# Advanced Manufacturing is a NIST Priority

## NIST Technical Laboratories

<table>
<thead>
<tr>
<th>Laboratory Name</th>
<th>Focus Area</th>
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<tbody>
<tr>
<td>Manufacturing Engineering Laboratory (MEL)</td>
<td>Discrete mechanical parts / Mfg systems, processes, &amp; equipment</td>
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<tr>
<td>Materials Science and Engineering Laboratory (MSEL)</td>
<td>Materials / forming processes</td>
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<tr>
<td>Electronics and Electrical Engineering Laboratory (EEEL)</td>
<td>Electronics / semiconductor</td>
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<tr>
<td>Chemical Science and Technology Laboratory (CSTL)</td>
<td>Chemical / process industries</td>
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<tr>
<td>Building and Fire Research Laboratory (BFRL)</td>
<td>Construction industries</td>
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<tr>
<td>Information Technology Laboratory (ITL)</td>
<td>Information / software</td>
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## NIST Extramural Programs

<table>
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<th>Program Name</th>
<th>Focus Area</th>
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<tr>
<td>Hollings Manufacturing Extension Partnership (MEP)</td>
<td>Small-to-medium size companies</td>
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<tr>
<td>Technology Innovation Program (TIP)</td>
<td>Innovative, high risk research</td>
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<tr>
<td>Baldrige National Quality Program (BNQP)</td>
<td>Quality improvement / awards</td>
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Multiple MEL Programs Impact Advanced Manufacturing

- Dimensional Metrology
- Nanomanufacturing Metrology
- Next Generation Nanometrology

- Measurements & Standards for Science-Based Manufacturing
- Mechanical Metrology
- Metrology for Advanced Optics

- Robots and Automation Interoperability Standards
- Intelligent Manufacturing Industrial Control Systems and Network Standards
- Measurement Science for Manufacturing Robotics and Automation

- Supply Chain Integration
- Sustainable Manufacturing
Focus of this Briefing

- Dimensional Metrology
- Nanomanufacturing Metrology
- Next Generation Nanometrology
- Measurements & Standards for Science-Based Manufacturing
- Mechanical Metrology
- Metrology for Advanced Optics
- Robots and Automation Interoperability Standards
- Intelligent Manufacturing Industrial Control Systems and Network Standards
- Supply Chain Integration
- Sustainable Manufacturing
- Measurement Science for Manufacturing Robotics and Automation
MEL Program at a Glance

**Program Title:** Measurements and Standards for Science-Based Manufacturing

**Lead Division, Program Manager:** MMD, Alkan Donmez

**Resources:** about $3M funding; approx. 12 NIST staff and guest researchers; facilities include NIST Shop Floor, Pulse-Heated Kolsky Bar, Micro-scale Machining Laboratory

**Program Challenge:** Provide competitive advantage and stimulate innovation for U.S. manufacturers by developing the metrology and standards infrastructure necessary for a science-based approach to the manufacture of complex, high-value, knowledge-intensive products

**Primary Outputs:** New metrology devices, methods, performance metrics, & standards; industry workshops; technology transfer

**Customers and Collaborators (sampling):** Third Wave Systems, Kennametal, Caterpillar, United Technologies Corp., U.S. Army, Los Alamos National Laboratory, AMT, Lockheed Martin, Atometric, Agilent
A Future Vision of U.S. Manufacturing

- Fundamental changes in U.S. manufacturing have occurred due to global economic and technological forces.
- Manufacturers must adapt to new challenges and market demands:
  - e.g., shorter innovation cycles; improved quality, functionality, and performance; flexible and reconfigurable automated systems; integrated supply networks; reduced environmental impacts.
- New cornerstones for growth and prosperity: complex, high-value, knowledge-intensive, highly-customized products and processes.
- Future strategy must be focused on innovative products and processes:
  - "the big winners ...will be those who develop talent, techniques, and tools so advanced that there is no competition." (PCAST)
Unique NIST Role - Measurements and Standards

- Emphasis on infrastructural metrology and non-proprietary, standardized metrology methods that address a broad class of measurement challenges
- Emphasis on rigorous and generic procedures to characterize measurement uncertainty that comply with international standards
- Long-term commitment, expertise, and neutrality essential for harmonized and unbiased national and international standards
- Leverage NIST core competences in measurement science, rigorous traceability, and development and use of standards -- as well as specific expertise in measurements and standards for manufacturing systems, processes, and equipment
Program Strategy

- Focus is on overcoming key barriers to innovation caused by insufficient measurements and standards infrastructure.

- Each program area to have direct relevance and impact on the future vision of U.S. manufacturing.

- Fundamental metrology and standards to be relevant to a wide variety of new and emerging manufacturing processes and equipment:
  - e.g., multi-function and reconfigurable fabrication systems, additive manufacturing systems, intelligent assembly systems, meso/micro-scale fabrication systems.

- Build upon NIST expertise, along with substantial partnerships with industry, academia, and other government agencies.
<table>
<thead>
<tr>
<th>Future Vision of U.S. Manufacturing</th>
<th>Current Barrier to Innovation</th>
<th>Impact on U.S. Manufacturers</th>
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<tbody>
<tr>
<td>Knowledge-intensive products and processes</td>
<td>Insufficient science-based understanding of manufacturing processes to achieve desired products with high productivity</td>
<td>Limits ability to produce knowledge-intensive products and to make cost-effective decisions in response to changing conditions</td>
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<tr>
<td>High-value, complex products and processes</td>
<td>Lack of fundamental metrology, standards, and performance metrics for accurate, complex motion of manufacturing equipment (five or more degrees-of-freedom)</td>
<td>Limits ability to produce complex, high-value products</td>
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<tr>
<td>Accurate, intelligent, and automated manufacturing processes</td>
<td>Lack of metrology methods, standards, and performance metrics to achieve accurate, real-time, on-machine (in-situ) part measurement and certification</td>
<td>Increased production time and higher costs, resulting from current need for off-line inspection of manufactured parts based on time-consuming methods that need equipment and specialized environments removed from the production floor</td>
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**Science-Based Manufacturing - Objective 1**

**Objective 1:** Develop advanced process metrology methods and tools to increase scientific understanding of manufacturing processes to enable cost-effective production of knowledge-intensive products and cost-effective decision making in response to changing conditions in the manufacturing environment.

*Project 1.1: Fundamental metrology for material processing*

*Project 1.2: Investigation of measurements and standards needs for metal-based additive processes*
Fundamental Metrology for Material Processing

- Competitiveness requires process planning based on scientific principles to efficiently produce the first and every part to specification
- Industry roadmaps highlight the need for generic process models that address:
  - a large variety of process conditions
  - high-performance manufacturing equipment and tooling
  - complex part geometries and high-performance materials
- Advancement of such generic models requires:
  - Advanced simulation tools
  - Material properties under manufacturing conditions
  - Data on phenomena during material processing
Material Properties under Manufacturing Conditions

- Material handbooks do not address the extreme conditions of high-performance processes (high strain rates, high temperature rates)
  - Industry still requires application oriented (machining) experiments
- NIST pulse-heated Kolsky bar provides data under extreme conditions
  - Also for modeling catastrophic events and (body) armor performance

- Unique capability to heat sample to 1200 K in less than 0.5 s
- Strains up to 50%
- Strain-rates up to 8000 s\(^{-1}\)
- Thermal camera
- High-speed visual camera
Measurement of Process Phenomena
(for example machining of Ti-6Al-4V)

- Machining of titanium is a challenge that requires careful process design:
  - Low modulus of elasticity (part springback, tool rubbing, chatter)
  - Work hardening (high cutting pressure, heat generation)
  - Low heat conductivity (tool wear)
  - Chemical reactivity (tool wear)

- NIST develops measurement methods and provides data for:
  - Temperature distribution (tool, chip, workpiece)
  - Material flow and strain distribution
  - Cutting forces and surface quality
  - Chip morphology (e.g., segmentation)

- Results are used by developers of cutting tools and process simulations

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![Cutting speed](image1)

Material flow during segmented chip formation estimated using high-speed microvideography

![Temperature distribution](image2)

Temperature distribution of tool, chip, and workpiece obtained using high-speed infrared micro-videography
NIST Contributions to Process Improvement

**Process Characteristics:**
- Strain: 200 % to 2000 %
- Strain Rates: \(10^{3}\) s\(^{-1}\) - \(10^{7}\) s\(^{-1}\)
- Temperatures: 100 °C – 1000 °C
- Heating rate: up to \(10^{6}\) °C /s

**Workpiece Process**
- Geometry
- Material
- Morphology
- Predeformation
- Fixturing

**Cutting tool**
- Geometry
- Material
- Coating

**Process**
- Speed
- Feed
- Depth
- Path
- Lubricant

**Machine**
- Stiffness
- Damping
- Accuracy

**Model or Simulation**

**Input**

**Output**
- Part form and size
- Surface finish
- Subsurface layer (e.g. residual stress)
- Tool wear (failure)
- Chip morphology
- Cutting forces and power
- Machining time

**Measurement methods and data**
- Material properties
- Temperature distribution
- Velocity field (strain)
- Chip morphology
- Cutting forces
- Deflections
- Subsurface properties
- Tool wear
New Focus on Additive Manufacturing

- Substantial MEL expertise in equipment and process metrology, process control, and remote sensing to be applied to Additive Manufacturing

- Known limitations and barriers:
  - surface finish of contoured surfaces
  - part accuracy
  - fabrication speed
  - material density and associated material properties
  - approximated part model as data interface

- Recent formation (Jan. 2009) of new ASTM standards committee F42 on Additive Manufacturing Technologies
  - Initiated with Society of Manufacturing Engineers (SME), Rapid Technology & Additive Manufacturing community
  - Subcommittees formed for Terminology; Test Methods; Processes; Materials; Design
Objective 2: Develop fundamental metrology, standards, and performance metrics for accurate complex motion of manufacturing equipment enabling the production of complex high-value products

Project 2.1: Metrology and standards for coordinated 5-axis motion
Metrology of Complex Motion

- Many high-value components have complex shapes (e.g., turbine blades) that require precise complex motion of the manufacturing equipment.
- Quick assessment of the accuracy of complex motion is difficult.
- No standard measurement methods exist for 4-axis and 5-axis motion (coordination of linear and rotary axes).
Metrology of Complex Motion

- Modeling and simulation of complex motion to predict limiting behavior and to develop test patterns
- Developing new measurement methods to characterize the accuracy of complex motion using:
  - Circular tests
  - Rotation tests about a single point (R-test)
  - Cutting test artifacts
- Contributing to new ISO and ASME standards ensuring harmonization
Objective 3: Develop metrology methods, standards, and performance metrics to achieve accurate, real-time, on-machine (in-situ) part measurement and certification, to enable future elimination of off-line part inspection

*Project 3.1: In-situ 3D optical and mechanical metrology of fabricated parts*

*Project 3.2: Performance metrics for manufacturing equipment used as measuring tools*

*Project: 3.3: Manufacturing process monitoring and control using wireless sensor networks*
In-situ Optical Measurements of Fabricated Parts

- Of several possible measurement approaches, recent MEL efforts have investigated the fringe projection technique.

- Fringe projection answers many in-situ measurement challenges:
  - Decoupling of machine uncertainty and measurement uncertainty
  - Large field of view, No moving parts
  - Small work volumes of micro/meso-scale machine tools and unique machine designs
  - Large variety of part shapes and sizes
  - Flexible setup
  - Withstanding the harsh machining environment
  - Long working distance
Fringe Projection

- Fringe projection measurement is based in photogrammetry
  - Photogrammetry is the process of obtaining information about physical objects by interpreting photographic images
- 3-D part geometry is obtained through triangulation
- Projecting known patterns provides a reference for transformation from camera coordinates to real world coordinates
NIST Fringe Projection System

Prototype implementation on a meso-scale machine tool
Industry is pressured to use machine tools for on-machine part verification (reduced cost, faster turn-around)

On-machine part probing requires a clear understanding of measurement uncertainty

There are no standards enabling such assessment

NIST is contributing to new ISO standards that describe methods to assess the measuring capability of machine tools
(Initial focus: machines with probing systems)
Manufacturing Process Monitoring and Control Using Wireless Sensor Networks

- Developing algorithms to identify and diagnose process conditions in “noisy” manufacturing environments

- Integration and correlation of data from multiple sensors that monitor different aspects of the manufacturing system

- Contributing to IEEE standards for specifying plug-and-play smart sensor interfaces and sensor networks

- Participating in AMT MTConnect effort as a member of the Technical Advisory Group (TAG)

Wavelet Envelop Spectrum (WES) diagnoses spindle condition with increased sensitivity for early fault detection, preventing costly spindle failures
Conclusion

- Program builds on MEL core competences in manufacturing equipment, processes, sensors, and system integration
- Program addresses high-priority needs that will help U.S. manufacturers
- Your feedback and collaboration are welcome!
  - Future vision of U.S. manufacturing
  - MEL program activities
- Further information provided during lab visits on Thursday afternoon - visit to NIST Shops
Questions?
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