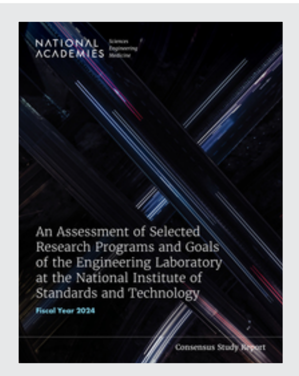

An Assessment of Selected Research Programs and Goals of the Engineering Laboratory at the National Institute of Standards and Technology: Fiscal Year 2024 (2025)

DETAILS

88 pages | 8.5 x 11 | PAPERBACK

ISBN 978-0-309-71456-3 | DOI 10.17226/27444

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SUGGESTED CITATION

National Academies of Sciences, Engineering, and Medicine. 2025. *An Assessment of Selected Research Programs and Goals of the Engineering Laboratory at the National Institute of Standards and Technology: Fiscal Year 2024*. Washington, DC: The National Academies Press. https://doi.org/10.17226/27444.

NATIONAL ACADEMIES *Sciences Engineering Medicine*

NATIONAL ACADEMIES PRESS
Washington, DC

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Fiscal Year 2024

Panel on Assessment of the National Institute of Standards and Technology (NIST) Engineering Laboratory

Laboratory Assessments Board

Division on Engineering and Physical Sciences

Consensus Study Report

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

This activity was supported by task order 1333ND24FNB100003 under contract 1333ND23DNB100003 between the National Academy of Sciences and 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 organization or agency that provided support for the project.

International Standard Book Number-13: 978-0-309-71456-3
International Standard Book Number-10: 0-309-71456-7
Digital Object Identifier: https://doi.org/10.17226/27444

This publication is 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. 2025. *An Assessment of Selected Research Programs and Goals of the Engineering Laboratory at the National Institute of Standards and Technology: Fiscal Year 2024*. Washington, DC: The National Academies Press. https://doi.org/10.17226/27444.

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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 thank the following individuals for their review of this report:

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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 **ELSA REICHMANIS (NAE)**, Lehigh University, and **DAVID W. JOHNSON, JR. (NAE)**, Bell Laboratories, Lucent Technologies. They were 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 committee and the National Academies.

Contents

Summary

BACKGROUND AND TASK

Since 1959, the National Institute of Standards and Technology (NIST) has engaged the National Academies of Sciences, Engineering, and Medicine annually to assemble expert panels consisting of professionals from academia, industry, and other scientific and engineering communities and assess the quality, effectiveness, and resource adequacy of NIST's six measurement and standards laboratories.[1] NIST initiates these evaluations through a contract with the National Academies. For fiscal year 2024, NIST tasked the National Academies with evaluating its Engineering Laboratory (EL). This review by the Panel on Assessment of the National Institute of Standards and Technology (NIST) Engineering Laboratory is based on read-ahead materials, a site visit where the panel toured the laboratory and engaged with EL researchers in one-on-one discussions, a session with postdocs and junior staff, and post-meeting questions. Drawing on its collective expertise, the panel reviewed EL based on the statement of task and provided relevant recommendations.

The statement of task has four key components. First, the panel was tasked to evaluate EL's technical programs, comparing the quality of its research to similar international programs, and determining whether the programs are sufficient for EL to meet its objectives. Second, the panel was tasked to assess EL's portfolio of scientific and technical expertise, evaluating whether it is world-class and how effectively it supports EL's programs and objectives. Third, the panel was tasked to review the adequacy of EL's facilities, equipment, and human resources in supporting its technical work and overall goals. Finally, the panel was tasked to evaluate EL's effectiveness in disseminating its program outputs, including how well these efforts are driven by stakeholder needs, the comprehensiveness of the dissemination and technology transfer mechanisms, and how effectively EL monitors stakeholder use and the impact of its output.

ENGINEERING LABORATORY

EL comprises five divisions, including the Building Energy and Environment Division, Fire Research Division, Intelligent Systems Division (ISD), Materials and Structural Systems, and Systems Integration Division. These divisions are housed on the NIST campus in Gaithersburg, Maryland. These divisions contribute to the EL mission 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" (NIST 2021).

[1] The laboratories are the Center for Neutron Research, Communications Technology Laboratory, Engineering Laboratory, Information Technology Laboratory, Material Measurement Laboratory, and Physical Measurement Laboratory.

KEY RECOMMENDATIONS

What follows are overarching themes and related key recommendations for EL as a whole. They represent things that all of the subpanels observed in the course of the meeting. There are also chapter-specific recommendations in each chapter. Chapter 7 presents the overarching themes, key recommendations, and chapter-specific recommendations in one place.

Strategic Direction and Strategic Planning

The panel found that the strategies and strategic directions guiding EL's work were not clearly defined. To properly assess the effectiveness of EL's programs, the panel needed a clearer understanding of EL's goals and objectives. How does EL ensure that its research areas align with the mission of the laboratory, NIST as a whole, and with stakeholder needs? The panel was not provided with a strategic plan, short- or long-term implementation plans, key performance indicators, or reporting requirements that could help to answer these questions.

Without clear strategic goals, evaluating whether EL has the necessary expertise, budget, and facilities to support globally competitive programs becomes difficult. A key concern was the perception that EL undertakes projects because they are feasible, rather than because they meet a clearly defined set of needs. A well-defined strategic planning process would clarify the purpose behind each program, establish clear benchmarks to measure progress, and identify go/no-go decision points. When selecting projects, an internal management review to look across the laboratory, NIST, and the broader stakeholder community could help ensure that efforts are not duplicated and help to identify opportunities for collaboration.

Many research programs presented to the panel appeared to operate independently, with little interaction between them. This isolated approach may stem from the practice of assigning individual projects to a single principal investigator (PI), who takes sole responsibility for the project. Additionally, funding is often provided to individual PIs annually rather than to EL based on strategic initiatives, which makes fostering collaboration more difficult. EL could consider consolidating research projects that could benefit from collaboration, improving overall efficiency. Activities such as attending conferences, hosting workshops (both on and offsite), and organizing events that bring together industry and research entities could help EL allocate its limited resources more effectively. Strategic planning would also guide staff recruitment with an eye to the big picture.

For maximum impact, EL's strategic planning would need to align with the needs of its stakeholders, including industry. It is unclear how EL determines whether its work aligns with stakeholder priorities. Without this alignment, it is challenging to assess whether EL is making the most relevant, cost-effective, and meaningful contributions. Engaging more deeply with industry and other stakeholders would provide insights into their needs, allowing EL to develop projects that directly address those challenges. This approach would enhance the relevance and effectiveness of EL's work, fostering innovation and progress within the stakeholder communities.

Key Recommendation 1: The Engineering Laboratory (EL) should determine and describe the strategic directions it will pursue and how personnel and resources will be allocated to pursue those directions. Management reviews during project selection should use the strategic directions to avoid duplication, look for collaboration opportunities, and guide the recruiting of any new staff. EL should also develop and publish a long-term strategic plan that includes input from stakeholders such as industry.

Metrics and Stakeholder Relevance

Although EL's mission 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," the panel was left questioning *how* EL measures its success. Specifically, how does EL evaluate whether it is meeting its mission, and what metrics are used to gauge success? There is a need for clear evaluation criteria and metrics to both select projects and assess their success. The panel found no obvious criteria for evaluating how programs are selected, nor were there clear metrics to measure a program's success or that could be used in deciding whether to maintain or terminate a program of research. Additionally, it was unclear if programs are periodically assessed for their relevance to industry stakeholders. The panel was unable to obtain detailed information on how projects are benchmarked or how key performance indicators are measured. Effectiveness and impact are best assessed at the individual project level within EL. Metrics do not need to be perfect to be useful. Some suggested metrics (a few of which may already be in place) include completion rate for project milestones, schedule compliance, software downloads, publications, citations, industry adoption of engineering technology, integration of standards, report generation, patents, licensing, and recognition through awards.

If EL is already periodically evaluating performance and program success metrics, it would be beneficial to share this track record to demonstrate the value of both past and future programs. This would allow stakeholders to appreciate the wide range of outputs from EL's work. As NIST strives to be a world-class organization, it may benefit from further defining what "world-class" means. A clear definition would help guide EL and provide assessment panels with feedback on progress toward that goal.

The pace of research is also critical for industry relevance. EL's typical 2–5-year project cycles align with standard industry timelines, but the rapid pace of technological advancement risks rendering long-term research outdated by the time it concludes. To better meet industry demands, EL might consider reassessing project milestones every 12 months. This would provide an opportunity to adjust milestones as needed to ensure that the work remains relevant and impactful.

Currently, EL does not seem to communicate externally the success metrics that demonstrate the impact of its research. Also, as shown in Figure 2-5, the budgets for EL's goals have either remained stable, increased slightly over time, or decreased (the decrease shown in Figure 2-5 was due to a reorganization, with some of EL's groups moving to the Communications Technology Laboratory). These data, however, are not corrected for inflation. This means that EL has likely either been barely maintaining purchasing power in the face of inflation or losing purchasing power. Clear metrics of the sort recommended here, and the clear communication of them to stakeholders and funders, could also be used to demonstrate EL's value proposition to appropriators.

Key Recommendation 2: The Engineering Laboratory (EL) should communicate the current clear metrics for project adoption and success that are already in place. A management review of the work portfolio should be considered as a tool to determine whether to keep a project going or terminate it. EL should communicate the metrics externally to stakeholders and review panels. The adoption of standards by industrial groups to which EL has contributed should be externally communicated to stakeholders regularly. EL should also define what it means to be "world-class" so it can know when it is meeting this goal.

REFERENCE

NIST (National Institute of Standards and Technology). 2021. "About EL." Updated June 2. https://www.nist.gov/el/about-el.

1
Introduction

STATEMENT OF TASK

The National Academies of Sciences, Engineering, and Medicine have, starting in 1959, annually assembled panels of experts—from academia, industry, medicine, and other scientific and engineering communities of practice—to assess the quality and effectiveness of the National Institute of Standards and Technology (NIST) measurements and standards laboratories, of which there are six,[1] as well as the adequacy of the laboratories' resources. These reviews are conducted under contract at the request of NIST.

For fiscal year 2024, the National Academies reviewed NIST's Engineering Laboratory (EL). The assessment of EL addressed the following factors at the request of the NIST Director:

1. Assess the organization's technical programs.
   - 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, in what areas should it 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?
4. Assess the effectiveness by which the organization disseminates its program outputs.
   - How well are the organization's research programs driven by stakeholder needs?
   - How effective are the dissemination methods and technology transfer mechanisms used by the organization? Are these mechanisms sufficiently comprehensive?
   - How well is this organization monitoring stakeholder use and impact of program outputs? How could this be improved?

[1] The six NIST laboratories are the Center for Neutron Research, Communications Technology Laboratory, Engineering Laboratory, Information Technology Laboratory, Material Measurement Laboratory, and Physical Measurement Laboratory.

CONDUCT OF THE ASSESSMENT

The overall structure of EL, its goals, and the associated programs are laid out in Chapter 2. At the request of EL, this assessment is structured along the lines of the following two major EL goals[2] and their associated programs:

- Advanced Manufacturing Goal
  - Advanced Manufacturing Data Infrastructure and Analytics program
  - Measurement Science for Additive Manufacturing program
  - Measurement Science for Manufacturing Robotics program
- Energy-Efficient, High-Performance Buildings Goal
  - Embedded Intelligence in Buildings program
  - Net-Zero Energy, High-Performance Buildings program

The panel held a meeting and site visit on May 14–16, 2024, at the NIST campus in Gaithersburg, Maryland. At this meeting, the panel received an introductory overview of NIST and EL. Then the panel broke into five separate subpanels that met independently and in parallel with the EL staff aligned with the programs assessed in this report. These subpanel meetings included structured presentations, discussions, and tours. The panel also had a working lunch with early-career EL staff and postdocs.

STRUCTURE OF THIS REPORT

As described in Chapter 2, EL comprises five divisions. However, rather than structuring this assessment along the lines of its divisions, EL chose to present its information to the panel organized along the lines of the goals and programs outlined above. This work is distributed across multiple EL divisions, as appropriate. Thus, this report is structured according to the goals and programs listed, not the EL divisions.

This report opens with this introductory chapter, followed by an overview of EL. Then each chapter assesses an EL program and one or more related goals. The structure within each of these chapters is aligned with the statement of task presented above to aid the reader in understanding the panel's assessment. The final chapter presents the recommendations from this report in one place for ease of reference. The structure of this report is thus:

- Chapter 1: Introduction
- Chapter 2: Overview of the Engineering Laboratory
- Chapter 3: Advanced Manufacturing Goal: Measurement Science for Additive Manufacturing Program
- Chapter 4: Advanced Manufacturing Goal: Measurement Science for Manufacturing Robotics Program
- Chapter 5: Advanced Manufacturing Goal: Advanced Manufacturing Data Infrastructure and Analytics Program
- Chapter 6: Energy-Efficient, High-Performance Buildings Goal: Net-Zero Energy, High-Performance Buildings and Embedded Intelligence in Buildings Programs
- Chapter 7: Overarching Themes, Key Recommendations, and Chapter-Specific Recommendations

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[2] A third major EL goal, Disaster Resilience, is not assessed in this report.

To draft this report, the panel reviewed the material provided by EL before and during the review meeting. EL chose what information to provide to the panel. The panel applied a largely qualitative approach to the assessment, using the members' professional experience, expertise, and judgment to conduct the assessment. The panel was quantitative where possible, but much of this assessment is, by its nature, subjective, with the panel's opinions being based on the facts presented to it.

Because this assessment depends on the information presented by EL, it is not exhaustive. Similarly, there are natural variations between the assessment chapters (Chapters 3–6) in terms of length, level of detail, and approach. These variations convey no message about the quality of work being performed by EL or the information provided to the panel. Each assessment chapter was drafted by one of the subpanels and reflects what content the EL staff chose to present to each subpanel and the level of detail provided to that subpanel. The assessment chapters are also not a comprehensive presentation of the entirety of the information provided to the subpanels. Rather, each subpanel selected what stood out to its members in fulfillment of the statement of task and drafted the chapter around those items. Thus, the omission in this report of any particular EL project is not a negative reflection of the omitted project.

Finally, the statement of task asks in some places if the work of EL is "world-class" or how it compares with work at other international institutes. This is always a subjective assessment based on the totality of the panelists' knowledge and experience. Also, in many instances, NIST's work is unique in the world. This, itself, makes much of the work world-class or world-leading.

USE OF THE 2023 NIST *CAPITAL FACILITY NEEDS* REPORT IN THE PANEL'S WORK

This report adopts the full description of the problems identified in *Technical Assessment of the Capital Facility Needs of the National Institute of Standards and Technology* (NASEM 2023). Box 1-1 summarizes that report and its findings and recommendations.

BOX 1-1
Technical Assessment of the Capital Facility Needs of the National Institute of Standards and Technology

In February 2023, the National Academies of Sciences, Engineering, and Medicine released the report *Technical Assessment of the Capital Facility Needs of the National Institute of Standards and Technology* (NASEM 2023, hereafter the *Capital Facility Needs* report). The committee that authored this report was tasked to assess National Institute of Standards and Technology's (NIST's) facilities and utility infrastructure, review and assess plans and projects to reinvigorate NIST's facilities and utility infrastructure, the cost estimates for doing so, and the factors that NIST should consider in developing a comprehensive capital strategy for the facilities and utility infrastructure at NIST's campuses in Boulder, Colorado, and Gaithersburg, Maryland. The committee engaged with the Department of the Interior, the National Institutes of Health, the U.S. Army Engineer Research and Development Center, and the Johns Hopkins University Applied Physics Laboratory to learn about their methods and metrics for assessing facility conditions and maintaining their facilities.

The condition of NIST's facilities and utility infrastructure has been a concern since 2002 when the Visiting Committee on Advanced Technology (VCAT) issued a report calling NIST's facilities condition and the related funding situation "alarming" and "critical." Over the following 20 years, the VCAT returned consistently to this theme with increasingly dire language. Eventually, the conference report accompanying the Consolidated Appropriations Act of 2021 (P.L. 116-260) requested that NIST "contract with an independent entity to develop a report that assesses the comprehensive capital needs of NIST's campuses." In response, NIST's Office of Facilities and Property Management approached the National Academies to conduct a study based on a successful study and report completed for the National Institutes of Health in 2019 (NASEM 2019). The result was the *Capital Facility Needs* report (NASEM 2023).

TABLE 1-1-1 Overview of NIST Facility and Infrastructure Funding Needs

Funding Component	Amount Needed Annually
Construction and major renovations (CMR)	$300 million to $400 million
Safety, capacity, maintenance, and major repairs (SCMMR)	$120 million to $150 million
Total needed for construction of research facilities (CRF)	$420 million to $550 million

NOTE: CRF funding is the sum of CMR and SCMMR funding.
SOURCE: NIST (2022).

The committee that authored the *Capital Facility Needs* report visited both the Boulder, Colorado, and Gaithersburg, Maryland, campuses. It discovered that many NIST facilities are inadequate to support the world-leading research that is NIST's mission. Both the quality and the reliability of power can be problematic, resulting in slowed work, lost work, and unnecessary time spent recalibrating sensitive instruments. Inadequacies in basic environmental controls can result in laboratories that are too hot or cold, too humid, or not humid enough, and lack proper vibration insulation. In one 1950s-era Boulder laboratory, the gaps between the windows and frames allow dust to blow straight into the laboratory. Roof leaks have destroyed multimillion-dollar pieces of equipment, such as tunneling electron microscopes in both Boulder and Gaithersburg. A water leak in Gaithersburg resulted in permanent damage to the world-leading Kibble balance that tied the standard kilogram to the speed of light. There are many more instances and stories. In all, the committee found that the NIST research staff loses between 10–40 percent of its working time fighting against facility inadequacies, also consuming research money to do so. Things have reached the point where NIST researchers will not be able to continue their world-class research no matter their efforts. This is already impacting the ability to recruit and retain staff and the willingness of foreign researchers to do work at NIST. At risk is also NIST's international credibility and influence and its ability to support national security, U.S. international competitiveness, medical therapeutics, and a wide range of other activities upon which users in the U.S. government, industry, and academia rely.

In the course of its work, the committee found that NIST's internal facility and property management policies are not responsible for this situation. Rather, the cause is more than two decades of erratic, unpredictable, and inadequate funding for NIST's construction of research facilities (CRF) budget, which includes facility sustainment, restoration, modernization, and expansion. Exacerbating this problem is congressionally directed pass-through funding for things like building laboratories on university campuses that are not used by NIST. This pass-through funding is not revenue-neutral to NIST, costing staff time and money to administer, draining even more much-needed money from NIST's facilities coffers.

In short, the committee found that the situation requires serious and sustained attention, particularly from leadership levels above NIST. The committee also endorsed the coordinated recovery plan drafted by NIST's Office of Facilities and Property Management and recommended its continued refinement and shortening it to complete it in 12 years. Critically, the committee identified the need for significant and sustained funding to address NIST's facilities and utility shortcomings and bring them to the standard necessary for modern metrology. This funding is the critical piece of the recovery plan. The committee recommends $420 million–$550 million per year in funding for NIST's CRF budget over at least 12 years. As shown in Table 1-1-1, this includes $120 million–$150 million per year for safety, capacity, maintenance, and major repairs funding to address the more than $800 million deferred maintenance backlog and bring existing facilities to an acceptable condition and keep them there. It also includes $300 million–$400 million per year over at least 12 years for the construction and major renovations budget to upgrade, renovate, and build the new laboratories with the new capabilities needed to conduct modern metrology research.

The picture is not unremittingly bleak. NIST has already begun to modernize laboratories as its current budget allows. These new laboratories are state of the art and enable the cutting-edge world-leading research that is NIST's mission. As an example, one NIST research group—after waiting 18 months to be relocated into a new, modern laboratory—won the 2021 Physics World Breakthrough of the Year award for a previously unprecedented demonstration of the quantum entanglement of microresonators. NIST's staff is world-class and capable of producing amazing results, results that will serve the nation and inspire the next generations of researchers, provided they are given the facilities and tools needed to do their work.

SOURCE: NIST (2023).

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NASEM (National Academies of Sciences, Engineering, and Medicine). 2019. *Managing the NIH Bethesda Campus Capital Assets for Success in a Highly Competitive Global Biomedical Research Environment*. The National Academies Press. https://doi.org/10.17226/25483.

NASEM. 2023. *Technical Assessment of the Capital Facility Needs of the National Institute of Standards and Technology*. The National Academies Press. https://doi.org/10.17226/26684.

NIST (National Institute of Standards and Technology). 2022. "NIST Facilities Summary for Representative Trone." Point Paper. Office of Facilities and Property Management.

2
Overview of the Engineering Laboratory

The Engineering Laboratory (EL) is one of the National Institute of Standards and Technology's (NIST's) six major laboratories and one of NIST's fundamental metrology laboratories.[1] It is located at NIST's Gaithersburg, Maryland, campus. EL describes its mission as promoting "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" (NIST 2021).

EL is organized into five divisions. These are the Building Energy and Environment Division (BEED), Fire Research Division, Intelligent Systems Division (ISD), Materials and Structural Systems, and Systems Integration Division (SID).

BEED focuses its work on buildings that are cost-effective, energy-efficient, integrated into the grid, healthy and comfortable for their occupants, and have reduced impacts on the environment. It accomplishes its work by advancing measurement science and developing standards.

The Fire Research Division quantifies the behavior of fire by developing, verifying, and using measurements and predictive methods. The goal is to find means to reduce the impact of fire on people, property, and the environment. This work integrates laboratory measurements, verified methods of prediction, and large-scale fire experiments to demonstrate the use and value of the research products.

ISD works to speed the development, adoption, and integration of leading-edge intelligent technologies to advance U.S. manufacturing performance. It does this by developing, advancing, and deploying measurement science and standards.

The Materials and Structural Systems Division develops and promotes science-based tools—such as measurements, data, models, protocols, and reference standards—and their use to enhance the global competitiveness of U.S. industry and the safety, security, and sustainability of the nation's buildings and physical infrastructure.

SID promotes U.S. innovation and industrial competitiveness in areas of critical national priority by anticipating and meeting the measurement science and standards needs for integrating engineering information systems used in manufacturing, construction, and cyber-physical systems in ways that enhance economic prosperity and improve the quality of life (NIST 2021).

As described in Chapter 1, EL's work is organized into goals and related programs rather than by division. For this report, EL requested that the panel assess the following goals and their associated programs:

- Advanced Manufacturing Goal (work performed by ISD and SID)
  - Advanced Manufacturing Data Infrastructure and Analytics Program
  - Measurement Science for Additive Manufacturing Program
  - Measurement Science for Manufacturing Robotics Program
- Energy-Efficient, High-Performance Buildings Goal (work performed by BEED)
  - Embedded Intelligence in Buildings program
  - Net-Zero Energy, High-Performance Buildings program (NIST 2021)

[1] The other five laboratories are the Center for Neutron Research, Communications Technology Laboratory, Information Technology Laboratory, Material Measurement Laboratory, and Physical Measurement Laboratory.

AWARDS, HONORS, AND PUBLICATIONS

Most of the information in this report is organized by goal and program. This is because that is how EL structured most of the information it provided to the panel. However, two categories of information provided—awards and honors, and publications—were presented broken out by division, in addition to the information provided at the meeting in the subpanel breakout meetings. The division-level information is presented here in the EL overview to give the reader the division-specific picture as well as the information contained in Chapters 4–6.

Awards and Honors

The information on staff awards and honors covers fiscal years (FYs) 2020 (for BEED only), 2021, 2022, 2023, and through April for FY 2024.[2]

In this assessment period, ISD staff won 17 awards and honors in FY 2021, 8 in FY 2022, 11 in FY 2023, and 4 to date in FY 2024 (some were shared by multiple people; the panel does not have a complete head count). These include awards and honors such as the following:

- Department of Commerce (DOC) Gold Medal
- NIST Bronze Medal
- NIST Slichter Award
- 2022 Acta Materialia Outstanding Reviewer Award
- American Society of Mechanical Engineers (ASME) Best Organizer of Symposium and Sessions Award
- 2020 ASME Outstanding Paper Award
- ASTM International[3] Award of Merit, with the accompanying title of ASTM fellow
- ASTM International Additive Manufacturing Young Professional Award
- Washington Academy of Sciences 2022, 2023, and 2024 Leadership Award in Manufacturing Engineering

In this assessment period, SID staff won 10 awards and honors in FY 2021, 3 in FY 2022, 4 in FY 2023, and 4 to date in FY 2024 (some were shared by multiple people; the panel does not have a complete head count). These include awards and honors such as the following:

- NIST Bronze Medal
- AgGateway President’s Award
- 2023 ASME Computers and Information in Engineering Distinguished Service Award
- ASTM Additive Manufacturing Award of Excellence in Research
- A staff member elected president of the North American Manufacturing Research Institute in FY 2023
- A staff member elected fellow of the American Association for the Advancement of Science in FY 2023
- A staff member elected fellow of the ASME in FY 2024

Altogether, staff members supporting the Advanced Manufacturing goal won 27 awards and honors in FY 2021, 11 in FY 2022, 15 in FY 2023, and 8 to date in FY 2024.

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[2] For the U.S. federal government, the fiscal year runs from October through September. Thus, FY 2021 began in October 2020 and ended in September 2021.

[3] ASTM International was formerly known as the American Society for Testing and Materials.

In this assessment period, BEED staff won 2 awards and honors in FY 2020, 5 in FY 2021, 11 in FY 2022, 9 in FY 2023, and 2 to date in FY 2024 (some were shared by multiple people; the panel does not have a complete head count). These include awards and honors such as the following:

- ASHRAE[4] Distinguished Service Award
- ASTM International Award of Merit
- NIST Edward Bennet Rosa Award
- NIST Eugene Casson Crittenden Award
- NIST Judson C. French Award
- NIST Jacob Rabinow Applied Research Award
- DOC Gold Medal
- Drexel University Excellence in Co-Operative Education Award
- International Building Performance Simulation Association-USA Emerging Contributor Award
- Johns Hopkins University Outstanding Instructor Award
- Purdue University Dave Tree Distinguished Service Award
- Washington Academy of Sciences 2024 Distinguished Career Award in Engineering Sciences

Publications

The three divisions supporting the research goals and programs assessed in this report have an extensive publication history, summarized as follows: ISD in Table 2-1 and Figure 2-1, SID in Table 2-2 and Figure 2-2, and BEED in Table 2-3 and Figure 2-3. The drop in ISD and SID publications from FY 2020 is the result of the COVID-19 pandemic affecting research and the resulting publications.

TABLE 2-1 Intelligent Systems Division Publications by Fiscal Year (FY) and by Type, 2014–2024

FY	Book	Conference	Journals	NIST Publications	Other	Total for FY
2014	0	16	16	11	1	44
2015	3	18	10	4	7	42
2016	1	39	23	14	6	83
2017	3	26	21	13	6	69
2018	2	35	25	14	2	78
2019	3	27	28	16	4	78
2020	4	17	33	19	5	78
2021	0	22	31	9	4	66
2022	2	17	13	13	2	47
2023	2	26	18	4	1	41
2024	0	7	8	4	1	20

NOTE: FY 2024 numbers are through April 26, 2024.
SOURCE: Data courtesy of NIST Engineering Laboratory.

[4] ASHRAE, formerly known as the American Society of Heating, Refrigerating, and Air-Conditioning Engineers.

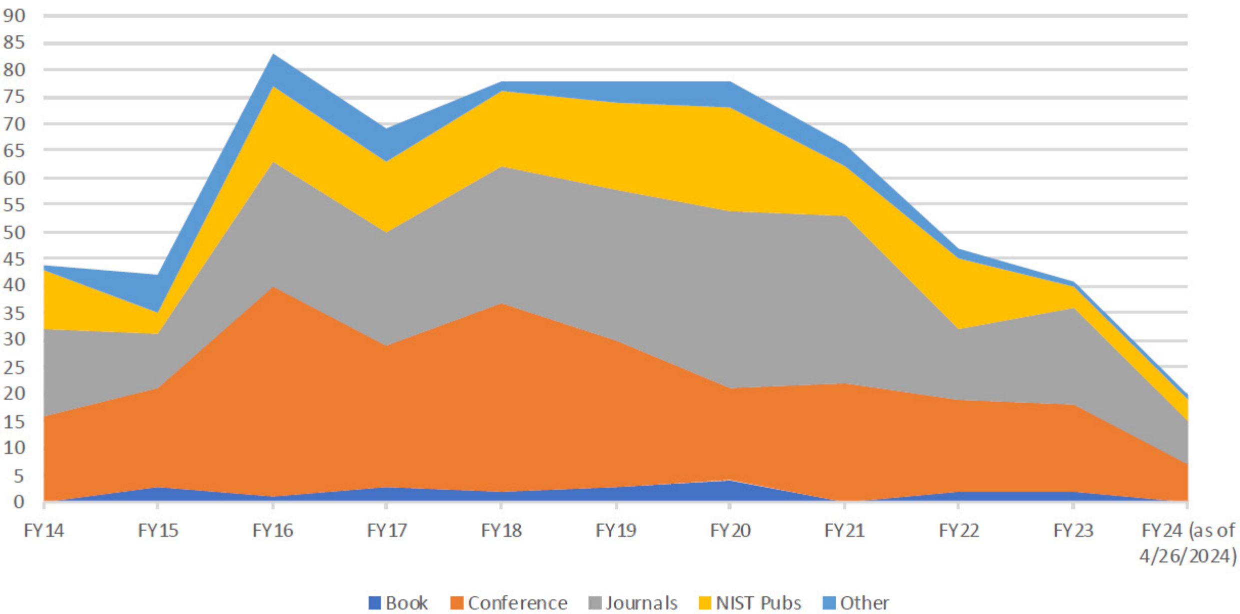

FIGURE 2-1 Intelligent Systems Division publications by fiscal year (FY) and type, 2014–2024 (as of April 26, 2024).
NOTE: NIST, National Institute of Standards and Technology.
SOURCE: Courtesy of NIST Engineering Laboratory.

TABLE 2-2 Systems Integration Division Publications by Fiscal Year (FY) and by Type, 2014–2024

FY	Book	Conference	Journals	NIST Publications	Other	Total for FY
2014	1	15	15	9	3	43
2015	2	25	17	8	3	54
2016	3	32	20	10	5	70
2017	5	30	15	7	3	60
2018	1	33	20	7	1	62
2019	0	33	17	9	2	61
2020	1	29	35	11	4	80
2021	0	23	21	6	1	51
2022	2	20	10	4	0	36
2023	3	29	9	3	3	47
2024	0	9	5	0	0	14

NOTE: FY 2024 numbers are through April 26, 2024.
SOURCE: Data courtesy of NIST Engineering Laboratory.

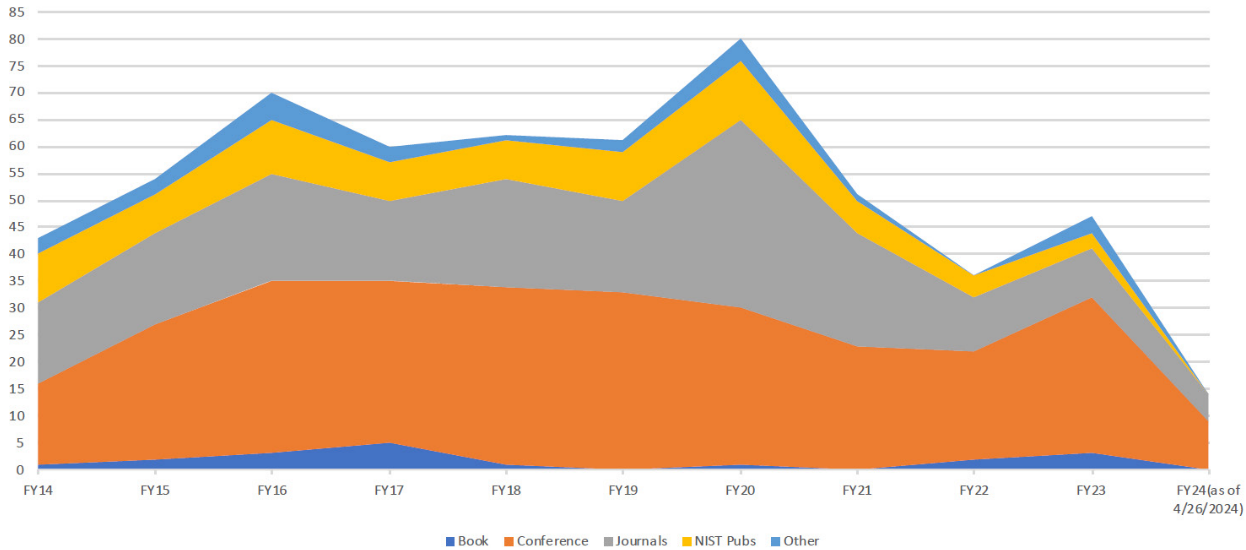

FIGURE 2-2 Systems Integration Division publications by fiscal year (FY) and type, 2014–2024 (as of April 26, 2024).
NOTE: NIST, National Institute of Standards and Technology.
SOURCE: Courtesy of NIST Engineering Laboratory.

TABLE 2-3 Building Energy and Environmental Division Publications by Fiscal Year (FY) and by Type, 2014–2024

FY	Book	Conference	Journals	NIST Publications	Other	Total for FY
2014	3	27	28	18	1	77
2015	0	20	26	11	3	60
2016	0	15	24	14	7	60
2017	1	20	20	11	4	56
2018	1	22	19	19	3	64
2019	0	10	17	15	4	46
2020	0	15	18	13	4	50
2021	3	14	22	14	2	55
2022	1	17	27	14	10	69
2023	2	10	20	12	2	46
2024	0	5	8	2	1	16

NOTE: FY 2024 numbers are through April 26, 2024.
SOURCE: Data courtesy of NIST Engineering Laboratory.

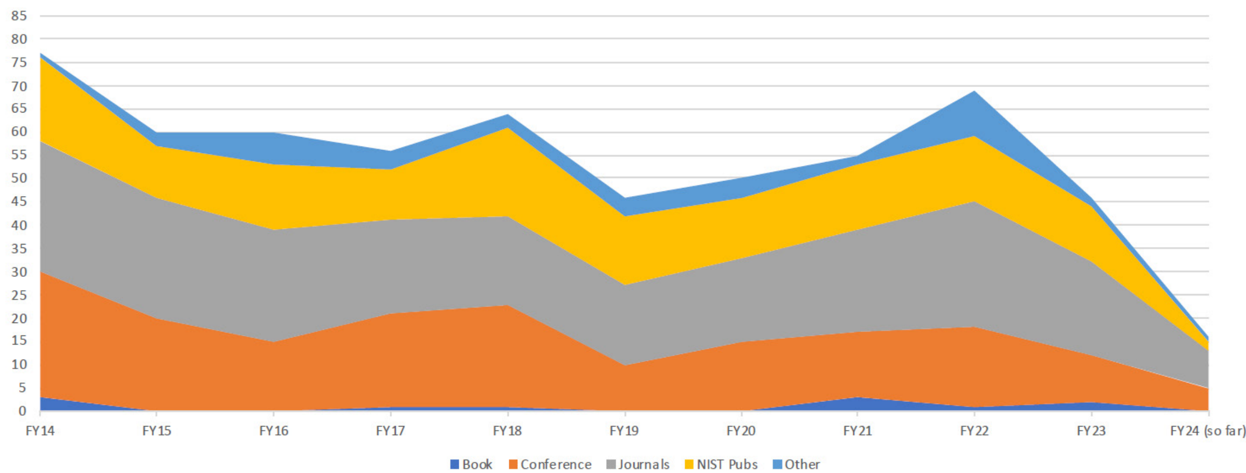

FIGURE 2-3 Building Energy and Environmental Division publications by fiscal year (FY) and type, 2014–2024 (as of April 26, 2024).
NOTE: NIST, National Institute of Standards and Technology.
SOURCE: Courtesy of NIST Engineering Laboratory.

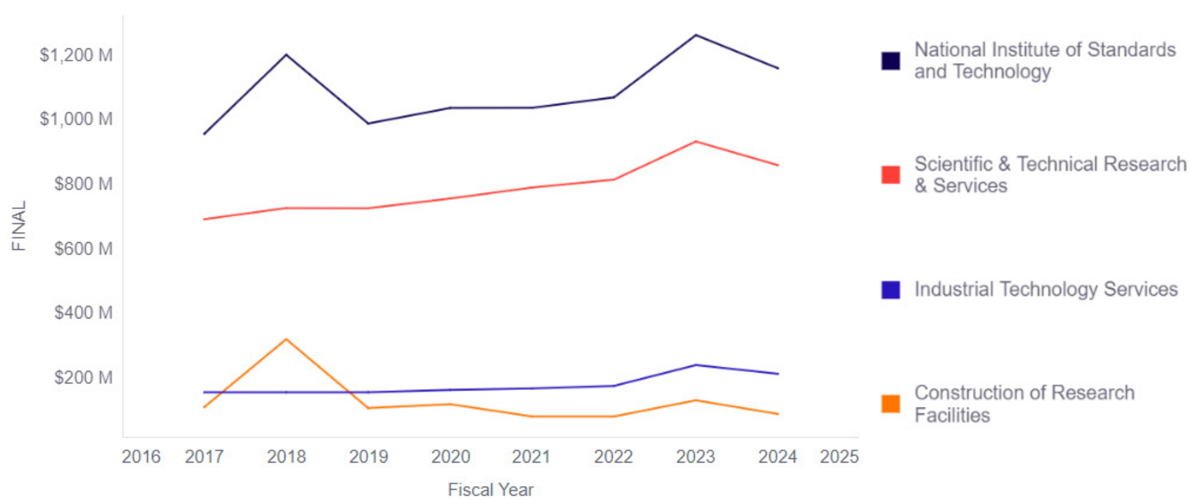

FIGURE 2-4 NIST's budget trends, fiscal years 2016–2024.
SOURCE: Courtesy of NIST Engineering Laboratory.

BUDGET

NIST's budget trends between FY 2016 and FY 2024 are shown in Figure 2-4. The budget information provided to the panel is not corrected for inflation. Three major categories of funding are shown. The Scientific and Technical Research Services (STRS) budget funds NIST's scientific and technical work. The Industrial Technology Services budget mainly funds the Manufacturing Extension

Partnership[5] and the Office of Advanced Manufacturing (Manufacturing USA).[6] The Construction of Research Facilities (CRF) budget is a separate appropriation for facility and utility major maintenance, renovation, and construction. CRF funds support the buildings, utilities, and other infrastructure for NIST; major facility funding is not included in STRS funding.

As can be seen, the total funding for NIST has seen modest growth with spikes in FY 2018 and FY 2023. The spike in FY 2018 was a one-time infusion of infrastructure funding. The spike in STRS funding in FY 2023 reflects a one-time funding bump. For the EL work assessed in this report, STRS funding included $1 million for high-performance premise plumbing and $2 million for a robotics training center (some of this was directed for use at an academic institution). EL also received $3 million for forward-looking building standards, $750,000 for pyrrhotite testing and mitigation, and $1.5 million for wildfires and wildland–urban interface fires research—all under EL's Disaster-Resilient Buildings, Infrastructure, and Communities Goal, which is not assessed in this report. While NIST's total funding has seen modest overall growth since FY 2016, the CRF budget has decreased over the same time. NIST is facing, increasingly, several facilities and infrastructure challenges that are, in some cases, endangering its ability to accomplish its core mission. The CRF funding is even more dire when one factors in inflation. See Box 1-1, which treats the facilities and budget issues in more depth, including budget recommendations from the 2023 National Academies of Sciences, Engineering, and Medicine report *Technical Assessment of the Capital Facility Needs of the National Institute of Standards and Technology* (NASEM 2023).

EL's budget trends broken out by goal are shown in Figure 2-5.

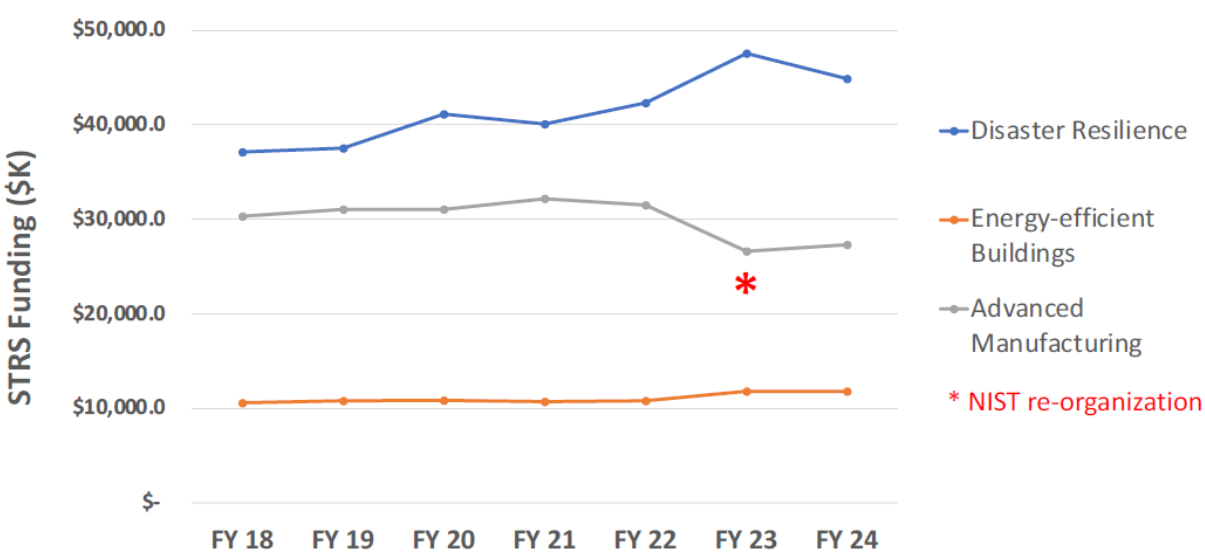

FIGURE 2-5 The Engineering Laboratory budget, broken out by its three major goals.
NOTES: FY, fiscal year; STRS, Scientific and Technical Research Services. The Disaster-Resilient Buildings, Infrastructure, and Communities Goal is not assessed in this report.
SOURCE: Courtesy of NIST Engineering Laboratory.

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[5] For more information, see NIST, "Manufacturing Extension Partnership," https://www.nist.gov/mep, accessed December 11, 2024.

[6] For more information, see NIST, "Office of Advanced Manufacturing," https://www.nist.gov/oam, and the Manufacturing USA website at https://www.manufacturingusa.com (both accessed December 11, 2024).

Again, these figures are not adjusted for inflation. As can be seen, the Disaster Resilience Goal budget has increased over time from FY 2018 through FY 2024. The Advanced Manufacturing Goal budget grew modestly from FY 2018 through FY 2022 and then decreased. This decrease resulted from a NIST reorganization in FY 2023 that saw three groups move from EL to the Communications Technology Laboratory. The Energy-Efficient, High-Performance Buildings Goal budget has been mostly steady over the same time (and, so, has lost ground to inflation). Budget observations appear in Chapters 3–6, where the panel has assessments to offer.

No attempts were made to correct the budget numbers for inflation, but when inflation is factored in, slowly growing budgets could easily be flat, and flat budgets are likely declining in real terms.

REFERENCES

NASEM (National Academies of Sciences, Engineering, and Medicine). 2023. *Technical Assessment of the Capital Facility Needs of the National Institute of Standards and Technology*. The National Academies Press. https://doi.org/10.17226/26684.

NIST (National Institute of Standards and Technology). 2021. “About EL.” Updated June 2. https://www.nist.gov/el/about-el.

3
Advanced Manufacturing Goal: Measurement Science for Additive Manufacturing Program

This assessment of the Advanced Manufacturing Goal in the Measurement Science for Additive Manufacturing (MSAM) program is based on the description of the program provided to the panel:

> 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, machines, processes and parts; and end-to-end digital implementation and integration of metal additive manufacturing processes, parts, and systems (EL).[1]

The panel noted the context of this program within the National Institute of Standards and Technology (NIST) for which the overall mission is providing the trusted data, best practices, test methods, and protocols to provide a scientific foundation for government, industry, and international standards. In summary, all the work conducted at NIST in support of this goal ought to be in service of establishing, developing, and refining measurement science to support industry and industrial standards.

Considering this context, the primary objective of the MSAM program, as stated above, is considered timely and appropriate. It is inclusive of most of the major themes of additive manufacturing (AM) research and development (R&D), with the possible exception of sustainability and supply chain issues, although those themes may be implied by the focus on end-to-end integration and implementation of AM. It is important to note that the entire program currently focuses on metal AM (and in practice, metal laser powder bed fusion), as explicitly mentioned in the primary objective, whereas the title of the program (MSAM) is focused on AM more broadly. The panel will return to this point when discussing challenges and opportunities, because metal powder bed fusion represents only a fraction of industrial practice, market share, and R&D.

To support its overall objective, the MSAM program was organized into seven projects from 2018 to 2023, as follows:

- AM Feedstocks, Machine, and Process Qualification
- AM Part Qualification
- AM Machine and Process Control Methods
- Metrology for Real-Time Monitoring of AM
- Metrology for Multi-Physics AM Model Validation
- Data Integration and Management for AM
- Data-Driven Decision Support for AM

[1] The National Institute of Standards and Technology (NIST) document “Measurement Science for Additive Manufacturing” was obtained by the panel on May 6, 2024, and is available are available in the public access file for this study (Email: paro@nas.edu).

The MSAM program has established a set of projects that are well aligned with NIST's mission. The goals of the projects are timely and appropriate. The group's productivity is very good in terms of service to professional societies, and the work has been recognized with significant awards from the government and professional societies. The group continues to lead and contribute to a broad suite of standards that are relevant to its mission. The experimental metal AM testbed and related work in metrology and controls are advancing the state of the art and serving a very important role in industry-related validation and qualification. The research under the MSAM umbrella has the potential to significantly advance measurement science in the field of AM.

There is room for improvement in two specific areas: strategic planning and impact. In this chapter, several areas where resource allocation and outcomes would be improved by strategic planning are described. A sound strategic plan will lead to success in the second area, impact. Both strategic planning and impact relate to NIST's mission to directly support U.S. industry and are identified as overarching themes, with key recommendations, in Chapter 7.

ASSESSMENT OF TECHNICAL PROGRAMS

In terms of addressing NIST's mission of advancing measurement science to support industry, some projects clearly meet that mission and provide outstanding technology and thought leadership to support it, whereas others appear quite disconnected from it. The projects that the panel believes are on the right track are addressed under "Accomplishments," and the ones the panel believes are not as well connected to the mission are addressed in "Opportunities and Challenges."

Accomplishments

The projects on AM Machine and Process Control Methods, Metrology for Real-Time Monitoring of AM, and Metrology for Multi-Physics AM Model Validation are examples of projects that have a significant impact on measurement science for industrial applications. The panel was especially impressed with ongoing work to establish one-of-a-kind instrumentation and fabrication equipment to support process monitoring and control and to establish data sets that can be used widely for calibration and process improvement by industry professionals. In an era in which most commercial machines are closed (or at least partially closed) in terms of process control and monitoring, these open architecture machines and monitoring capabilities are critical for moving the industry forward.

The AM Part Qualification project and Data-Driven Decision Support for AM project are viewed as useful but less well aligned with industry needs than the Metrology, Monitoring, and Controls projects. NIST's support of benchmarking efforts such as the AM Bench—a continuing series of highly controlled benchmark tests for AM with modeling challenge problems, the results of which are discussed at the corresponding conference series—is excellent, as is NIST's support of test artifacts.[2] NIST is encouraged to continue to develop collaborations with other organizations, agencies, and researchers to coordinate these benchmarking efforts more widely. In terms of data-driven decision support, the impact of NIST's efforts on standards is clear. For example, the American Society of Mechanical Engineers (ASME) standard Y14.46 addresses product definition methods and standards for AM, and ASTM International and the International Organization for Standardization (ISO) have issued a stream of standards related to design, including process-specific design guidelines and other design-related guides and standards.

Given the project topics on which MSAM focuses, the staff need to participate in as many relevant standards as possible; for example, as discussed in the "Assessment of Scientific Expertise" section, EL staff are very active in standards organizations and support the creation of new standards. Still, a very important process qualification standard, ISO/ASTM 52930, is not listed on the briefing

[2] See the NIST "Additive Manufacturing Benchmark Test Series (AM-Bench)" webpage at https://www.nist.gov/ambench, accessed October 21, 2024.

materials but appears to be highly relevant to NIST projects. Based on its understanding of the state of the AM industry, the panel's opinion is that the metrology and control projects are most directly impacting industry.

Opportunities and Challenges

There are opportunities to define the goals and objectives of some of the MSAM projects more tightly such that they are both measurable and achievable by the limited resources available in the MSAM program. Also, there are opportunities to better define NIST's unique contributions in each area, which, given the mission of NIST, ought to be focused on measurement science, and to collaborate with leading researchers in each area to leverage their work and to avoid the potential for duplication of effort in the future at NIST.

For the AM Feedstocks, Machine, and Process Qualification project and the Data Integration and Management for AM project, it was much more difficult for the panel to discern the potential impact on industry and broader stakeholders. The AM Feedstocks, Machine, and Process Qualification project appears to trail the state of the art in feedstock characterization and the effect of feedstock on powder spreading and other process characteristics. It is not clear that this research is advancing the state of the art in related measurement science. The impact of this project's work could be increased by having projects directed to standard methods for powder reuse and recommended methods and standards for in situ monitoring.

The Data Integration and Management for AM project aspires to significant goals of supporting data acquisition and management, but it is not clear exactly how its work supports those goals. The ties between the Data Integration and Management for AM project's work and the experimental work at NIST more broadly and elsewhere need to be strengthened, for example, by applying the data management work to one of the experimental testbeds available at NIST, perhaps as part of the process controls and metrology projects. Data management and fusion is an important topic with significant potential to have applications, but it is not clear that the work EL is currently conducting could be implemented in an industrial setting or guide industrial implementations of data fusion and integration in a tangible way. It is not clear how the schema and frameworks under development in the Data Integration and Management for AM project can be translated into implementations.

The MSAM program's experimental testbeds and their development are important assets to support fundamental measurement science. Testbeds as a tool could also be useful to support data-related projects and to support tighter integration between data-related projects and hardware-related projects.

Recommendation 3-1: The Measurement Science for Additive Manufacturing Program should expand the testbed concept to include data-related projects and to support tighter integration between data-related projects and hardware-related projects.

Another challenge is maintaining situational awareness of the broader field of AM, including the polymer AM industry, directed energy deposition, hybrid AM, and emerging materials. For example, powder-based metal AM, which is the exclusive focus of the MSAM program, represents a minority of AM machines and industrial applications with a significant portion of the AM industry focused on polymer AM and hybrid AM in its various forms. The panel understands that NIST programs are resource-constrained and need to focus on high-priority areas, but it is important to acknowledge that the entire program focuses on only one segment of the AM industry. This results in missed topics, such as heat treatment and post-processing, and opportunities for synergies such as the use of real data from the Machines, Monitoring, and Control project within the Data Management project. The program could have an additional impact by enhancing it to cover the entire AM process chain, including heat treatment and post-processing. A holistic consideration of the digital and physical processes required to transform feedstock material into end-use components is necessary to enable the qualification and industrial use of AM.

NIST is working with industry in some capacities, but ties with industry and academia could be strengthened. For example, closer ties with industry could help inform NIST priorities in this area. The practical impact of some projects can be enhanced through the use of industry-relevant data sets, generated internally or via industrial partners. Also, in many areas of interest to NIST, there are international experts in academia, national laboratories, and other venues that NIST could team with to move standards forward quickly and avoid trying to reinvent all that expertise in-house. In the future, sunsetting work that has become less relevant to industry or that duplicates work done in other places such as industry and academia would help with the effective allocation of limited resources.

Also, much of the current focus appears to be directed toward U.S. defense needs and objectives that, while critically important, may not align with the needs of commercial industry or the broader stakeholder community.

EL has identified five projects launched in 2024 on which the MSAM program intends to focus in the future:

- Fundamental Measurements for Metals AM
- Metrology for AM Model Validation
- Advanced Machines, Monitoring, and Controls for AM
- Advanced Informatics and Artificial Intelligence (AI) for AM
- Data Management and Fusion for AM Industrialization

It is quite early in the development of these projects, but the goals and plans indicate that they are well aligned with the EL mission. Cautionary statements about the alignment of previous projects apply to these new projects, as well, including the need to maintain the practical relevance of the data-related projects and to leverage the prodigious intellectual capital in academia and other groups concerning AI, informatics, and other related topics.

The goals for the Metrology for AM Model Validation project and the Advanced Machines, Monitoring, and Controls for AM project are appropriate, realistic, and achievable. These teams have established significant momentum toward their goals.

The goals for the Fundamental Measurements for Metals AM project are appropriate but very broad. Similarly, the goals defined for the Advanced Informatics and Artificial Intelligence for AM project and the Data Management and Fusion for AM Industrialization project are important and industry-relevant but much too broad for the team to accomplish with the resources available to them. These three projects would benefit from goals that are more focused and measurable, integrated with experimental practice, and aligned with resources that will be realistically available. As noted above, there is a vast amount of work being conducted in the AM space. It is important for EL to clearly define its role in this space. Collaborations could be very useful in helping EL to leverage and achieve a maximum return on the investment of its resources.

Recommendation 3-2: The Measurement Science for Additive Manufacturing (AM) Program's leadership should refine the goals of the Fundamental Measurements for Metals AM, Advanced Informatics and Artificial Intelligence for AM, and Data Management and Fusion for AM Industrialization projects to be more focused and measurable, integrated with experimental practice, and aligned with realistically available resources. The program's leadership should clearly define its role in the wider AM space and explore collaborations to leverage and achieve a maximum return on the investment of its resources.

ASSESSMENT OF SCIENTIFIC EXPERTISE

Research within the MSAM program encompasses a diverse range of expertise, including mechanical engineering, physics, materials engineering, industrial or manufacturing engineering, computer science or electrical engineering, biomedical engineering, and AM. Team members include federal employees, associates (e.g., guest researchers and postdoctoral fellows), and students. Out of approximately 34 employees, approximately 18 are federal employees, 11 are associates, and 5 are students. The majority of federal staff and associates hold doctoral degrees. Staffing levels appear stable and near-term attrition does not appear to be of significant concern.

Accomplishments

Several MSAM personnel are deeply engaged with professional organizations, journals, and conference events, and many have been recognized for awards for their outstanding accomplishments, service, and contributions to standardization. Members of the team have a proven track record of accomplishment in relevant areas demonstrating their ability to deliver on the proposed research goals. These provide evidence that the personnel are integrated into their professional communities and building bridges between NIST and other R&D entities.

Skillsets are well aligned to the stated goals of most projects. The panel assessed that the team has a well-rounded mix of expertise across different disciplines or technical areas. The program has sufficient qualified personnel to conduct the research, including researchers, technicians, support staff, and any necessary consultants. In most cases, roles and responsibilities are defined for each team member. Research teams are exceptionally well qualified, and well composed, and have made significant contributions in fiscal year (FY) 2018–2023 projects covering AM Machine and Process Control Methods, Metrology for Real-Time Monitoring of AM, and Metrology for Multi-Physics AM Model Validation. Projects beginning in FY 2024 follow similar objectives and staff composition to past projects. Research teams are well composed for Metrology for AM Model Validation and Advanced Machines, Monitoring, and Controls for AM.

MSAM's publication track record—with more than 60 journal papers, 45 conference proceedings, 10 NIST publications, 6 book chapters, and 23 public data sets in the past 3 years—indicates that the work is recognized to have archival value. The MSAM program is heavily involved in standards development for AM, as well, with participation in more than 40 standards over the past few years. Staff members participate in ASTM, ASME, ISO, and American National Standards Institute (ANSI) panels. This level of standards involvement is important for translating NIST work into industrial impacts. Staff hold several awards from technical societies, conferences, and journals along with awards from the Department of Commerce, NIST, and other government agencies. Notable awards include the following:

- Several ANSI Washington Academy of Sciences Leadership Awards in Manufacturing Engineering
- ASTM International Additive Manufacturing Young Professional Award
- ASTM International Award of Excellence in Standardization
- Fellow of the ASME
- Society of Manufacturing Engineering Eli Whitney Productivity Award.

Opportunities and Challenges

There are opportunities to better align and expand team expertise to meet program objectives. While the AM Feedstocks, Machine, and Process Qualification team holds diverse expertise in areas including but not limited to microscopy, in situ metrology, and AM process developments, direct prior expertise related to powder metrology is lacking. This is reflected in the limited strength, impact, and rigor of presented and published works on AM feedstocks, machines, and process qualification. The resources dedicated to the effort—4.25 full-time equivalent staff, including 5 federal employees and 2 associates—appear high relative to relevant outputs. An emphasis on qualification, despite its inclusion in the project title, is also lacking in the team's backgrounds, outputs, and methods used. The addition of experts knowledgeable in powder rheology, the state of the art in powder testing and modeling techniques, and qualification methods for machines and processes that use powder feedstock would benefit the team and its work.

The Data Integration and Management for AM team would benefit from closer alignment with the needs of industry and the problems limiting measurement sciences. This team would also benefit from more direct integration with teams generating experimental data sets. Both this team and the Data-Driven Decision Support for AM team could be enhanced through additional team members or collaborations with experts, particularly industry practitioners in data science and AI. Upskilling current staff or the addition of experts in applied data science and AI is also warranted. As projects beginning in FY 2024 follow similar objectives and staff composition to past projects, opportunities and challenges associated with the AM Feedstocks, Machine, and Process Qualification, Data Integration and Management for AM, and Data-Driven Decision Support for AM projects also apply to the Fundamental Measurements for Metals AM, Advanced Informatics and Artificial Intelligence for AM, and Data-Driven Decision Support for AM projects.

Recommendation 3-3: The Measurement Science for Additive Manufacturing program should better align team member expertise with practical, industrial measurement science needs. This can be accomplished through upskilling in applied data science and artificial intelligence. Also, they should add experts with relevant skills, such as powder rheology, the state of the art in powder testing and modeling techniques, and qualification methods for machines and processes that use powder feedstock. Finally, more direct engagement with industry would greatly help.

BUDGET, FACILITIES, EQUIPMENT, AND HUMAN RESOURCES

Budget

From the information provided, it appears that the MSAM program budget is adequate for continuing the current level of productivity. It is realistic and sufficient to cover all the anticipated expenses of the research program. However, an increased budget would enable the team to more fully address their objectives and expand the reach of their work. This includes personnel costs, equipment, materials, travel, and any potential contingencies. The budgets for the projects in the MSAM program are shown in Figure 3-1.

Equipment and Facilities

The MSAM program has access to the necessary equipment and facilities required for its research, including specialized laboratory equipment, computational resources, software licenses, and dedicated research spaces. The work by the team during FY 2018–2023 was heavily focused on the metal laser powder-bed process using a commercial machine (an EOS M290/M270) and an in-house-developed system that is ground-breaking in terms of its ability to control the power input and to measure and predict in situ temperature, which are all important to the quality of the final produced part. The in-house system provides information that is very useful to better understand process variability and inconsistent powder-bed performance. However, the other equipment available to the team—such as the Optomec LENS MR7 and the ExOne Mlab—are under used. More effort needs to be directed to the use of other additive modalities. Efforts are needed to plan for the replacement of commercial equipment in a time frame that is consistent with what is happening in industry.

Project	FY 2024 Funds
Fundamental Measurements for Metals AM	$1.75 million
Metrology for AM Model Validation	$1.725 million
Advanced Machines, Monitoring, and Controls for AM	$1.837 million
Advanced Informatics and Artificial Intelligence for AM	$1.25 million
Data Management and Fusion for AM Industrialization	$1.25 million
Total FY24 Base Funds for MSAM Program:	**$7.812 million**

FIGURE 3-1 Fiscal year (FY) 2024 budget for the projects in the Measurement Science for Additive Manufacturing (MSAM) program.
NOTES: The projects in yellow fall under the Intelligent Systems Division. The projects in blue fall under the Systems Integration Division. AM, additive manufacturing.
SOURCE: Courtesy of NIST Engineering Laboratory.

Inconel 625 has been the main alloy studied so far; there is an indication of a pending report on Inconel 718 and CoCr alloys, but these were not discussed during the panel meeting. Studies on other widely used alloy types in the industry, such as Ti-6Al-4V, 316L, $AlSi_{10}Mg$, and F357, in addition to polymers, are needed to help the U.S. industry and the broader stakeholder community.

The panel was unable to fully assess the equipment needs for metrology and data integration modules (FY 2021–2023) based on the information provided during the meeting.

Defect detection is listed as a priority for work in FY 2024. The objective is to develop a new artifact for evaluating different algorithms for defect detection in AM parts using X-ray computed tomography. The panel suggests including other non-destructive testing methods such as ultrasound and thermography in this defect evaluation program (Duarte et al. 2021). These other non-destructive testing processes are more readily accessible to small- and medium-sized businesses.

Human Resources

As noted above, the MSAM team is a cross-disciplinary one with some individuals who are world-renowned and participate in or organize conferences to share the results of their research and participate in many standards panels. The inclusion of other AM processes, alloys, and non-destructive testing modalities may be a tough challenge given the budget and human resources available. The panel suggests working in collaboration with other government laboratories and agencies to access additional expertise without necessarily having to bring it all onto EL's staff.

EFFECTIVENESS OF DISSEMINATION EFFORTS

The MSAM research team has established collaborations with industry, academia, and institutions with relevant expertise. Staff members participate in ASTM, ASME, ISO, and ANSI panels, workshops, and committees and have contributed to more than 40 standards. There are active engagements with small businesses, large corporations, industry consortia, government agencies, and over a dozen universities. To ensure efforts have a significant, practical impact on the U.S. economy, further development of professional networks with industry, particularly beyond the defense industrial base, is necessary. Such engagement can provide access to additional resources (e.g., real data sets), knowledge (e.g., industry-specific qualification processes), and potential opportunities for broader impact.

As discussed above in "Assessment of Scientific Expertise," the research team's publication record in reputable journals, conferences, and NIST reports demonstrates their ability to disseminate research findings effectively. Figure 3-2 shows a plot of the publication rate of research products, including peer-reviewed literature publications, book chapters, conference papers, NIST reports, and data sets for each of the projects. The rate is defined as the number of research publications per full-time equivalent (FTE) per year. The number of FTEs includes staff with PhD, MS, and BS degrees. The five new projects for FY 2024 are too new to assess the number of publications that are under review or are in preparation. The seven projects that ended in FY 2023 all had publication rates greater than one per FTE per year. Four projects had publication rates greater than two per FTE per year. The panel's experience from managing research staff is that publication rates that are less than two per FTE per year are less than might be expected from staff who are dedicated to research full time.

Engagement with industry is a weakness of the MSAM program. There is an overreliance on literature publications as opposed to the direct transfer of knowledge to industry partners. The reliance on technical publications to transfer knowledge to industry may not be the optimal choice. Not all industries follow the peer-reviewed literature closely. Close direct engagement with industry appears to be lacking in this program. It follows that the program has a partial strategy and metrics for disseminating its research findings. Therefore, the projects only marginally meet expectations for dissemination strategy and metrics. One option to improve the visibility of NIST research to industry might be to maintain a mailing list of relevant industrial staff and use that list to make notifications of new publications. Another option would be to increase the number of NIST reports, especially for areas that are industry-relevant but less likely to result in peer-reviewed papers.

The MSAM program has an incomplete plan for ensuring the long-term accessibility and impact of its research outputs. This includes archiving data, making findings openly accessible, providing access to computer codes, and developing strategies for ongoing knowledge translation. Peer-reviewed papers could be made openly accessible, consistent with intellectual property rights. The project would benefit from developing and executing a plan to archive its research products and ensure they are readily available and accessible to stakeholders.

Recommendation 3-4: The Measurement Science for Additive Manufacturing program should explore other ways to disseminate the results of its work directly to industry. These could include mailing lists to inform industry stakeholders of new publications in a timely manner, producing more National Institute of Standards and Technology reports in areas that are industry-relevant but less likely to result in peer-reviewed papers, and making as many peer-reviewed papers openly accessible as possible.

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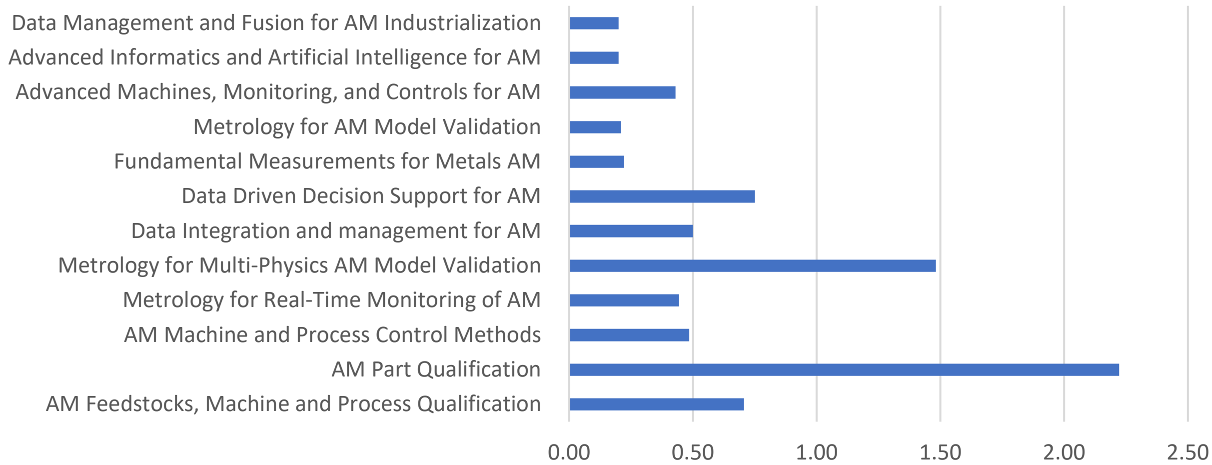

FIGURE 3-2 Publication rate of research publications per full-time equivalent per year for the projects in the Measurement Science for Additive Manufacturing program. The first five rows are projects that were launched in 2024 and are ongoing. The last seven rows are projects that ran from 2018–2023. The seven complete projects were measured over 3 years. The five new projects were measured over 1 year.
NOTE: AM, additive manufacturing.
SOURCE: Data courtesy of NIST Engineering Laboratory.

4
Advanced Manufacturing Goal: Measurement Science for Manufacturing Robotics Program

Domestic manufacturing is essential to U.S. national security and economic competitiveness. In March 2024, there were 570,000 manufacturing job openings, and 3.8 million new positions are expected by 2033 (DeLoitte 2024; NAM 2024). Robotic manufacturing addresses critical workforce shortages, especially in areas needing highly skilled, experienced workers. Robotics offers the potential to reduce the proportion of "dull, dirty, and dangerous" jobs, so that the remaining positions are safer, more interesting, and more rewarding to attract and retain new talent in the manufacturing sector.

The Measurement Science for Manufacturing Robotics (MSMR) program develops and deploys measurement science that advances manufacturing robotic system performance, collaboration, agility, autonomy, safety, and ease of implementation to enhance U.S. innovation and industrial competitiveness. The work of this program is designed to support the creation of better products, manufacturing processes, and, importantly, new and improved standards for manufacturing robotics. Emerging technologies such as artificial intelligence (AI), machine learning, autonomy, cognitive science, and human–robot interactions (HRIs) are already impacting the development of new robotic manufacturing capabilities. The MSMR program needs to maintain its high standard of technical leadership to keep pace with industry and other stakeholder needs, and to disseminate its contributions in a manner accessible to small- and medium-sized manufacturers that contribute a large fraction of U.S. production as well as the larger manufacturers.

The MSMR program is organized into the following eight projects:

- Grasping, Manipulation, and Contact Safety Performance of Robotic Systems
- Perception Performance of Robotic Systems
- Agility Performance of Robotic Systems
- Mobility Performance of Robotic Systems (Exosuits)
- Performance of Human–Robot Interaction
- Emergency Response Robots
- Embodied AI and Data Generation for Manufacturing Robotics
- Digital Twins and Emerging Technologies for Small-and-Medium Enterprise (SME) Work Cells

GENERAL OBSERVATIONS

MSMR has strong technical competence in measurement science as applied to agility, grasping and manipulation, mobility, exosuits, perception, HRI, and emergency response. Equipment and facilities are sufficient to meet the project objectives and are in some cases state of the art compared to leading universities and research institutions. The program's staff have strong representation and leadership in working groups at ASTM International and other standards-setting organizations. The experimental, theoretical, and data analytics results of the program's projects support technical leadership in the working groups. Information that supports standards is disseminated effectively to research communities through publications and presentations in leading refereed journals and conferences.

MSMR addresses the need in the external research community for the objective testing of competing technical solutions for manufacturing-relevant problems. The strongest example is the dissemination of Assembly Task Boards (ATBs). ATBs present manipulation challenges that go beyond the state of the art, commercially available technology and are used widely in competitions at leading international conferences, encouraging collaboration on multi-disciplinary teams.

The information MSMR presented to the panel was insufficient to assess the quality and strength of a strategic plan and technical roadmap on how (1) each task in the plan contributed directly to clearly defined goals, (2) integration with technologies and results from external sources, (3) gaps not addressed, and (4) mechanisms for engagement and transition to end users in industry.

There were also no clear metrics that quantify and track the success and impact of MSMR's work and whether its work is on target with its mission. Engineering Laboratory (EL) programs frequently reference benefits to SMEs without quantifying operational productivity, quality, or financial impacts, nor mechanisms for collecting and tracking the data. Such metrics have value in setting priorities, resource allocation, and accountability for results, and enhance credibility and engagement with industry and other stakeholders. Strategic planning and metrics are discussed in more detail in Chapter 7.

ASSESSMENT OF TECHNICAL PROGRAMS

Accomplishments

Grasping, Manipulation, and Contact Safety Performance of Robotic Systems

Most manufacturing manual labor requires the grasping and manipulation of mechanical objects such as raw materials, workpieces, tooling, and fixtures. End-of-arm tooling grippers enable the automation of many manufacturing processes, with leading suppliers offering a wide variety of gripper geometries and actuation mechanisms to meet the requirements of specific applications. The Grasping, Manipulation, and Contact Safety Performance of Robotic Systems project develops and standardizes performance metrics, test methods, and associated measurement tools that support the development of robotic systems that have human-like dexterity and force control characteristics.

Mechanical grippers are widely available based on mature technologies for rigid objects for a wide range of geometries. Data from leading gripper suppliers are limited to the specification of gripping force, actuation time, finger strength, and repeat accuracy, with no reference to standards or test methods used. This project continues to play an important supporting role in developing standards for performance metrics, test methods, and measurement tools for grasping and manipulation, addressing industry needs for robot system integrators and end users. Specific contributions include participation on the ASTM International subcommittee F45.05 on Grasping and Manipulation and technical publications for ASTM Working Groups WK83863 and 86189 covering grasp strength performance and measurement apparatus. Test protocols included pinching and wrapping types for small, medium, and large workpiece artifacts, with methods for calculating statistical confidence limits.

Compared to rigid body grippers, technologies supporting human-like dexterity are much less mature. Assembly tasks for rigid parts such as gears and threads require more precise control and touch than basic gripping. Tasks for assembling belt drives and wire harnesses are more challenging due to variations in their stiffness and changes in shape as the products move from their initial to final states. The research community benefits from unified sets of benchmark tasks and results for reliable and repeatable comparisons. Working through ASTM Working Groups WK87214 and WK82713, the EL staff working on this project has developed National Institute of Standards and Technology (NIST) ATBs. ATBs are supported by protocols for use, time-based comparisons to human performance, and support for competitions globally such as the Institute of Electrical and Electronics Engineers (IEEE) International Conference on Robotics and Automation Competitions in May 2024. Advancements in the manipulation of flexible materials such as textiles and ceramic composites will benefit the aerospace, personal protective equipment, and fashion segments.

A more recent initiative addresses the development of new safety standards for the impact on humans from power, force, and torque-limited (PFL) robots[1] that could induce pain, assisting in the development of International Organization for Standardization (ISO) Technical Specification 15066 and ISO Publicly Available Specification 5672:2023. Building on the EL tradition of innovation in measurement, the project staff has developed a soft pressure sensor that matches the biomedical response of the human forearm, using a linear change in capacitance with applied force.

Perception Performance of Robotic Systems

Using robotics in industrial applications frequently involves sensors and related data analysis to enable perception capabilities. The types of sensors (and ancillary devices like lighting) have a range of use cases and means of capturing and generating data. Equally important is how the data are analyzed and resolved to be used by robotic systems. This foundational capability set affects other topics like mobility, grasping and manipulation, and HRI, among others.

The project's five key areas of research emphasis address a range of topics and integrate well with adjacent projects like Grasping, Manipulation, and Contact Safety Performance of Robotic Systems and Performance of HRI. The first of the five, bin-picking, encompasses a deceptively broad array of perception issues and is of growing industry use and importance making it a reasonable use case on which to base project deliverables. Other areas—three-dimensional (3D) vision under variable lighting, resolving geometric features, estimating atypical part poses, and 3D vision selection criteria—all logically relate to and complement one another. This project has good evidence of engagement with industry through participation at relevant industry events like the Association for Advancing Automation (A3) Automate and The Vision Show, as well as co-hosting a workshop with ASTM's Committee E57 to uncover challenges and solutions related to 3D perception systems for robotics and to develop a roadmap of highest priority needed standards to work on most urgently. There is a clear focus on translating testing research into standards collaboratively with ASTM's subcommittee E57.23 leading to four new working groups. This resulted in the publication and adoption by industry of the ASTM E57 standard for point cloud data formatting.

Agility Performance of Robotic Systems

This project aims to develop measurement science to evaluate and ensure the agility of robotic systems. This includes metrics, test methods, information models, and planning approaches, validated in a combined virtual and real testing environment. This will enable manufacturers to reconfigure and re-task robots more quickly, making them more accessible to smaller organizations and increasing efficiency in larger ones.

A major accomplishment of this program is establishing the Agile Robotics for Industrial Automation Competition (ARIAC), which has been running since 2018. ARIAC is a yearly contest, involving over 50 competitors, that evaluates robots' adaptability, efficiency, and autonomy in performing tasks in a simulated manufacturing facility. The competition aids in the development of algorithms for real-world manufacturing, and EL uses the findings to establish standard metrics and test methods for future robotic agility. The participants in ARIAC have typically been students and postdoctoral researchers. In addition, the team members have been engaged in four IEEE standards working groups. The project team also presented a framework for agility performance evaluation that it is developing. The framework included elements of hardware, software, and communication reconfigurability (agility) that considered robot sensing, perception, reasoning, task representation, task planning, and execution.

[1] Power, force, and torque-limited robots were called "cobots" when first introduced. This term is now obsolete, replaced by safety definitions in ISO Standard 10218/R15.06.

Mobility Performance of Robotic Systems (Exosuits)

This project's research is focused on (1) the dynamic localization of autonomous guided vehicles (A-UGVs) and mobile manipulators operating with no human guidance, in relation to tooling and workpiece targets while considering both continuous and non-continuous motion and (2) developing metrics and test methods for evaluating the performance of exoskeletons for industrial applications. The work is leading edge and relevant to industry, as is the evaluation of localization as a function of uncertainty in workpiece location and other attributes, a common real-world experience. Incorporating additional sensor suites (e.g., light acuity and optical tracking) on top of industrially relevant components (e.g., Omron Autonomous Mobile Robot and Universal Robots manipulator) is a good way to facilitate broader test conditions and establish ground truth.

There is a strong rationale to support this project's research direction, related to wearables and international coordination with a reasonably wide segment of stakeholders, even if it is somewhat skewed to the academic side of things.

Performance of Human–Robot Interaction

Robots deployed in manufacturing and industrial environments tend to be prohibited from being in the immediate working area of their human operators. To increase production throughput dramatically, collaborative and more direct interactions between humans and robots are necessary to minimize process variation and enhance operational efficiencies. This project employs measurement science to assess and assure the usability, performance, and trustworthiness of HRIs in manufacturing environments. Target outputs will assist system integrators and manufacturer end users, especially in high-mix, low-volume operations.

This project's laboratory provides the user community with a glimpse of what peer-like interactions are possible between a robot and a human. The results will lead to future trust-based models and explorations into ethics. Project staff appear to reflect a solid engineering science knowledge base, with a great set of skills and understanding the current state of the art in human–machine interfaces.

This project's staff team is on par in conference and journal publications compared to peer laboratories, such as universities in the same field. The laboratory participates in and leads various Association for Computing Machinery (ACM) and IEEE entities to generate emerging HRI standards for use in industry. The project's facility contains state-of-the-art equipment and computational hardware that is on par with other research facilities and is adequate to achieve the stated research objectives. Besides robots, sensors, and commercially available augmented reality and virtual reality devices, the laboratory has a motion capture and rigid body tracking system to enable the initial exploration of collaborative interactions beyond existing techniques based on force and torque. All equipment as well as the facility are relevant and up to date.

Emergency Response Robots Project

Over the past few decades, robots have evolved into the tools of choice for first responders in extremely hazardous scenarios. This project employs the use of measurement science to evaluate the capabilities of autonomous and remotely operated robotic systems—ground, aerial, and aquatic—for emergency response applications. This project also examines the training and resultant proficiency of remote operators in a variety of emergency response applications.

This project has developed more than 50 test procedures with 25 of these procedures leading to ASTM standards. Recently, the laboratory has convened or participated in challenges involving quadruped platform mobility through various terrains and obstacles, which has led to additional standardized test procedures. For ground robotics, standards were published for terminology (e.g., definition of a ground robot), logistics, maneuver, terrain mobility, confined mobility with obstacles, dexterity, situational awareness, sensing, endurance, and radio communications. For aerial drones, a standard was published for endurance, with another standard currently in draft for remote operatory proficiency. Finally, for aquatic robots, various test methods are in draft form. Besides the numerous awards over the past decade, such as the Department of Homeland Security Secretary's Award for Excellence in Innovation, the project has supported more than $200 million in data-driven commercial procurements, which shows project impact by assisting in the user acquisition of such systems.

Embodied Artificial Intelligence and Data Generation for Manufacturing Robotics

The objective of this project is to facilitate the adoption of AI-based robotic approaches in practical manufacturing scenarios by creating test methods that target AI-enabled robotic systems, evaluating the performance of AI-enabled robotic systems, and creating manufacturing-relevant and AI-centric data sets. The technical idea is to provide manufacturers and integrators with a streamlined way of assessing the productive impact of AI systems, which NIST can provide through AI-specific productivity metrics and test methods.

The project developed an advanced six-degree-of-freedom sensor to support the use of PFL robots in high-accuracy applications. PFL robots face rigidity and accuracy challenges compared to traditional industrial robots. The sensor is novel using line features instead of point features to create a coordinate system. The project was presented at the IEEE 2023 International Conference on Automation Science and Engineering and received U.S. patent 10885368.

The Manufacturing Objects for Assembly Data Set (MOAD) effort is developing two-dimensional and 3D visual sensor data to be used in support of robot system solutions. The database provides high-resolution red-green-blue depth scans, physical properties, and geometric models of objects for easy incorporation into manipulation and planning software platforms. This effort demonstrates excellent collaboration with the Grasping, Manipulation, and Contact Safety Performance of Robotic Systems team.

Digital Twins and Emerging Technologies for Small-and-Medium Enterprise Work Cells

This project aims to identify automation technologies suitable for SMEs, develop tools to facilitate their integration, and address the need for robots to operate in unstructured environments. It will leverage emerging technologies like digital twins to ease the selection and installation of robotic systems, enhance operational robustness, and enable seamless integration of sensors and other tools. The digital twins will encompass software, models, prototype artifacts, test methods, metrics, and standards that facilitate the integration and evaluation of emerging technologies in SME environments. These outputs will use sensor-derived information about the workspace to address situations in which robots must perform tasks in less-structured surroundings. This program will also serve as a bridge for interactions with small manufacturers, systems integrators, the NIST Manufacturing Extension Partnership (MEP) centers, and other stakeholders to identify the major obstacles to greater adoption of robots and the ongoing needs of SMEs when using manufacturing robots.

One of the program's accomplishments was an extensive 2023 survey of SMEs querying their current levels of automation, providing insights into small manufacturing in the United States. In-depth analysis of the results of this survey is ongoing. All 51 MEPs were used as a mechanism to reach SMEs across the United States.

Opportunities and Challenges

Grasping, Manipulation, and Contact Safety Performance of Robotic Systems

MSMR is not aligned with ISO standards and A3 in the definition of the term "cobot." PFL robots were called "cobots" when first introduced. This term is now obsolete, replaced by safety definitions in ISO Standard 10218 and ANSI/RIA Standard R15.06, which defines an "industrial robot" as the arm plus controller, "industrial robot system" as robot plus end effector, and "industrial robot application" as robot system, workpiece, and ancillary equipment. The distinctions between industrial robots, systems, and applications are very important because each category has different entities responsible and accountable for safety.

Recommendation 4-1: The Measurement Science for Manufacturing Robotics Program should discontinue the use of the term "cobot" and align with International Organization for Standardization Standard 10218 and ANSI/RIA Standard R15.06.

Agility Performance of Robotic Systems

The project team could engage more with industry to ensure that the developed framework, metrics, and evaluation methods are industry-relevant. If possible, it is advisable to include more industrial participants (particularly SMEs) in the ARIAC event to ensure that it surfaces the challenges faced in industry. The results presented to the panel seemed a bit too academic. They did not seem to be very connected to the pressing industrial needs around rapid and easy re-tasking and reprogramming of robots. The tasks in ARIAC seemed to focus a lot more on the adaptability of robots rather than rapid re-tasking and reprogramming which, arguably, are more pressing needs for SMEs. The presented framework seemed to be very complex and academic. More could be done to simplify it so that it is easily digestible by industry (particularly SMEs).

Perception Performance of Robotic Systems

Vision-based human tracking systems are an industrially relevant and important technology. While mentioned briefly and with sparse detail in the read-ahead materials for the panel, it was not addressed within the scope of this project during the visit. Additionally, the project's understanding of challenges and solutions related to 3D perception systems for robotics and needed standards is dated, based on a workshop 5 years ago co-hosted with ASTM (Committee E57). Vision-based tracking systems are also relevant to HRIs and work on mobility and exoskeleton projects.

Recommendation 4-2: The Perception Performance of Robotic Systems project should develop an intentional work statement focused on vision-based tracking systems with clear connections into adjacent projects addressing human–robot interactions and mobility and exoskeleton projects.

Now 5 years removed from the referenced co-hosted workshop, it would be helpful to have a follow-up report or another workshop, possibly both, to share progress and revisit and revise directives as appropriate.

The Perception Performance of Robotic Systems project lacks measurement methods for cognition in the context of perception. Additional emphasis on the adoption and use of open-source perception tool sets and methods—including Robot Operating System (ROS) and Point Cloud Library, as well as relevant simulation capabilities like Gazebo—would complement the project team's skill set and body of work. It would also help connect NIST's academic capability with low-cost solutions available for cost-effective proliferation across SMEs. It would also be an opportunity to bolster EL's engagement with industry stakeholders (inclusive of technology providers and end users) by leveraging collaborative entities like the ROS-Industrial Consortium and the Advanced Robotics for Manufacturing Institute (ARM), because these entities and EL have a significant overlap in topics of interest.

Mobility Performance of Robotic Systems/Exosuits

Measurement science for exosuits would benefit from an expansion of the evaluation method scope to include relevant human factors and cognitive psychology implications, and such an expansion is advised.

The project's efforts to develop and integrate sophisticated model-based controls—including AI—seem ambitious and to reach beyond what is necessary to achieve the project's objectives.

Performance of Human–Robot Interaction

Exploring the transparency of the interactive behaviors to allow for a peer-like relationship between humans and robots would advance this project's work. Intuitive input and output modalities can be verbal (such as common natural language) or non-verbal (such as vision and hand gestures). This may lead to greater insights into human trust, and for the robot to recognize the physical and emotional limitations of the human and adapt accordingly for a given set of manufacturing tasks. A potential challenge could be the development of measurement science to determine human—or machine—cognitive abilities.

This project would benefit from exploring emerging human-centric cognitive and physical standards such as IEEE P7017, *Recommended Practice for Design-Centered Human–Robot Interaction and Governance*. The dissemination of data and models such as those in the NIST repository would be important for researchers employing AI and machine learning, and for potential future research activities and collaborations. If the laboratory accepts the challenges of exploring human cognition within HRI, it would need to obtain cognitive architecture capabilities as well as associated high-performance computational hardware.

Recommendation 4-3: The Performance of Human–Robot Interaction (HRI) project should explore emerging human-centric cognitive and physical standards such as Institute of Electrical and Electronics Engineers P7017, Recommended Practice for Design-Centered Human–Robot Interaction and Governance. The data and models from this project in the National Institute of Standards and Technology repository should be disseminated to researchers employing artificial intelligence and machine learning to help drive future research activities and collaborations. If this project explores human cognition within HRI, it should obtain cognitive architecture capabilities as well as associated high-performance computational hardware.

Emergency Response Robots

This project needs to explore new opportunities to avoid being out of touch with the state of the art in this area and stakeholder needs. The publications cited by EL to the panel are pre-2017. One possibility is to explore operators' cognitive abilities while using robotic technologies in emergency situations. Other research possibilities include advanced sensor payloads (e.g., chemical and biological sensors), computational capabilities (e.g., the use of advanced graphics processing unit architectures), and novel power techniques (e.g., lightweight batteries and "green" techniques such as solar).

The project is understaffed. If this is a NIST EL priority, additional personnel need to be hired to explore additional research opportunities. Due to the challenge of laboratory space, opportunities exist to design and develop a more agile and modular approach to obstacles, synthetic terrains, and layout representation.

Embodied Artificial Intelligence and Data Generation for Manufacturing Robots

Robotic systems that involve AI algorithms, training paradigms, and metrics are important topics to explore. These topics are largely absent from the list of publications given to the panel. Some projects lack roadmaps aligned with project objectives, showing the introduction and integration of emerging technologies, resulting in a scattershot approach with ineffective impact. Creating guidelines, standards, and other industry resources based on AI metrics will benefit from direct engagement with system integrators and end users.

Recommendation 4-4: The Embodied Artificial Intelligence (AI) and Data Generation for Manufacturing Robots project should develop and communicate clear roadmaps to achieve their stated research objectives that characterize robotic systems that involve AI algorithms, training paradigms, and metrics.

Digital Twins and Emerging Technologies for Small-and-Medium Enterprise Work Cells

During the panel meeting, the team presented a program on digital twins in manufacturing but did not have a presentation regarding this specific program aimed at robots and SME work cells. The program seems to have only a few accomplishments so far—that is, the 2023 survey of small and medium-sized manufacturers cited above. The program did not provide any information about the outcomes of the survey, even if it was preliminary. No publications, reports, or standards were cited as accomplishments from this program. It would be great to see more publications and output from the program. The program did not seem to have any team members who were familiar with the peculiar challenges of SMEs. A team member or consultant who is familiar with SMEs could be very valuable in ensuring that the program objectives and efforts are best suited to SMEs.

ASSESSMENT OF SCIENTIFIC EXPERTISE

Accomplishments

Grasping, Manipulation, and Contact Safety Performance of Robotic Systems

The EL staff in this project provides strong technical leadership and contributions to ASTM working groups, with supporting publications relevant to standards and test procedures. They are actively engaged with the research community, especially at major international conferences such as the IEEE International Conference on Robotics and Automation.

Perception Performance of Robotic Systems

Based on presentations and discussions during the tour as well as publications referenced in read-ahead materials, the scientific expertise of this team appears to be of high caliber. The team has an expert grasp of the technology domain, based on publications and presentations associated with external journals and events.

Agility Performance of Robotic Systems

The expertise of the staff has solid external recognition through the ARIAC competitions and contributions to IEEE standards working groups.

Mobility Performance of Robotic Systems/Exosuits

EL’s role in developing various aspects of the Exo Games, officially hosted by ASTM, gives them international recognition and adds credibility to their measurement science research. For both the mobile manipulator and A-UGV areas as well as wearables, the project’s strong involvement with ASTM is clear. Leadership in the development of ASTM F45 and F48 standards such as the F45.05 subcommittee on grasping and manipulation is evidence of their contributions. The specific role project personnel play and the extent of their contributions in setting standards is not clear, but this is not uncommon in collaborative standards development.

The early-career staff assigned to the mobile manipulator/A-UGV project appears well qualified and capable of working effectively toward achieving the defined project objectives. The exosuit team was enthusiastic and is successfully applying technical knowledge, even considering limitations in subject-matter expertise.

Performance of Human–Robot Interaction

This project's staff team is on par in conference and journal publications compared to peer laboratories, such as universities in the same field. The laboratory participates in and leads various ACM and IEEE entities to generate emerging HRI standards for use in industry.

Emergency Response Robots

Before 2017, the team developed 50 test procedures, of which 25 became ASTM standards. They enhanced their expertise through the design of challenges for competitions, with strong engagement with emergency responder communities.

Embodied Artificial Intelligence and Data Generation for Manufacturing Robotics

Staff expertise is strongest in the development of sensors and the generation of data sets of objects with relevance to robotic manufacturing, especially assembly.

Digital Twins and Emerging Technologies for Small-and-Medium Enterprise Work Cells

This is a new program, so it is too early to assess scientific expertise. But the panel did not want to even imply a criticism by omitting mention of it.

Opportunities and Challenges

Grasping, Manipulation, and Contact Safety Performance of Robotic Systems

The staff could improve limited engagement with robot industry suppliers, system integrators, and end users. This would improve their understanding of improvement opportunities on the factory floor level. The staff expressed a need to better understand SME needs.

Perception Performance of Robotic Systems

The project staff's understanding of challenges and solutions related to 3D perception systems for robotics and needed standards is dated, based on a workshop 5 years ago co-hosted with ASTM (Committee E57).

Agility Performance of Robotic Systems

The staff are too academically focused and need more industry engagement to enhance the relevance of their work.

Mobility Performance of Robotic Systems/Exosuits

This project has had strong ties with ASTM, resulting in several ASTM F45 and F48 standards. However, one staff member, recently named an ASTM Fellow specifically for his contributions, has since retired from NIST, so the future strength of the relationship with ASTM is in question.

It was difficult to determine the make-up of the full team supporting these projects and how many experienced staff are in place to lead and support technical work alongside early-career researchers from the information provided. Also, due to a recent retirement, there is ambiguity concerning the current team's expertise because the retired researcher brought world-class expertise to the team. Of those researchers with whom the panel members interacted, the exosuit research team seems to lack an individual with a substantial background in human factors or ergonomics, and there was no indication of a plan to address this. Possibilities to address this expertise gap include collaborating with other entities or soliciting a visiting university researcher with the requisite background expertise.

Performance of Human–Robot Interaction

The project team would benefit from the inclusion of subject-matter experts in cognitive, emotional, and physiological sciences. This may lead to opportunities to explore the expansion of the workforce to include participants who are cognitively or physically challenged.

Emergency Response Robots

Contributions to this field post-2017 were not presented making it impossible to judge the current expertise of the staff.

Embodied Artificial Intelligence and Data Generation for Manufacturing Robotics

The level of technical competence is inconsistent and not always at the high standard expected from EL. In some groups, the number of contributions cited in refereed journals and conferences has been thin over the past 5 years. For example, in the publication on the EL-developed six-degree-of-freedom sensor, no quantitative data were presented on the target measurement accuracy for the sensor, how it compares with sensors commercially available to system integrators and end users, or the results achieved in laboratory testing. No information was presented on the steps required to transition the sensor to system integrators and end users interested in high-accuracy PFL robot applications. No data were presented to assess the stated objective of improving PFL robot performance in high-accuracy manufacturing applications. The absence of quantitative data is a concern, below the standards of other work in the MSMR program. The team would benefit from using the Perception Performance of Robotic Systems project as a model for technical standards. Stronger cross-team mentoring would help to raise technical competencies and contributions to the consistent high-level historically expected of the MSMR program.

Emerging AI, cognitive science, and HRI technologies will have broad impacts across all project areas. If EL is not up to speed in these areas, it risks losing relevance to industry. Expertise relevant to planning and executing the AI components of this project needs to be strengthened. Especially for projects where emerging technologies are essential components, the EL MSMR teams will need to include members with relevant academic training or research experience. Examples include reinforcement learning, generative and autonomous AI, cognitive science, and ergonomics.

Recommendation 4-5: The Measurement Science for Manufacturing Robotics Program (MSMR) should partner with universities and other research institutions with expertise in the rapidly advancing technologies relevant to its work, such as artificial intelligence, cognitive science, and human-robot interaction technologies. This would help MSMR to maintain its relevance to, and maximize its impact on, industry and U.S. competitiveness.

The MSMR program is represented externally by highly respected technical leaders who may be nearing or post-retirement. Strong contingency planning is needed, including focused recruiting, training, and retaining of staff in emerging and rapidly developing technology areas.

Digital Twins and Emerging Technologies for Small-and-Medium Enterprise Work Cells

This is a new program, and it is too early to assess it.

FACILITIES AND EQUIPMENT

Facilities

Perception Performance of Robotic Systems

This project uses a recently constructed controlled laboratory environment inside of a larger high-bay structure testing laboratory space. While somewhat confined, it appears sufficient and houses a variety of up-to-date relevant equipment including metrology equipment and PFL manipulators incorporated in the bin-picking testbed.

Adding equipment and a dedicated space in the laboratory for human tracking systems capabilities is suggested. As referenced in the section "Assessment of Technical Programs," this is an important industrial relevant technology, and this capability would be especially valuable to the Mobility Performance of Robotic Systems project, based on its physical and topical proximities. Additional collaboration with other project laboratories to share robot manipulator resources if and as needed would also be beneficial.

Mobility Performance of Robotic Systems/Exosuits

Both the A-UGV/mobile manipulator and exosuit teams appear to be successfully accomplishing major portions of the project's stated objectives, despite facility limitations. The new A-UGV high-fidelity optical tracking system for reliable ground truth is an indicator of an adequate non-labor budget. A variety of active and passive exosuit measurement devices have also been obtained and used in test method development.

Exosuit facilities appear make-shift, being in the back corner of a high bay used for testing structures with inconsistent environmental control and do not lead to a perception of world-class work.

The mobile manipulator facilities, while apparently adequate for currently defined work, appear make-shift and do not give world-class perception. One aspect lacking is the ability to emulate the potential variety of environmental conditions related to mobile manipulation use cases, especially in terms of lighting and other visibility conditions.

Equipment

Performance of Human–Robot Interaction

The project's facility contains state-of-the-art equipment and computational hardware that is on par with other research facilities and is adequate to achieve the stated research objectives. Besides robots, sensors, and commercially available augmented reality and virtual reality devices, the laboratory has a motion capture and rigid body tracking system to enable the initial exploration of collaborative interactions beyond existing techniques based on force and torque. All equipment as well as the facility are relevant and up to date.

EFFECTIVENESS OF DISSEMINATION EFFORTS

Accomplishments

Grasping, Manipulation, and Contact Safety Performance of Robotic Systems

There are two primary dissemination mechanisms. The first mechanism is active contributions to ASTM Working Groups in Committee F45 on Robotics, Automation, and Autonomous Systems, eventually leading to industry standards. Team members also present new standards and supporting technologies at major industry events such as A3 Automate. The second mechanism is the development of ATBs that are used by research teams worldwide and leading conferences.

Perception Performance of Robotic Systems

Dissemination of this group's work is through participation in industry events such as A3 Automate and The Vision Show and co-hosting ASTM Committee E57: 3D Imaging Systems workshops and meetings. Dissemination is also accomplished through the development of the technical basis for new standards in ASTM Committee E57. For example, a new standard for point cloud data formatting has been published.

Agility Performance of Robotic Systems

Dissemination mechanisms include contributions to ARIAC and engagement with IEEE standards working groups. ARIAC participants are mainly students and post-doctoral researchers.

Mobility Performance of Robotic Systems/Exosuits

The International Exo Games and participation in ASTM Committee F48 on Exoskeletons and Exosuits are the primary means of dissemination and validation of the 10 defined testing methods thus far. Project results and test methods for mobile robots and mobile manipulators are disseminated through new standards in ASTM Committee F45 on Robotics, Automation, and Autonomous Systems.

Embodied Artificial Intelligence and Data Generation for Manufacturing Robotics

The principal dissemination mechanism is through the NIST MOAD data set. One component of this project uses the NIST ATBs developed by the Grasping, Manipulation, and Contact Safety Performance team.

Digital Twins and Emerging Technologies for Small-and-Medium Enterprise Work Cells

The MOAD data sets provide an effective mechanism for dissemination to support advanced robotic manufacturing research and product development, as part of the larger ATB initiative. The NIST MOAD ATB Dataset v1 was released in January 2024. The ATBCOMP data set was released to support the 2024 IEEE International Conference on Robotics and Automation competition.

Emergency Response Robots

Participation in ASTM Committee E54.09 on Response Robots is the primary means of dissemination of test methods of response robots.

Opportunities and Challenges

Grasping, Manipulation, and Contact Safety Performance of Robotic Systems

The dissemination of standards information is largely limited to ASTM working groups and presentations at annual events such as the annual A3 Automate Show. Beyond these venues, there is little awareness of this MSMR work, especially among robot system integrators and subject-matter experts. Furthermore, the use of ATBs is largely limited to the research community, with limited evidence of industry impact or use. More broadly, MSMR staff expressed a need for a better understanding of real-world requirements and technology gaps on the factory floor. Expanded engagement with manufacturing innovation institutes (MIIs)—particularly the ARM Institute (Advanced Robotics for Manufacturing),[2]

[2] For more information, see the ARM Institute website at https://arminstitute.org, accessed December 11, 2024.

MxD (Manufacturing x Digital),[3] and CESMII (the Smart Manufacturing Institute)[4]—would aid in the dissemination of research results and also garner feedback about what is needed by stakeholders. This could also foster a shared awareness of technical roadmaps between EL and MIIs.

Agility Performance of Robotic Systems

No information was presented about any direct engagement with industry robot suppliers, integrators, or end users. If there is not any, this is not only a significant lack of dissemination, but potentially a blind spot for this project.

Mobility Performance of Robotic Systems/Exosuits

The exosuits team has collectively published seven external journal papers, articles, or conference papers during the assessment period and has issued seven papers to internal NIST publications, although the internal papers' impact is unclear. More engagement with and presentations at industry-focused events such as A3 Automate and ARM is advisable. Publication of their work on NIST's domain website is passive; additional dissemination paths such as social media marketing via LinkedIn, lunch-and-learn style webinars, and the like could be valuable dissemination modes.

Performance of Human–Robot Interaction

More engagement with MEPs through more frequent or substantial leveraging of the MEP-Assisted Technology and Technical Resource program could help with dissemination to SMEs, broadening and deepening impact. The focus areas of this project are highly relevant to manufacturers looking to implement automation to help them with high-mix, low-volume applications.

Emergency Response Robots

No information was presented on dissemination post-2017. This, itself, is a weakness.

Embodied AI and Data Generation for Manufacturing Robotics

No direct engagement with industry robot suppliers, integrators, or end users was presented.

Recommendation 4-6: All projects in the Measurement Science for Manufacturing Robotics Program should expand their engagement with manufacturing innovation institutes to bolster dissemination and engagement with large and small system integrators and end users.

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[3] For more information, see the MxD website at https://www.mxdusa.org, accessed December 11, 2024.

[4] For more information, see the CESMII website at https://www.cesmii.org, accessed December 11, 2024.

5
Advanced Manufacturing Goal: Advanced Manufacturing Data Infrastructure and Analytics Program

Throughout the panel meeting, several overarching observations were noted. First and foremost, a clear takeaway was that the National Institute of Standards and Technology (NIST) Engineering Laboratory (EL) staff in the Advanced Manufacturing Data Infrastructure and Analytics (AMDIA) Program are highly skilled, motivated, and passionate about their work and organization, with particular emphasis on the early-career individuals who presented a spirit of high morale and satisfaction in their work and career choice. On the other hand, there appears to be a disconnect between the EL staff's perception of the impact of their work on industry and the level of their engagement with industry, and this panel's assessment, as guided by the provided materials. Based on the information provided to it, the panel does not believe that they are as effective as they believe they are.

Due to lean resourcing—in supply chain work in particular—it is not evident that the NIST EL mission to promote "the goal of promoting U.S. innovation and competitiveness by advancing measurement science, standards, and technology" (NIST 2021) can be achieved. The projects presented and assessed in the AMDIA Program showed little coordination between them and appeared to be a set of disparate research studies. Greater collaboration between projects could further enhance the outcomes and maximize the use of limited resources across the portfolio of this program's work.

Recommendation 5-1: The Engineering Laboratory should increase internal collaboration across different programs within it to leverage existing expertise and resources to maximum effect.

Finally, much of the work performed by EL appears to be basic science with a technology readiness level (TRL) of 1–4. While it is not within the purview of this panel to address the type of work that EL does, the question remains whether the low TRL level work aligns with the stated mission of the NIST EL and overall NIST mandate.

ASSESSMENT OF TECHNICAL PROGRAMS

Four AMDIA topics were presented by EL for assessment. These are the following:

- Circular economy—comprising the Circular Economy Product Design and Digital Thread Project and the Circular Economy Closed Loop Recovery Project;
- Biomanufacturing—comprising the Data Infrastructure for Biomanufacturing Process Control Project and the Advanced Data Exchange Standards for the Biomanufacturing Supply Chain Project;
- Supply Chain Traceability—comprising the Enabling and Using Traceability and Data Linking for Sustainable and Efficient Supply Chains Project; and

- The Augmented Intelligence for Manufacturing Systems Project.

When assessing the projects presented, the panel considered several factors: the objectives of the work, the market and industry relevance and need, the merit of the work, dissemination plans, and the potential impact of the work.

Accomplishments

Circular Economy Product Design and Digital Thread Project and the Circular Economy Closed Loop Recovery Project

The objective of circular economy work is to provide measurement science standards and tools that will enable the development of product design, manufacturing, and life-cycle assessment and information to support circular economy implementations. The effort by NIST EL in the past several years in the circular economy area is in line with NIST's objectives and role in addressing emerging areas in the manufacturing area.

The project team's participation in the new International Organization for Standardization (ISO) circular economy standards is good. The circular economy is an area where industry can benefit from common standards and definitions. The team has also made several efforts to connect and participate in industry forums to better understand industry needs. Other projects for the team are ongoing and promise to address other important industry needs. The focus on life-cycle data and design is an important area to address. Other examples are digital twins for sustainable manufacturing, improvements of system standards for design and manufacturing, and closed-loop recovery of manufactured products.

Data Infrastructure for Biomanufacturing Process Control Project and the Advanced Data Exchange Standards for the Biomanufacturing Supply Chain Project

The importance of developing standardized data interfaces and best practices to enable consistent and reliable data access across industries has been highlighted by national initiatives and policies. There is an ever-growing need for interoperable, agile, and cost-effective data solutions, especially as biomanufacturing becomes increasingly automated and data-driven. Currently, many companies in this sector use customized, frequently disjointed data management systems that impede effective integration and interoperability. These businesses stand to gain a great deal from an advanced data infrastructure, which will supply standardized, interoperable data systems that will increase overall efficiency and streamline procedures.

These projects aim to conduct measurement science that enables U.S. biomanufacturers to digitally connect supply chain systems more efficiently. They also seek to improve the capabilities of biomanufacturers to access data via the development of software tools, architectures, data frameworks, and various standards.

These projects have successfully created some of the standards and technologies required for the biomanufacturing sector to improve their data automation infrastructures. Other notable achievements include delivering the draft National Institute for Innovation in Manufacturing Biopharmaceuticals (NIIMBL) Core ontology, integrating with the National Aeronautics and Space Administration's Quantity and Unit ontology, and releasing the Open Applications Group Integration Specification Metadata and Dataset Metadata standards. The NIST Score Tool 3.0 has allowed the more effective exchange of data and interoperability within industry. Through the creation of tools such as the score tool and ontology-based data standards, these projects provide a generally applicable approach to data management that overcomes the drawbacks of conventional, compartmentalized techniques. In addition, the focus of this work on the real-time release of data, continuous manufacturing, and digital transformation is in line with industry trends toward automation and data-driven decision-making. The standardized interfaces created by this project may help the biomanufacturers to integrate discrete complicated supply chain data sets more efficiently. As a result, there may be less chance of yield loss in production processes.

Enabling and Using Traceability and Data Linking for Sustainable and Efficient Supply Chains Project

There is a great market need for supply chain traceability in industrial sectors such as aerospace and electronics manufacturing, food preparation, agriculture, and pharmaceuticals. Many industries have dealt with this problem for several decades and have created in-house solutions (e.g., aerospace and defense) to benefit their particular needs. Traceability allows material provenance and authenticity to be assured, mitigates counterfeit components, enables knowledge creation from the relationship between performance and history, and enables continuous feedback and improvement of the production life cycle.

The objectives of this NIST EL project on supply chain traceability are to create a robust traceability model that supports standards and tools that use consistent semantics and enable the sharing and integration of traceability data for insight across value chains with little effort.

A traceability model has been created that tracks grain processes from the origin to the customer, which builds upon a prior model for grain traceability. Because this project has been active for less than 1 year, continued work focused on testing, validating, and demonstrating the traceability model to non-agricultural use cases—such as circular economy, bio-manufacturing, or pharmaceuticals—is ongoing. Furthermore, the project is seeking to incorporate elements of the models into standards beyond agriculture.

The potential impact of this work resides in the ability of the supply chain traceability model to address industry needs and to fill current gaps so that it may be adopted in industry. Hence, a review of current industry best practices and industry gaps in supply chain traceability is needed to ensure that the model is addressing industry-relevant questions.

Augmented Intelligence for Manufacturing Systems Project

This project addresses a critical market need by tackling the issue of unplanned downtime in machine tools, which can lead to substantial industry losses. By emphasizing on-machine measurement and diagnostics, the project aims to optimize production and prevent the creation of defective parts. The initiative is well aligned with national priorities and policies, underscoring the necessity of enhanced health monitoring and control within the industry.

The primary objective of this project is to advance measurement science through the integration of sensor technologies and augmented intelligence within manufacturing systems. It aims to enhance manufacturing capabilities across various industry sectors, and it focuses on the following four areas: linear axis monitoring, spindle and cutting force monitoring, thermal drift monitoring, and semiconductor manufacturing. These efforts are designed to significantly improve manufacturing efficiency and precision.

The research team has made commendable efforts to connect its work with various industries, including aerospace, by collaborating with major companies like Boeing and Rolls Royce. International collaborations have also been initiated (e.g., with Fraunhofer and several European universities), broadening the scope and impact of the research. The project has facilitated technology and knowledge transfer through partnerships with manufacturers, promoting further collaboration and innovation in the field.

A significant accomplishment is the development of a portable system for monitoring linear axis positioning, which has led to the issuance of a U.S. patent and collaboration with an industry supplier to Rolls Royce for commercialization.

Challenges and Opportunities

Before addressing challenges and opportunities particular to specific work, some challenges apply to the AMDIA Program in general. There appears to be a disconnect between the work done by EL and the applicability of the outcomes of EL's work to the challenges and needs of industry. It is not clear that the measurement science advanced by EL is useful in addressing industry's needs. The projects under the AMDIA Program did not clearly define a problem statement coupled with industry needs. While such problem statements may exist, they were not evident in any of the information provided to the panel, written or verbal. Furthermore, the panel felt that the deliverables (e.g., standards, journal articles, workshops, and presentations) were not well stated, and possibly not known by the staff performing the work.

It is not evident that the current framework of the research plan enables the successful development of a data infrastructure for manufacturing and analytics. A focus on the standardization of data formats would be of interest so that data infrastructure across a manufacturing data stream could be enabled; such an infrastructure is a currently key lack in manufacturing practices. There was little or no discussion on data formatting for data infrastructure for a circular economy or digital twin, which enables interoperability, a worthy goal that has been articulated.

Finally, there do not appear to be detailed schedules with specified deliverables that would make it possible to hold staff accountable for outcomes. It appears that work is evaluated internally in 3- or 5-year cycles, promoting a culture lacking a sense of urgency. It is advised that each project have a clearly defined schedule with milestone deliverables that are reviewed internally annually.

Given the above concerns related to the lack of problem statements, schedules, accountability, and connecting work to industry needs, it is felt that it would be beneficial for EL to put forth a strategy that defines project priorities and how the project outcomes will address industry needs. Furthermore, specific metrics need to be defined and implemented that assess the impact of the performed work as it relates to improving U.S. competitiveness in manufacturing.

An overarching opportunity is to create a plan to transition the results of measurement science to industry and other stakeholders for each of the projects, thereby ensuring the relevance of the work performed and its alignment with industry needs that promote the manufacturing competitiveness of the United States.

Recommendation 5-2: The Engineering Laboratory should assess the obstacles in current industrial practices preventing the advancement of a data infrastructure that will improve productivity, resiliency, and sustainability for manufacturing operations and supply chains, and identify targeted research programs to overcome these obstacles.

Recommendation 5-3: The Engineering Laboratory should create yearly a prioritized list of industry challenges and develop corresponding National Institute of Standards and Technology problem statements that align with those industrial needs. The list and problem statements should specify goals and include a detailed schedule and specify the deliverables that are to be disseminated. All of this should be used to obtain the resources—both people and funding—to achieve the goals in the problem statements.

Circular Economy Product Design and Digital Thread Project and the Circular Economy Closed Loop Recovery Project

It is not clear that an effective analysis of industry needs has been done to identify obstacles and develop a long-term plan to address those. There is a need to focus on areas of high impact that are compatible with the NIST mission. There are also significant efforts in the national and international arenas where strong collaboration between NIST and those efforts can optimize and extend NIST's impact in this area. Partnerships and participation in existing forums and consortiums can ensure a better understanding of industry needs and integration with related efforts.

Examples of opportunities for collaborations include existing established organizations such as the REMADE Institute with its annual roadmap assessment of industry needs and, on the international front, the World Business Council for Sustainable Development efforts in circular economy. It is advised that a clear needs assessment be developed along with a timeline to address those needs.

Recommendation 5-4: The Engineering Laboratory (EL) should conduct a clear needs assessment to understand industry's needs and how EL can best address them, integrating its efforts into the broader efforts under way in industry. A timeline to address those needs, reflecting the speed at which things move in industry, should also be developed.

There is a clear need for standardization of product life-cycle assessment and data as well as for circular and end-of-life processes. It is difficult to assess the strategic focus and potential impact of the team's work based on the information provided on work in the area of life-cycle data and design. While certain life-cycle data exist, other circular and end-of-life processes need a unified data approach to support broad implementations of the circular economy. A unified data approach is of interest across industries to allow them to generate the data needed to develop a full life-cycle assessment of engineering products.

Data Infrastructure for Biomanufacturing Process Control Project and the Advanced Data Exchange Standards for the Biomanufacturing Supply Chain Project

The general challenges to establishing data exchange standards are rooted in the complexity of biopharmaceutical processes and the need to integrate an automated supply-chain data stream. It is stated that the industry uses hybrid mechanistic and data-driven process control models to achieve an elevated level of automation and lowered risk of yield loss. One of the critical approaches this project took to tackle the problem is creating an open-source life-cycle management tool for data exchange standards, named Score. This tool offers a data repository and a suite of functionalities that enable standards developers to create, publish, and maintain data exchange standards with higher precision, quality, and productivity. The Score tool was published publicly on GitHub in fiscal year (FY) 2020 and underwent significant development updates in 2023. It was stated that it has been used in production by the Open Application Group standards organization and several major manufacturing enterprises. However, given the lack of publicly available evidence, it is unclear how industrial partners use the tool and how deeply the tool is involved in industrial value-creating processes. Instead of focusing on continuing work on creating and improving tools and standards, it would be beneficial to both the project, and EL as an organization, to work with industrial partners to understand the added value delivered by the tools and standards resulting from the project's work.

Enabling and Using Traceability and Data Linking for Sustainable and Efficient Supply Chains Project

The impact of the current work appears to be limited to those in the agricultural community who are inclined to adopt the supply-chain traceability model produced in this work. This project is in the nascent stages of development and the fidelity of the model has not been validated beyond agricultural data. Additionally, the model adoption from agricultural stakeholders has not been evaluated. The ever-present challenges in obtaining real data exist and point to the need for increased collaborations with stakeholders of different industries.

It would be useful to understand the nature of the industrial state of the art. That is, how supply-chain traceability is currently addressed in different industries and how this project could benefit those industries that are already implementing their homegrown supply-chain traceability regimes and are unlikely to shift their decades-old practices for the benefit of conforming to industry semantics. The particular application of agricultural grain supply-chain traceability is important; however, measures of anticipated adoption by agricultural stakeholders have not been provided.

There is a significant opportunity to create a widespread industry-agnostic model that is supported by manufacturing sector agencies or organizations ensuring material provenance and manufacturing authenticity.

Augmented Intelligence for Manufacturing Systems Project

While this project aligns with industry challenges, the current efforts are somewhat basic. Modern commercial manufacturing and cutting tools already offer advanced health monitoring solutions with sophisticated sensor technologies. There is a notable gap in the lack of benchmarking against commercially available options, which could provide a clearer understanding of its competitive edge and areas for improvement.

This project would benefit from advancing its research to higher TRLs by incorporating more sophisticated sensor technologies that align with current industry advancements. This progression is essential to ensure the project's relevance and competitiveness in the rapidly evolving manufacturing landscape.

Recognizing that NIST is the coordinating body for the Manufacturing USA institutes, a much stronger connection with industry is necessary. Strong collaborations with other established consortia and institutes are also advised to achieve a larger impact across industry. This goal can only be accomplished with proper strategic planning, appropriate staffing and staff assignments, and a clear timeline.

> **Recommendation 5-5: The Augmented Intelligence for Manufacturing Systems Project should develop strong collaborations with established industry consortia and institutes such as those comprised under Manufacturing USA.**

ASSESSMENT OF SCIENTIFIC EXPERTISE

Accomplishments

The EL staff contributing to the reviewed projects have strong educational backgrounds and are highly qualified for their stated work objectives. Among the staff, accomplishments include several fellows of the American Association for the Advancement of Science and the Society of Manufacturing Engineers and several awardees of the Department of Commerce Bronze Medal. Additional awards include the Society of Manufacturing Engineers Outstanding Young Engineer Award, the American Society of Mechanical Engineers (ASME) Best Paper Award, and the ASTM[1] E60 Award of Special Service. The staff has been instrumental in facilitating many important outcomes including but not limited to the NIST/ASTM *Report on Standards Needs for Circular Economy*, ISO standards on circular economy, ASTM standards for sustainable manufacturing, release of a supply chain ontology, the NIIMBL Draft Core ontology covering end-to-end biopharmaceutical processes, and a new ASME standard for linear axis performance. Besides facilitating standards and releasing ontology, the staff has a steady presence in conferences and prolifically publishes conference articles. Many, but not all, the staff actively publish in peer-reviewed journals. However, the outcomes of the projects are not particularly uniform or coherent. More published activity appears to emanate from the circular economy group. This is possibly due to disproportionate resourcing among the goals and projects.

Opportunities and Challenges

Overall, a greater staff understanding of the connection between the relevance of their work and industry's needs would be beneficial. Such an understanding was not uniformly demonstrated.

World-class expertise in manufacturing and data analytics was not demonstrated, because the research performed (or planned to be performed in the case of the digital twin) is behind the current industrial curve. Several projects appeared to be under-resourced, which further hinders industry leadership in these areas. For example, only one staff member is working on the Enabling and Using Traceability and Data Linking for Sustainable and Efficient Supply Chains Project and only two staff

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[1] ASTM International, formerly known as the American Society for Testing and Materials.

members are working on the Augmented Intelligence for Manufacturing Systems Project. More staffing and resources have been provided for the projects related to the circular economy and biomanufacturing, in a likely shift due to the shifting strategic direction of NIST. The thinly resourced projects appeared to be incomplete, with the Enabling and Using Traceability and Data Linking for Sustainable and Efficient Supply Chains Project stalled at grain traceability in agriculture, where broader industrial applicability has not been demonstrated, and the Augmented Intelligence for Manufacturing Systems Project appears to be paused due to lack of investment or industry acceptance or support.

The biomanufacturing projects, despite their more generous resourcing, have produced a relatively lean number of peer-reviewed journal articles for the size of the team and length of the projects, and hence the opportunity lies in greater dissemination. The circular economy projects, while demonstrating several outcomes with respect to the number of peer-reviewed journal articles, seemed to be disconnected from how industry would apply such standards or implement the results from their work.

BUDGET, FACILITIES, EQUIPMENT, AND HUMAN RESOURCES

Budget

The Advanced Manufacturing Goal budget has decreased notably since FY 2022. This is due to a NIST reorganization in which three EL groups were moved to the Communications Technology Laboratory. Between FY 2018 and FY 2022, the budget was relatively flat, but these budget levels have not been adjusted for inflation. This likely means that the Advanced Manufacturing Goal has had less money to work with every year. The panel is concerned about there being adequate budgetary resources for EL to meet the needs in this goal area.

Facilities and Equipment

The AMDIA projects presented and assessed did not require the use of experimental research facilities except for computational resources and off-the-shelf sensors such as accelerometers. The panel did not visit the computing laboratories or hear of deficiencies therein, and it is presumed that the EL computing facilities and the equipment available to the research staff are adequate.

Human Resources

Although the panel meeting coincided with a work onsite day, the parking lot was largely empty and many buildings lacked a bustling and collaborative sense of activity, giving the impression that many employees continue to work from home. The panel is concerned about the effects of too much remote work on mentorship, apprenticeship, collaboration, and innovation. Attention needs to be paid to the balance of remote and onsite work to provide staff with the flexibility they desire, and that is proving critical to attracting and retaining top-level talent while also ensuring adequate opportunities for the mentorship of junior staff and postdocs and maximizing opportunities for collaboration to increase the efficiency of the program's projects. This could significantly improve many metrics such as collaborative publications, possibly returning them to pre-COVID-19 numbers. The panel recognizes that this is a large issue and a matter of larger federal policy. As such, the panel understands that they cannot readily propose a single or simple solution.

Opportunities exist regarding initiating a mechanism for continuous upskilling so that the staff's skills evolve at the pace of evolving technology. Finally, a common theme addressed by the EL staff was the inability to hire new talent, partially due to a lack of new funding.

EFFECTIVENESS OF DISSEMINATION EFFORTS

The dissemination of work varied by project and the length of time that each project has been under way. For example, the staff of the circular economy projects, which have been active for a few years, have participated in the ISO committee working on new standards in this area. Notably, one senior staff member working in circular economy and sustainability has authored or co-authored 11 peer-reviewed journal articles, 14 conference papers, and 3 NIST reports in the past 3 years. While this appears to be the most prolific researcher in the projects under review, colleagues in the same area are also actively participating in conferences and journal publications. On the other hand, dissemination of results from the Advanced Data Exchange Standards for the Biomanufacturing Supply Chain Project is relatively lean (e.g., one peer-reviewed journal publication in the past 5 years and nothing published in the past 2 years), which can be attributed to the shorter research period and lower staffing resources devoted to the project in comparison to other projects. The dissemination efforts of the other two projects reviewed fell between the two example cases mentioned.

The level of dissemination is in line with a university research group in similar areas. Given the national role of NIST and its ability to make a high-level impact, the dissemination level and impact were expected to be much higher. In addition, the reach to industry and business was limited.

Circular Economy Product Design and Digital Thread Project and the Circular Economy Closed Loop Recovery Project

These projects plan to share their findings through publications and share both findings and best practices through participating in relevant forums and conferences. The team also participates in standards organizations such as ISO and ASTM to develop standards in the circular economy area. The team’s strong participation in the ISO and ASTM standardization efforts may help to address many industrial implementation challenges. The design for the circularity project also can lead to useful findings with a focus on life-cycle data and measurement science.

While producing a respectable number of peer-reviewed journal articles, the project staff seemed to be disconnected from how industry would apply such standards or implement the results from their work, likely hampering the effectiveness of their work and the dissemination of the results.

Data Infrastructure for Biomanufacturing Process Control Project and the Advanced Data Exchange Standards for the Biomanufacturing Supply Chain Project

These projects plan to share their findings and aid in the dissemination of software tools, best practices, and standards by partnering with organizations like NIIMBL and the Industrial Ontologies Foundry. It also intends to make established ontologies and data management tools widely accessible by publishing toolkits on open-source platforms.

Despite their more generous resourcing compared to other projects, these projects have produced a relatively lean number of peer-reviewed journal articles for the size of the team and length of the project. There is an opportunity for greater dissemination.

Enabling and Using Traceability and Data Linking for Sustainable and Efficient Supply Chains Project

Interactions with EL staff during the meeting left the impression that the current dissemination plans of this project appear to be limited to dissemination to the agriculture community through agricultural publications and standards related to goods movement (not including processing or manufacturing steps). If disseminated more broadly, other non-agricultural industrial sectors may find value in the project results and potentially find ways to leverage the overall framework for their needs.

Augmented Intelligence for Manufacturing Systems Project

This project has successfully culminated in the development of an ASME standard, attracting significant industrial participation. Additionally, the work has led to the publication of numerous high-impact articles and the issuance of a patent. These dissemination efforts underscore the project's contribution to the field and its potential to influence industry practices.

Recommendation 5-6: The Engineering Laboratory should make a plan to transition the results of its measurement science work to industry to ensure that its work is relevant to industry's needs.

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6
Energy-Efficient, High-Performance Buildings Goal: Net-Zero Energy, High-Performance Buildings and Embedded Intelligence in Buildings Programs

The work within the National Institute of Standards and Technology (NIST) Engineering Laboratory (EL) on the Energy-Efficient, High-Performance Buildings Goal is aimed at enabling cost-effective, energy-efficient, grid-integrated buildings that have healthy and comfortable indoor environments and reduced environmental impacts through advances in measurement science and standards development.

ASSESSMENT OF TECHNICAL PROGRAMS

This work on the Energy-Efficient, High-Performance Buildings Goal is conducted under two programs: Net-Zero Energy, High-Performance Buildings Program and the Embedded Intelligence in Buildings Program.

Net-Zero Energy, High-Performance Buildings Program

The Net-Zero Energy, High-Performance Buildings Program's objective is to develop and deploy advances in measurement science to move the United States toward net-zero energy, high-performance buildings while maintaining healthy indoor environments. The program has four technical focus areas:

1. Whole-building metrics: this area approaches the building as a whole system and evaluates indoor environmental quality, water quality, energy consumption, and the cost-effectiveness and sustainability of whole buildings.
2. Building load reduction: this area aims to reduce a building's energy load. Space conditioning (including heating, cooling, cooling, and outdoor air ventilation) is the largest energy consumer in the United States. The goal is to reduce energy needs by improving the building envelope.
3. Equipment efficiency: this area aims to increase space heating, space cooling, and water heating equipment efficiency through vapor compression heat pumps for energy-efficient buildings; evaluate low-global-warming-potential alternatives; and assess alternative air distribution methods in residential buildings.
4. Onsite energy generation: this thrust examines the use of photovoltaics (PV) to generate energy for a building.

Buildings account for 40 percent of the primary energy consumption, 74 percent of the electricity consumption, and 39 percent of the CO_2 emissions in the United States (NIST 2024). Reducing energy consumption from the building sector is an ambitious but important effort. This will save consumers and businesses money and eliminate wasteful recurring annual energy costs due to inefficient building envelopes and heating and cooling equipment.

Decarbonization aims to reduce or eliminate CO_2 emissions from building construction and operations. Decarbonization is achieved by switching to low-carbon energy sources. To decarbonize buildings and reduce building energy use, many leading organizations are working to reduce building energy use. One concept being pursued is the net-zero energy building, which generates as much energy as is consumed by the building. To achieve net-zero energy buildings, the building industry uses existing energy-efficient building technologies and emerging smart building technologies, develops new mechanical equipment to increase efficiency, and increases onsite energy generation.

Embedded Intelligence in Buildings Program

The Embedded Intelligence in Buildings Program seeks to develop and deploy advances in measurement science that will improve building operations, thus lowering operating costs; higher energy efficiency; and occupant comfort, safety, and security using intelligent building systems. The program provides measurement science to realize energy-efficient building operation through integrated sensors and building control systems with distributed, embedded intelligence that can optimize the performance of building systems, detect and respond to faults and operational errors, and enable the integration of building systems with smart grid technologies.

Intelligent controls used to regulate and operate heating, ventilation, and air conditioning (HVAC) systems in buildings are a rapidly growing area of emphasis in the broader HVAC market. Eighty percent of a building's energy use over its life cycle is associated with operating the building. While large commercial buildings in the United States use complex (in terms of interrelationships) and sophisticated (in terms of capabilities) building automation systems to manage the operation of their HVAC systems, most of these buildings are not properly commissioned, operated, or maintained, negating some of the benefits of these automation systems. It is possible that fully functional automated controls in these buildings could save more than 30 percent of the primary energy they currently consume annually (Fernandez et al. 2017; Sofos and Langevin 2018). Due to the large energy use associated with operating buildings, information on energy consumption in buildings can assist in the future stability and reliability of the electric grid.

Accomplishments

Net-Zero Energy, High-Performance Buildings Program

The Net-Zero Energy, High-Performance Buildings Program supports the move toward net-zero energy, high-performance buildings that have healthy and resilient indoor environments. Broad categories of work within the technical program include (1) research activities, (2) facilities, (3) outreach activities, and (4) engagement with professional organizations and groups. The program accomplishes its goals through work on metrics for indoor environmental quality, water quality, energy consumption, cost-effectiveness, and sustainability; reducing the building load on the grid and improving the building envelope and ventilation for contaminants; developing more efficient equipment such as heat pumps and low global warming potential alternatives; and investigating onsite energy generation such as PV technologies.

The Net-Zero Energy Residential Test Facility is unique and provides excellent opportunities to conduct research related to the operation of energy-efficient homes. It can test multiple mechanical systems, duct systems, and dedicated dehumidification systems. It also has excellent capabilities to support indoor air quality research including contaminant sources, air filtration, and assessing the long-term health impacts of contaminants such as formaldehyde, which is emitted by many building materials and poses health concerns. Additional highlights include the ability to assist in evaluating energy use, building envelope losses, and building control strategies. This test facility has assembled a portfolio of research projects from more than 12 universities in areas such as indoor air quality, space conditioning equipment, air distribution, and demand-controlled ventilation. The work at this facility has led to important research products for multi-zone heating and cooling balancing issues; a comparison of desired and actual airflow levels in a room; and practical implications of mechanical system cycling for heating, cooling, and ventilation.

There are very few laboratories in the world that can calculate absolute spectral response, with EL being the only one in the United States. EL was the first to provide standards for indoor lighting conditions relevant to indoor building–integrated PV. This was an accomplishment specifically suggested in the 2021 assessment (NASEM 2021) that has since been achieved. The ability of this program to calculate absolute spectral response and provide reference test cells for other laboratories to calibrate their equipment is an invaluable service activity to ensure accurate measurements of record-breaking PV efficiencies. However, the program could benefit from looking into how it can make an impact in other areas relevant to PV, such as calibrations, measurement metrics, or procedures for increasing the diversity of PV technologies and uses.

Embedded Intelligence in Buildings Program

The Embedded Intelligence in Buildings Program has addressed the needs of intelligent building systems by supporting better communications protocol standards for integrated HVAC, lighting, energy management, and fire systems. Several ways this program has supported the needs of intelligent building systems include (1) a laboratory testbed used to emulate normal and fault conditions related to equipment failure and abnormal operations, (2) development of information models and software tools to improve design and commissioning and embedded building controls, and (3) advancing real-time communication of building systems with a smart grid.

A highlight of the program is standardizing interoperability between building systems, such as ASHRAE[1] Standard 135-2016, *BACnet: Intelligent Building Agents, and Semantic Interoperability for Building Data*, work done on intelligent building agents, and semantic interoperability for building data. EL's work on interoperability accomplishes activities that are often difficult to coordinate or for which it is difficult to build consensus among manufacturers and producers of equipment.

As intelligent building systems become more complex and interconnected, the need for distributed optimization and decision-making grows. The projects in this goal area have the aim of demonstrating data-driven advanced controls for commercial building systems optimization, commissioning, fault detection and diagnostics, the semantic interoperability of building information, and grid interactions. Research and the resultant publicly available data have the potential to drive innovation and catalyze new research across the nation. The investigations conducted by EL in this area are often difficult to justify and develop in private industry, so the result of this research has the potential to be rapidly and widely adopted. The quality of work maintains the high reputation and authority of NIST in measurement science. The work and experimental methodologies used by the projects in this goal have been used to support the funded projects by the Department of Energy's Building Technologies Office project and to test ASHRAE-developed controls such as Guideline 36-2018, *High-Performance Sequences of Operation for HVAC Systems*. By leveraging EL's cutting-edge capabilities, the goal team is well positioned to evaluate intelligent distributed decision-making approaches and generate valuable benchmarking data.

In the past 5 years, EL has focused research on the challenges of distribution grid control as outlined in the NIST Smart Grid Interoperability Framework 4.0.[2] The scope of this research includes the challenge of integrating smart customer devices: loads, storage, and renewable generation.

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[1] ASHRAE, formerly known as the American Society of Heating, Refrigerating, and Air-Conditioning Engineers.

[2] The NIST Smart Grid Interoperability Framework 4.0 is available at https://www.nist.gov/publications/nist-framework-and-roadmap-smart-grid-interoperability-standards-release-40, accessed December 11, 2024.

The Transactive Energy for Effective Integration of Customer Flexibility project explores how the electric power system is changed by distributed energy resources (PV power generation, battery energy storage, and smart loads including electric vehicles) to the distribution grid. These new load, generation, and storage assets can respond to grid signals, including price signals. The move to distributed energy resources and the growth of both customer electricity generation and demand encourages utilities to engage with customer resources to provide grid services such as frequency and voltage support.

The NIST Transactive Energy Testbed, which will be ready by 2026, will collaborate with the energy industry and provide the scientific basis for the effective integration of customer-owned distributed energy resources into the grid using transactive methods. Simulation studies using the Transactive Energy Testbed are to be carried out to investigate how transactive exchanges can optimally engage the flexibility of different distributed energy resources to provide frequency and voltage stability support to the distribution grid while maintaining the customer's control of their distributed energy resources. Furthermore, simulation results are expected to guide important research on the development of standards to provide a foundation for interoperable transactive energy solutions. Transactive Energy Flex also assesses the impact of dynamic prices on customer finances and distribution grid voltage by comparing two dynamic electricity pricing tariffs: day-ahead hourly prices versus 5-minute real-time prices. The study highlighted the potential benefits and negative impacts of dynamic prices. The results of this project will provide critical knowledge needed by utilities to support the development of the next-generation electric grid, by standards development organizations to create foundational standards for transactive energy methods, by utilities and regulators to develop new tariffs and transactive energy market regulations, and by appliance and building control system manufacturers to guide the development of their next generation of products and services.

Opportunities and Challenges

Strategy Planning, Strategic Direction, Industry Relevance, and Metrics

It was not clear to the panel how the strategies and strategic directions of the Net-Zero Energy, High-Performance Buildings Program, and Embedded Intelligence in Buildings Programs are set. The research projects presented appear to operate in a stand-alone manner, not as part of an integrated plan that establishes the strategic directions and goals necessary to meet the Building Energy and Environment Division's mission and ensure that the individual projects all advance the work of the division toward its goals and mission.

It is also not apparent that the division's work is structured to meet the needs of EL's stakeholders, that is, industry. There appears to be a need to better understand the needs of industry and to incorporate stakeholder needs into the strategic planning process.

Appropriate metrics will help with strategic planning and ensuring stakeholder relevance in this division's work. Metrics could include things such as achieving project milestones on schedule, on-time completion of work, software downloads, publications, citations, industry adoption of software, standards integration, report generation, patents and licensing, and recognition through awards. The panel is not saying these are necessarily the right metrics—determining that is a job for the division staff. Periodic project evaluations against the established metrics can help to evaluate project success, ensure that work remains aligned with the mission and stakeholder needs, and provide a tool to clearly communicate successes and, when appropriate, gaps to appropriators.

Artificial Intelligence and Machine Learning

Artificial intelligence (AI), machine learning (ML), and cloud-based applications, along with software tools for building management, comprise a very important area for the future of intelligent buildings and energy management. Increasing and strategic investment in AI and cloud-based services provide a significant opportunity for EL to expand in this area. EL lacks staff in AI, cloud computing, and software development, although the software is relevant to about 40 percent of research activities in the

Energy-Efficient, High-Performance Buildings Goal. Incorporating AI and ML into embedded intelligence projects is a transformative approach that can significantly enhance outcomes and strengthen the innovation and impact of EL's program. EL also has an opportunity to articulate and demonstrate the ways that AI and ML can be used in intelligent building systems.

It is not clear how AI and ML are being leveraged in specific projects. For example, automated fault detection and diagnostics can take advantage of lightweight machine learning technology instead of expert rules technology. There is a significant opportunity to collaborate with other laboratories (such as national laboratories), other government organizations, industry, and academia for expertise in this area. The NIST Information Technology Laboratory would be a logical place to start.

Recommendation 6-1: The Engineering Laboratory should foster collaboration with other laboratories specializing in artificial intelligence and machine learning to leverage their expertise. The Information Technology Laboratory would be a good place to start.

Photovoltaic Cell Research

The Solar Photovoltaic Cells and Arrays Project has excellent resources that could contribute even further to usefulness and effectiveness with further cooperation with industry. This laboratory could provide electrical performance measurement services to calibrate other laboratories' reference cells, in addition to providing ones for purchase as a standard reference material. Furthermore, continued engagement with the PV community via conferences and other meetings and workshops would give the laboratory opportunities to collaborate directly with stakeholders and ensure that the project objectives align with the field's needs. A better dissemination plan is needed to share the outcomes of the research in particular software programs.

ASSESSMENT OF SCIENTIFIC EXPERTISE

Accomplishments

The work in this goal is supported by a high-quality research staff. The research staff produces a high level of accomplishment, such as creating numerous tools for helping the building community, for the small number of researchers and contractors involved, and are to be commended.

Many of the EL technical staff working on the Energy-Efficient, High-Performance Buildings Goal have demonstrated impressive and, in many instances, world-class expertise in critical and strategic research focus areas. The staff has unique expertise in indoor air quality, fault detection, measurement science, and research that identifies the issues and advantages of new energy efficiency and embedded building intelligence technologies.

The staff includes more than eight current and past ASHRAE fellows. The staff is active both as members and leaders in many standards bodies such as the American National Standards Institute (ANSI), ASHRAE, the American Society of Mechanical Engineers (ASME), ASTM International, Bureau International des Poids et Measures (BIPM), the International Organization for Standardization (ISO), the Portable Generator Manufacturers' Association (PGMA), and Underwriters Laboratories (UL). It is difficult to find equivalent international organizations that have a comparable track record of accomplishments. For example, work in the Building Energy and Environment Division has contributed to the success of the ANSI/ASHRAE BACnet Standard 135, which has been adopted internationally. The staff have also been involved in ASHRAE 223P, *Designation and Classification of Semantic Tags for Building Data*; ASHRAE 241, *Control of Infectious Aerosols*; and ASHRAE Guideline 36, *High-Performance Sequences of Operation for HVAC Systems*. In all, EL staff associated with this goal hold leadership positions in standards and technical committees including 2 with the ISO, 2 with the International Electrotechnical Commission standards activities, 2 with ASTM, 2 with the Institute of Electrical and Electronics Engineers, and 1 with the Organization for the Advancement of Structured

Information Standards. Staff also hold a number of leadership positions within ASHRAE, including 2 in society management, 7 in standards and guidelines activities, and 11 on technical committees. This listing is a sampling of their overall activity.

EL staff lead in indoor air quality research, ventilation performance work using CO_2, air cleaner testing procedures, and transactive energy research. They participate in the Smart Grid Interoperability Panel, the Framework for Improving Critical Infrastructure Cybersecurity, and the National Strategy for Trusted Identities in Cyberspace.

The many awards won by staff in this goal area include the following (this list is not exhaustive):

- ASHRAE Distinguished Service Award
- ASME ECLIPSE Award
- ASTM Award of Appreciation
- ASTM Award of Merit
- Department of Commerce (DOC) Gold Medal Award
- DOC Bronze Medal Award
- Energy Storage and Conversion Horizons Conference Best Poster Award
- International Building Performance Simulation Association-USA Emerging Contributor Award
- NIST Edward Bennet Rosa Award
- NIST Judson C. French Award
- NIST Safety Award
- Purdue University Dave Tree Distinguished Service Award

Due to the one-of-a-kind, specialized equipment that is needed for measurement science research, the staff goes above and beyond to enable their work. For example, when there are unique issues with complex equipment that is not working due to age or issues with performance that are outside of the technical expertise of other support staff, the EL staff have become technical experts in operating and maintaining the specialized equipment they use and are committed to their work. This is also a challenge because it takes valuable time away from research experts fixing and solving equipment issues.

Opportunities and Challenges

About 39 percent of EL's staff are eligible for retirement. This is a challenge for succession planning to hire, train, and prepare replacements for staff who retire. Specifically, the institutional knowledge of refrigerants needs to be transferred to the next generation of researchers. There are staff members who work beyond the retirement age. When hiring new people, it may be advantageous to consider staff experience and skills in agile development. This is also an opportunity to increase collaboration with low-global warming-potential refrigerant stakeholders. A well-defined succession plan is essential for ensuring the continuity and stability of NIST. Proactive planning allows flexibility for changes and encourages growth and development.

Information gathering and discussions with staff make it clear that long-term, in-person work is crucial for team collaboration and advancing research, especially for new staff members who need mentoring from senior researchers. Yet some balance of in-person and telework has proven crucial to staff recruitment and retention in many different places. Work flexibility is now a workforce expectation. The extent of this balance is the subject of much debate and a variety of policies across federal agencies and the panel did not engage in an in-depth investigation of this topic, so it is not in a position to make any specific recommendations. However, it is advisable for EL leadership to explore the proper balance of work to allow for the mentoring and development of newer, more junior staff.

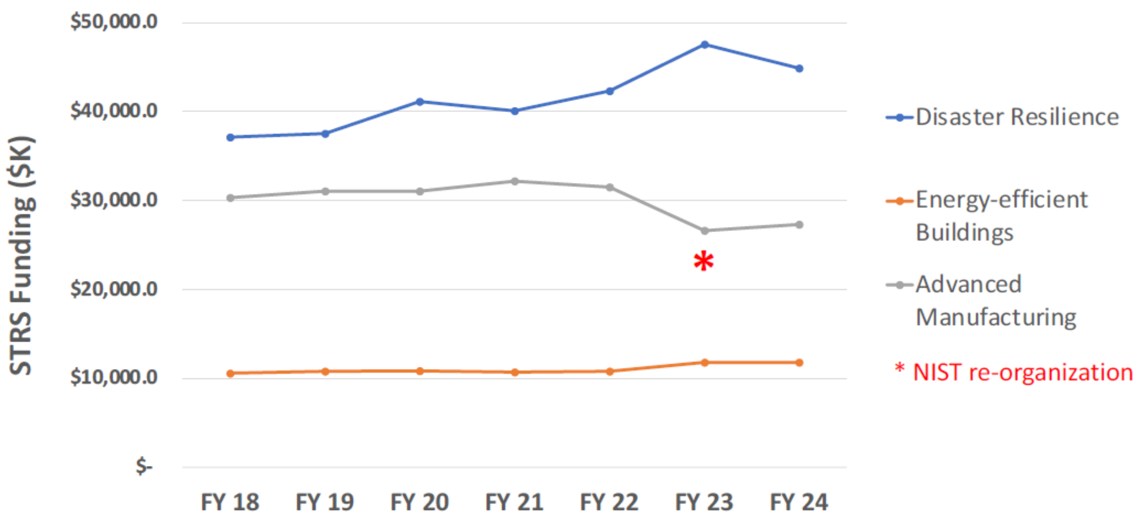

FIGURE 6-1 Engineering Laboratory's budget broken out by its three major goals.
NOTE: FY, fiscal year; NIST, National Institute of Standards and Technology; STRS, scientific and technical research services.
SOURCE: Courtesy of NIST Engineering Laboratory.

BUDGET, FACILITIES, EQUIPMENT, AND HUMAN RESOURCES

Budget

As can be seen in Figure 6-1, funding for the Energy-Efficient, High-Performance Buildings Goal has been largely flat for years. Funding for the work in this goal remains stagnant and is the lowest compared to other areas such as disaster resilience and advanced manufacturing. Given the United States' commitment to reducing greenhouse gas emissions by 50–52 percent below 2005 levels by 2030, funding for this goal does not seem to match its importance. The panel recognizes that, as a federal agency, NIST and its component laboratories must rely on appropriations, for which they make a budget request each year. If EL desires to put greater resources against the work on this goal, it would help greatly to provide better documentation of the contributions of this work to achieving greenhouse gas reduction goals and how it is impactful to justify a more favorable budget request to the administration and Congress.

Facilities and Equipment

Facility issues are becoming more prominent. The facility is old, but the staff is finding creative workarounds to meet project goals. However, the age of the facility may hinder the staff from working on projects that require the latest technologies and better equipment. Time spent by researchers on overcoming facility failures and maintaining older one-of-a-kind systems needs to be tracked and a comparison of that cost weighed against the cost of increased facilities funding or upgrading or replacing those systems.

Due to the significant amount of deferred maintenance, the research staff is spending their time and some of their budgets to address shortcomings and failings. As noted in the 2023 report *Technical Assessment of the Capital Facility Needs of the National Institute of Standards and Technology* (NASEM

2023), researchers can lose between 10–40 percent of their time addressing facilities problems.[3] It needs to be noted that EL cannot address its most pressing facilities issues on its own. Rather, they must submit their needs to the Office of Facilities and Property Management for inclusion in that office's budget request to Congress.

Recommendation 6-2: The leadership of the Energy-Efficient, High-Performance Buildings Goal should clearly communicate their facility shortcomings and needs to the Office of Facilities and Property Management so those needs can be reflected in annual budget requests and in facility master planning activities.

The research staff are also spending their time nursing older one-of-a-kind equipment. While maintaining such systems may seem cost-effective in the short term, it's important to consider the hidden costs associated with downtime, decreased productivity, and potential risks to research quality. Upgrading or replacing these systems may require a significant initial investment, but it can lead to substantial long-term savings by reducing maintenance requirements, improving equipment reliability, and enabling researchers to focus more on their core work. Moreover, modernizing laboratory equipment often brings additional benefits such as enhanced functionality, improved safety features, and compatibility with emerging technologies. By investing in state-of-the-art systems, laboratories can position themselves at the forefront of scientific innovation, attract top talent, and remain competitive in their respective fields. While the decision to upgrade or replace outdated laboratory systems requires careful consideration of costs and benefits, prioritizing efficiency and productivity is paramount. By investing strategically in equipment modernization, laboratories can optimize their resources, streamline operations, and empower researchers to achieve breakthrough discoveries more effectively.

Building technologies are evolving rapidly, so upgrading existing equipment and investing in new technologies is critical for the future. Not doing so poses the risk of falling behind as other global laboratories work on innovative technologies.

The Net-Zero Energy Residential Test Facility is a fully instrumented laboratory fit to accomplish exceptional research that would be difficult and expensive to do in a normal residential home. This facility can bring 20–30 people to evaluate various technologies to improve energy efficiency; it is a research house to facilitate research. The overhead of these kinds of laboratories is high, and the question, Is it worth it? inevitably arises. There is good evidence this facility is worth it; however, there is no clear plan about who will be responsible for maintenance. Based on current funding information provided to the panel, the maintenance would be in part funded through project money. If the maintenance is not done on this test facility, the value of the research will be reduced.

Also, the Net-Zero Energy Residential Test Facility may be underused at times. There appears to be a need to prioritize and coordinate testing schedules to achieve high usage. The facility staff may need to examine the facility's readiness to accommodate changing industry trends, such as the use of flammable refrigerants.

Multiple environmental chambers need maintenance. This maintenance is being deferred due to a lack of funds, thus, compromising the quality of the research conducted in them. However, the chambers seemed to be underused. The use of a chamber schedule calendar shared among projects could allow the use of fewer chambers and reduce the fiscal burden of the needed deferred and ongoing maintenance costs.

It would be beneficial for the EL leadership to develop and communicate a long-term strategic plan and prioritization of allocated funds available to create a long-term facility that is flexible enough to adapt to changes in future program needs.

During a session with feedback from early-career staff, there were several comments related to obstacles to execution related to acquiring equipment quickly. EL management would benefit from identifying this and other related acquisition and approval issues.

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[3] A summary of this report can be found in Chapter 1, Box 1-1.

Space Management

A space management plan and a system are needed to track the use of space and equipment to prioritize and improve the use of its resources (e.g., the use of environmental chambers by multiple projects). The panel noted the lack of a structured approach to space planning, which has resulted in opportunistic layouts, inefficient use of available space, and a disjointed overall experience for workers and visitors. The lack of systemic space planning presents a significant challenge in facilities supporting multiple research programs. It can result in cramped laboratories, obstructed workflow, inadequate storage, and a lack of functionality, hindering researchers' comfort and daily routines. Ultimately, it may impact the overall working environment and lead to worker dissatisfaction or negatively impact outcomes. It is warranted to have a systematic approach to space planning, whether through professional consultation or collaborative efforts.

Within these challenges lies an opportunity for improvement. By reevaluating layout designs, implementing innovative storage solutions, and optimizing spatial arrangements, there's the potential to transform underused spaces into purposeful spaces. Implementing a robust space use tracking system would offer an opportunity to optimize space and equipment use. Such a tracking system would enable researchers to view real-time data on the use of facilities, identify available slots for experiments or projects, and schedule their activities accordingly. Moreover, these systems can facilitate seamless communication and coordination among different research groups, allowing for the efficient sharing of resources among multiple projects, ultimately enhancing functionality and productivity, fostering creativity, and facilitating collaboration among research teams, providing for a more satisfying working experience.

Furthermore, scheduling software provides valuable insights into use patterns and trends, allowing laboratory managers to identify underused resources and prioritize improvements or adjustments accordingly. For example, if a facility or piece of equipment is found to be frequently idle during certain time slots, measures can be taken to optimize its use, such as opening it up to additional research projects or adjusting scheduling protocols. Additionally, implementing a tracking system for space and equipment use promotes accountability and transparency within the laboratory environment. Researchers can easily log their usage of facilities and equipment, providing a comprehensive record of activities for future reference or auditing purposes. By leveraging technology to track and manage space and equipment use, laboratories can streamline operations, enhance productivity, and maximize the return on investment in research infrastructure.

Recommendation 6-3: The Engineering Laboratory (EL) should develop and implement a space management plan that ties in with the strategic plan proposed in Key Recommendation 1. EL should use scheduling software where research laboratories can create central platforms to manage and monitor the availability and use of spaces and equipment.

Human Resources

As discussed in the "Opportunities and Challenges" section under "Adequacy of Scientific Expertise," above, a well-defined succession plan is essential for ensuring the continuity and stability of EL's work by identifying and developing potential leaders from within EL. This will foster a culture of growth and development, ensuring a pipeline of skilled resources. As a part of this, an important task is to develop a plan and budget to transfer skills and experience from mid and senior career staff to younger staff. There are mentoring opportunities and other opportunities to gain experience across the entire NIST organization, possibly including formal mentoring plans with clear objectives, and opportunities to work in other laboratories.

The team has some younger staff members in temporary positions. However, there is a significant imbalance between the number of federal staff members with more years of experience and the number of young researchers. There also does not appear to be enough mid-career people with sufficient expertise.

A recurring theme observed is the need for funding to replace retired personnel**.** Annual salary increases and flat funding leave less money for research every year, squeezing the budget available to conduct EL's technical program work. Ongoing decreases in research funding negatively impact the morale of the team and, naturally, their work. The tight fiscal picture also negatively impacts the ability to hire subject-matter experts in needed areas (e.g., hiring experts in AI if the goal is to incorporate more AI into EL's work). Collaboration with other organizations, such as other federal agencies, universities, and industry groups, might help to address this need.

Recommendation 6-4: The Engineering Laboratory leadership needs to develop and implement a long-term staffing plan to identify leaders and develop people in key areas. This plan should include elements such as the transfer of knowledge and experience from older workers to younger ones, formalized mentoring arrangements, and finding opportunities for EL researchers who show promise to work in other laboratories and divisions across the whole of the National Institute of Standards and Technology to develop them professionally.

An observation of the team is that there are few or even only one staff assigned to critical skills in fast-moving disciplines. The flexibility of staff to work across different related disciplines is a very important attribute of planning, hiring, and assignments. The integration of numerous disciplines, such as building science and engineering, HVAC mechanical equipment, AI, ML, building protocols, control languages for direct digital controls, semantic interoperability for buildings, and intelligent building agents has resulted in a complex multi-disciplinary technical environment that is fast changing.

An area that may benefit from improvement is employee performance evaluations. The metrics for individual employee performance evaluations do not appear to be referenced to a cross-laboratory standard (e.g., evaluation areas appear to be weighed on an individual basis). This makes it difficult to produce a performance measure to objectively reward exemplary employees and address those in need of support to improve performance.

The panel acknowledges its limited knowledge of federal government personnel regulations. EL management may have additional concerns to address, such as federal employees with relatively good stability and motivation but fixed salaries with specific opportunity areas. EL management needs to continue to attract people with competitive skills while the federal government is operating at a disadvantage when it comes to salaries.

EFFECTIVENESS OF DISSEMINATION EFFORTS

Accomplishments

As noted throughout this chapter, EL continues to be engaged with different standards organizations, and their staff are active in publishing and attending industry conferences and seminars. Since 2020, a non-exhaustive listing of publications associated with the staff working in this goal area includes 77 peer-reviewed journal articles, 46 conference papers, 39 NIST publications, 15 other publications such as books and software, and 3 contractor reports. 12 data sets for net-zero energy and high-performance buildings have been published. Software published includes modeling indoor microbial aerosols, natural ventilation, and $QICO_2$ for CO_2 concentration. There are also HVAC simulations (e.g., HVACSIM+), a BACnet data source; a BACnet performance test (i.e., FPTM); and ZandrEA, which gives real-time fault detection and diagnosis. Publications by staff across EL are discussed in more detail in Chapter 2.

The common dissemination paths for the results of work in this goal include the NIST website; presentations at ASHRAE conferences; publication through NIST Technical Notes and bulletins, and publication through ANSI, ASHRAE, ASME, ASTM, BIPM, ISO PGMA, Business for Social Responsibility (BSR), and UL standards. Dissemination of EL results can also occur through software downloads and reference materials. Depending on the nature of the work, different groups naturally have different dissemination portfolios.

In particular, EL's work in this goal area has contributed to developing highly impactful standards and disseminating the results of its work effectively and widely. the ANSI/ASHRAE Standard 135-2016, *BACnet—A Data Communication Protocol for Building Automation and Control Networks*, has nearly universal international adoption. ASHRAE Standard 223P, *Semantic Data Model for Analytics and Automation Applications in Buildings*, went through its first advisory public review in March 2024 and is a critical technology for the future of intelligent building communication. NIST is a strong advocate for Standard 223P in industry. ASHRAE Standard 241, *Control of Infectious Aerosols*, establishes minimum requirements aimed at reducing the risk of disease transmission through exposure to infectious aerosols in buildings and renovations. BSR/ASHRAE Standard 231P, *A Control Description Language for Building Environmental Control Sequences*, is meant to be an "open and interoperable standard for the description of the control logic used in building control systems" (BIG 2024). These standards will all work together to provide a unified approach to intelligent building control and operation.

Opportunities and Challenges

There are some opportunities regarding the dissemination of efforts. Dissemination activities are not uniform across all the projects in this goal area. It would be helpful for the staff to know the agreed success metrics for the effectiveness of dissemination. In terms of the publication of refereed papers, EL or goal-area leadership needs to clarify for its staff whether the number of papers or the number of citations of the papers is an important metric for the staff in this goal area. Additionally, the number of standards to which the projects in this goal area have contributed that have been adopted has not been tracked.

EL publishes technical reports that contain a great deal of detailed information. EL would do well to advertise these reports widely to ensure that parties that can benefit from them know they exist. This is true of EL broadly as well as of the projects in this goal area. It has been noted that industry does not always track peer-reviewed and technical publications closely. This can mean that important information is generated and missed by industry.

The Intelligent Agents Laboratory makes test data available to the public; they create different testbeds and test the control strategies for electrical and thermal load shifting. It would be very beneficial if the results from tests and control strategies were put into databases available to utility companies and researchers. If a test uses thermal energy storage, the thermodynamic model for that thermal energy storage could be incorporated into the Lawrence Berkeley National Laboratory's Modelica open-source model, which is publicly available for researchers to use.

Beyond simply tracking the number of standards published, number of patents, and number of downloads, there is the question of how to measure the traction and effectiveness of various dissemination products among the members of the stakeholder communities. Having collaborative partners is a good way to keep on the cutting edge. It is advisable for there to be a constant effort by the leadership in this goal area to identify and measure the effectiveness of the dissemination of the results of their work.

EL appears to be light on benchmarking and performance metrics. An opportunity for improvement is a focus on dissemination efforts. For example, it may be beneficial to define and communicate to the audience of interest for a particular research area. Identifying some specific targets and establishing benchmarking continuously will assist current and future projects. Although NIST does not have peer competitors, not in the sense that industry does, or even academics who compete for grants and other funding opportunities, it is still important to identify the actual benchmark numbers and record them, even if only for NIST to compare to itself. It is not sufficient to find that a program is unique or in an area of interest to the nation. It is more critical to understand if it is sustainable, meets important needs, and achieves important and impactful outcomes.

Recommendation 6-5: The leadership in the Energy-Efficient, High-Performance Buildings Goal area should define succinct metrics to measure dissemination. They should look for ways to go beyond counting numbers and look for ways to judge the impact of this goal's work products.

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7
Overarching Themes, Key Recommendations, and Chapter-Specific Recommendations

OVERARCHING THEMES AND KEY RECOMMENDATIONS

In the course of conducting its work—reviewing printed materials, receiving presentations, taking tours, and talking with Engineering Laboratory (EL) staff—some common themes appeared across the different subpanels and their chapters. Because the subpanels worked mostly independently of each other, this is indicative of situations that pertain to the institution being assessed as a whole rather than something that only pertains to a part of its work. These are overarching themes and the recommendations to address them are key recommendations.

In this assessment, the overarching themes that emerged were (1) strategic direction and strategic planning and (2) metrics to help determine when a project has been successful, to determine when it is time to sunset a project to free up resources for new efforts, and to ensure that the work is relevant to the stakeholders.

Strategic Direction and Strategic Planning

It was not clear to the panel how the strategies and strategic directions of EL's work are set. To understand and assess the effectiveness of programs at EL, the panel needed to understand the goals and objectives of EL. How does EL know that the program areas in which its researchers are working align with the mission of the laboratory, the National Institute of Standards and Technology (NIST) more broadly, and stakeholder needs? The panel was not provided with a strategic plan, a short- or long-term implementation plan, key performance indicators, or reporting requirements.

Without strategic guidance from clearly set goals, it is very difficult to evaluate whether the necessary expertise, budget, and facilities are in place to sustainably support globally competitive programs in EL's areas of interest. An important concern is a perception that EL does things because they can be done, not that they pursue work directed as meeting a defined set of needs. A useful strategic planning process will make it clear why the programs are doing what they are doing. It will establish clear benchmarks through which to judge progress and, in turn, establish clear go/no-go decision points. When projects are being selected, it would be useful to have an EL management review to look across the laboratory, NIST, and the broader stakeholder community and ensure that there are no duplications of effort and to help identify opportunities for collaboration.

Many of the research programs presented to the panel seem to operate in a stand-alone and non-interactive way. EL may consider ways to combine and consolidate research projects that can benefit from collective efforts, thereby enhancing overall efficiency. Some of the appearance of stand-alone and non-interactive programs may be a consequence of individual projects being assigned to one principal investigator that focuses on a single project and undertakes all the work of the project themselves. When principal investigators are funded individually for their research annually, rather than EL being funded based on strategic initiatives, it becomes difficult to foster a collaborative environment that promotes program success. Examples of things that could help to ensure that EL is applying its limited resources most effectively are conference attendance, hosting onsite and offsite workshops, and hosting activities that include a mix of industry and research entities. Strategic planning would also guide staff recruitment with an eye to the big picture.

To ensure maximum impact, it is desirable that EL's strategic directions and planning align with needs of its stakeholders, including industry. It is unclear how EL determines that its work is best aligned with stakeholder needs. Without this strategic alignment, it is difficult to determine if EL is providing the most relevant, cost-effective, and meaningful contributions to its stakeholders. Engaging with relevant industry and other stakeholder groups would facilitate a deeper understanding of their needs, enabling targeted project development that directly addresses stakeholder challenges and priorities. This approach would enhance the relevance and effectiveness of projects, fostering meaningful contributions to advancements and innovation in industry and other stakeholder communities.

Key Recommendation 1: The Engineering Laboratory (EL) should determine and describe the strategic directions it will pursue and how personnel and resources will be allocated to pursue those directions. Management reviews during project selection should use the strategic directions to avoid duplication, look for collaboration opportunities, and guide the recruiting of any new staff. EL should also develop and publish a long-term strategic plan that includes input from stakeholders such as industry.

Metrics and Stakeholder Relevance

While its mission states that EL "promotes 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," the question left with the panel is "How?" How does EL know that it is meeting its mission, and what are the metrics used to determine success? Another need is for evaluation criteria and metrics to be used to select and then judge the success of projects. It was not obvious to the panel that there are criteria for evaluating how programs are selected, nor are there metrics to measure the success of programs or that could be used in deciding whether to maintain or terminate a program of research. It was also not clear if programs are evaluated periodically for validity or stakeholder relevance. The panel was unable to acquire granular information on project benchmarking and the measurement of key performance on projects. Individual measurements of effectiveness and their impact need to be done at the individual project level in EL. Metrics do not have to be perfect to be useful. Some suggested metrics (some of which are in place) may include things such as achieving project milestones on schedule, on-time completion of work, software downloads, publications, citations, industry adoption of software, standards integration, report generation, patents and licensing, and recognition through awards, among others.

Presuming that EL is already periodically evaluating the performance and program success metrics, it would be useful for EL to communicate its track record and success with past and future programs and value, allowing for the consideration of the diverse range of outputs from EL's work. NIST aims to become a world-class organization, and it may benefit from further efforts to define the meaning of "world class"—such a definition would assist assessment panels in providing feedback on achieving that goal.

The pace of work also impacts industry relevance. Research projects typically follow 2–5-year cycles, which is common in industry. However, due to rapid technological advancements, long-term research projects risk producing outdated results by the time they are completed. To meet industry needs in particular, EL might consider reassessing project milestones every 12 months. This would provide an opportunity to adjust milestones as needed to ensure that the work remains relevant and impactful.

In general, EL appears to not be externally communicating success metrics that demonstrate how its research is impactful. As shown in Figure 2-5, the budgets for EL's goals have either remained stable, increased slightly over time, or decreased (the decrease in Figure 2-5 was due to a reorganization with some of EL's groups moving to the Communications Technology Laboratory). These data, however, are not corrected for inflation. This means that EL has likely either been barely maintaining purchasing power in the face of inflation or losing purchasing power. Clear metrics of the sort recommended here, and the clear communication of them to stakeholders and funders, could also be used to demonstrate EL's value proposition to appropriators.

Key Recommendation 2: The Engineering Laboratory (EL) should communicate the current clear metrics for project adoption and success that are already in place. A management review of the work portfolio should be considered as a tool to determine whether to keep a project going or terminate it. EL should communicate the metrics externally to stakeholders and review panels. The adoption of standards by industrial groups to which EL has contributed should be externally communicated to stakeholders regularly. EL should also define what it means to be "world-class" so it can know when it is meeting this goal.

CHAPTER-SPECIFIC RECOMMENDATIONS

Advanced Manufacturing Goal: Measurement Science for Additive Manufacturing Program

Recommendation 3-1: The Measurement Science for Additive Manufacturing Program should expand the testbed concept to include data-related projects and to support tighter integration between data-related projects and hardware-related projects.

Recommendation 3-2: The Measurement Science for Additive Manufacturing (AM) Program's leadership should refine the goals of the Fundamental Measurements for Metals AM, Advanced Informatics and Artificial Intelligence for AM, and Data Management and Fusion for AM Industrialization projects to be more focused and measurable, integrated with experimental practice, and aligned with realistically available resources. The program's leadership should clearly define its role in the wider AM space and explore collaborations to leverage and achieve a maximum return on the investment of its resources.

Recommendation 3-3: The Measurement Science for Additive Manufacturing program should better align team member expertise with practical, industrial measurement science needs. This can be accomplished through upskilling in applied data science and artificial intelligence. Also, they should add experts with relevant skills, such as powder rheology, the state of the art in powder testing and modeling techniques, and qualification methods for machines and processes that use powder feedstock. Finally, more direct engagement with industry would greatly help.

Recommendation 3-4: The Measurement Science for Additive Manufacturing program should explore other ways to disseminate the results of its work directly to industry. These could include mailing lists to inform industry stakeholders of new publications in a timely manner, producing more National Institute of Standards and Technology reports in areas that are industry-relevant but less likely to result in peer-reviewed papers, and making as many peer-reviewed papers openly accessible as possible.

Advanced Manufacturing Goal: Measurement Science for Manufacturing Robotics Program

Recommendation 4-1: The Measurement Science for Manufacturing Robotics Program should discontinue the use of the term "cobot" and align with International Organization for Standardization Standard 10218 and ANSI/RIA Standard R15.06.

Recommendation 4-2: The Perception Performance of Robotic Systems project should develop an intentional work statement focused on vision-based tracking systems with clear connections into adjacent projects addressing human–robot interactions and mobility and exoskeleton projects.

Recommendation 4-3: The Performance of Human–Robot Interaction (HRI) project should explore emerging human-centric cognitive and physical standards such as Institute of Electrical and Electronics Engineers P7017, *Recommended Practice for Design-Centered Human–Robot Interaction and Governance*. The data and models from this project in the National Institute of Standards and Technology repository should be disseminated to researchers employing artificial intelligence and machine learning to help drive future research activities and collaborations. If this project explores human cognition within HRI, it should obtain cognitive architecture capabilities as well as associated high-performance computational hardware.

Recommendation 4-4: The Embodied Artificial Intelligence (AI) and Data Generation for Manufacturing Robots project should develop and communicate clear roadmaps to achieve their stated research objectives that characterize robotic systems that involve AI algorithms, training paradigms, and metrics.

Recommendation 4-5: The Measurement Science for Manufacturing Robotics Program (MSMR) should partner with universities and other research institutions with expertise in the rapidly advancing technologies relevant to its work, such as artificial intelligence, cognitive science, and human-robot interaction technologies. This would help MSMR to maintain its relevance to, and maximize its impact on, industry and U.S. competitiveness.

Recommendation 4-6: All projects in the Measurement Science for Manufacturing Robotics Program should expand their engagement with manufacturing innovation institutes to bolster dissemination and engagement with large and small system integrators and end users.

Advanced Manufacturing Goal: Advanced Manufacturing Data Infrastructure and Analytics Program

Recommendation 5-1: The Engineering Laboratory should increase internal collaboration across different programs within it to leverage existing expertise and resources to maximum effect.

Recommendation 5-2: The Engineering Laboratory should assess the obstacles in current industrial practices preventing the advancement of a data infrastructure that will improve productivity, resiliency, and sustainability for manufacturing operations and supply chains, and identify targeted research programs to overcome these obstacles.

Recommendation 5-3: The Engineering Laboratory should create yearly a prioritized list of industry challenges and develop corresponding National Institute of Standards and Technology problem statements that align with those industrial needs. The list and problem statements should specify goals and include a detailed schedule and specify the deliverables that are to be disseminated. All of this should be used to obtain the resources—both people and funding—to achieve the goals in the problem statements.

Recommendation 5-4: The Engineering Laboratory (EL) should conduct a clear needs assessment to understand industry's needs and how EL can best address them, integrating its efforts into the broader efforts under way in industry. A timeline to address those needs, reflecting the speed at which things move in industry, should also be developed.

Recommendation 5-5: The Augmented Intelligence for Manufacturing Systems Project should develop strong collaborations with established industry consortia and institutes such as those comprised under Manufacturing USA.

Recommendation 5-6: The Engineering Laboratory should make a plan to transition the results of its measurement science work to industry to ensure that its work is relevant to industry's needs.

Energy-Efficient, High-Performance Buildings Goal: Net-Zero Energy, High-Performance Buildings and Embedded Intelligence in Buildings Programs

Recommendation 6-1: The Engineering Laboratory should foster collaboration with other laboratories specializing in artificial intelligence and machine learning to leverage their expertise. The Information Technology Laboratory would be a good place to start.

Recommendation 6-2: The leadership of the Energy-Efficient, High-Performance Buildings Goal should clearly communicate their facility shortcomings and needs to the Office of Facilities and Property Management so those needs can be reflected in annual budget requests and in facility master planning activities.

Recommendation 6-3: The Engineering Laboratory (EL) should develop and implement a space management plan that ties in with the strategic plan proposed in Key Recommendation 1. EL should use scheduling software where research laboratories can create central platforms to manage and monitor the availability and use of spaces and equipment.

Recommendation 6-4: The Engineering Laboratory leadership needs to develop and implement a long-term staffing plan to identify leaders and develop people in key areas. This plan should include elements such as the transfer of knowledge and experience from older workers to younger ones, formalized mentoring arrangements, and finding opportunities for EL researchers who show promise to work in other laboratories and divisions across the whole of the National Institute of Standards and Technology to develop them professionally.

Recommendation 6-5: The leadership in the Energy-Efficient, High-Performance Buildings Goal area should define succinct metrics to measure dissemination. They should look for ways to go beyond counting numbers and look for ways to judge the impact of this goal's work products.

Appendixes

A
Acronyms and Abbreviations

A3	Association for Advancing Automation
ACM	Association for Computing Machinery
AI	artificial intelligence
AM	additive manufacturing
AMDIA	Advanced Manufacturing Data Infrastructure and Analytics
ANSI	American National Standards Institute
ARIAC	Agile Robotics for Industrial Automation Competition
ARM	Advanced Robotics for Manufacturing Institute
ASHRAE	American Society of Heating, Refrigerating and Air-Conditioning Engineers
ASME	American Society of Mechanical Engineers
ATB	Assembly Task Board
A-UGV	autonomous guided vehicle
BEED	Building Energy and Environmental Division
BIG	Building Intelligence Group
BIPM	Bureau International des Poids et Measures
CMR	construction and major renovation
CRF	Construction of Research Facilities
DOC	Department of Commerce
EL	Engineering Laboratory
FTE	full-time equivalent
FY	fiscal year
HRI	human–robot interaction
HVAC	heating, ventilation, and air conditioning
IEEE	Institute of Electrical and Electronics Engineers
ISD	Intelligent Systems Division
ISO	International Organization for Standardization
MEP	Manufacturing Extension Partnership
MII	Manufacturing Innovation Institute
ML	machine learning
MOAD	Manufacturing Objects for Assembly Data
MSAM	Measurement Science for Additive Manufacturing
MSMR	Measurement Science for Manufacturing Robotics

MxD	Manufacturing x Digital
NIIMBL	National Institute for Innovation in Manufacturing Biopharmaceuticals
NIST	National Institute of Standards and Technology
OAGIS	Open Applications Group Integration Specification
PFL	power, force, and torque-limited
PGMA	Portable Generator Manufacturers' Association
PI	principal investigator
PV	photovoltaic
R&D	research and development
ROS	robot operating system
SCMMR	safety, capacity, maintenance, and major repair
SID	Systems Integration Division
SME	Small-and-Medium Enterprise
STRS	Scientific and Technical Research Services
TRL	technology readiness level
VCAT	Visiting Committee on Advanced Technology

B
Panel Member Biographical Information

JOSEPH J. BEAMAN, *Chair*, is currently the Earnest F Gloyna Endowed Professor in Engineering in the Walker Department of Mechanical Engineering at The University of Texas at Austin. His career work has been in both manufacturing and control. His specific manufacturing research interest is in additive manufacturing (AM). Dr. Beaman was the first academic researcher in the field. One of the most successful AM approaches, selective laser sintering, was a process that was developed in his laboratory. Dr. Beaman is a fellow of both the American Society of Mechanical Engineers (ASME) and SME (formerly the Society of Manufacturing Engineers) and was elected to the National Academy of Engineering in 2013 and the National Academy of Inventors in 2015. He was elected the Distinguished Engineering Graduate, Cockrell School of Engineering, The University of Texas at Austin in 2015, received the SME Albert M. Sargent Award in 2016, the SM Wu Implementation Award from North American Manufacturing Research Institution/SME in 2018, the CIRP Nicolau Award in 2021 at the CIRP General Assembly, and was elected an honorary member of ASME in 2023. He joined the mechanical engineering faculty at The University of Texas in 1979 after receiving his ScD from the Massachusetts Institute of Technology (MIT) in mechanical engineering. Dr. Beaman was the chair of the Walker Department of Mechanical Engineering (2001–2012) and was the director of the Advanced Manufacturing and Design Center (2012–2020) at The University of Texas. He was elected and served on the SME board of directors (2012–2014) and nominated and appointed to the U.S. Army Science Board of the U.S. Army (2012–2015). His most recent research publications include AM carbon fiber reinforcement, data-driven control for laser powder bed fusion, the first investigation of selective laser flash sintering for ceramic parts, the design of in situ microscope for selective laser sintering processes, and multi-material AM (2022–2023).

VERONICA ADETOLA is a chief research scientist at the Pacific Northwest National Laboratory (PNNL), where she leads the Resilient Control Methods Team and oversees multi-million-dollar projects to develop methods and algorithms for enhancing the efficiency, reliability, and resiliency of energy systems. Her expertise and research interests include model-based and data-driven controls, optimization and control co-design for grid-interactive, energy-efficient buildings; microgrids; cyber-physical power and energy systems; and power electronics-dominated systems. Before joining PNNL in 2019, Dr. Adetola made significant contributions at the United Technologies Research Center (now Raytheon Technologies). During her tenure, she successfully led efforts for multiple United Technologies Corporation (UTC) businesses and government-funded research programs. In recognition of her accomplishments, she received several awards, including the 2013 Outstanding Achievement Award from the research center for her work on developing, demonstrating, and transitioning model-based control technologies to UTC businesses. Dr. Adetola's accolades also include the prestigious American Society of Heating, Refrigerating, and Air-Conditioning Engineers (ASHRAE) Science and Technology Best Paper Award for her research on "Fault-Tolerant Optimal Control of a Building HVAC [heating, ventilation, and air conditioning] System" and the International Federation of Automatic Control prize for the Best Methodology/Theory Paper in the *Journal of Process Control* for her work on integrating real-time optimization and model predictive control. Dr. Adetola served as a peer reviewer for Department of Energy (DOE) Building Technology Office (BTO)-funded projects in 2018. She also contributed to the

BTO Grid-Interactive Efficient Buildings technical report series on Whole-Building Controls, Sensors, Modeling, and Analytics in 2020. Dr. Adetola was a board of governors member of the Institute of Electrical and Electronics Engineers (IEEE) Control Systems Society in 2019 and currently serves as the associate editor for *IEEE Transactions on Control Systems Technology* and the vice chair for the IEEE Control Systems Society's Technical Committee on Energy Systems. She earned her PhD from Queen's University, Ontario, Canada. She holds 10 U.S.-granted patents and has authored a book, 3 book chapters, and more than 50 journal publications and peer-reviewed conference papers.

SOMAYEH ASADI is currently a professor in the Department of Civil and Environmental Engineering at the University of Virginia. Before that she was an associate professor at The Pennsylvania State University (Penn State). She leads a diverse research group to advance smart, connected buildings and cities. Her research group's work focuses on studying the performance of buildings, building systems, and occupant behavior to improve the energy performance, efficiency, and energy demand contributions of the built environment. She is a member of the American Society of Civil Engineering. Dr. Asadi received her PhD in engineering science from Louisiana State University in 2012. Her research efforts have resulted in more than 200 peer-reviewed journal articles, book chapters, books, and 60 peer-reviewed conference papers.

ASHLEY GAULDING is a research scientist at the National Renewable Energy Laboratory (NREL), working in the field of photovoltaics (PV) for more than a decade. She leads projects in the areas of PV reliability and degradation and PV circularity (design, reuse, recycling). She is the leader of the international Photovoltaic Quality Assurance Task Force Task Group 15, which focuses on "Repair, Reuse, Recertification, and Recycling." She was named an American Chemical Society (ACS) "Women Scientist at the Forefront of Energy Research" in 2023 and appointed to the U.S. Technical Advisory Group for the International Electrotechnical Commission in 2021. She received her bachelor's degree in chemical engineering from the University of Minnesota and her PhD in materials science engineering from the University of Pennsylvania, where her research focused on investigating the electronic properties of quantum dot films for emerging PVs. She completed 1 year as a postdoc at Lawrence Berkeley National Laboratory synthesizing and characterizing photonic and plasmonic materials for CO_2 reduction before being awarded the Director's Fellowship at NREL to lead a project on perovskite/quantum dot hybrid materials. While in her current position at NREL, she has co-planned multiple workshops, including the PV Reliability Workshop, PV Circularity Workshop, and the workshop "Confronting Degradation Science to Enable a Long-Lasting Clean Energy Economy." She has also chaired multiple sessions at various society hosted conferences, including the Materials Research Society, IEEE Photovoltaic Specialists Conference, and Gordon Research Conference.

EMILY HERNDON is a senior consultant in Woolpert's Strategic Consulting Group. Ms. Herndon has spent her career working with clients to develop strategic, long-term asset management programs. She has expertise in goal setting, policy development, strategic planning, capital investment planning, business processes development, change management, and communications. She is a member of the Institute of Asset Management, a co-chair of the National Institute of Building Science (NIBS) Facility Maintenance and Operations Council, and a Prosci Certified Change Manager. Ms. Herndon recently provided a webinar on Total Cost of Ownership for NIBS and presented with the Department of State on data-informed decision-making at the 2022 North American Institute of Asset Management Conference.

GREGORY HUDAS is currently the Department of Defense (DoD) program manager for Advanced Robotics for Manufacturing Innovation Institute (DoD Manufacturing USA Network). He also serves as a senior research scientist for the U.S. Army DEVCOM Ground Vehicle Systems Center-Ground Vehicle Robotics Group. He provides technical expertise and strategic support to Army senior leadership and DoD senior leadership for autonomy, artificial intelligence (AI), and robotics technologies in such applications as advanced manufacturing and mobility. Dr. Hudas also serves as a primary technical reviewer for the Army Research Office (proposals and Multidisciplinary University Research Initiatives), the Defense Advanced Research Projects Agency technical proposals and efforts, and Small Business Innovative Research proposals concerning robotic and vehicle technologies. He also was a government advisor on the Defense Science Board Summer Study on Autonomy (2015). Dr. Hudas is a member of the Acquisition Corps and Level III certified in multiple areas. He received his BS and MS in electrical and computer engineering from Wayne State University and PhD in electrical and systems engineering from Oakland University in 2003. Dr. Hudas has authored/co-authored more than 40 technical journal articles and major conference papers.

WAYNE KING is an internationally recognized leader in metal AM, having worked in the field since 2011. He is a Principal ADDvisor® with The Barnes Global Advisors. He has more than 30 years of experience ranging from fundamental materials research and applied science to research management. Mr. King served as the project leader of the Accelerated Certification of Additively Manufactured Metals Project at Lawrence Livermore National Laboratory. He has developed a deep understanding of the AM process through this work. Past work includes radiation effects, high-temperature oxidation, atomic structure of interfaces, and grain boundary engineering. He is a 2004 Distinguished Alumnus from Thiel College. Over the past 5 years, Mr. King published several papers in AM and has made several social media posts about AM.

ADE MAKINDE is currently an independent consultant in AM. Previously, he was a principal simulation engineer at VulcanForms, Inc., a manufacturer of a novel AM machine and a supplier of parts to original equipment manufacturers in the orthopedic and aerospace industries. His experience includes the application of numerical methods to optimize the additive parts build process and subsequent post-processing to meet desired property and performance requirements. He was a principal engineer at the GE Global Research Center from 1997 to 2022. While at GE, he supervised researchers in the use of finite element analysis, computational fluid dynamics, and the development of specialized numerical and microstructural tools to optimize manufacturing processes and part design for manufacturability. He was also part of the management staff responsible for overseeing the development of analytical tools and processes to aid the design of new products and parts for all of GE's businesses. Dr. Makinde worked closely with GE's suppliers using analytical tools to solve time-sensitive technical issues and to ensure that yield and quality targets were met.

NABIL NASR is currently the associate provost and founding director of the Golisano Institute for Sustainability at the Rochester Institute of Technology and also the founding chief executive officer of the REMADE Institute, which is a public–private partnership (170 members) with support from DOE. Dr. Nasr also serves as an expert for the United Nations Environment Programme International Resource Panel and is a trustee of the Ellen MacArthur Foundation. He previously served on two National Academies of Sciences, Engineering, and Medicine boards (Board on Manufacturing and Engineering Design and National Materials and Manufacturing Board). Dr. Nasr's expertise is in the areas of sustainable manufacturing, sustainable design, life-cycle engineering, and remanufacturing engineering. He has two master's degrees from Rutgers University and Penn State in industrial and systems engineering and a PhD in industrial engineering from Rutgers University.

ABDALLA NASSAR is the vice president for Additive Manufacturing Forward Technologies at the Applied Science and Technology Research Organization of America, a 501(c)(3) nonprofit, nonpartisan research institute and think tank. He leads initiatives to accelerate the adoption of advanced manufacturing and AM within the U.S. defense industrial base. This includes conducting enabling research, supporting supplier technology access, and fostering workforce development. Previously, Dr. Nassar served as the Enterprise AM Lead for John Deere, where he developed and implemented global strategies and roadmaps for metal and polymer AM. His leadership resulted in the integration of AM into production, a 50 percent reduction in in-house metal AM production costs, the publication of new internal standards, and projected new AM product revenue in the millions. Prior to John Deere, he was a department head within the Materials Science Division of the Applied Research Laboratory and an associate research professor at Penn State. There, he managed a team of faculty, engineers, and support specialists, executing research programs (TRL 1–8) to meet sponsor needs. He also developed and taught graduate-level courses on AM principles and laser-materials interactions. Dr. Nassar has secured more than $10 million in funding for government and industry projects, published more than 50 peer-reviewed articles, and holds more than a dozen patents and invention disclosures. He is a co-author of the 2023 textbook *Additive Manufacturing with Metals—Design, Processes, Materials, Quality Assurance, and Applications*. Dr. Nassar received his BS and PhD degrees in engineering science and mechanics from Penn State in 2008 and 2012, respectively. His contributions to the field have been recognized with awards such as the 2020 Freeform and AM Excellence (FAME) Jr. Award, the 2020 Applied Research Laboratory Research Publication award, and the 2021 Black Engineer of the Year Awards' Modern Day Technology Leader and Science Spectrum Trailblazer awards. Additional engagements include serving as a division editor for the 2023 *ASM Handbook, Volume 24A, Additive Manufacturing Design and Applications*, severing as a co-lead on the 2023 Army Research Laboratory AM Tech Forecasting virtual workshop, and as a panelist and speaker at the 2023 National Institute of Standards and Technology's Workshop on Empowering Small and Medium Size Enterprises Through Effective AM Data Management.

RALPH NUZZO is the G.L. Clark Professor of Chemistry Emeritus (as of 2022) at the University of Illinois at Urbana-Champaign. He is the author or co-author of more than 350 peer-reviewed papers and 48 awarded U.S. patents. He joined the Illinois faculty in 1991, where he also held an appointment as a professor of materials science and engineering. In 2014, he was appointed as an affiliated member of the Chemistry Faculty at the KTH Royal Institute of Technology in Stockholm, Sweden. He is currently a faculty associate in applied physics and materials science at the California Institute of Technology, where he served as the director of the Department of Energy Light-Materials Interactions in Energy Conversion Energy Frontier Research Center. He also was appointed as a faculty visitor in chemistry at Harvard University in 2022. Professor Nuzzo received an AB with high honors and highest distinction in chemistry from Rutgers College in 1976 and earned a PhD in organic chemistry from MIT in 1980. He accepted the position of member of technical staff in materials research at Bell Laboratories in 1980, where he was named a Distinguished Member of the Staff in Research in 1987. He is an elected member of the National Academy of Sciences, the American Academy of Arts and Sciences, and the Norwegian Academy of Science and Letters. He is a named fellow of the American Association for the Advancement of Science, ACS, the American Vacuum Society, and the Royal Society of Chemistry. He was named the Kavli Laureate in Nanotechnology in 2022. His other awards include the Forschungspreis of the Alexander von Humboldt Foundation, co-recipient of the George E. Smith Award of IEEE, co-recipient of the Wall Street Journal Innovators Award for Semiconductors, and the Adamson Award of ACS.

CHINEDUM (CHI) OKWUDIRE is a professor of mechanical engineering and a Miller Faculty Scholar at the University of Michigan. Prior to joining the University of Michigan in 2011, he was the mechatronic systems optimization team leader at DMG Mori USA. His research is focused on exploiting knowledge at the intersection of machine design, control, and computing to boost the performance of manufacturing automation systems at low cost. Dr. Okwudire has received a number of awards and recognitions, including the National Science Foundation (NSF) CAREER Award, the Young Investigator Award from the International Symposium on Flexible Automation, the Outstanding Young Manufacturing Engineer Award from SME, the Ralph Teetor Educational Award from SAE International, the SME Education Award, and the Russell Severance Springer Visiting Professorship from the University of California, Berkeley. Dr. Okwudire received his PhD in mechanical engineering from the University of British Columbia in 2009. He previously served on the 2022 National Academies' Committee on Options for a National Plan for Smart Manufacturing and on the 2021 Committee on

Strengthening the Talent for National Defense: Infusing Advanced Manufacturing in Engineering Education.

ZHENG O'NEILL is the J. Mike Walker '66 Associate Professor in the J. Mike Walker '66 Department of Mechanical Engineering at Texas A&M University and a registered Professional Engineer. She was an assistant professor/associate professor at the University of Alabama, Tuscaloosa, from 2013 to 2019. Dr. O'Neill was a principal investigator (PI) at the United Technologies Research Center (UTRC), where she led a multi-million-dollar industry and university consortium in the development and implementation of scalable modeling and control solutions for energy-efficient HVAC systems from 2006 to 2013. She is an ASHRAE fellow and International Building Performance Simulation Association fellow, current vice chair and incoming chair of ASHRAE TC 7.5 Smart Building Systems, and on the editorial board of the *Journal of Building Performance Simulation* and an associate editor of ASHRAE's *Science and Technology for the Built Environment*. She currently serves as a member of ASHRAE's Research Administration Committee, which oversees and coordinates all ASHRAE research activities. Dr. O'Neill has 25 years of industry and academic experience in building sciences and has been the PI/co-PI for projects totaling $30 million since 2014. Her current research portfolio emphasizes and exploits intelligent building operations with advanced sensors and controls; smart ventilation; grid-interactive efficient buildings; smart, resilient, and connected community; heat pump technologies; and well-being in the built environment. Dr. O'Neill has published more than 195 journal articles and conference papers. She received her PhD in mechanical engineering from the Building and Environmental Thermal Systems Research Group at Oklahoma State University in 2004.

MELISSA ORME is the vice president for additive manufacturing at The Boeing Company, where she leads AM activities ranging from engineering and manufacturing of new designs that differentiate Boeing products, to developing new materials and processes, to establishing the digital thread of the end-to-end values stream. Dr. Orme is a renowned pioneer, innovator, and leader in AM, where her seminal work spans three decades and has resulted in 15 U.S. patents and numerous peer-reviewed journal articles. She has a rich and diverse professional background, having begun her career in academia where she rose to the rank of full professor of mechanical and aerospace engineering at the University of California, Irvine. There, she established globally recognized research laboratories in the field that is now termed "additive manufacturing," where she developed methods for controlled electrostatically charged and deflected molten metal droplet deposition for precision manufacturing, direct writing of electronic components, and precise powder production. Subsequently, she transitioned from academia to high-tech startups where she served as the chief technology officer of Morf3D, a company that is focused on producing and delivering flight qualified AM hardware to the aerospace industry. From Morf3D, she was recruited by Boeing to lead AM across all business units. Dr. Orme holds a PhD in aerospace engineering from the University of Southern California.

PHILIP PARISI, JR., is an associate principal at MG Engineering DPC, a private consulting engineering firm in the building construction industry. He has more than 24 years of experience in plumbing and fire protection engineering and responsibilities, including office and project management, specification, and standards development for plumbing and fire protection systems. His expertise includes the design of health care facilities, life science and research laboratories, high-rise commercial and residential buildings, building repositioning, and major infrastructure upgrades. Mr. Parisi is a licensed Professional Mechanical and Fire Protection Engineer in the State of New York and 17 additional states and a U.S.G.B.C. LEED Accredited Professional passionate about water conservation, rainwater harvesting, and reuse. He is an active member and past president of the American Society of Plumbing Engineers New York City (NYC) Chapter, as well as member of the National Fire Protection Association and the Society of Fire Protection Engineers. Mr. Parisi served as an adjunct professor at the New York University School for Continuing and Professional Studies and as a guest professor at the Columbia University School for Professional Studies teaching plumbing and fire protection design in the construction industry. He graduated from Rutgers, the State University of New Jersey, with a bachelor's degree in mechanical engineering in 2000. He is currently the chair of the NYC Plumbing Code Revision Committee and for International Code Council (ICC) Standard 805 Rainwater Harvesting Systems Committee and is the vice chair of the ICC 815 Sizing Water Distribution, Sanitary Drainage and Vent Piping Systems committee.

MICHAEL POUCHAK currently works as a research and development engineer, serving as a systems architect and engineering staff for Honeywell International in the Building Automation, Buildings Management Systems group. Before Honeywell, he worked on high-speed emitter-coupled logic (ECL) interfaces, ECL automated test equipment (ATE) computer design, ATE/PC network communications, a Unix Host controller server, data storage hardware/software design interface, electrical hardware design engineering, and network computer systems for the ATE industry. Mr. Pouchak has contributed significantly to the art and science of HVAC and has been issued more than 26 U.S. and international patents and products related to air HVAC systems, DDC controls, and hydronic controls for commercial buildings. He has substantial expertise in the development of building automation controls and high-volume, low-cost embedded software development of commercial unitary HVAC zone controllers, including VAV and CVAHU controllers. Mr. Pouchak received the Dick Fitzgerald Technical Award, the Honeywell Excellence in Innovation award (division level), and the Big "H" award for excellence in high-value product development. He is a senior member of IEEE, a fellow of ASHRAE, and is currently the president of the ASHRAE College of Fellows. He is the recipient of the Exceptional Service Award and the Distinguished Service Award and has had a wide range of society committee leadership roles. He has served as the chair of the technical committees TC 1.4 Control Theory and Application and TC 1.5 Emerging Computing Application and serves on the ASHRAE Technical Council and the Residential Buildings Committee as a voting member. Mr. Pouchak has a BEE from the University of Minnesota in Minneapolis and an MS in software engineering from the University of St. Thomas in St. Paul, Minnesota.

CURTIS A. RICHARDSON is a technical fellow at Spirit AeroSystems in the area of automation and the enterprise distinctive capability leader for Industry 4.0. In these roles, he leads technical oversight of strategy for automation and digital manufacturing capabilities at the corporate level. With more than 25 years of experience developing and deploying automation technology for production environments at Boeing and now Spirit, Mr. Richardson has worked with a diverse assortment of aircraft manufacturing processes. These span various levels of fabrication, assembly, and repair for both metal and composite material systems. Throughout most of his career, he has actively engaged with a broad array of consortia and similar collaborative organizations linking industry, academia, and government. He served on the Robotic Industries Association board of directors for almost 10 years and has been an active member of the Advanced Robotics for Manufacturing (ARM) Innovation Institute's Stakeholder Executive Council for 7 years. In 2022, he was recognized as SAE's Thomas H. Speller award winner for significant career contributions to manufacturing processes and methodologies related to automated fastening and was named a 2023 ARM Institute Champion. Mr. Richardson received his BS in aerospace engineering from Wichita State University in 1998 and his MS in industrial engineering from Wichita State University in 2003. He was a contributor to the 2013 edition of the *Roadmap for US Robotics—From Internet to Robotics* and has been a regular presenter at a range of professional and academic conferences, including SAE Aerotech, the International Federation of Robotics' International Symposium on Robotics, the Defense Manufacturing Conference, and the North Atlantic Treaty Organization's Science and Technology Research Symposium on Digital Twin Technology Development and Application. Mr. Richardson is also the owner of the Industrial Robotics LinkedIn group with more than 130,000 members.

BALAJI SANTHANAKRISHNAN is an experienced sustainability leader with more than 30 years of experience and has developed hundreds of strong customer relationships by understanding their environmental challenges, desired outcomes, and success criteria while developing carbon reduction programs. He is currently a global technical leader with IBM Sustainability Software. Before this role, he was a product manager with Siemens Building Technologies and an enterprise program manager with Johnson Controls. He has a bachelor's degree in mechanical engineering and a master's degree in energy management. He is a member of ASHRAE and the Association of Energy Engineers and a Certified Energy Manager from a LEED-accredited professional.

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MOHSEN SEIFI is the vice president of Global Advanced Manufacturing Programs at ASTM International, ascending to this pivotal role in 2022 after initiating his journey with the organization as the director of Additive Manufacturing Programs in 2018. With more than 13 years of enriched experience in advanced manufacturing and business development, Dr. Seifi has demonstrated exemplary leadership and technical expertise. Prior to his engagement at ASTM, he managed and contributed significantly to various research and business programs, particularly those funded by the government, showcasing his deep technical expertise and adeptness in business development. Currently, Dr. Seifi spearheads several critical programs at ASTM, including Additive Manufacturing, Robotics & Autonomous Systems, and Wohlers Associates. He guides a team of industry and technical experts in advancing ASTM's initiatives in advanced manufacturing. His responsibilities also extend to driving standardization activities across ASTM's technical committees related to advanced manufacturing, fostering new partnerships, and developing AM standards-related programs and services across diverse ASTM portfolios. Besides his professional commitments, Dr. Seifi serves as an adjunct faculty member at Case Western Reserve University and holds positions on several advisory boards for major advanced manufacturing programs. His scholarly contributions include co-authoring more than 50 peer-reviewed publications and amassing more than 4,500 citations. Dr. Seifi's extensive engagement with the scientific and professional community is further highlighted by his delivery of more than 150 invited and keynote lectures at various technical meetings, industry events, and government agencies, alongside chairing numerous conferences and symposia. His profound contributions to the field have been recognized with numerous honors and awards from technical societies.

VISHALDEEP SHARMA is a research and development staff member in the Building Equipment Research Group at Oak Ridge National Laboratory (ORNL) for the past 13 years. At ORNL, he has been involved in the assessment and evaluation of low global warming potential refrigerants and refrigeration systems. He has expertise in system design optimization, refrigerant compatibility, and refrigerant fractionation analysis. He has authored and co-authored more than 60 peer-reviewed journal articles, conference papers, and reports. He has served as a reviewer for leading journals, including *International Journal of Refrigeration*, *Applied Thermal Engineering*, *Applied Energy*, and *International Journal of Heat and Mass Transfer*. Mr. Sharma is member of ASHRAE, where he is chairing the Research Subcommittee of ASHRAE 10.7 Commercial Food and Beverage Refrigeration Equipment.

LARRY M. SWEET is currently the director of engineering at the ARM Institute. He is a widely recognized robotics and automation expert, working in both commercial organizations and academia. He provides experience in bringing emerging technologies into production by increasing their technology readiness level, concurrent with improvements in factory floor processes and workforce skills. At Amazon, he led the technology transition of all internally developed robotics and automation products from laboratory status into end-to-end systems in Amazon's global network, responsible cumulatively for 70 percent of Amazon's installed robotics. The ROBIN robot was deployed during the COVID-19 pandemic to meet urgent customer demand requiring field deployment at scale, concurrent with innovations of AI/machine learning algorithms, advanced manipulation, exception handling, and synchronization with mobile robot traffic flows. As the chief technology officer at Symbotic, he led the development of systems now deployed across Walmart's network, delivering aisle-specific pallets to grocery stores, an NP-hard problem with more than 20,000 SKUs of varying dimensions, weights, compliance, and aisle assignment, while delivering cartons to palletizing cells in precise sequence by fleets of high-speed autonomous mobile robots picking orders from a multi-level storage structure. As the Frito-Lay vice president of engineering and technology, he transformed, with three industry-first inventions, 1,200 integrated automated seasoning, packaging, and case packing lines from inflexible single-SKU systems to multi-SKU capability, improving 24/7 product flows by two times. Dr. Sweet also held senior manufacturing and technology roles at ABB Industrial & Building Systems, United Technologies, GE Fanuc, and GE Corporate Research. Industry recognition includes 35 patents, the Edison Award, Manufacturing Leadership Council Outstanding Achiever Award for Supply Chain Excellence for the Symbotic system, and the IR-100 Award. For the U.S. National Roadmap for Robotics Research, Service Robotics, where he co-authored the "Real-Time Planning and Control" section. He was a founding associate editor for the IEEE *Transactions on Robotics and Automation Systems*. He received his PhD and MS from MIT and a BS from the University of California, Berkeley. He was a tenured faculty member and Guggenheim Foundation Fellow at Princeton University and the associate director at the Institute of Robotics and Intelligent Machines at Georgia Tech.

G. KUMAR VENAYAGAMOORTHY is the Duke Energy Distinguished Professor of Power Engineering and a professor of electrical and computer engineering at Clemson University since 2012. Prior to that, he was a professor of electrical and computer engineering at the Missouri University of Science and Technology (2002–2011) and a senior lecturer in the Department of Electronic Engineering at Durban University of Technology in South Africa (1996–2002). Dr. Venayagamoorthy is the founder (2004) and director of the Real-Time Power and Intelligent Systems Laboratory. He received his PhD and MScEng in electrical engineering from the University of Natal in Durban, South Africa. He received his BEng degree with a first-class honors in electrical and electronics engineering from Abubakar Tafawa Balewa University in Bauchi, Nigeria. He holds an MBA in entrepreneurship and innovation from Clemson University. In the past 30 years, Dr. Venayagamoorthy's research has primarily emphasized the development and implementation of advanced computational methods and AI-based algorithms for smart grid applications (e.g., nonlinear modeling and control of power systems, power system optimization, predictions and forecasting of wind and solar energies, energy management systems, wide area monitoring and control systems, dynamic optimal power flow, electric vehicles, micro-grid systems, demand-response management). He has developed situational awareness and intelligence tools based on synchrophasor data for electric power control center operations and management. He is the pioneer in the development and implementation of adaptive and optimal neuroidentifiers and neurocontrollers for power systems. Indirect adaptive control and adaptive critics based optimal controllers have been implemented to control synchronous generators under normal operating conditions and disturbances on actual micro-machines. The adaptive critic control framework has been extended to other smart grid applications, including FACTS control, wide area control systems, PV energy management systems, wind farm control, and electric vehicle-to-grid transactions. Dr. Venayagamoorthy has demonstrated that distributed SmartParks (plug-in vehicles/electric vehicles parking lots) can be used as virtual FACTS devices and grid shock absorbers (damp oscillations), and with intelligent control can mitigate power system oscillations caused by dynamic operation of wind farms and system disturbances. He is an inventor of technologies for scalable computational intelligence for complex systems, energy management systems, and dynamic stochastic optimal power flow. He is a 2004 NSF CAREER awardee, a 2007 Office of the Naval Research Young Investigator Program awardee, and a 2008 NSF Emerging Frontiers in Research and Innovation awardee. He led the brain2grid project funded by NSF. He has published more than 550 refereed technical articles that are cited ~24,000 times with a h-index of 70 and i10-index of more than 300. Dr. Venayagamoorthy has given more than 500 invited technical presentations, including keynotes and plenaries in more than 40 countries. He has provided research guidance and/or mentoring to more than 150 graduate and undergraduate students and post-doctoral fellows. He is a fellow of IEEE, IET (UK), the South African Institute of Electrical Engineers, and Asia-Pacific Artificial Intelligence Association, and a senior member of the International Neural Network Society (INNS). He is the editor of the IEEE *Press Series on Power and Energy Systems*. He is also a member of the board of governors and the vice president for industry relations of INNS.

GARY WALKER is currently the vice president, Facilities and Capital Projects, at Seattle Children's Hospital. Previously, Mr. Walker was the executive director, Facilities Infrastructure and Safety, at Stanford Health Care. He has specialized in the development and implementation of asset management and digital solutions for Owners. Mr. Walker has more than 30 years of experience as an asset manager for the built environment; as a director, advisor, and consultant at General Motors Corporation, Jacobs Engineering, DOE at the National Ignition Facility, and Stanford Health Care. He is also an active thought leader on the national and international stages being a frequent presenter of content and keynote presentations, serving in the International Organization for Standardization Technical Committee 251 for Asset Management representing the United States internationally through an American National Standards Institute–authorized, ASTM-sponsored Technical Advisory Group. In addition, Mr. Walker remains active in the industry as a member of the Institute of Asset Management and the American Society of Healthcare Engineering, and as a licensed Professional Engineer. He received his BS in mechanical engineering from the University of Illinois at Urbana-Champaign in 1985.

YUNSONG XIE is currently a data scientist at the ExxonMobil Technology & Engineering Company. Prior to this position, he served in process integration engineering in Samsung Austin Semiconductor, where he supervised the semiconductor manufacturing chips for 45nm, 28nm, and 14nm node technologies. Before working at Samsung, he was a post-doctoral researcher at Argonne National Laboratory, where he conducted research on developing the next generation of wearable electronics and tracing human activity. Dr. Xie received his BA in electrical engineering from the University of Electronic Science and Technology of China in 2009 and his PhD in physics from the University of Delaware.