proceeding with the collection and analysis of test cases, with the goal of structuring appropriate standards. While this work is going well and is important to building a technically sound foundation for future work, this program should be strategic in its selection of pilot programs and should not be seduced by the opportunity simply to build demonstrations. The DHS funds several projects within the simulation program. The MSID should not entirely rely on this soft money to grow this program. Since this integration infrastructure that the DHS funding partially supports has dual uses and can be applied to manufacturing, the division has opportunities to seek other agency funding to sustain its core mission and expertise.

Within the MSID, the groups researching and influencing interoperability standards[7] are performing technical work that ranks with the best in the field. This has been demonstrated with the development and testing of standards and the assisting of vendors in the implementation of the new functionality. Such activities have also been recognized through awards to staff members—for example, the Fellow of the American Society of Mechanical Engineers (ASME) award, and the Product Data Exchange using STEP (PDES, Inc.) Technical Excellence award for the technical efforts and leadership in developing the STEP modular architecture. Furthermore, standards bodies are engaged and practical problems are formulated and piloted in collaboration with key vendors and end customers. For example, recent MSID collaborative efforts include its work with the Automotive Industry Action Group (AIAG), aerospace companies, and the National Archives and Records Administration in the area of standards-based data archiving, and its work with the DHS in the area of simulation.

ADEQUACY OF INFRASTRUCTURE

Given the MSID's information-centric paradigm, its equipment and facilities are adequate to meet project objectives. The scale of specific projects and work planning are appropriate, given limited resources.

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[7] See http://www.isd.mel.nist.gov/projects/metrology_interoperability/. Accessed September 2, 2008.

As of January 2008, staffing for the Manufacturing Systems Integration Division included 57 full-time-equivalent personnel, which included approximately 30 full-time permanent positions, as well as 41 visiting researcher or part-time workers who were equivalent to 27 full-time employees. The trend over the past 5 years has been a steady decrease in full-time permanent positions and an increase in part-time and visiting personnel. The actual-dollar annual budget has remained relatively constant over this same period, 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 this division's achieving its goals:

- The MSID is approaching a critical mass threshold, and it is not provided with an appropriate budget for developing and executing a succession plan. This will soon affect the division's effectiveness, agility, and competitiveness.
- Increasing reliance on guest researchers is necessary to accomplish tasks but not sufficient to sustain the MSID's mission. An infusion of temporary new help is very useful, but it is not a substitute for a continuous flow of permanent new hires.
- Given current funding and the need to be opportunistic, the MSID is applying more tactical technical planning strategies than it prefers.

ACHIEVEMENT OF OBJECTIVES AND IMPACT

With the limited resources that the MSID has, it has carefully scoped its focus and has aggressively sought out the most effective partnerships to identify and address the requirements and the gaps in the standards. For example, as a result of collaborations with automotive and aerospace companies, the MSID has had a very strong impact in interoperability. The MSID disseminates its work through government and industry, NIST-wide, and at internal forums. Work has also been disseminated through a significantly high number of workshops, technical seminars, reports, publications, newsletters, board memberships, and consortia. Some examples are AIAG and the involvement with STEP development.

The MSID should be innovative with its marketing strategy and standards development in order to further increase its impact on U.S. competitiveness in the manufacturing arena.

CONCLUSIONS

The conclusions of the panel based on its assessment of the Manufacturing Systems Integration Division are as follows:

- The MSID has expertise in electronic information exchange, rich semantic structures, and systems integration that ranks it among the best in these fields. It has appropriately focused its scope on three major programs: Supply Chain Integration, Sustainable and Lifecycle Information-based Manufacturing, and Simulation-based Interoperability Standards and Testing. For each of these programs, the outputs from MSID include rigorously defined standards and protocols, realistic pilot programs, and software and interoperability testing services. The division's scope is in line with its budget, and it has produced high-quality research with concrete results.
- The overall quality of research in the MSID is high. In general, the division is doing excellent technical work. In many areas, the work at MSID is state of the art. In the MSID, the groups researching and influencing interoperability standards are

performing work that ranks among the best in the field. This has been demonstrated, for example, with interoperability standards—with the development and testing of standards, simulation, and the assisting of vendors in the implementation of the new functionality. Core personnel work very well as a team, providing overall strong technical leadership.

- The effective budget has been severely reduced over the past 5 years, responded to by a shift from permanent personnel to guest researchers. Current funding may be adequate to achieve tactical results, but more strategic projects and programs are being sacrificed due to lack of funding.
- The MSID is approaching a critical-mass threshold, and the division is not provided with an appropriate budget for having employee succession planning in place in order to reduce the number of guest researchers over the years and to hire new permanent employees. If this situation is not addressed in a timely manner, it will very negatively impact the MSID's ability to remain effective, agile, and competitive.
- An improved dissemination of information and results would increase the national impact of the excellent work done in the MSID. For example, semantic interoperability has had significant impact potential far beyond the Supply Chain Integration project.
- The MSID staff has demonstrated commendable success in getting outside funding (such as that received from DHS).
- The MSID is collaborating well with the Intelligent Systems Division, the Manufacturing Metrology Division, and the Precision Engineering Division on interoperability standards projects. Because of its lean budgets, the MSID should continue to leverage its expertise with other organizations in order to solve problems of national interest.

Precision Engineering Division

The Precision Engineering Division continues to maintain activities and services, many of which are among the best in the field, in many areas of research despite significant, cumulative cuts in staffing and budgets. For a relatively small amount of funds, the PED is performing a critical role for the nation, carrying on the ever-changing and challenging legacy of the National Bureau of Standards and now NIST. The work of this division is crucial to the current and future competitiveness of U.S. industry and in standards development and traceability to the SI. The PED staff is knowledgeable, dedicated, and highly motivated in its work.

Since the previous assessment, the PED has made major strides in the following areas:

- The realization of the improved laboratory environment that it now has in the Advanced Measurements Laboratory (AML);
- New equipment that the division has acquired, augmented, put to use, and developed for improved capability in establishing new and forward-looking calibrations and measurement service capabilities;
- The generation of a significant number of new capabilities, artifacts, procedures, publications, and standards—all to make significant improvement in order to meet its mission and the needs of its customer base.

TECHNICAL MERIT RELATIVE TO STATE OF THE ART

All of the PED programs reviewed by the panel push the state of the art in their areas. They appear to be well connected to the PED's stated objectives and to industrial and scientific community needs. The leaders of the different thrusts of the PED are all internationally recognized within their fields and are providing excellent technical leadership for the PED programs. There are very clear ties in their programs to the NIST, MEL, and PED vision and mission statements. They are appropriately aware of the work done by other NMIs, and they are maintaining strong collaboration with them in the appropriate areas.

The PED has made significant strides in the past few years to satisfy the traceability and low uncertainty requirements of the semiconductor industry. Some examples are as follows:

- Modeling capability and methods are being routinely developed together with experimental measurement technology and are used jointly to address next-generation problems;
- New technologies such as helium-ion microscopy, worked on in collaboration with Zeiss, are being advanced in collaboration with the original equipment manufacturer (OEM) and are being explored for their impact on measurement capability and correlation to the SI;
- The ability to perform three-dimensional coordinate measurement using microfiber probes is being developed to measure complex, submillimeter geometries. This work is performed in a coordinate measurement machine with demonstrated correlation to the SI to within ±20 nm;
- Expertise is growing in standards associated with broad new fields of application, such as bionanoparticles.

A minority of PED programs involve continuations of technically mature methodologies for which similar capabilities may exist in non-NIST laboratories and industry. Overall, the technical efficacy of the effort is very high. The PED should perform more of its own benchmarking with industrial (user) laboratories in addition to other NMIs.

ADEQUACY OF INFRASTRUCTURE

The move to the new AML has provided state-of-the-art facilities for equipment that is in many cases the most advanced available. This has translated into instrument performance beyond OEM expectations. The new AML building is clearly a significant positive factor differentiating NIST from the other NMIs. Within the next 1 to 2 years, a strategy will be needed for tool placement and space prioritization in the AML.

Equipment availability in the division has improved significantly over the past 3 years. The PED has demonstrated resourcefulness in securing state-of-the-art equipment from its collaborators with only a modest capital equipment budget. However, this approach has its limitations. Due to the lack of an adequate capital budget, there is a significant risk that infrastructure and equipment needs will go unfilled in the future. Current infrastructure strengths are as follows:

- Line scale interferometry capability,
- Calibrated atomic force microscopy,
- New full-wafer scanning electron microscope capability,
- A second Moore coordinate measurement machine,
- Roundness measurement capability to under ±5 nm,
- New Taylor-Hobson form and finish measurement instrumentation, and
- Laser-interferometer-based calibration methods for spherical-coordinate large-scale three-dimensional measurement devices (laser trackers) traceable to the SI.

The PED has a small number of highly qualified staff who lead the work of individual programs. Yet, there is generally only one such qualified staff member per program, in many cases a quite senior contributor, with little provision having been made for future program longevity. Budget issues appear to be driving the attrition of the staff, with only ad hoc opportunities for replacement. The PED has maintained its quality and capacity by using contractor personnel, guest researchers, and retiree volunteers. This is an effective tactic for the short term, but a strategic identification of core competencies and succession planning are required in order to maintain the economies of experience from which the division currently benefits.

ACHIEVEMENT OF OBJECTIVES AND IMPACT

There is excellent work in the dimensional metrology area, where measurement uncertainty is being improved to new levels and closer traceability to the SI is being established. Examples include the following:

- Coordinate measurement with the Moore M48 coordinate measuring machine,
- Laser interferometry in spherical-coordinate instrument calibration, and
- Artifact and calibration methodologies for ballistics measurement.

There are many notable metrology capabilities supporting current and future needs in micro- and nanotechnology, including the following:

- The first commercial helium-ion microscope,
- Improved uncertainty in the critical-dimension atomic force microscope,
- Atom-based dimensional metrology,
- Optical tweezers,
- Improved optical overlay, and
- Continued improvement in critical-dimension metrology.

The PED has achieved its objectives by developing important new capabilities in measurement services needed in industry. Examples include the following:

- Measurement of fiber-optics standard lengths,
- Noncooperative target measurement in the 60 meter laboratory,
- The ability to measure submillimeter features on the M48 with very low uncertainty and high traceability to the SI, and
- New national calibration artifacts and calibration methodologies for spherical-coordinate metrology devices (e.g., laser trackers) and for ballistics measurements.

Maturation of this metrology research and development will lead to new metrology methods. The PED showed a clear path toward achieving this goal.

The division provides a valuable service to industry with its measurement and calibration services. Examples include photomask measurements, forensics measurements, and survey tape calibration.

The PED was very active in delivering 11 physical standards (standard reference materials and reference materials) and participating in the formation of 15 procedural standards (ANSI/ASME, ISO, ASTM [ASTM International, originally known as the American Society for Testing and Materials], SEMI [Semiconductor Equipment and Materials International]).

The division exhibits an extensive list of publications, presentations, educational workshops, and advisory board memberships. More than 10 major awards were achieved in the past 3 years. The division has many strong ties to industry, including SEMATECH (Semiconductor Manufacturing Technology), key equipment suppliers, and other NMIs. The PED should take a more active role in bridging the metrology gap between NIST and industry capabilities and customers.

The PED provides services to NASA; the Bureau of Alcohol, Tobacco, and Firearms; the Federal Bureau of Investigation; the Department of Energy; Bethesda Naval Medical Center; and other government entities.

CONCLUSIONS

The conclusions of the panel based on its assessment of the Precision Engineering Division are as follows:

- The PED research staff is knowledgeable, dedicated, and highly enthusiastic about its work.
- The PED has made significant improvements over the past 3 years in meeting the needs of the semiconductor industry.

- The move to the Advanced Measurements Laboratory resulted in dramatic improvement in metrology capabilities, in several cases elevating the division's capability to its being among the best in its field.
- The PED has maintained its state-of-the-art equipment capabilities through innovative partnerships with equipment suppliers and other outside entities.
- The PED has been engaged in forward-looking efforts in helium-ion microscopy, atom-based metrology, nanoparticle work in biosystems, and whole wafer/photomask capability.
- The PED has had major impact both nationally and internationally by delivering new standard reference materials, calibration services, and documentation.
- Opportunities exist for the PED to promote its specific mission regarding traceability and standards development. For example, in nanomanufacturing, the PED's research differs substantially from research that others are doing in this area, both within and outside NIST, in that the PED's focus is on traceability to the SI.
- There is a need to define the core competencies of the PED and to define a succession plan for every key position. There are currently approximately 32 permanent staff members, 2 NRC postdoctoral researchers, and 34 guest researchers. Of the 34 guest researchers, 10 are retirees.
- The PED would be well served by strategic planning in the following areas: capital equipment, human resources, technical focus area roadmapping, and investment and disinvestment in calibration and measurement services.
- Opportunities exist for the dimensional metrology groups to establish methodologies for receiving feedback from U.S. industry—for example, through workshops held both at NIST and at professional society meetings and through surveys by trade organizations.
- Opportunities exist for the dimensional metrology groups to be more proactive in improving their visibility within the national technical community.
- Benchmarking is performed currently for other NMIs, but this activity should be expanded to include industry in order to capture significant cutting-edge capabilities.
- Opportunities exist for exploring alternative cost structures for the calibration and measurement services—for example, machine charges, consumables charges, service center charges, and activity-based cost accounting.

Programs Funded Under the America COMPETES Act

The Supply Chain Integration and Bio-Imaging projects in the Manufacturing Systems Integration Division have gained incremental funding under the America COMPETES Act of 2007. The funding has been used to bolster the more strategic segments of the semantic mediation work in supply chain. This will speed its deployment for the benefits of the nation. Specific accomplishments include the following:

- Development and demonstration (in the IV&I/ATHENA program[8]) of a tool to automatically translate between Resource Description Framework and Extensible Markup Language schemas, both of which are heavily used standards in the operation of global supply chains;
- Development and demonstration (in the IV&I/ATHENA program) of a universal framework for testing conformance to the Open Applications Group supply chain standards; and
- Development and demonstration (in the Material Off-Shore Sourcing project) of expanded information mapping tests that advance the ability to manage data across supply chains that use ocean freight.

The funding has been used to further the collaboration with the NIST's Information Technology Laboratory (ITL). Specific accomplishments include the following:

- Developments of standard representations schemes and archival techniques that support very rapid context-based search, semantic annotation, and image recognition, including endoscopic video data;
- A Workshop on Ontologies (as a collaboration between the MSID, the ITL, and Stanford University) to identify the barriers to effective utilization of ontologies. This will be very useful in the context of directing future work on standards and the testing of standards.

The Precision Engineering Division received $87,000 to support bionanoparticle research, in which researchers are imaging, locating, and tracking nanoparticles in cancer cells for drug delivery applications. It is too early in the funding cycle to assess the progress of this work, but the effort demonstrates initiative for applying sensing, measurements, and fabrication technology to this very important biomedical need.

[8] IV&I/ATHENA is a program funded by the European Commission Information Societies Technology (EC/IST). See http://www.athena.ic.ac.uk/. Accessed March 27, 2008.

Overall Conclusions

Overall, the four divisions in the Manufacturing Engineering Laboratory reviewed by the panel are performing to the best of their capabilities, and much of the work being performed is among the best in the field. Their programs in measurement science and standards support NIST's mission to contribute to the economic well-being of the nation. However, reduced funding and other factors are limiting (and are likely to increasingly limit) the degree to which MEL programs can achieve their objectives and are threatening the future impact of these programs. These factors include a significant percentage of division budgets relying on opportunistic funding, an overhead structure that has put increasing reliance on guest researchers and makes the postdoctoral rates noncompetitive, a lack of successor personnel in key technical positions, and a dwindling supply of workers in certain areas such as metrology. High-impact progress in the future will likely require disinvestment in some areas and strategic refocusing. NIST and the MEL have the technical capability to do this, driven by the rapidly changing scope and nature (and by the very definition) of manufacturing in the nation.