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

FISCAL YEAR 2017

Panel on Review of the Engineering Laboratory at the
National Institute of Standards and Technology

Committee on NIST Technical Programs

Laboratory Assessments Board

Division on Engineering and Physical Sciences

A Consensus Study Report of
The National Academies of
SCIENCES • ENGINEERING • MEDICINE

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

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

This study was supported by Contract No. SB1341-12-CQ-0036 with the National Institute of Standards and Technology. Any opinions, findings, conclusions, or recommendations expressed in this publication do not necessarily reflect the views of any agency or organization that provided support for the project.

Digital Object Identifier: https://doi.org.10.17226/24976

Copies of this publication are available from

Laboratory Assessments Board
National Academies of Sciences, Engineering, and Medicine
500 Fifth Street, NW #928
Washington, DC 20001

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

Printed in the United States of America

Suggested Citation: National Academies of Sciences, Engineering, and Medicine. 2017. *An Assessment of the Smart Manufacturing Activities at the National Institute of Standards and Technology Engineering Laboratory: Fiscal Year 2017*. Washington, DC: The National Academies Press. https://doi.org.10.17226/24976.

The National Academies of

SCIENCES • ENGINEERING • MEDICINE

The **National Academy of Sciences** was established in 1863 by an Act of Congress, signed by President Lincoln, as a private, nongovernmental institution to advise the nation on issues related to science and technology. Members are elected by their peers for outstanding contributions to research. Dr. Marcia McNutt is president.

The **National Academy of Engineering** was established in 1964 under the charter of the National Academy of Sciences to bring the practices of engineering to advising the nation. Members are elected by their peers for extraordinary contributions to engineering. Dr. C. D. Mote, Jr., is president.

The **National Academy of Medicine** (formerly the Institute of Medicine) was established in 1970 under the charter of the National Academy of Sciences to advise the nation on medical and health issues. Members are elected by their peers for distinguished contributions to medicine and health. Dr. Victor J. Dzau is president.

The three Academies work together as the **National Academies of Sciences, Engineering, and Medicine** to provide independent, objective analysis and advice to the nation and conduct other activities to solve complex problems and inform public policy decisions. The National Academies also encourage education and research, recognize outstanding contributions to knowledge, and increase public understanding in matters of science, engineering, and medicine.

Learn more about the National Academies of Sciences, Engineering, and Medicine at **www.nationalacademies.org**.

PANEL ON REVIEW OF THE ENGINEERING LABORATORY AT THE NATIONAL INSTITUTE OF STANDARDS AND TECHNOLOGY

NEIL A. DUFFIE, University of Wisconsin, Madison, *Chair*
HADI ABU-AKEEL, Brachium, Inc.
JOSEPH J. BEAMAN, JR., University of Texas, Austin
DAVID L. BOURELL, University of Texas, Austin
DIANNE CHONG, Boeing Company
DEAN R. COLLINS, DRC Consulting, LLC
DAVID E. CROW, University of Connecticut
RAINER HEBERT, University of Connecticut
S. JACK HU, University of Michigan
MOHSEN A. JAFARI, Rutgers University
ZHENYU (JAMES) KONG, Virginia Polytechnic Institute and State University
JAY LEE, University of Cincinnati
EUGENE MEIERAN, Intel Corporation (retired)
JOHN ONEY, PostProcess Technologies
LYNNE E. PARKER, University of Tennessee, Knoxville
WILLIAM F. POWERS, Ford Motor Company (retired)
H. DONALD RATLIFF, Georgia Institute of Technology
EMANUEL M. SACHS, Massachusetts Institute of Technology
LAURENCE C. SEIFERT, AT&T Corporation (retired)
F. STAN SETTLES, University of Southern California
VENKATA VEDULA, United Technologies Corporation
JOHN WEN, Rensselaer Polytechnic Institute
KATE S. WHITEFOOT, Carnegie Mellon University
DAVID D. YAO, Columbia University

Staff

AZEB GETACHEW, Senior Program Assistant
LIZA HAMILTON, Associate Program Officer
EVA LABRE, Administrative Coordinator
JAMES P. MCGEE, Director

COMMITTEE ON NIST TECHNICAL PROGRAMS

ELSA REICHMANIS, Georgia Institute of Technology, *Chair*
MICHAEL I. BASKES, Mississippi State University
LEWIS BRANSCOMB, University of California, San Diego
MARTIN E. GLICKSMAN, Florida Institute of Technology
JENNIE S. HWANG, H-Technologies Group
CHRISTOPHER W. MACOSKO, University of Minnesota
C. KUMAR PATEL, Pranalytica, Inc.
BHAKTA B. RATH, Naval Research Laboratory
ALICE WHITE, Boston University

Staff

AZEB GETACHEW, Senior Program Assistant
LIZA HAMILTON, Associate Program Officer
EVA LABRE, Administrative Coordinator
JAMES P. MCGEE, Director

Acknowledgment of Reviewers

This Consensus Study Report was reviewed in draft form by individuals chosen for their diverse perspectives and technical expertise. The purpose of this independent review is to provide candid and critical comments that will assist the National Academies of Sciences, Engineering, and Medicine in making each published report as sound as possible and to ensure that it meets the institutional standards for quality, 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:

Agnes Chau Klucha, UTC Aerospace Systems,
Wallace J. Hopp, University of Michigan,
Yoram Koren, University of Michigan,
Hau L. Lee, Stanford University,
Deborah J. Nightingale, Massachusetts Institute of Technology,
Robert E. Schafrik, General Electric Aircraft Engines, and
Matthew J. Zaluzec, Ford Motor Company.

Although the reviewers listed above provided many constructive comments and suggestions, they were not asked to endorse the conclusions or recommendations of this report nor did they see the final draft before its release. The review of this report was overseen by Michael I. Baskes, Mississippi State University. He was responsible for making certain that an independent examination of this report was carried out in accordance with the standards of the National Academies and that all review comments were carefully considered. Responsibility for the final content rests entirely with the authoring panel and the National Academies.

Contents

Summary

The mission of the Engineering Laboratory (EL) of the National Institute of Standards and Technology (NIST) is to "promote U.S. innovation and industrial competitiveness by advancing measurement science, standards, and technology for engineered systems in ways that enhance economic security and improve quality of life."[1] To support this mission the EL has developed thrusts in smart manufacturing, construction, and cyberphysical systems; in sustainable and energy-efficient manufacturing materials and infrastructure; and in disaster-resilient buildings, infrastructure, and communities. The technical work of the EL is performed in five divisions—Intelligent Systems, Materials and Structural Systems, Energy and Environment, Systems Integration, and Fire Research—and in two offices—the Applied Economics Office and the Smart Grid Program Office.

In 2017, at the request of the acting director of NIST, the National Academies of Sciences, Engineering, and Medicine formed the Panel on Review of the Engineering Laboratory at the National Institute of Standards and Technology (referred to in this report as "the panel") and established the following statement of task for the panel:

> The Panel on Review of the Engineering Laboratory at the National Institute of Standards and Technology will assess the scientific and technical work performed by the National Institute of Standards and Technology (NIST) Engineering Laboratory (EL). The panel will review technical reports and technical program descriptions prepared by NIST staff, and will visit the facilities of the NIST laboratory. The visit will include technical presentations by NIST staff, demonstrations of NIST projects, tours of NIST facilities, and discussions with NIST staff. The panel will deliberate findings in a closed session panel meeting and will prepare a report summarizing its assessment findings.

The acting director of NIST requested that in 2017 the panel confine its assessment to the following smart manufacturing programs conducted at the Engineering Laboratory: Measurement Science for Additive Manufacturing (MSAM), Robotic Systems for Smart Manufacturing (RSSM), Smart Manufacturing Operations Planning and Control (SMOPAC), and Smart Manufacturing Systems Design and Analysis (SMSDA).

CONCLUSIONS AND RECOMMENDATIONS

General Conclusions and Recommendations

Smart manufacturing programs in the EL at NIST have significantly evolved in the last five years, matching increased national recognition of the importance of manufacturing in the economy, as well as international recognition of the importance of integration of digital computing and information technologies into manufacturing systems. For example, the additive manufacturing program area was

---

[1] National Institute of Standards and Technology, "About EL," https://www.nist.gov/el/about-el, accessed May 22, 2017.

established approximately three and one-half years ago and is now an impressive effort in an area of rapid technology growth, staffed by competent early-career researchers, and facilitated by a measurement testbed of their own design with unique and powerful capabilities. Standards are being given a high priority, and there is excellent collaboration with other organizations and leadership in these efforts. There is significant focus on small and medium enterprises (SMEs), which is a valuable objective that is difficult to achieve. There are good research collaborations with industry, but perhaps an overreliance on (hoped for) trickle down from work with larger industries; more extensive outreach to SMEs, especially young SMEs, would be beneficial.

The EL's smart manufacturing program appears to lack a roadmap and measurable milestones, as do the individual programs and projects. Without roadmaps and measurable milestones, the quality and value of NIST's smart manufacturing programs and their management were more difficult to assess, and therefore the value, quality, and results of individual projects were more difficult to measure. Although some excellent research outputs, evinced by strong publication records in peer-reviewed journals, are being obtained and significant progress in standards is being made, many project plans did not show intermediate project milestones, and so it was difficult to determine in some cases whether projects were making the expected amount of progress and achieving the desired results. Roadmaps and measurable milestones would be invaluable tools for NIST management.

There is also, in some cases, a lack of crosscutting activities that can take advantage of the synergistic objectives of individual projects. Examining the project's plans, together to find opportunities for cross-fertilization and integrating the testing and evaluation work across the overall smart manufacturing program, could provide more synergy across the projects, as well as an opportunity to achieve broader impact of the program work as a whole, rather than only at the project level. This is not helped by the current distance between laboratory spaces, and it would be better to have a larger and more contiguous space so that multiple projects and programs could be integrated into a larger, more complex testbed that more resembles some manufacturing environments.

The new program areas are well covered by both junior and senior staff, who have significantly and successfully adapted their efforts to new technologies. Some areas appear to be short on permanent staff and expertise, but staffing appears to be generally sufficient to support the research that is under way. The journal publication record is excellent. There has been significant external recognition of the staff and its research, but additional efforts need to be made to promote and apply for external awards for the staff. This also would promote recognition of the smart manufacturing research programs at NIST.

Measurement Science for Additive Manufacturing

The majority of national laboratories within the federal government currently pursue additive manufacturing (AM), and the significant progress that has been made within the Measurement Science for Additive Manufacturing (MSAM) program could benefit these other laboratories that, in turn, could likely help the MSAM program. Additionally, closer engagement and alignment with other U.S. government laboratories could ensure that the MSAM program is effectively leveraging the investments being made in this area.

RECOMMENDATION 1: The Engineering Laboratory should consider closer engagements with other national laboratories' additive manufacturing groups.

A dialogue needs to be intensified with the Material Measurement Laboratory (MML) and its Polymers Processing Group in order to exploit common strengths and overlapping research interests. This dialogue could build on existing meetings with the MML and the Polymers Processing Group and evolve toward common research projects, such as feedstock characterization or the design of additive manufacturing machines.

RECOMMENDATION 2: The Engineering Laboratory should consider beginning an intensified dialogue with the Material Measurement Laboratory and the Polymers Processing Group.

There are several highly industry relevant topics within AM that are not currently pursued with sufficient emphasis by the MSAM program. These topics include support structures and their design, the effects of different build orientations, design limitations for AM, and the post-processing side of AM. Broadening the focus into post- or secondary processing will help researchers understand what limitations within the technologies cannot be overcome with post-processing methods. Expanding research veins into support structures and post-processing, and defining new procedures in this field, would allow an opportunity to develop new standards, which could help industry find common ground.

RECOMMENDATION 3: The Engineering Laboratory should consider expanding its research into the measurements and standards needed to assist industry in the following areas: support structures and their design, the effects of different build orientations, design limitations for additive manufacturing, and the post-processing side of additive manufacturing.

Robotic Systems for Smart Manufacturing

Overall, the laboratory facilities, equipment, and human resources are top-notch and sufficient for impactful standards development activities in the Robotic Systems for Smart Manufacturing (RSSM) program. The program staff has done an excellent job of identifying the top brands of robotic and sensor equipment that will likely be used by SMEs and has acquired and activated the equipment for its research. The staff has been successful in operating the equipment to develop best practice methods for using the hardware and related software and to conduct a wide variety of experiments and demonstrations to evaluate potential metrics, test artifacts, and methods for multi-robot collaboration, agility, interoperability, and integration.

The RSSM program is providing important contributions to the development of standards, metrics, and applicable technologies in the areas of performance assessment, collaborative robotics, agility, interoperability, and integration. The focus on the development of standards and performance metrics and tests in these areas aligns well with the mission of the EL. In particular, the program has made important advances in identifying weaknesses with existing metrics and standards in robotic mobility and agility, anticipating unmet needs for future industry challenges, and developing new metrics and standards to address these issues.

The RSSM program staff has an opportunity to lead in the development of a more systematic methodology for generating test and use cases. Such a methodology could include needs assessment, gap identification, research, metrics development, test methods and artifacts development, standards development, evaluation, and dissemination.

RECOMMENDATION 4: The Engineering Laboratory should consider leading the development of methodological approaches for standards development in all component areas of its robotic systems for smart manufacturing research, including the areas of needs assessment, gap identification, research, metrics development, test methods and artifacts development, standards development, evaluation, and dissemination.

The RSSM program could broaden its industrial impact through stronger interactions with the Manufacturing Extension Partnership (MEP) centers or other industrial consortia. Through these deepened interactions, the RSSM program could develop a set of use cases and obtain more in-depth feedback on standards development.

RECOMMENDATION 5: The Engineering Laboratory should consider interacting on a regular basis (e.g., twice annually) with the Manufacturing Extension Partnership (MEP) centers or other industry consortia to source use cases and receive feedback on the effectiveness of their development of metrics and standards.

Although vision sensors are used in several RSSM testbeds, the EL has an unexplored opportunity to investigate how machine vision can be used to enhance the flexibility and user-friendliness of robots for SMEs. The exploration of how to take advantage of machine vision to simplify robot programming, develop self-teaching techniques, ensure safe human-robot interaction, and adapt to the varied application environments at SME facilities is a good fit with the EL's objectives for the RSSM program.

RECOMMENDATION 6: The Engineering Laboratory should consider exploring the use of machine vision to enhance the value of robots for small and medium enterprises (SMEs) by reducing programming complexity for short-run manufacturing applications.

There is an increasing utilization of cloud and edge resources for robotics and industrial automation. The Industry 4.0, Microsoft Azure, and Amazon Web Services (AWS) efforts are trying to integrate resources in a consistent and efficient framework, and the RSSM program has the opportunity to contribute to and lead this nascent field.

RECOMMENDATION 7: The Engineering Laboratory should consider exploring methodological approaches and standards development related to cloud robotics by contributing to activities in this area (e.g., Industry 4.0), and taking a leadership role in this field.

Given the level of expertise and contribution of the RSSM research team, additional peer recognition is possible in the form of merit-based robotics awards, elevation in professional societies, invitations to delivering opening and keynote presentations at conferences, and early-career investigator awards. This type of external recognition can serve not only to award deserving individuals but also to raise the visibility of EL in the field.

RECOMMENDATION 8: The Engineering Laboratory should be more proactive in seeking individual recognition for accomplished robotics staff personnel, rather than waiting to be discovered.

Human-machine collaboration is an important challenge in robotics for manufacturing. The RSSM program appears to have an expertise gap in human robot interaction due to lack of permanent staff in this area. Active recruiting of such researchers into NIST permanent staff is important to establish this topic as an active research area.

RECOMMENDATION 9: The Engineering Laboratory should establish permanent staff expertise in its human-robot interaction area to avoid a future expertise gap.

The RSSM could more systematically leverage and seek out expertise from other organizations, including universities and industries, and through an extended use of guest researcher programs. A consortium of industrial companies, both large and small, as well as universities that meet with the RSSM on an annual or a semi-annual basis, could serve as additional sources of expertise for needs assessment, gap identification, and the testing and validation of standards.

RECOMMENDATION 10: The Engineering Laboratory should consider systematically leveraging and seeking out expertise from other organizations, including university, industry,

and Manufacturing USA Institutes who can serve as additional sources of expertise for needs assessment, gap identification, and the testing and validation of standards.

The RSSM program has researched the capabilities of a wide variety of robotic grippers. They have developed many test methods, artifacts, and metrics to guide in the design and use of grippers for dexterous grasping. They have an opportunity to leverage this research to create community-wide test sets that can assist the research community in developing new approaches to dexterous grasping. For example, the Yale-CMU-Berkeley (YCB) Object and Model Set data set is a related contribution to the research community that helps advance robotic manipulation, and a similar contribution based on the RSSM research would be highly beneficial to the research community.

RECOMMENDATION 11: The Engineering Laboratory should consider coordinating with other organizations to develop community-wide test sets for dexterous grasping.

Although the research facilities are adequate, they are also distributed across the NIST campus and are physically disconnected across multiple buildings on the campus. Given that the RSSM research projects share many common technologies, science, and resource needs, and can benefit from knowledge exchanges, such separations between the project teams might contribute to less cohesiveness and overall impact than might be possible through co-located facilities. The lack of crosscutting activities across all the projects of the RSSM program is not helped by the distance between laboratory spaces.

RECOMMENDATION 12: The Engineering Laboratory should consider co-locating test facilities to enhance integration of Robotic Systems for Smart Manufacturing (RSSM) program activities across the entire program.

There is an opportunity to develop software infrastructure resources to facilitate the interoperability of testbeds developed in individual projects. Several of the testbeds developed for individual projects have overlapping capabilities but cannot currently be integrated because they do not have interoperable software.

RECOMMENDATION 13: The Engineering Laboratory should strive for interoperability of software infrastructure for their testbeds.

The ability of RSSM staff to share videos, images, and other information through social media is hindered by the lengthy approval process at NIST and the lack of staff with expertise in social media outreach. As a result, the program has very little visibility on social media, which is a missed opportunity to improve the impact of the RSSM program's activities.

RECOMMENDATION 14: The Engineering Laboratory should consider adding staff who can improve dissemination of technical accomplishments through social media, trade publications, and/or popular press and should work with NIST management to identify ways to streamline approval processes for applying these methods.

Smart Manufacturing Operations Planning and Control

The Smart Manufacturing Operations Planning and Control (SMOPAC) program needs to develop an overarching, integrated roadmap with measurable milestones that shows the relationships of the various markets (automotive, aerospace, etc.) and requirements to the technologies, as well as the relationships between the technical areas themselves. The roadmap needs to be an integrated, high-level plan, not a set of semi-related programs.

RECOMMENDATION 15: The Engineering Laboratory should consider developing an overarching roadmap with measurable milestones for the Smart Manufacturing Operations Planning and Control (SMOPAC) program that integrates market needs, product requirements, and technologies.

The EL needs to examine its activities within the context of national and global activities at other organizations to identify competitive and duplicative areas.

RECOMMENDATION 16: The Engineering Laboratory should consider benchmarking its work in smart manufacturing operations planning and control against other manufacturing programs, such as those in EU Horizon 2020, to identify competitive and duplicative areas.

In order to ensure alignment with manufacturers' needs, and to identify early adopters of advanced technologies, programs, tools, and processes, the SMOPAC program needs to engage additional manufacturers, including new entrants to the manufacturing sector, such as start-up manufacturing companies and suppliers. They could partner, for example, with Manufacturing USA to facilitate information exchange.

RECOMMENDATION 17: The Engineering Laboratory should consider engaging new manufacturers and suppliers to ensure alignment with manufacturers' needs and to identify early adopters of advanced technologies, programs, tools, and processes.

RECOMMENDATION 18: The Engineering Laboratory should consider partnering with Manufacturing USA to establish Standard for the Exchange of Product Data (STEP)-like computer-aided design (CAD), computer-aided manufacturing (CAM), and computer-integrated manufacturing (CIM) product information exchange standards.

The SMOPAC program needs to develop and show project plans with measurable milestones to describe their 5-year projects. Such project plans can be used as communication tools to inform management, the staff working on the project, users, emerging companies, and the public about the value of the project's goals and when the results will be made available.

RECOMMENDATION 19: The Engineering Laboratory should develop project plans with measurable milestones that describe their 5-year projects and use these plans as communication tools.

The definition of "life cycle" that the Digital Thread for Smart Manufacturing project is using shows the end of the cycle as being when the initial product is delivered to the customer. This is different from the Department of Defense (DoD) ManTech projects, which include the Army, Navy, and Air Force projects on digital thread and digital twin, where life cycle also includes the life of the aircraft. In aerospace and automotive industries (as well as with health care devices and others), the manufacturer needs to have the ability to track the vehicles and devices in the field for potential part defects as long as they are in service; and so life cycle is from cradle to grave. In all fields, products have increasingly tremendous sensory and computational capabilities, and in-the-field capabilities for diagnostics and prognostics need to be considered as part of the life cycle in the digital thread.

RECOMMENDATION 20: The Engineering Laboratory should improve and clarify the definition of "life cycle" to be more comprehensive and include manufacturing activities after the product is delivered.

The concept of the digital thread can be applied to multiple industries of various sizes. The Digital Thread for Smart Manufacturing project is targeting medium-size manufacturers. While smaller manufacturers may either already have or be able to adopt these tools and standards, the team needs to address how large-scale industries (e.g., aerospace, automotive) will adopt NIST's unique tools.

RECOMMENDATION 21: The Engineering Laboratory should put together a business case for small-, medium-, and large-scale industries to adopt their digital thread tools.

The Prognostics, Health Management, and Control (PHMC) team has developed an efficient and effective linear axis error detection methodology based on data collected from an inertial measurement unit (IMU), which has been developed and verified on the linear axis testbed and machine tools within the PHMC project at NIST. Validation efforts are ongoing both internally within NIST and externally with several manufacturing collaborators. The developed IMU sensor is very practical to assess machine health degradation rapidly. The team has demonstrated platform-based technologies to allow diversified users to connect to the machine and share their data. The team is planning to promote its research to system levels; however, the research scope needs to be more clearly defined (e.g., type of applications, sensors, and analytics) before this happens. Collaboration with the Clean Energy Smart Manufacturing Innovation Institute (CESMII) will help to define, identify, and satisfy industry needs and requirements as well as provide efficiencies in areas of overlapping research.

RECOMMENDATION 22: The Engineering Laboratory should consider collaborating with the Clean Energy Smart Manufacturing Innovation Institute to help to identify, prioritize, and satisfy industry needs and requirements and to provide efficiencies in areas of overlapping research.

The Cybersecurity for Smart Manufacturing project has established a testbed to validate the cybersecurity framework manufacturing profile. Data obtained from this testbed will be used to develop guidance for implementation of this framework. The testbed needs to include a simulation system that can generate virtual cyber threats to evaluate the resilience of the system.

RECOMMENDATION 23: The Engineering Laboratory's testbed for the Cybersecurity for Smart Manufacturing project should include a simulation system that can generate virtual cyber threats to evaluate the resilience of the system.

The Wireless Systems for Industrial Environments project research is just beginning, and it needs to be considered more broadly. The team needs to develop testbeds that include both cybersecurity and wireless technology and consider integrating with a cloud-based or edge-based environment to support more tether-free monitoring system applications.

RECOMMENDATION 24: The Engineering Laboratory should consider developing a testbed that includes both cybersecurity and wireless technology.

RECOMMENDATION 25: The Engineering Laboratory should consider integrating with a cloud-based or edge-based environment to support more tether-free monitoring system applications.

In some of the testbeds, there are arrangements being made to integrate with other programs, such as robotics. This is a good start; however, the integration is small. It would be better to have a larger space so that multiple projects and programs could be integrated into a bigger, more complex testbed that more resembles an actual manufacturing environment. Validation of models under these conditions would provide meaningful data.

RECOMMENDATION 26: The Engineering Laboratory should consider dedicating an area or a facility for the integration of multiple projects and programs to simulate an industrial environment.

Smart Manufacturing Systems Design and Analysis

The NIST Smart Manufacturing Systems Design and Analysis (SMSDA) program would greatly benefit from and could contribute to an overarching roadmap of smart manufacturing for the nation.

RECOMMENDATION 27: The Engineering Laboratory should consider collaborating with the Smart Manufacturing Leadership Coalition (SMLC) and the newly formed Clean Energy and Smart Manufacturing Innovation Institute (CESMII) to develop for the National Institute of Standards and Technology and the United States an overarching roadmap with measurable milestones for smart manufacturing.

Where best practices for smart manufacturing capabilities do not exist, the task is to develop structures, databases, prototypes, and techniques to define best practices. During execution of tasks of this type, the inclusion of a domain expert on the team would greatly improve the output.

RECOMMENDATION 28: Where a smart manufacturing best practice does not exist, the Engineering Laboratory should consider embedding domain experts on the project teams to ensure the quality of their output.

The SMSDA program needs to ensure that the output of projects where a smart manufacturing best practice does not exist is tested in at least two SMEs. These SMEs need to become an integral part of the project teams to ensure that the developed structures, databases, and techniques make it easier for SMEs to utilize smart manufacturing.

RECOMMENDATION 29: The Engineering Laboratory should ensure that where a smart manufacturing best practice does not exist, the output of projects is tested in at least two small and medium enterprises (SMEs).

Where there is a lack of existing standards or guidelines, the SMSDA program needs to broaden its scope to include identifying smart manufacturing best practices in a select set of industry sectors. Given that the program has been actively collaborating with various standards communities and has access to a wide range of industries, this broadening of scope appears both feasible and practical.

RECOMMENDATION 30: Where there is a lack of existing standard or guidelines, the Engineering Laboratory should consider broadening its scope to include identifying smart manufacturing best practices in a select set of industry sectors.

Project planning for multiyear projects needs to include measurable intermediate milestones so that progress and midcourse correction can easily be understood and executed. The projects need to have a clear definition of deliverables and measurable milestones. Additionally, deliverables need to include SME demonstrations and testing.

RECOMMENDATION 31: The Engineering Laboratory should consider planning multiyear projects with measurable intermediate milestones so that progress and midcourse correction needs are readily visible.

1

The Charge to the Panel and the Assessment Process

At the request of the National Institute of Standards and Technology (NIST), the National Academies of Sciences, Engineering, and Medicine has, since 1959, annually assembled panels of experts from academia, industry, medicine, and other scientific and engineering communities to assess the quality and effectiveness of NIST measurements and standards laboratories, of which there are now seven,[1] as well as the adequacy of the laboratories' resources. 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. NIST laboratories conduct research to anticipate future metrology and standards needs, to enable scientific and technological advances, and to improve and refine existing measurement methods and services.

At the request of the acting director of NIST, in 2017 the National Academies formed the Panel on Review of the Engineering Laboratory at the National Institute of Standards and Technology and established the following statement of task for the panel:

> The Panel on Review of the Engineering Laboratory at the National Institute of Standards and Technology will assess the scientific and technical work performed by the National Institute of Standards and Technology (NIST) Engineering Laboratory (EL). The panel will review technical reports and technical program descriptions prepared by NIST staff, and will visit the facilities of the NIST laboratory. The visit will include technical presentations by NIST staff, demonstrations of NIST projects, tours of NIST facilities, and discussions with NIST staff. The panel will deliberate findings in a closed session panel meeting and will prepare a report summarizing its assessment findings.

The acting director of NIST requested that in 2017 the panel confine its assessment to the following smart manufacturing programs conducted at the Engineering Laboratory, which conducts activities in other areas as well: Measurement Science for Additive Manufacturing (MSAM), Robotic Systems for Smart Manufacturing (RSSM), Smart Manufacturing Operations Planning and Control (SMOPAC), and Smart Manufacturing Systems Design and Analysis (SMSDA).

The acting director of NIST also suggested that the panel consider during its assessment the following factors:

1. Assess the organization's technical programs.

---

[1] The seven National Institute of Standards and Technology (NIST) laboratories are the Engineering Laboratory, the Physical Measurement Laboratory, the Information Technology Laboratory, the Material Measurement Laboratory, the Communication Technology Laboratory, the Center for Nanoscale Science and Technology, and the NIST Center for Neutron Research.

- How does the quality of the research compare to similar world-class research in the technical program areas?
- Is the quality of the technical programs adequate for the organization to reach its stated technical objectives? How could it be improved?

2. Assess the portfolio of scientific expertise within the organization.

- Does the organization have world-class scientific expertise in the areas of the organization's mission and program objectives? If not, what areas should be improved?
- How well does the organization's scientific expertise support the organization's technical programs and the organization's ability to achieve its stated objectives?

3. Assess the adequacy of the organization's facilities, equipment, and human resources.

- How well do the facilities, equipment, and human resources support the organization's technical programs and its ability to achieve its stated objectives? How could they be improved?

To accomplish the assessment, the National Academies assembled a panel of 24 volunteers whose expertise matched that of the work performed by the EL staff.[2]

On March 28-30, 2017, the panel assembled at the NIST facility in Gaithersburg, Maryland, for a two and a half day assessment, during which it received welcoming remarks from the EL director, heard overview presentations by EL management and presentations by researchers at the EL, toured portions of the EL facility, and attended an interactive session with EL management. The panel also met in a closed session to deliberate on its findings and to define the contents of this assessment report.

The panel's approach to the assessment relied on the experience, technical knowledge, and expertise of its members. The panel did not attempt to report an exhaustive assessment of every project reviewed. Rather, the panel's goal was to identify and report accomplishments and opportunities for further improvement with respect to the following: the quality of the technical programs at the EL; the portfolio of scientific expertise within the laboratory; and the adequacy of the laboratory's facilities, equipment, and human resources. The panel illustrated its conclusions with salient examples of programs and projects that are intended collectively to portray an overall impression of the laboratory, while preserving useful suggestions specific to projects and programs.

To accomplish its mission the panel reviewed the material provided by the EL prior to and during the review meeting. The choice of projects to be reviewed was made by the EL. The panel applied a largely qualitative approach to the assessment. Given the nonexhaustive nature of the review, the omission in this report of any particular EL project should not be interpreted as a negative reflection on the omitted project.

[2] See the NIST Engineering Laboratory website, at https://www.nist.gov/el, for information on the Engineering Laboratory organization and programs (accessed April 21, 2017).

2

Measurement Science for Additive Manufacturing

INTRODUCTION

The Intelligent Systems Division within the Engineering Laboratory (EL) focuses on the key areas of smart manufacturing. The smart manufacturing program areas within the Intelligent Systems Division include Measurement Science for Additive Manufacturing (MSAM), Robotic Systems for Smart Manufacturing (RSSM), and Smart Manufacturing Operations Planning and Control (SMOPAC).

Additive manufacturing (AM), also known as three-dimensional (3D) printing, continues to be dubbed as the "next best thing" in advanced manufacturing owing to its promise to fundamentally revolutionize part designs and manufacturing methods. By printing parts directly from a 3D computer-aided design (CAD) digital file, the technology enables unique organic shapes that cannot be manufactured through conventional manufacturing methods. Additionally, additive technologies can reduce the manufacturing lead time, part cost, and materials use. In spite of these benefits, the technology has not had widespread adoption within the U.S. manufacturing industry—except for niche applications. The key barriers for adoption are the following: material characterization, including types of defects and impact on mechanical properties; lack of design tools and allowables; investment costs of additive equipment; added cost and time for making components; qualification and certification requirements; process controls and variability; and lack of industry standards.

The AM work in the MSAM program is aimed at developing and deploying measurement science that will enable rapid design-to-product transformation through advances in four projects: (1) Characterization of Additive Manufacturing Materials; (2) Qualification for Additive Manufacturing Materials, Processes, and Parts; (3) Real-Time Monitoring and Control of Additive Manufacturing Processes; and (4) Systems Integration for Additive Manufacturing. The MSAM program is approximately three and one half years into a five-year program duration. The current total budget is $7.05 million, with a total staff of 21 federal employees, 4 NIST associates, and 4 students.

ASSESSMENT OF TECHNICAL PROGRAMS

Accomplishments

The individual projects within the MSAM program are well aligned with the overall program objective to

> Develop and deploy measurement science that will enable rapid design to product transformation through advances in: material characterization, in-process sensing, monitoring and model based

optimal control; performance qualification of materials, processes and parts, and end-to-end digital implementation of metal additive manufacturing processes and systems.[1]

The MSAM projects, which are discussed below, are designed to address some of these barriers for metal laser powder bed machines. The MSAM staff have been leading and driving the development of additive standards that are required to establish the metal additive manufacturing industry.

The Characterization of Additive Manufacturing Materials project addresses current needs and challenges for AM practitioners in the areas of powder characterization and handling. These two areas apply not only to powder bed AM technologies but also to other AM techniques. The strategy pursued in this project is to determine the limits and errors of major measurement techniques for AM powders in order to quantify uncertainties in the characterization of powders and along the processing chain. The project has resulted in excellent contributions that are helping to advance the state of the art in powder and powder bed characterization.

The project excellence is displayed, for example, in the approach to powder characterization where several different characterization techniques have been set up, including powder size distribution and shape analysis, a custom powder spreading device, different flow and density measurement devices, as well as a suite of X-ray tomography instruments for defect analysis in additively manufactured parts.

The project has generated, and continues to generate, new standards on the use of this equipment to characterize powders and parts. These new standards will help in comparing results from different groups on powder characterization. Another factor contributing to the excellence in the Characterization of Additive Manufacturing Materials project is the cross-project availability of the AM testbed. This testbed system is crucial to creating variables in the hardware and software of additive production systems. The experiments this testbed enables have great possibilities to advance system capabilities to produce higher quality parts.

Another example of the excellence in the Characterization of Additive Manufacturing Materials project is the work on powder recycling. Powder recycling is of great value to industry, and a round robin study has been initiated on the effects of powder recycling that will lead to guidelines on measurement techniques and uncertainties, and information on how these effects influence the results of recycling studies.

The Characterization of Additive Manufacturing Materials project aims at developing an AM database. Features of the web-based AM database include a viewable and navigable AM schema and currently accessible data and attributes (which include microstructure information on properties and dimensional information). The database is currently composed of NIST-funded round robin data collected in 2012 and 2014. Progress, so far, has been made to develop the framework of the database, and, if successful, this AM open database effort could significantly help U.S. industry.

The Qualification for Additive Manufacturing Materials, Processes, and Parts project includes three MSAM research areas. The first is generation and interpretation of reference data to serve model-based qualification efforts. The second is the development of preproduction run and post-processing test methods to assist in equivalence efforts. The third is the establishment of minimum requirements for testing to reduce the cost for empirical approaches. Through research in qualification, the EL will reduce the cost of empirical approaches and provide foundational information, which will support equivalence and model-based qualification approaches.

Work in the MSAM program contributes to model-based qualification through high-fidelity temperature measurements for metal laser-based powder bed fusion, which are used to validate multi-

[1] National Institute of Standards and Technology (NIST), "Measurement Science for Additive Manufacturing Program," updated December 08, 2016, https://www.nist.gov/programs-projects/measurement-science-additive-manufacturing-program.

physics models simulating individual melt tracks in an additive manufacturing process and low-fidelity temperature measurements typically made with an infrared (IR) camera. For example, reflections on the powder bed surface from spatter may be erroneously interpreted to be hot spots on the surface. Machine qualification studies have also led to the development of AM XY scanner test patterns. Additionally, an MSAM AM test artifact has been developed and is being distributed to assist with equivalence-based qualification and system performance characterization. The EL developed a CAD file for a metal plate with specific geometrical features, the test artifact. This plate and its features are designed for additive manufacturing, and different laboratories could use this particular CAD design to build the part and compare geometrical features or microstructures. The test artifact thus represents a key standard for additive manufacturing, and similar standards need to be developed for other aspects of additive manufacturing. The artifact is, essentially, a square plate containing features or assessing process accuracy and repeatability. From surface roughness measurement studies, MSAM researchers have concluded that standard R_A roughness measures do not fully capture important surface morphology. Use of R_{pc} and R_{Sm} has given better surface discrimination than the R_A measurement. Research is under way to explore relationships found between surface texture and microstructure. X-ray computed tomography is a powerful tool for assessing internal defects. MSAM researchers are analyzing the process to establish detection limits and to properly interpret images.

To support empirically based qualification, a methodology for round robin testing has been articulated by MSAM staff. The plan is to publish the information as an International Organization for Standardization (ISO) American Society for Testing and Materials (ASTM) guide standard. If properly conducted, round robin studies distribute the cost burden of testing and provide statistically valuable information.

The Real-Time Monitoring and Control of Additive Manufacturing Processes project team is working on visual monitoring of the melt pool in metal laser powder bed machines. They are motivated by the need to monitor the process so that correlations between the data and visually detectable flaws in parts can be investigated, to use the data as a quality control signature for the part, and to use the data for real-time control.

Selective laser sintering (SLS) is the dominant method for AM of metal parts, and control of this process is a significant issue. The intent of the MSAM work—to improve the process control of selective laser melting (SLM)—is sound. Visual monitoring of the melt pool is a good target, and, in fact, visual monitoring of the melt pool in SLS has been under investigation by various groups for approximately 20 years. In principle, NIST's prowess in measurement technology can form the basis of useful contributions to this field.

This work has been pursued on two hardware platforms: the testbed and the EOS M270 machine. A considerable portion of the testbed effort is allocated to an in situ measurement of the emissivity of the powder bed. The expectation is that the increased accuracy of the emissivity measurement will allow for better process monitoring and, hopefully, better real-time control. A thermal imaging camera has been adapted to an EOS M270 machine by fabricating a custom door and a camera mounting system. This camera is not concentric with the beam, but views the powder bed at an angle, perhaps in the range of 30 to 45 degrees from normal to the surface of the powder bed. In an effort to measure emissivity the team has done experiments with powder on hot plates at temperatures up to approximately 500ºC. The team reported experiments on emissivity measurements during the 27th International Solid Freeform Fabrication Symposium at the University of Texas, Austin, in 2016. They have explained that measurements at higher temperatures are exceedingly difficult—due to the fact that there is a challenge in uniformly heating.

Another MSAM program focus is the Systems Integration for Additive Manufacturing project, the objective of which is to deliver an information systems architecture, including metrics, information models, and validation methods, to shorten the design-to-product cycle time in AM.[2] The major deliverables for this project are separated into six thrust areas: (1) Additive Manufacturing Product Life Cycle Management and Digital Support in what is commonly called the "digital thread;" (2) Product Definition for Additive Manufacturing; (3) Design Allowable Database for Additive Manufacturing Materials (which focuses on statistically based mechanical property data and represents a subset of the Characterization of Additive Materials AM database); (4) Design Rules for Additive Manufacturing Parts; (5) Characterization and Uncertainty Quantification of Physics-Based Models for Additive Manufacturing; and (6) Process Planning Guidelines for Additive Manufacturing. The Systems Integration for Additive Manufacturing team has designed the architecture of each of these databases using state-of-the-art database methods and software project design tools. They have initially focused on just AM metal laser powder bed methods. In particular, they have planned for product definition and tolerance representations; AM design rules for metal parts; the characterization of powder bed fusion metal physics-based models; data structures for AM metal parts, processes, and materials; and path and process planning related to their home-grown powder bed fusion metal machine.

Opportunities and Challenges

A key challenge and opportunity for the MSAM program is to identify the limit of NIST's territory within the U.S. science and technology landscape of AM. Some of the activities in the Characterization of Additive Manufacturing Materials project—for example, the database development or the powder recycling study—overlap with similar activities in the private sector and in academia. The MSAM projects seem to be on a good track; however, there is a need to hone in on the measurement and standards aspect throughout the diverse range of AM topics currently pursued in the program, and the Characterization of Additive Manufacturing Materials project in particular.

The round robin studies in the Characterizations of Additive Manufacturing Materials project were conducted with
outside partners. The many challenges in controlling AM machines render round robin studies rather difficult, and a gradual approach might be better than the full-scale study that was conducted. The in-house real-time monitoring capabilities could be used even more than they currently are to start with a study of repeatability and variations for parts built on the same machine, as well as post-processing. The round robin study may also be too ambitious and could benefit from narrowing the parameter space or even from using polymers and polymer machines first. The primary goal of the round robin study might be modified to focus on the development of round robin testing procedures, and applying these testing procedures over multiple runs to understand the variance on a machine (with the constant parameter settings as a baseline), rather than determining differences in the properties from different sources per se. There are many different materials, machine brands, and build themes—and a quantification of variations for all combinations seems to be too broad.

In connection with powder recycling, more information is needed on material discontinuities or consistency within new powders. The Characterization of Additive Manufacturing Materials project team has the opportunity to work with material manufacturers (powder producers) on better consistency of powders, and to identify critical powder properties for the AM process. This could also result in better density in the mechanical powder spreading process. There are many variables: geography, systems, calibrations, powders, method of powder shipment, shelf life of the powder, operator or technician experience, and the system surroundings or atmosphere. Findings cannot be trusted unless all of these variables can be controlled. The testing could possibly involve the same parts, build orientation, and

[2] See NIST, "Systems Integration for Additive Manufacturing," updated July 13, 2017, https://www.nist.gov/programs-projects/systems-integration-additive-manufacturing.

support structure. Recycling could have many variables involving differences within the new powder added, including physical chemical properties, chemical composition, and the size and shape of powder, and these variables could play into the testing if they vary throughout different orders or lot numbers from the manufacturer. These factors need to be studied before recycling testing.

The MSAM AM database competes with commercial codes and it is not clear what the pathway is to populate the database. It may be better to focus this endeavor on a database structure and format, which could be very useful as a framework to be made openly available to the AM community—specifically, schema.

Another opportunity would be to broaden the manufacturing focus within AM, or consider closed loop manufacturing for additive technologies. In almost every manufacturing process or method there are challenges to produce high integrity or quality parts or components that do not need secondary processes or mechanical treatment. Within the limitations of AM to produce high-quality parts, secondary processes will be needed to produce suitable parts or components for many industries. Broadening the focus into post- or secondary processing will help researchers understand what limitations within the technologies cannot be overcome with post-processing methods. Expanding research veins into support structures and post-processing, and defining new procedures in this field, would create an opportunity to develop new standards, which could help industry find common ground.

The use of software to analyze images utilizing algorithms to understand the laser effects within the powder bed would help to improve the technology itself. Another opportunity within the Characterization of Additive Manufacturing Materials project is to examine more closely (with the inclusion of a measurement of the degree of planarity in powder spreading) the mechanical powder spreading methods, being blade or rollers.

The project could advance AM if software, in situ measurement data and images, and hardware could be correlated. While progress in that direction is under way for laser effects on powder, the integration of software and hardware needs to be continued and expanded into additive printing systems.

For the Qualification for Additive Manufacturing Materials, Processes, and Parts project, the team is addressing key elements of precompetitive AM part and process qualification. They are overall doing a very good job of advancing the primary research tasks. The results will be helpful to industry in qualifying parts for service; however, for other areas within AM, it would be helpful to expand the study to include AM processes other than metal laser-based powder bed fusion.

Real-time monitoring imposes a significant computational burden and for the Real-Time Monitoring and Control of Additive Manufacturing Processes project, the overriding concern is that there is not enough evidence of having laid the proper groundwork before embarking on a costly and time-consuming research path. It would be good to see more evidence of an informed effort to measure emissivity off-line. The team might also want to consider experiments designed to bracket the possible impact of uncertainty in emissivity values on the SLS process. For the temperature measurements a case could be made for why two-color pyrometry—a standard approach to simultaneous measurement of temperature and emissivity—could not be used.

On a more fundamental level it is noted that the measurement of emissivity is actually a proxy for a measurement of absorptivity. That is, the optical property of most interest in SLS is the absorptivity of the powder bed. At steady state it is known from instantaneous power balance that absorptivity = emissivity + transmissivity. For an opaque body, transmissivity = 0, leading to the familiar result that absorptivity = emissivity. In this case measuring emissivity will also give absorptivity. A powder bed, however, is opaque only over some depth. Measuring emissivity indicates only what the absorptivity is through a depth of powder. It is possible for two powder beds to have the same emissivity (and absorptivity), one absorbing essentially all energy within the first 100 microns of powder, and the other, in an extreme case, requiring 5 millimeter (mm), or 50 times the depth to fully absorb the power. The latter will require far more power to achieve sintering and melting than the former. And so, knowledge of emissivity alone is not sufficient. The proposition that it is difficult to uniformly heat a small target of metal powder up to temperatures above 500ºC is simply not correct. In fact, there are several types of relatively low-cost electric furnaces that will do this job admirably. Up to temperatures of 1200ºC, Kanthal wire may be used as a heating element. Silicon carbide heating elements can be used to temperatures of 1500ºC. Moly di-silicide elements (a bit more expensive) can be used up to 1800ºC. All three types are readily available as off-the-shelf units, and there are many vendors who will build custom units. The combination of a well-insulated furnace—which would act like an integrating sphere—and a light chopping wheel for the incident light- and phase-sensitive, wavelength-dependent detection could provide accurate data.

It is highly desirable to see a series of experiments where the powder is deliberately modified to vary the emissivity. These powders used in an SLS machine, in order to get a sense of the magnitude of emissivity difference, need to have an impact on process control. For example, the emissivity of the powder could be increased by etching the powder so as to create surface texture, and the impact on the process could then be assessed.

It is also desirable to see results where the robustness of SLS against changes in laser power or scanning speed are assessed for impact on part quality. For example, a 5 percent increase in laser power could be used to simulate a 5 percent relative increase in emissivity. If this makes a noticeable difference in the sintering process, then that is an indication that measurement of emissivity differences of 5 percent is useful. Several such experiments would bracket the accuracy of emissivity measurement that is desired.

At the temperatures of a typical melt pool (1400ºC and higher), two-color pyrometry is very widely used. In this application, the light emitted at two wavelengths is measured. Under the assumption that the emissivity is the same at both wavelengths, both temperature and emissivity can be extracted from the data. At these temperatures the two wavelengths can be relatively close together, making emissivity dependence on wavelength less likely. For example, silicon detectors with filters have been used to select approximately 550 nanometers (nm) and 950 nm. A comparison of emissivity measurement using an off-the-shelf two-color pyrometer with off-line measurements would be a good starting point.

Furthermore, it would be useful to see experiments on light penetration into powder beds as a function of depth—even at room temperature. The depth of penetration would be compared with the depth of a melt pool. If the depth of penetration is larger than the thickness of a melt pool, this factor would need to be taken into account.

For the Systems Integration for Additive Manufacturing project, the focus on metal laser-based powder bed fusion systems is a good starting point; however, planning needs to include processes that are used more frequently today for manufacturing, such as powder bed fusion polymer systems and extrusion systems. Archiving better design rules and methods for AM is a very useful and important mission for NIST. Also, developing new and improved dimensioning and tolerance methods for this new technology is a task that is very appropriate for this organization. Both of these project elements could lead to new standards in the field.

Although the architecture of these databases is very comprehensive, populating these databases with useful data represents a real challenge. These data are often held very close by commercial entities and they will be reluctant to share this information with others. The EL might want to consider licensing or giving out the architecture as open source and letting commercial database companies use it. These companies could buy the data as required and sell the results.

Although the desire to focus on carefully selected areas to start is understood, one item that seems glaringly absent is the design and use of support structures in metal parts. The design of these supports and their removal represents a substantial amount of the manufacturing time to deliver a metal AM part. Support structures may already be addressed in the project; however, they were not clearly discussed during the review.

The vast majority of National Laboratories currently pursue AM, and the significant progress that has been made within the MSAM program could benefit other laboratories that, in turn, could likely help the MSAM program. Additionally, a dialogue could be intensified with MML and its Polymers Processing Group in order to exploit common strengths and overlapping research interests to evolve toward common research projects, such as feedstock characterization or the design of additive manufacturing machines. Such a dialogue could build on existing meetings with the MML and the Polymers Processing Group.

Several highly industry relevant topics within AM are not currently pursued with sufficient emphasis. These topics include support structures and their design, the effects of different build orientations, design limitations for AM, and, as previously mentioned, the post-processing side of AM. Expanding research veins into support structures and post-processing, and defining new procedures in this field, would create an opportunity to develop new standards, which could help industry find common ground.

Last, for the MSAM program, the dynamic and fast-changing nature of metal laser powder bed machines requires continual project reviews, but also decisions to end projects early if project goals and elements become obsolete.

PORTFOLIO OF SCIENTIFIC EXPERTISE

Accomplishments

MSAM staff are very qualified with good trajectories for achieving broad internationally recognized technical leadership. They are a new group that was formed about 3 years ago. The MSAM is composed of 21 Federal employees, 4 NIST associates, and 4 students—62% of their staff have Ph.Ds, and 17% have masters degrees. The group is technically qualified to perform the experimental investigations and accomplish the project objectives. The overall team is comprised of diverse engineering backgrounds that undoubtedly help with the overall program goals.

The MSAM has published 14 journal papers since the last review, and the key personnel involved with the Qualification for Additive Manufacturing Materials, Processes, and Parts project efforts have contributed to this number through the publishing of archival journal articles as well as standards. Several project researchers have been recognized for outstanding contributions and collaborations, including the 2016 America Makes Distinguished Collaborator Award. Additionally, staff within the Characterization of Additive Manufacturing Materials project have won the 2015 Best Paper/Presentation Award at the 26th International Solid Freeform Fabrication Symposium and the 2016 Editor's Choice Article in the *Journal of Materials Engineering and Performance* . Overall, these teams are developing into a strong talent pool of AM expertise.

The Real-Time Monitoring and Control of Additive Manufacturing Processes project brings together several NIST researchers with different backgrounds. For the tasks the team has set out to achieve, this broad array of scientific expertise is particularly well-suited.

The two key personnel involved with the Systems Integration for Additive Manufacturing project efforts have been recognized for outstanding contributions and collaboration and are both publishing archival journal articles and standards at an acceptable rate. Although the team is small, its size appears to be appropriate with respect to the early stage of many elements of the design rules, commercial processes, and machine development, as well as other aspects of metal laser powder bed machines.

The team is quite capable and the architecture it has developed is very comprehensive.

Opportunities and Challenges

The Characterization of Additive Manufacturing Materials project currently uses several different commercial equipment items for powder characterization and also for mechanical testing and for post-processing. Given the goal not only to use the equipment but also to understand its limitations and measurement uncertainties, it is quite a challenge for the team to master all equipment items and techniques at the necessary level. The MSAM could consider convening a meeting to obtain user input on the round robin study in order to define ways to narrow the scope to focus activities on NIST's mission in supporting industry.

Like other areas within the EL AM effort, the Qualification for Additive Manufacturing Materials, Processes, and Parts team consists of junior researchers who are, for the most part, recent graduates. Their trajectory to outstanding experienced researchers is impressive, and as they continue doing excellent, relevant research, they are likely to become better known and will be suitably recognized.

The Real-Time Monitoring and Control of Additive Manufacturing Processes project appears to touch upon several different scientific and engineering topics, and the current and future monitoring projects might benefit from additional expertise—for example, in control theory or solid state physics—within NIST. If the MSAM was to move into support structures, it could benefit from additional expertise in component designs.

ADEQUACY OF FACILITIES, EQUIPMENT, AND HUMAN RESOURCES

Accomplishments

State-of-the-art powder characterization equipment was set up to support the Characterization of Additive Manufacturing Materials project and the cross-project availability of the AM testbed. The equipment includes a custom raking device to study the motion of powder particles during powder spreading, as well as a range of commercial equipment. As previously mentioned, several different characterization techniques have been set up. These techniques include the following: powder size distribution and shape analysis; a custom powder spreading device; different flow and density measurement devices; and a suite of X-ray tomography instruments for defect analysis in additively manufactured parts. Collectively, the equipment is highly adequate to meet the project objectives. The database part of the project draws from experts on database development within NIST.

For the Real-Time Monitoring and Control of Additive Manufacturing Processes project, the AM testbed facility is a major investment both for the actual testbed and for the added equipment—for example, the EOS M270 machine and testbed and the temperature measurement equipment that is coupled to the beam parameter values. Enabling full control over the laser and galvo system is invaluable for the team in setting up the testbed for calibrations of secondary equipment.

The Qualification for Additive Manufacturing Materials, Processes, and Parts project and the Systems Integration for Additive Manufacturing project both appear to have adequate facilities, equipment, and human resources.

Opportunities and Challenges

For the Qualification for Additive Manufacturing Materials, Processes, and Parts project expansion to other metal-based AM processes will necessitate purchase of new equipment.

A major challenge is that the Real-Time Monitoring and Control of Additive Manufacturing Processes project testbed represents one particular AM technology—powder bed AM. Other metal AM technologies exist, and new technologies could emerge very quickly that could render the powder-bed technology less relevant than it currently is. The testbed and other real-time monitoring equipment need to be devised with the greatest possible flexibility in mind. A larger vacuum chamber in the testbed, for example, could possibly accommodate a small robot for electron-beam or plasma gun AM.

The Systems Integration for Additive Manufacturing project needs to develop a plan for population of its database that can bring in statistically significant information.

3

Robotic Systems for Smart Manufacturing

INTRODUCTION

The mission of the Robotic Systems for Smart Manufacturing (RSSM) program is to

> Develop and deploy advances in measurement science that enhance the U.S. innovation and industrial competitiveness by improving robotic system performance, collaboration, agility, and ease of integration into the enterprise to achieve dynamic production for assembly-centric manufacturing.[1]

This is achieved through a variety of technical activities, including the following: discussions with stakeholders to assess needs; identifying gaps in standards; researching in relevant hardware to define useful metrics; developing technological best practices; defining test methods and artifacts; disseminating results that contribute to standards development; forming working groups of relevant stakeholders; and leading in standards development. This work is conducted primarily by personnel from the EL Intelligent Systems Division. The scientific staff is organized into five groups: (1) Cognition and Collaboration Systems; (2) Manipulation and Mobility Systems; (3) Networked Control Systems; (4) Production Systems; and (5) Sensing and Perception Systems. The program has a budget of $7 million. There are 16 full-time equivalent (FTE) NIST employees in this area, along with 3 guest researchers and one contractor.

ASSESSMENT OF TECHNICAL PROGRAMS

Accomplishments

The technical activities of the RSSM program seek to address several current challenges experienced by SMEs in their use of robotics. In particular, the vision is for SMEs to have access to robots that are easy to install and integrate into their industrial enterprise; that are reconfigurable, adaptable, and agile; and that can partner with humans to amplify productivity and quality. Technical work is organized around five projects that address these open challenges: (1) Performance Assessment Framework for Robotic Systems; (2) Performance of Collaborative Robotic Systems; (3) Tools for Collaborative Robots within SME Workcells; (4) Agility Performance of Robotic Systems; and (5) Robotic Systems Interoperability and Integration. The RSSM program has acquired state-of-the-art equipment and developed appropriate testbeds for the respective projects. The RSSM vision and projects are well aligned with the current state

[1] National Institute of Standards and Technology, "Robotic Systems for Smart Manufacturing Program," updated July 20, 2017, https://www.nist.gov/programs-projects/robotic-systems-smart-manufacturing-program.

of the field, and adeptly address the key challenges faced by SMEs that currently limit the use of robotics in industry.

The RSSM staff has demonstrated good alignment with NIST's mission through leadership and active participation in standards and metrics developments. The researchers have gathered input and identified needs from stakeholders to formulate project objectives and directions. To engage the broader community and ensure impact, the staff has participated in leadership roles in standards committees, professional organizations, and trade organizations. Results have been disseminated through publications, workshops with professional societies, and inputs to consortia. The staff needs to be particularly commended for using competitions at major robotics conferences (e.g., Intelligent Robots and Systems [IROS] and International Conference on Robotics and Automation [ICRA]) to engage the community and generate inputs and requirements. The five technical projects within the RSSM program have all made notable technical contributions.

Significant accomplishments of the RSSM program involve substantial contributions to important new standards. The Agility Performance of Robotics Systems project has led to the development of a new standard for knowledge representation for robot systems, *Institute for Electrical and Electronics Engineering (IEEE) 1872-2015 Standard Ontologies for Robotics and Automation*, which has been adopted and used by other organizations.

The Performance of Collaborative Robot Systems project has provided critical contributions to the development of multiple standards for safe operations of collaborative robots, including the first international technical specification for safe operation of collaborative industrial robot systems, *ISO Technical Specification 15066 Robot and Robotic Devices—Collaborative Robots*.

The RSSM Performance Assessment Framework for Robotic Systems project team founded the Committee on Performance Standards for Industrial Vehicles, and developed the *ANSI/ITSDG B56.5 Safety Standard for Driverless, Automatic Guided Industrial Vehicles and Automated Functions of Manned Industrial Vehicles*. It also led the standards development through *ASTM E57 3D Imaging Systems* for image-based test systems, including test methods for six-dimensional pose measurement.

The RSSM staff has also served in a leadership role in several activities that will drive future standards. These include the development of evaluation metrics for robotics, led by the Performance Assessment Framework for Robotic Systems project, which resulted in the formation of the IEEE Grasp Metrics Working Group for grasping metrics. The Agility Performance of Robotic Systems project and the Robotic Systems Interoperability and Integration project created a canonical robot command language and tools that have been adopted by other organizations. The agility project also conceived, developed, and conducted competitions in conjunction with the IEEE Conference on Automation Science and Engineering (CASE) conference to drive future standards on robot agility with participation within the United States and internationally, including both industry and academia. These projects also developed test methods to identify inadequacies in existing tools, such as Robot Operating System (ROS) Industrial, that impede interoperability and agility.

The RSSM staff have also successfully built a set of relevant testbeds for generation of technical input to standards, including the mobile manipulation, collaborative robotics, multifinger grasp, and robot agility testbeds. These testbeds offer the opportunity to explore and evaluate interoperability and integration. These testbeds are critically important for the RSSM research that leads toward standards development.

All of the RSSM projects have actively disseminated their results through publications, data sharing, and invited talks. In particular, the RSSM staff have established a healthy and strong publication record in leading robotics journals and conferences such as *IEEE Transactions on Automation Science and Engineering*; *IEEE Transactions on Systems, Man, and Cybernetics*; and others. The Performance Assessment Framework for Robotic Systems project has shared some of its test data with the research community, including its grasp test data for commercial multifinger hands. They also regularly speak at relevant technical venues to discuss their activities in standards development.

The RSSM staff also actively engage with the user community through workshops and other meetings. For example, the team conducted the 2015 Collaborative Robotics Workshop and reached out to Manufacturing Extension Partnership (MEP) centers to develop a deeper understanding of the key obstacles to robotics adoption, as well as the technology needs of SMEs. They have also actively participated in various consortiums, including the ROS-Industrial Consortium, Robotic Industries Association, and the Advanced Robotics for Manufacturing (ARM) Institute to discuss standards development. They regularly collaborate with other organizations, including universities, companies, and consortiums, to conduct joint tests and leverage results.

Opportunities and Challenges

The robotics technical area is rapidly changing, especially in software and data-driven methods, such as deep learning, and this creates a number of technical challenges in keeping up with the state of the field and the practical impact of the approaches being developed in the RSSM program. However, the RSSM program also has unique opportunities to leverage NIST's traditional leadership in standards and technology, its in-house expertise, and its broad array of coalitions to forge consensus, break new paths, and deliver lasting impact. One example of an opportunity would be for EL to broaden its industrial impact through stronger interactions with MEP centers and through other industrial consortia. EL can develop a set of use cases and obtain more in-depth feedback on standards development through these deepened interactions. EL can also ensure that the selected projects achieve the broadest impact on industry.

Furthermore, the RSSM staff could lead in the development of a more systematic methodology for generating test and use cases. This methodology could include gap identification, research, developing metrics, developing test methods and artifacts, standard development, evaluation, and dissemination.

The RSSM program can further ensure relevance by working more closely with industry (including newer companies) in testing and evaluation. The RSSM staff could also aim more of their dissemination activities to industry by publishing more articles in trade magazines and by holding workshops in industry tradeshows (e.g., Automate).

The RSSM program has a lack of crosscutting activities that take advantage of synergistic objectives of the individual projects. Integrating the testing and evaluation work across the overall program would provide more synergy across the projects, as well as an opportunity to achieve broader impact of the program work as a whole, rather than only at the project level. The RSSM staff also has potential opportunities to leverage other fast-developing robotics domains, such as driverless cars, for relevant knowledge of standards development in smart manufacturing and industrial automation.

While vision sensors are used in several testbeds, the RSSM program has an unexplored opportunity to investigate how machine vision, and associated algorithms such as deep learning, can be used to enhance the flexibility, user-friendliness, and safety of robots for SMEs. The exploration of how to take advantage of machine vision to simplify robot programming, develop self-teaching techniques, ensure safe human-robot interaction, and adapt to the varied application environments at SME facilities conforms well to the EL objectives for the RSSM program. There is also an increasing utilization of cloud and edge resources for robotics and industrial automation. The Industry 4.0, Microsoft Azure, and Amazon Web Services (AWS) efforts are trying to integrate resources in a consistent and efficient framework, and the RSSM program has the opportunity to contribute to and take a leadership role in this emerging field.

The RSSM has developed many test methods, artifacts, and metrics to guide in the design and use of grippers for dexterous grasping. They could leverage this research to create community-wide test sets that can assist the research community in developing new approaches to dexterous grasping. They could make a contribution to the research community similar to that of the Yale-CMU-Berkeley (YCB) Object and Model Set data set, which helps advance robotic manipulation.

PORTFOLIO OF SCIENTIFIC EXPERTISE

Accomplishments

NIST has a long history in robotics research. The RSSM program has assembled a team of researchers with expertise in computer vision and perception, human-machine interaction, collaborative robots, machining learning, mathematics and algorithms, performance metrics, and testing. Their educational backgrounds include computer science, computer engineering, electrical engineering, and mechanical engineering, as well as engineering sciences and mathematics. Across the team, 52 percent of the research staff hold Ph.D.s, 36 percent hold master's degrees, and the remainder have B.S. degrees.

The RSSM program's scientific staff is strong and intellectually diverse, with broad expertise and educational preparation in the many technical areas that are necessary for achieving the program goals. This excellent mix of research interests and professional preparation enables the staff to accomplish the research necessary to support the development, testing, and evaluation of performance standards for robotics in manufacturing.

Several RSSM staff members are well established in their fields, as evidenced by their high number of top-quality peer-reviewed publications; their leadership roles in standards development, professional societies, and conferences; as well as their many invited presentations. They have achieved a high level of productivity comparable to highly performing faculty in top research universities. RSSM researchers are also recipients of several external awards, including the IEEE Standards Association Emerging Technology Award and the ASTM International Robert J. Painter Memorial Award for meritorious service.

Because the RSSM researchers are experts in their respective fields of research and have many collective years of experience in the profession, they understand the state of the art in robotics for manufacturing. They are also active in technical meetings and have established strong connections with relevant professional organizations and collaborators. Members of the staff serve in leadership roles in technical committees (TCs), including the IEEE Robotics and Automation Society (RAS) TC on Performance Evaluation and Benchmarking, and the IEEE RAS TC on Robotic Hands Grasping and Manipulation. The RSSM staff are also active as organizers of professional conferences, workshops, competitions, and summer schools. The RSSM program has established collaborations with a number of universities and companies. Four guest researchers currently on the RSSM staff are from the collaborative partner universities. All of these engagement activities are important for enabling the RSSM staff to understand the needs of the industrial user community and draw on the collective manufacturing robotics expertise across the technical community.

Opportunities and Challenges

Given the strong records of performance of the RSSM researchers, greater recognition for the program (and for NIST) could be achieved through external merit-based robotics awards, early-career investigator awards, elevation in professional societies, as well as invitations to deliver opening and keynote presentations at conferences. NIST researchers are eligible for many prestigious awards, depending on their current career stage. Examples of relevant awards include fellows of professional societies, the Robotics Industry Association (RIA) Engelberger Robotics Award, invitations to Frontiers of Engineering meetings, the Society of Manufacturing Engineers Outstanding Young Manufacturing Engineer Award, the International Symposium for Flexible Automation Young Investigator Award, and the IEEE RAS Early Career Award. This type of external recognition can serve not only to award deserving individuals but also to raise the visibility of EL in the field.

The RSSM program could more systematically leverage (and seek out) expertise from other organizations, including university and industry, and through an extended use of the guest researcher programs. A consortium of industrial companies, both large and small, as well as universities that meet with the RSSM staff on an annual or semi-annual basis, could serve as additional sources of expertise for needs assessment, gap identification, and the testing and validation of standards. The RSSM program could also leverage regional programs and facilities affiliated with MEPs. In the interoperability area, the RSSM program could coordinate with broader efforts in industrial automation, including Industrial Internet, Industry 4.0, ROS 2.0, and commercial activities such as Microsoft Azure and Amazon AWS.

RSSM researchers publish their work in highly technical journals and professional conferences. While such publications are encouraged, the RSSM could also expand its scientific network and the impact of its work by enhancing translation of its technical work through publication of critical use cases in trade magazines. They could also conduct a road show to discuss important standards-relevant challenges, coordinating with ARM and other organizations such as ROS-Industrial in the roll-out of standards and performance testing and evaluation methods.

Human-machine collaboration is an important challenge in robotics for manufacturing. The RSSM program appears to have an expertise gap in human robot interaction due to lack of permanent staff in this area. It is important to actively recruit researchers in human-robot interaction into the EL permanent staff in order to establish this topic as an active research area.

ADEQUACY OF FACILITIES, EQUIPMENT, AND HUMAN RESOURCES

Accomplishments

The RSSM researchers have several well-equipped laboratories for conducting their research projects. These laboratories include testbeds and facilities for safety validation systems, multirobot collaboration, human-robot interaction, dexterous grasping performance measurement, task-oriented performance measurement, mobile industrial vehicle testing, mobile manipulator performance, agility testing, and sensor/robot calibration and registration. These facilities are well equipped with many state-of-the-art industrial and collaborative robots from top robotics vendors (e.g., Kuka, Rethink Robotics, Universal Robots, ABB Robotics, Fanuc, and Motoman); state-of-the-art versatile grippers and high-degree-of-freedom hands with touch sensors (e.g., Schunk, Robotiq, Allegro Robotics LDT, SoftRobotics, and Empire Robotics); mobile industrial vehicles with manipulation (e.g., America in Motion Automatic Guided Vehicles [AGVs], Adept Lynx); many relevant sensor systems (e.g., monocular and stereo vision and structured light); devices for human-robot interaction (e.g., consumer wearables, and devices for virtual and augmented reality); and high-accuracy ground truth position tracking measurement systems. These facilities are comparable to the best-equipped robotics laboratories in the world, and so provide an excellent environment in which to conduct standards development research in the RSSM.

In summary, the RSSM program has adequate facilities and equipment supportive of the type and requirements of their projects. The laboratory facilities are well equipped with machines, robots, instruments, equipment, and related materials that are necessary to conduct high-quality research. For the type and number of projects pursued, the human resources are also qualified and adequate. These resources appear to be appropriate for the capacity of the assigned space, without observable waste or redundancy.

Opportunities and Challenges

The RSSM program has two main opportunities to better accomplish its objectives through enhanced facilities, equipment, and human resources. The first is to improve the visibility of the program's activities and output by increasing human resources for media outreach and information dissemination. The ability of RSSM staff to share videos, images, and other information through social media is hindered by the lengthy approval process at NIST and the lack of staff with expertise in social media outreach. As a result, the RSSM has very little visibility on social media, which is a missed opportunity to improve the impact of the program's activities. The RSSM needs to consider adding staff who can improve dissemination of technical accomplishments through social media, trade publications, and/or popular press. While the RSSM program does have some presence in scientific and trade associations, such as the IEEE and the American Society of Mechanical Engineers (ASME), it could increase its visibility in trade publications and popular press that are read by industry practitioners. For example, increasing media coverage of the limitations of current standards for robotic safety and agility and the work the EL has done to address these limitations would help disseminate the work of the EL to more practitioners.

The second area of opportunity is to arrange the equipment and facilities to allow for closer integration of activities across the program. While research facilities are adequate, they are distributed across the NIST campus and are physically disconnected across multiple buildings on the campus. The lack of crosscutting activities across all the projects of the RSSM program is not helped by the distance between laboratory spaces. Given that the RSSM research projects share many common technologies, science, and resource needs, and can benefit from knowledge exchange, these separations between the project teams might contribute to less cohesiveness and overall impact than might be possible through co-located facilities.

Several of the testbeds developed for individual projects have overlapping capabilities, but cannot currently be integrated because they do not have interoperable software. There is an opportunity to develop software infrastructure resources to facilitate the interoperability of testbeds developed in individual projects.

4

Smart Manufacturing Operations Planning and Control

INTRODUCTION

Smart Manufacturing Operations Planning and Control (SMOPAC) is one of the programs under the EL's smart manufacturing research focus. The mission of this program is to

> Develop and deploy advances in measurement science that enable performance, quality, interoperability, wireless, and cybersecurity standards for real-time prognostics and health management, control, and optimization of smart manufacturing systems.[1]

This program currently has a budget of $9.7 million. There are 24 full-time equivalent (FTE) employees that include 22 federal staff, 3 guest researchers, and 12 new hires.

ASSESSMENT OF TECHNICAL PROGRAMS

Accomplishments

During the review five SMOPAC projects were presented: (1) Digital Thread for Smart Manufacturing; (2) Prognostics, Health Management, and Control; (3) Wireless Systems for Industrial Environments; (4) Cybersecurity for Smart Manufacturing Systems; and (5) Systems Analysis Integration for Smart Manufacturing Operations. In all of these projects, the teams have demonstrated multiple accomplishments through the standards that have been produced and the awards and recognition that have been received. All five projects exhibit sound approaches; each project has captured the state of the industry, identified current practices and standards, defined the challenges, and presented proposals for obtaining solutions. The projects all have inputs or collaborations with industry, academia, and/or government agencies and laboratories.

Over the past three decades certain industries (e.g., integrated circuits) have developed tools that allow the development of a product from concept to tracking in the field utilizing near-perfect models at each stage in the process. Industries associated with mechatronic products (i.e., a blend of mechanical and electronic systems), have attempted to develop a similar concept to the field tracking model-based approach as well, and the phrase "digital thread" has been employed for this concept. A great deal of resources have been devoted to such approaches, especially in the aerospace and automotive industries. These industries have validated approaches for all the key individual processes involving product development, manufacturing, and field diagnostics. However, it is desired that basic information be

---

[1] National Institute of Standards and Technology (NIST), "Smart Manufacturing Operations Planning and Control Program," updated March 17, 2017, https://www.nist.gov/programs-projects/smart-manufacturing-operations-planning-and-control-program.

utilized throughout the total process, as opposed to inefficient starting and stopping as the product moves from initial concept to placement in the field.

The EL is well aware of this problem area and was instrumental in developing one of the major standards involved in this process, namely the Standard for the Exchange of Product Data (STEP). The development of standards beyond STEP has been a very difficult process, and remains a major challenge for numerous reasons (e.g., industries protecting proprietary information and total systems models involving multiple time and spatial scales).

The goal of the Digital Thread for Smart Manufacturing project is to reduce the time required for part production by ensuring that the correct part requirements are provided. The team is developing a sound toolkit in order to support industry in managing their integrated design, manufacturing, and product lifecycle data based on a number of standards. It has been well-received to date, and information has been disseminated widely. There are similarities between the Digital Thread for Smart Manufacturing project and the DoD ManTech projects, which include the Army, Navy, and Air Force projects on digital thread and digital twin. It appears that there is communication between these groups. This is to be encouraged, as it allows NIST to have a government customer for collaboration.

The goal of the Prognostics, Health Management, and Control (PHMC) project is to deliver methods, protocols, and tools for robust sensing, diagnostics, prognostics, and control that enable manufacturers to respond to planned (e.g., scheduled change-overs, new productivity targets) and unplanned (e.g., faults, failures) performance changes, thereby enhancing the efficiency of smart manufacturing systems. This is done through the identification and analysis of key data that would support decision making. This project is also focused on providing vendor-neutral approaches and plug-and-play solutions. The work covers all levels—component, work cell, and systems, and is an area of great opportunity. This is clearly demonstrated by the automotive and aerospace industries' use of diagnostics (e.g., determining on-board emissions sensor deterioration on the automobile in the field and in aircraft monitoring) that allow users to assess the health of the platform. Analysis of the data from the systems' health monitoring is used to develop prognostics used for vehicle maintenance and sustainment.

An efficient and effective linear axis error detection methodology based on data collected from an inertial measurement unit (IMU) has been developed and verified on the linear axis testbed and machine tools within the PHMC project. Validation efforts are ongoing both internally within NIST and externally with several manufacturing collaborators. The team has developed a very unique program and testbed for prognostics and health management, and it has the proper hardware to work on machining projects for the manufacturing sector. The developed IMU sensor is a practical means for rapidly assessing machine health degradation. The team has demonstrated platform-based technologies to allow diversified users to connect machines and share Prognostics, Health Management, and Control project data. There is an expectation that this will be deployed in actual industrial settings. The plan is to develop an updated testbed with more integrated sensors to diagnose some typical problems in machining.

The Cybersecurity for Smart Manufacturing Systems project will establish a cybersecurity risk management program and validate this in real and virtual manufacturing systems. The roadmapping activity has established concerns of manufacturers relative to cybersecurity. The problem that was identified was that manufacturers are reluctant to adopt cybersecurity technologies because they are concerned about potential negative impacts to their manufacturing systems. The team has also identified the different cybersecurity standards that are currently in use. Tools and guidelines that the SMOPAC program has had a part in developing are well disseminated and are being tested on industrial control systems. A manufacturing profile is being published that will be applied to industry practices. A testbed has been established to validate the cybersecurity framework manufacturing profile. Data obtained from this research will be used to develop guidance for implementation of the framework.

The Wireless Systems for Industrial Environments project is designed to provide radio frequency (RF) measurements in factory environments that will be used to develop tools for measuring wireless and factory performance. The challenges that this project faces are in understanding how solutions may differ with the various systems, understanding the relationship between performance and the data being measured, and understanding how this information is used for prediction in future systems. The team has invested in an RF channel emulator and has created a testbed that simulates industrial environments. This will provide significant capabilities for measurement and prediction. The approach recognizes the variability and resulting complexity of different manufacturing processes. Advanced data analytics methods will need to be demonstrated to manage interpretation of this data.

Opportunities and Challenges

The Digital Thread for Smart Manufacturing project is using a definition of "life cycle" that shows the end of the cycle as being when the initial product is delivered to the customer. This end of the life cycle is different from the DoD ManTech projects, which include the Army, Navy, and Air Force projects on digital thread and digital twin, where life cycle also includes the life of the aircraft. In all fields products have increasingly tremendous sensory and computational capabilities, and "in the field" capabilities for diagnostics and prognostics need to be considered as part of the life cycle in the digital thread. In aerospace and automotive industries (as well as with health care devices and others), the manufacturer needs to have the ability to track the vehicles and devices in the field for potential part defects as long as they are in service, and so life cycle is from cradle to grave. The SMOPAC program needs to extend the definition of life cycle to be more comprehensive and include manufacturing activities after the product is delivered.

While some of the tools and standards that are currently being developed may apply to post-delivery manufacturing, the manufacturing that occurs in maintenance, repair, and overhaul (MRO) and in depots may be different due to limitations on materials and equipment. These limitations may make the SMOPAC tools not useful in depots and in MROs. Modifications are constantly being made to many platforms for a variety of reasons that include upgrades of equipment, redesigns to improve performance, new materials, and incorporation of new technologies for manufacturing. The system needs to be flexible enough to accommodate these changes so that the goal can be achieved. The Digital Thread for Smart Manufacturing team needs to demonstrate clearly how modifications to the products and advanced technologies will be handled in the system that is being developed. The team can further consider sensor-rich and sensorless environments to integrate process and usage sensor data into closed-loop product design support.

The concept of digital thread can be applied to multiple industries of various sizes. This project is targeting medium-size manufacturers. While smaller manufacturers may either already have, or be able to adopt, these tools and standards, there is a question as to how large integrators (e.g., aerospace, automotive) will adopt NIST's unique tools. What are the implications and challenges, technically and economically, for the range of companies that could use these tools? The SMOPAC program needs to put together a business case for small-, medium-, and large-scale industries to use these tools.

As previously mentioned, the Prognostics, Health Management, and Control team has developed an effective and efficient linear axis error detection methodology based on data collected from an inertial measurement unit (IMU), which has been developed and verified on the linear axis testbed and machine tools within the PHMC project. Validation efforts are ongoing both internally within NIST and externally with several manufacturing collaborators. The developed IMU sensor is very practical to assess machine health degradation rapidly. The team has demonstrated platform-based technologies to allow diversified users to connect to the machine and share their data, and it is planning to promote its research to system levels; however, the research scope needs to be more clearly defined (e.g., type of applications, sensors, analytics, etc.) before this happens. This is a relatively well studied and crowded research area investigated by both academia and industry. Collaboration with the Clean Energy Smart Manufacturing Innovation Institute (CESMII) will help in defining, identifying, and satisfying industry needs and requirements, as well as provide efficiencies in areas of overlapping research. The team also needs to address the need to apply this technology to other materials and processes such as those used for manufacturing polymeric materials or composites. Additionally, while this project is directed at machine shops, the team needs to define how the technology would work at the larger systems levels that deal with integration and assembly of complex products.

The goal of the Systems Analysis Integration for Smart Manufacturing Operations project is to develop information models and transformations for submission to standards organizations to enable a more efficient integration of systems analysis. This is being done in collaboration with a number of industry and academic institutions. Currently, there are software packages that are employed in the design and manufacturing of products, and some of these are integrated to some degree. While the approach and areas for integration were well described during the review, it was not clear what had already been accomplished. There needed to be a clear linking of this project to the other projects and a description of the interdependence for data gathering and analytic development to maintain an integrated modeling environment. The relationship of this analysis and the physical findings of the testbed then needs to be demonstrated as validation of the data analytics. This project needs to be integrated with the others to show how it supports digital thread and prognostics.

The Cybersecurity for Smart Manufacturing Systems project has established a testbed to validate the cybersecurity framework manufacturing profile. The data obtained from this research will be used to develop guidance for implementation of this framework. In order to evaluate the resilience of the system, the testbed needs to include a simulation system that can generate virtual cyber threats.

A very sound approach has been established to address the impacts of cybersecurity systems on manufacturing systems. However, the team also needs to take into consideration companies that are reluctant to move to smart manufacturing because of the fear of being hacked. The frameworks and profiles that are being developed could also be enablers for companies that are considering the implementation of digital or smart manufacturing. There may be opportunities to incorporate the use of the standards at the initial setup of smart manufacturing for these companies. The team is also encouraged to include manufacturers that are not currently digital in the discussion of cybersecurity needs.

Wireless technology is important to all the other SMOPAC projects as well as the other smart manufacturing programs. There needs to be more integration in the testbeds of the Wireless Systems for Industrial Environments project with other projects and programs to determine the best wireless technologies. While the project research is just beginning, it needs to be considered more broadly.

Additionally, the team needs to demonstrate the approach to data analytics for the wireless systems. It also needs to develop testbeds that include both cybersecurity and wireless technology, and it needs to consider integrating with a cloud-based or edge-based environment to support a more tether-free monitoring system.

Several overarching suggestions for the SMOPAC program were identified during the review. First, the SMOPAC program needs to develop a high-level, integrated roadmap with measurable milestones. Such a roadmap would show the relationships of various markets (automotive, aerospace, etc.) and requirements to the technologies and between the technical areas themselves. This roadmap could help to define strategies for technology planning, resources needs, and the transition to manufacturing systems. This roadmap needs to be an integrated, high-level plan, not a set of semi-related programs. They can also develop and show project plans with measurable milestones to describe these 5-year projects. These project plans could be used as communication tools to inform management, the staff working on the project, users, emerging companies, and the public about the value of the project's goals and when the results will be made available.

The impact to, and the role of, the manufacturers' supply chains also needs to be defined for the projects. The SMOPAC program can also engage additional manufacturers, including new entrants to the manufacturing sector, such as start-up manufacturing companies and suppliers to ensure alignment and identify early adopters of advanced technologies, programs, tools, and processes. They could also partner with Manufacturing USA to establish STEP-like computer-aided design (CAD), computer-aided manufacturing (CAM), and computer-integrated manufacturing (CIM) Product Information Exchange Standards. They could also benchmark other smart manufacturing programs, such as those in EU Horizon 2020, to identify duplicative areas.

PORTFOLIO OF SCIENTIFIC EXPERTISE

Accomplishments

All of the SMOPAC projects had a good mix of technical experts with varying levels of experience. With the Cybersecurity for Smart Manufacturing Systems and Wireless Systems for Industrial Environments projects, technical experts from other NIST laboratories (the Information Technology Laboratory for Cybersecurity and Wireless and the Communication Technology Laboratory for Wireless) were part of the teams. The credentials that were found in all the biographies showed achievements and recognition in their areas of expertise, such as PDES, Inc., Technical Excellence and Technical Management Awards and the DOC Bronze Medal. The technologists were very knowledgeable about the projects they had managed. The SMOPAC personnel collaborate well with each other and others outside the EL and NIST. Additionally, they have actively disseminated the results of their work in 19 journal articles and 29 conference papers.

Opportunities and Challenges

As mentioned, SMOPAC technologists were very knowledgeable about the projects they had managed. They are well-published and their publications are cited; still, more publications need to be submitted in juried technical journals.

Some of the technical personnel had industry experience that allows them to understand smart manufacturing and the challenges of an industrial environment. To improve this industry understanding, the SMOPAC program could solicit visiting scientists from manufacturing companies.

ADEQUACY OF FACILITIES, EQUIPMENT, AND HUMAN RESOURCES

Accomplishments

Investments have been made in equipment that is required to gather data and verify the SMOPAC models in virtual environments. All of the testbeds that were toured during the review were well arranged to accomplish the work of the various SMOPAC projects; these testbeds included the Cybersecurity for Manufacturing Systems Testbed; Linear Axes Testbed; and the Industrial Wireless Systems Testbed.

Opportunities and Challenges

In some of the SMOPAC testbeds, arrangements are being made to integrate with other EL programs, such as robotics. While this is a good start to integrating the projects, they are very localized, and the level of integration is low. It would be better to have a larger space so that multiple projects and programs could be integrated into a larger, more complex testbed that more resembles some manufacturing environments. Validation of models under these conditions would provide meaningful data.

In conclusion, the SMOPAC program possesses much of the expertise, facilities, and equipment to accomplish the goals for each of its projects. While an overall perspective may still be needed, the individual projects themselves are well managed and incorporate manufacturing needs with technical challenges. The program area needs to consider related areas outside the boundaries of the work that they have defined to ensure that the technologies being measured and standardized are comprehensive.

Publishing in juried publications and making presentations at higher level conferences would help the scientists and technologists to develop their careers at a more international level.

5

Smart Manufacturing Systems Design and Analysis

INTRODUCTION

The Smart Manufacturing Systems Design and Analysis (SMSDA) program has the objective of delivering measurement science, standards, and tools needed to design and analyze smart manufacturing systems. Accomplishment of this objective would enable manufacturers to improve productivity, agility, sustainability, and quality of their products. The SMSDA program consists of six major projects, staffed by 19 NIST personnel, 2 contractors, and 10 guest researchers. These projects are in the following areas: (1) Agri-Food Manufacturing System and Supply Chain Integration; (2) Data Analytics for Smart Manufacturing Systems; (3) New Technology Adoption and Industry Operations Analysis for Smart Manufacturing; (4) Modeling Methodology for Smart Manufacturing Systems; (5) Operations-Driven Performance Measurement for Smart Manufacturing Systems; and (6) Service-Oriented Architectures for Smart Manufacturing Systems.

The SMSDA budget is approximately $7 million per year, and the SMSDA is envisioned to be a 5-year program. With the exception of the Agri-Food Manufacturing System and Supply Chain Integration project, which has been under way for approximately one year, all SMSDA projects have been ongoing for approximately three and one half years. During the assessment, four of the six SMSDA projects were reviewed. The two projects that were not reviewed in depth were the Agri-Food Manufacturing System and Supply Chain Integration project and the New Technology Adoption and Industry Operations Analysis for Smart Manufacturing project.

SMSDA personnel stated that their work was in two different categories. The end objective of both of these categories was to produce standards; however, in the first category, best practices were known or could be determined. Therefore, the job was to encode the best practice. This definition of standards as encoding best practices was very useful during the review of the projects. The Service-Oriented Architectures for Smart Manufacturing Systems project is discussed below and is an example of this first category of work. The second category of work is one where the best practice is not known. In this case the job of the researchers is to produce the structure, databases, prototypes, or techniques that will form the basis of a best practice. Three of the projects reviewed are in this second category. The Operations-Driven Performance Measurement for Smart Manufacturing project will be utilized as an example of this type of work and is discussed below.

ASSESSMENT OF TECHNICAL PROGRAMS

Accomplishments

During the review it became evident that all the activities of the reviewed projects where aligned with, and supportive of, the stated project objectives. To begin, the Service-Oriented Architectures for Smart Manufacturing project remediates the problem of moving syntax information (verbal or written orders) across an organization with different enterprise platforms. For example, an engineering change from the parent company's engineering organization needs to be passed to the scheduling organization (material organization), which in turn will send the change to manufacturing floor and vendors. Vendors may, in turn, send it to subtier vendors. Inside the parent company the engineering change is also sent to the customer support organization, which in turn needs to order spare parts and put warrantee reserves in place. The change is then sent to the finance department, where the engineering change is billed to customers. As engineering changes pass through each of the organizations, the attributes of the engineering change affecting that organization need to be entered into the organization's computer system by hand. It is not unusual for engineering change attribute data to be input by hand into 20 to 30 different computer programs and several different computer languages. The cost of people entering the data is very large, the reentry of data by hand into different operating systems over and over slows the process, and increases the possibility of errors. The Service-Oriented Architectures for Smart Manufacturing Systems project remediates the inefficiency of this problem by developing a smart manufacturing solution. The solution consists of developing a large database of standard syntax terms (e.g., engineering change and purchase order) together with the attributes of each syntax term. The database allows individual users to add attributes if their application requires them. The database of integration message standards allows translation into the commonly used language for systems integration. Three translations are in development, and, as requirements for new languages emerge, new translators can be developed. The team has transferred the first version of syntax-independent database and computer language translators to the not-for-profit Open Applications Group Integration Specification (OAGIS) organization for maintenance and dissemination to the public.

This project is a major success, and it is likely to have a profound impact on smart manufacturing. Providing improvements in company speed, cost, quality, and supply chain integration. This project is best in class and could be a benchmark for other NIST projects. Regardless of what a particular company's goal is—speed, efficiency, cost, flexibility, competitiveness, and so on—the great simplification of standard syntax database and translation systems that the SMSDA program has developed and made available to the public domain will be of great value. This database will continue to grow, and will benefit companies who are deploying Enterprise Resource Planning (ERP) systems, integrating supply chains, and integrating new companies or products into their portfolio. Similarly, this standard is also beneficial to large factories producing and consuming large amounts of data and information, which have the requisite staff to help manage all of this data, as well as small and medium enterprises (SMEs), which usually do not have sufficiently talented staff to deal with the data explosion.

The SMSDA program staff recognizes the impact that information technology has had. The staff has identified the Internet of Things, cloud services, service-based integration, and data analytics as technologies with specific potential for impact on smart manufacturing. It has as one of its primary goals the enablement of SMEs to participate in smart manufacturing, and it has defined agri-food manufacturing as a new section for its program, through its Agri-Food Manufacturing System and Supply Chain Integration project.

The identified technologies are transformative for smart manufacturing, and agri-food manufacturing is an ideal domain for the SMSDA program to explore the need for standards development and measurement science, to aid in developing the required capability to enable SMEs. Agri-food manufacturing is a critical industry involving hundreds of thousands of SMEs in the United States alone. Many of the participating entities are independent and geographically distributed. There is a flood of new low-cost sensors appropriate for monitoring food products from farms to consumers. There is increasing capability to connect these sensors to the Internet, and there are evolving technologies and platforms to effectively use the resulting data captured to improve food manufacturing. However, to date, the standards and measurement capabilities have not nearly kept pace with the technology becoming available.

The Agri-Food Manufacturing System and Supply Chain Integration project could provide a unifying domain for all of the SMSDA program's current projects as well as a manufacturing domain that everyone can understand for presenting their research accomplishments. They already have two very large agri-food manufacturing collaborators, Land O'Lakes and General Mills, and need to add multiple SMEs from each segment of the agri-food manufacturing supply chain (i.e., farmers, packers, transporters, wholesalers, distributors, and retailers). They also need to add an international component to their research effort because a large quantity of U.S. food is imported. This project represents an opportunity for the SMSDA program to make a profound impact on a large and very important industry. Therefore, it needs to be pursued vigorously.

Opportunities and Challenges

The SMSDA program, as well as other NIST smart manufacturing programs, seems to be somewhat ad hoc and disconnected—they are involved with a variety of domain experts and different entities that produce standards. This is not a criticism restricted to NIST—even the U.S. National Smart Manufacturing Initiative does not have a clear and comprehensive set of objectives, and more importantly a time-based roadmap. As the definition of smart manufacturing is elusive and ever-changing owing to the fact that new technology is constantly introduced into the workplace, the difficulty NIST faces is understandable.

For clarity a best-in-class example is offered to demonstrate the value of a comprehensive roadmap. For over 50 years the semiconductor industry has been driven by what has become a self-fulfilling prophecy known as Moore's law. The goal is to double the complexity of computer chips on every device generation (a generation is about 18 months). This simple law has been followed despite numerous enormous, cultural, economic, and technical obstacles. It became the driving force for the industry when it was codified as the Semiconductor Industry Association (SIA) roadmap, which for 20 years has helped define the specific programs within the industry that are needed to remain on the Moore's law curve. Although the semiconductor industry is ferociously competitive, numerous manufacturers, equipment makers, material suppliers, research institutions, and other support facilities have cooperated to make the SIA roadmap a best-in-class example of how to cooperate on a global scale. This law, or vision, has remained unchanged despite 50 years of progress over many dimensions and domains. It drives technology (feature size, wafer size, speed, capacity, reliability, etc.), economics (cost productivity, wealth generation, etc.), and innovation (smart phones, IPads, household devices, etc.), and it has led to the U.S. dominance in new technology.

Without a roadmap such as this, the quality and value of NIST's approach to managing the smart manufacturing program is difficult to assess, and therefore the value and quality of individual projects are difficult to measure. In particular, the SMSDA program has specific projects aimed at addressing specific topics. However, without a general roadmap with measurable milestones that define smart manufacturing, it is difficult for the program, and for NIST, to determine if it is working in the more critical or most impactful areas to improve smart manufacturing, or even in the most important areas at a given point in time. Regardless of these challenges, smart manufacturing has become a U.S. national priority, and so the question is: How could the efforts and resources focused on smart manufacturing be prioritized to best achieve the initiative's inferred intent?

A Smart Manufacturing Leadership Coalition (SMLC) was established some years ago for this purpose. More recently a nonprofit organization, the Clean Energy Smart Manufacturing Innovation Institute (CESMII), has been established to support the coalition. CESMII was established by Congress and is located in Los Angeles. NIST is involved with both of these organizations. The EL or NIST could, in cooperation with these organizations, develop an overarching roadmap with measurable milestones for smart manufacturing for the nation.

Additionally, while all the SMSDA projects had been under way for approximately three and one half years, the project plans did not show intermediate project milestones, and so it was not possible to determine whether the project was making the expected amount of progress. Project planning for multiyear projects need to include intermediate milestones in order for progress and midcourse correction to be easily understood and executed. The projects need to have a clear definition of deliverables and measurable milestones. Deliverables need to include demonstration and testing at SMEs.

The objectives of each of the reviewed projects focused, in part, on making smart manufacturing easier and more available for SMEs. Most of the company partners shown in the project demonstrations were large to very large companies. It appears to be an implicit assumption that the technology and standards will trickle down from large to small manufacturers, or be mandated by them to their small to medium-size suppliers. A more direct approach involving direct contact with SMEs is desirable.

It was also noted that the SMSDA program does not have a laboratory inside NIST to test the output of its projects. Testing the project output is particularly important where best practices do not exist and the new databases, techniques, and prototypes are being aimed to help SMEs.

The stated objective of the Operations-Driven Performance Measurement for Smart Manufacturing Systems project is to "develop and deploy standards, guidelines and reference data for measuring the performance of manufacturing systems to inform the design and aid in analysis of factory improvements."[1]

To this end the project team has chosen to focus, rightly, on four key performance objectives as identified by the SMLC: agility, productivity, sustainability, and quality. This project is in the second category of work undertaken by the SMSDA. That is, no clear best practice exists for this project. The main project effort has been to develop a unit manufacturing process (UMP) depository that will become a resource center to house the collective community knowledge, reference data sources, and performance baselines and trade-offs. This particular project is in the manufacturing engineering domain, and a domain expert needs to be an integral part of the project team.

Once the database is populated, these UMP models could then be utilized for several functions. For example, a group of UMP models could be linked to model an entire production line for a given product. Optimization programs could be deployed to determine the best mix and location of machines.

A demonstration of the utilization of a UMP modeled process was shown during the review. The demonstration consisted of the processing of a small metal part—a heat sink for an avionics board. The process is divided into 11 steps of various milling and drilling operations. Input to the model is product-process info—design specifications, the type and nature of the materials, required electrical energy (which is both speed and process dependent). Along with resource data (operator, machine tool, fixture, software, etc.), the model goes through a set of equations that govern the physics and thermodynamics of the product and process and generates a set of outputs that include the total heat and waste generated. The model is a sophisticated tool—for each of the 11 processing stages, the control variables (e.g., machine speed) are optimized, under constraints (e.g., on total energy consumption).

One stated use case for the UMP is to generate life cycle inventory data. For such a case it is questionable whether the model is developed at the right granularity and with the right proportion. Specifically, it is questionable whether the effort of detailed modeling and optimization of the processing of a tiny part of what could be a complex product (that may involve hundreds of similar parts) is commensurate with the life cycle analysis of the product. Other factors such as choice of raw material and end-of-life recycling provisions can easily wipe out any gains teased out of optimizing the machining speed and British thermal units (BTUs) saved, not to mention what can be achieved via a redesign and overhaul of the entire manufacturing process (as opposed to fine-tuning the tool speed), as embodied in the green manufacturing or remanufacturing movement in recent years.

Overall, in a case like this, where there is a lack of existing standards or guidelines, the SMSDA program needs to broaden its scope to include identifying best practices in a select set of industry sectors. This broadening of scope appears both feasible and practical given that the team is currently collaborating

[1] Simon Frechette, Smart Manufacturing Systems Design and Analysis Program Manager, "Smart Manufacturing Systems Design and Analysis Program, Project Descriptions," delivered to the panel on March 28, 2017.

with the American Society for Testing and Materials (ASTM), an international standards organization, on this project.

The Agri-Food Manufacturing System and Supply Chain Integration project intends to leverage other work being done to improve information flow among participants in the food chain, from growers to consumers. The U.S. agricultural industry is very large and diverse, and smart manufacturing technology can be and needs to be adapted to and deployed in agriculture applications. However, food and agriculture have major sectors with vastly different operations and needs. For example, harvesting operations for major crops are highly automated and dominated by very large corporations, while fresh foods, encompassing hundreds of products from vegetables to tree fruits and nuts to potatoes, are labor intensive. The latter is in dire need of automation, as labor shortages cause a significant portion of crops to rot on trees and in fields. Furthermore, fresh foods have short shelf lives and must be brought to the market quickly by 200,000 U.S. enterprises. The application of the outputs of the Service-Oriented Architectures for Smart Manufacturing Systems project to this project could have a profound effect on all aspects of the information processes food chain; however, they would have to meet the different needs of the different sectors, and need to engage different domain experts. One advantage the agricultural industry has is its strong network of commodity associations that can be used to provide both domain expertise and solution delivery channels.

A big issue that was missing from discussions during the review was the value generated by these programs and projects; there was an underlying assumption that more technology is good. In particular, SMEs will require some proof that smart manufacturing will be able to help their bottom lines. While the SMSDA is the right place to develop tools and standards for gap analysis and valuation of new technologies, it is questionable whether the program will be able to execute the gap analysis and valuation of technologies and standards to obtain low-hanging fruit without a smart manufacturing roadmap with measurable milestones.

PORTFOLIO OF SCIENTIFIC EXPERTISE

Accomplishments

The SMSDA staff are very involved in the standards and technical committees of the professional engineering societies, the academic community and partner companies. Over approximately the last three and one half years the SMSDA program has produced approximately 38 journal papers, created and organized approximately 30 workshops and conference sessions, and received honors, such as the ASTM International President’s Leadership Award and OAGi Outstanding Contributor Awards for its outstanding work. These personnel are also active in the correct standards committees of the U.S. professional societies. The staff were found to be, with a few exceptions that will be discussed below, very capable of executing its assigned tasks.

Opportunities and Challenges

The SMSDA personnel are very well trained and qualified to do the work necessary for the first category of work, which is to produce the basis and structure for a standard and to aid getting it into the public domain where it can be accessed by people and companies wishing to do smart manufacturing. Additionally, the personnel are capable of performing the tasks defined by the project objectives. They appear to work best and are most effective in problem areas where there exists an active standards community. In areas where there is a lack of existing standards or best practices, it is not clear that the SMSDA research is focused on the right problems or solutions to serve the SMEs.

In projects where a best practice does not exist (that is, the second category of work), the SMSDA needs to include a domain expert on the team for areas where NIST personnel may not have technical expertise. Having a domain expert as an integral part of this category of projects is a necessity. For example, if the project is to produce the structure, databases, prototypes, or techniques that will form the basis of best-practice production control, then a production control domain expert needs to be an integral part of the team working on this project. The SMSDA could acquire the domain expert either by hiring one, or by getting a partner company to provide one. Having a domain expert is required to ensure that developed structures, databases, prototypes, or techniques are truly needed, and will provide the best practice needed by the domain.

The SMSDA also needs to utilize real SMEs as its laboratory to test its output. Making at least two SMEs an integral part of each project team would give the team the means to test its outputs in a real-life environment.

The SMSDA program consists of a number of projects; however, it was unclear from the project presentations shown during the review how the different projects relate to the overarching objectives of the program. Further, it was unclear from the presentations what the main importance, goals, and progress to date are for each project, and how each project contributes to the overall goals of the program. While there are many enablers for smart manufacturing, it was not apparent how the project contributes to these enablers.

ADEQUACY OF FACILITIES, EQUIPMENT, AND HUMAN RESOURCES

Opportunities and Challenges

The SMSDA program does not have a laboratory inside NIST to test the output of their projects. Testing the project output is particularly important where best practices do not exist and the new databases, techniques, and prototypes are being aimed at helping SMEs.

6

Conclusions and Recommendations

General Conclusions and Recommendations

Smart manufacturing programs in the EL at NIST have significantly evolved in the last five years, matching increased national recognition of the importance of manufacturing in the economy, as well as international recognition of the importance of integration of digital computing and information technologies into manufacturing systems. For example, the additive manufacturing program area was established approximately three and one-half years ago and is now an impressive effort in an area of rapid technology growth, staffed by competent early-career researchers, and facilitated by a measurement testbed of their own design with unique and powerful capabilities. Standards are being given a high priority, and there is excellent collaboration with other organizations and leadership in these efforts. There is significant focus on small and medium enterprises (SMEs), which is a valuable objective that is difficult to achieve. There are good research collaborations with industry, but perhaps an overreliance on (hoped for) trickle down from work with larger industries; more extensive outreach to SMEs, especially young SMEs, would be beneficial.

The EL's smart manufacturing program appears to lack a roadmap and measurable milestones, as do the individual programs and projects. Without roadmaps and measurable milestones, the quality and value of NIST's smart manufacturing programs and their management were more difficult to assess, and therefore the value, quality, and results of individual projects were more difficult to measure. Although some excellent research outputs, evinced by strong publication records in peer-reviewed journals, are being obtained and significant progress in standards is being made, many project plans did not show intermediate project milestones, and so it was difficult to determine in some cases whether projects were making the expected amount of progress and achieving the desired results. Roadmaps and measurable milestones would be invaluable tools for NIST management.

There is also, in some cases, a lack of crosscutting activities that can take advantage of the synergistic objectives of individual projects. Examining the project's plans, together to find opportunities for cross-fertilization and integrating the testing and evaluation work across the overall smart manufacturing program, could provide more synergy across the projects, as well as an opportunity to achieve broader impact of the program work as a whole, rather than only at the project level. This is not helped by the current distance between laboratory spaces, and it would be better to have a larger and more contiguous space so that multiple projects and programs could be integrated into a larger, more complex testbed that more resembles some manufacturing environments.

The new program areas are well covered by both junior and senior staff, who have significantly and successfully adapted their efforts to new technologies. Some areas appear to be short on permanent staff and expertise, but staffing appears to be generally sufficient to support the research that is under way. The journal publication record is excellent. There has been significant external recognition of the staff and its research, but additional efforts need to be made to promote and apply for external awards for the staff. This also would promote recognition of the smart manufacturing research programs at NIST.

Measurement Science for Additive Manufacturing

The majority of national laboratories within the federal government currently pursue additive manufacturing (AM), and the significant progress that has been made within the Measurement Science for Additive Manufacturing (MSAM) program could benefit these other laboratories that, in turn, could likely help the MSAM program. Additionally, closer engagement and alignment with other U.S. government laboratories could ensure that the MSAM program is effectively leveraging the investments being made in this area.

RECOMMENDATION 1: The Engineering Laboratory should consider closer engagements with other national laboratories' additive manufacturing groups.

A dialogue needs to be intensified with the Material Measurement Laboratory (MML) and its Polymers Processing Group in order to exploit common strengths and overlapping research interests. This dialogue could build on existing meetings with the MML and the Polymers Processing Group and evolve toward common research projects, such as feedstock characterization or the design of additive manufacturing machines.

RECOMMENDATION 2: The Engineering Laboratory should consider beginning an intensified dialogue with the Material Measurement Laboratory and the Polymers Processing Group.

There are several highly industry relevant topics within AM that are not currently pursued with sufficient emphasis by the MSAM program. These topics include support structures and their design, the effects of different build orientations, design limitations for AM, and the post-processing side of AM. Broadening the focus into post- or secondary processing will help researchers understand what limitations within the technologies cannot be overcome with post-processing methods. Expanding research veins into support structures and post-processing, and defining new procedures in this field, would allow an opportunity to develop new standards, which could help industry find common ground.

RECOMMENDATION 3: The Engineering Laboratory should consider expanding its research into the measurements and standards needed to assist industry in the following areas: support structures and their design, the effects of different build orientations, design limitations for additive manufacturing, and the post-processing side of additive manufacturing.

Robotic Systems for Smart Manufacturing

Overall, the laboratory facilities, equipment, and human resources are top-notch and sufficient for impactful standards development activities in the Robotic Systems for Smart Manufacturing (RSSM) program. The program staff has done an excellent job of identifying the top brands of robotic and sensor equipment that will likely be used by SMEs and has acquired and activated the equipment for its research. The staff has been successful in operating the equipment to develop best practice methods for using the hardware and related software and to conduct a wide variety of experiments and demonstrations to evaluate potential metrics, test artifacts, and methods for multi-robot collaboration, agility, interoperability, and integration.

The RSSM program is providing important contributions to the development of standards, metrics, and applicable technologies in the areas of performance assessment, collaborative robotics, agility, interoperability, and integration. The focus on the development of standards and performance metrics and tests in these areas aligns well with the mission of the EL. In particular, the program has made important advances in identifying weaknesses with existing metrics and standards in robotic mobility and agility, anticipating unmet needs for future industry challenges, and developing new metrics and standards to address these issues.

The RSSM program staff has an opportunity to lead in the development of a more systematic methodology for generating test and use cases. Such a methodology could include needs assessment, gap identification, research, metrics development, test methods and artifacts development, standards development, evaluation, and dissemination.

RECOMMENDATION 4: The Engineering Laboratory should consider leading the development of methodological approaches for standards development in all component areas of its robotic systems for smart manufacturing research, including the areas of needs assessment, gap identification, research, metrics development, test methods and artifacts development, standards development, evaluation, and dissemination.

The RSSM program could broaden its industrial impact through stronger interactions with the Manufacturing Extension Partnership (MEP) centers or other industrial consortia. Through these deepened interactions, the RSSM program could develop a set of use cases and obtain more in-depth feedback on standards development.

RECOMMENDATION 5: The Engineering Laboratory should consider interacting on a regular basis (e.g., twice annually) with the Manufacturing Extension Partnership (MEP) centers or other industry consortia to source use cases and receive feedback on the effectiveness of their development of metrics and standards.

Although vision sensors are used in several RSSM testbeds, the EL has an unexplored opportunity to investigate how machine vision can be used to enhance the flexibility and user-friendliness of robots for SMEs. The exploration of how to take advantage of machine vision to simplify robot programming, develop self-teaching techniques, ensure safe human-robot interaction, and adapt to the varied application environments at SME facilities is a good fit with the EL's objectives for the RSSM program.

RECOMMENDATION 6: The Engineering Laboratory should consider exploring the use of machine vision to enhance the value of robots for small and medium enterprises (SMEs) by reducing programming complexity for short-run manufacturing applications.

There is an increasing utilization of cloud and edge resources for robotics and industrial automation. The Industry 4.0, Microsoft Azure, and Amazon Web Services (AWS) efforts are trying to integrate resources in a consistent and efficient framework, and the RSSM program has the opportunity to contribute to and lead this nascent field.

RECOMMENDATION 7: The Engineering Laboratory should consider exploring methodological approaches and standards development related to cloud robotics by contributing to activities in this area (e.g., Industry 4.0), and taking a leadership role in this field.

Given the level of expertise and contribution of the RSSM research team, additional peer recognition is possible in the form of merit-based robotics awards, elevation in professional societies, invitations to delivering opening and keynote presentations at conferences, and early-career investigator awards. This type of external recognition can serve not only to award deserving individuals but also to raise the visibility of EL in the field.

RECOMMENDATION 8: The Engineering Laboratory should be more proactive in seeking individual recognition for accomplished robotics staff personnel, rather than waiting to be discovered.

Human-machine collaboration is an important challenge in robotics for manufacturing. The RSSM program appears to have an expertise gap in human robot interaction due to lack of permanent staff in this area. Active recruiting of such researchers into NIST permanent staff is important to establish this topic as an active research area.

RECOMMENDATION 9: The Engineering Laboratory should establish permanent staff expertise in its human-robot interaction area to avoid a future expertise gap.

The RSSM could more systematically leverage and seek out expertise from other organizations, including universities and industries, and through an extended use of guest researcher programs. A consortium of industrial companies, both large and small, as well as universities that meet with the RSSM on an annual or a semi-annual basis, could serve as additional sources of expertise for needs assessment, gap identification, and the testing and validation of standards.

RECOMMENDATION 10: The Engineering Laboratory should consider systematically leveraging and seeking out expertise from other organizations, including university, industry, and Manufacturing USA Institutes who can serve as additional sources of expertise for needs assessment, gap identification, and the testing and validation of standards.

The RSSM program has researched the capabilities of a wide variety of robotic grippers. They have developed many test methods, artifacts, and metrics to guide in the design and use of grippers for dexterous grasping. They have an opportunity to leverage this research to create community-wide test sets that can assist the research community in developing new approaches to dexterous grasping. For example, the Yale-CMU-Berkeley (YCB) Object and Model Set data set is a related contribution to the research community that helps advance robotic manipulation, and a similar contribution based on the RSSM research would be highly beneficial to the research community.

RECOMMENDATION 11: The Engineering Laboratory should consider coordinating with other organizations to develop community-wide test sets for dexterous grasping.

Although the research facilities are adequate, they are also distributed across the NIST campus and are physically disconnected across multiple buildings on the campus. Given that the RSSM research projects share many common technologies, science, and resource needs, and can benefit from knowledge exchanges, such separations between the project teams might contribute to less cohesiveness and overall impact than might be possible through co-located facilities. The lack of crosscutting activities across all the projects of the RSSM program is not helped by the distance between laboratory spaces.

RECOMMENDATION 12: The Engineering Laboratory should consider co-locating test facilities to enhance integration of Robotic Systems for Smart Manufacturing (RSSM) program activities across the entire program.

There is an opportunity to develop software infrastructure resources to facilitate the interoperability of testbeds developed in individual projects. Several of the testbeds developed for individual projects have overlapping capabilities but cannot currently be integrated because they do not have interoperable software.

RECOMMENDATION 13: The Engineering Laboratory should strive for interoperability of software infrastructure for their testbeds.

The ability of RSSM staff to share videos, images, and other information through social media is hindered by the lengthy approval process at NIST and the lack of staff with expertise in social media outreach. As a result, the program has very little visibility on social media, which is a missed opportunity to improve the impact of the RSSM program's activities.

RECOMMENDATION 14: The Engineering Laboratory should consider adding staff who can improve dissemination of technical accomplishments through social media, trade publications, and/or popular press and should work with NIST management to identify ways to streamline approval processes for applying these methods.

Smart Manufacturing Operations Planning and Control

The Smart Manufacturing Operations Planning and Control (SMOPAC) program needs to develop an overarching, integrated roadmap with measurable milestones that shows the relationships of the various markets (automotive, aerospace, etc.) and requirements to the technologies, as well as the relationships between the technical areas themselves. The roadmap needs to be an integrated, high-level plan, not a set of semi-related programs.

RECOMMENDATION 15: The Engineering Laboratory should consider developing an overarching roadmap with measurable milestones for the Smart Manufacturing Operations Planning and Control (SMOPAC) program that integrates market needs, product requirements, and technologies.

The EL needs to examine its activities within the context of national and global activities at other organizations to identify competitive and duplicative areas.

RECOMMENDATION 16: The Engineering Laboratory should consider benchmarking its work in smart manufacturing operations planning and control against other manufacturing programs, such as those in EU Horizon 2020, to identify competitive and duplicative areas.

In order to ensure alignment with manufacturers' needs, and to identify early adopters of advanced technologies, programs, tools, and processes, the SMOPAC program needs to engage additional manufacturers, including new entrants to the manufacturing sector, such as start-up manufacturing companies and suppliers. They could partner, for example, with Manufacturing USA to facilitate information exchange.

RECOMMENDATION 17: The Engineering Laboratory should consider engaging new manufacturers and suppliers to ensure alignment with manufacturers' needs and to identify early adopters of advanced technologies, programs, tools, and processes.

RECOMMENDATION 18: The Engineering Laboratory should consider partnering with Manufacturing USA to establish Standard for the Exchange of Product Data (STEP)-like computer-aided design (CAD), computer-aided manufacturing (CAM), and computer-integrated manufacturing (CIM) product information exchange standards.

The SMOPAC program needs to develop and show project plans with measurable milestones to describe their 5-year projects. Such project plans can be used as communication tools to inform management, the staff working on the project, users, emerging companies, and the public about the value of the project's goals and when the results will be made available.

RECOMMENDATION 19: The Engineering Laboratory should develop project plans with measurable milestones that describe their 5-year projects and use these plans as communication tools.

The definition of "life cycle" that the Digital Thread for Smart Manufacturing project is using shows the end of the cycle as being when the initial product is delivered to the customer. This is different from the Department of Defense (DoD) ManTech projects, which include the Army, Navy, and Air Force projects on digital thread and digital twin, where life cycle also includes the life of the aircraft. In aerospace and automotive industries (as well as with health care devices and others), the manufacturer needs to have the ability to track the vehicles and devices in the field for potential part defects as long as they are in service; and so life cycle is from cradle to grave. In all fields, products have increasingly tremendous sensory and computational capabilities, and in-the-field capabilities for diagnostics and prognostics need to be considered as part of the life cycle in the digital thread.

RECOMMENDATION 20: The Engineering Laboratory should improve and clarify the definition of "life cycle" to be more comprehensive and include manufacturing activities after the product is delivered.

The concept of the digital thread can be applied to multiple industries of various sizes. The Digital Thread for Smart Manufacturing project is targeting medium-size manufacturers. While smaller manufacturers may either already have or be able to adopt these tools and standards, the team needs to address how large-scale industries (e.g., aerospace, automotive) will adopt NIST's unique tools.

RECOMMENDATION 21: The Engineering Laboratory should put together a business case for small-, medium-, and large-scale industries to adopt their digital thread tools.

The Prognostics, Health Management, and Control (PHMC) team has developed an efficient and effective linear axis error detection methodology based on data collected from an inertial measurement unit (IMU), which has been developed and verified on the linear axis testbed and machine tools within the PHMC project at NIST. Validation efforts are ongoing both internally within NIST and externally with several manufacturing collaborators. The developed IMU sensor is very practical to assess machine health degradation rapidly. The team has demonstrated platform-based technologies to allow diversified users to connect to the machine and share their data. The team is planning to promote its research to system levels; however, the research scope needs to be more clearly defined (e.g., type of applications, sensors, and analytics) before this happens. Collaboration with the Clean Energy Smart Manufacturing Innovation Institute (CESMII) will help to define, identify, and satisfy industry needs and requirements as well as provide efficiencies in areas of overlapping research.

RECOMMENDATION 22: The Engineering Laboratory should consider collaborating with the Clean Energy Smart Manufacturing Innovation Institute to help to identify, prioritize, and satisfy industry needs and requirements and to provide efficiencies in areas of overlapping research.

The Cybersecurity for Smart Manufacturing project has established a testbed to validate the cybersecurity framework manufacturing profile. Data obtained from this testbed will be used to develop guidance for implementation of this framework. The testbed needs to include a simulation system that can generate virtual cyber threats to evaluate the resilience of the system.

RECOMMENDATION 23: The Engineering Laboratory's testbed for the Cybersecurity for Smart Manufacturing project should include a simulation system that can generate virtual cyber threats to evaluate the resilience of the system.

The Wireless Systems for Industrial Environments project research is just beginning, and it needs to be considered more broadly. The team needs to develop testbeds that include both cybersecurity and wireless technology and consider integrating with a cloud-based or edge-based environment to support more tether-free monitoring system applications.

RECOMMENDATION 24: The Engineering Laboratory should consider developing a testbed that includes both cybersecurity and wireless technology.

RECOMMENDATION 25: The Engineering Laboratory should consider integrating with a cloud-based or edge-based environment to support more tether-free monitoring system applications.

In some of the testbeds, there are arrangements being made to integrate with other programs, such as robotics. This is a good start; however, the integration is small. It would be better to have a larger space so that multiple projects and programs could be integrated into a bigger, more complex testbed that more resembles an actual manufacturing environment. Validation of models under these conditions would provide meaningful data.

RECOMMENDATION 26: The Engineering Laboratory should consider dedicating an area or a facility for the integration of multiple projects and programs to simulate an industrial environment.

Smart Manufacturing Systems Design and Analysis

The NIST Smart Manufacturing Systems Design and Analysis (SMSDA) program would greatly benefit from and could contribute to an overarching roadmap of smart manufacturing for the nation.

RECOMMENDATION 27: The Engineering Laboratory should consider collaborating with the Smart Manufacturing Leadership Coalition (SMLC) and the newly formed Clean Energy and Smart Manufacturing Innovation Institute (CESMII) to develop for the National Institute of Standards and Technology and the United States an overarching roadmap with measurable milestones for smart manufacturing.

Where best practices for smart manufacturing capabilities do not exist, the task is to develop structures, databases, prototypes, and techniques to define best practices. During execution of tasks of this type, the inclusion of a domain expert on the team would greatly improve the output.

RECOMMENDATION 28: Where a smart manufacturing best practice does not exist, the Engineering Laboratory should consider embedding domain experts on the project teams to ensure the quality of their output.

The SMSDA program needs to ensure that the output of projects where a smart manufacturing best practice does not exist is tested in at least two SMEs. These SMEs need to become an integral part of the project teams to ensure that the developed structures, databases, and techniques make it easier for SMEs to utilize smart manufacturing.

RECOMMENDATION 29: The Engineering Laboratory should ensure that where a smart manufacturing best practice does not exist, the output of projects is tested in at least two small and medium enterprises (SMEs).

Where there is a lack of existing standards or guidelines, the SMSDA program needs to broaden its scope to include identifying smart manufacturing best practices in a select set of industry sectors. Given that the program has been actively collaborating with various standards communities and has access to a wide range of industries, this broadening of scope appears both feasible and practical.

RECOMMENDATION 30: Where there is a lack of existing standard or guidelines, the Engineering Laboratory should consider broadening its scope to include identifying smart manufacturing best practices in a select set of industry sectors.

Project planning for multiyear projects needs to include measurable intermediate milestones so that progress and midcourse correction can easily be understood and executed. The projects need to have a clear definition of deliverables and measurable milestones. Additionally, deliverables need to include SME demonstrations and testing.

RECOMMENDATION 31: The Engineering Laboratory should consider planning multiyear projects with measurable intermediate milestones so that progress and midcourse correction needs are readily visible.

Acronyms

3D	Three-dimensional
AGVs	Automatic Guided Vehicles
AM	additive manufacturing
ARM	Advanced Robotics for Manufacturing
ASME	American Society of Mechanical Engineers
ASTM	American Society for Testing and Materials
AWS	Amazon Web Services
BTU	British thermal unit
CAD	computer-aided design
CAM	computer-aided manufacturing
CASE	Conference on Automation Science and Engineering
CESMII	Clean Energy Smart Manufacturing Innovation Institute
CIM	computer-integrated manufacturing
DoD	Department of Defense
EL	Engineering Laboratory
ERP	Enterprise Resource Planning
FTE	full-time equivalent
ICRA	International Conference on Robotics and Automation
IEEE	Institute for Electrical and Electronics Engineering
IMU	inertial measurement unit
IR	infrared
IROS	International Robotics and Systems
ISO	International Organization for Standardization
MEP	Manufacturing Extension Partnership
MML	Material Measurement Laboratory
MRO	maintenance, repair, and overhaul
MSAM	Measurement Science for Additive Manufacturing
NIST	National Institute of Standards and Technology

OAGIS	Open Applications Group Integration Specification
PHMC	Prognostics, Health Management, and Control
RAS	Robotics and Automation Society
RF	radio frequency
RIA	Robotics Industry Association
ROS	Robot Operating System
RSSM	Robotic Systems for Smart Manufacturing
SIA	Semiconductor Industry Association
SLM	selective laser melting
SLS	selective laser sintering
SME	small and medium enterprise
SMLC	Smart Manufacturing Leadership Coalition
SMOPAC	Smart Manufacturing Operations Planning and Control
SMSDA	Smart Manufacturing System Design and Analysis
STEP	Standard for the Exchange of Product Data
TC	technical committee
UMP	unit manufacturing process
YCB	Yale-CMU-Berkeley