Manufacturing Metrology Programs

Advanced Manufacturing Systems

Annual FTEs:	14.0 NIST staff
	4.0 guest researchers
	18.0 total FTEs

NIST Kolsky Bar Lab

Challenge:

Develop, validate, and demonstrate the critical metrology, standards, and infrastructural tools needed by U.S. industry to realize cost-effective, knowledge-integrated, autonomous intelligent manufacturing systems.

Overview

U.S. manufacturing is undergoing fundamental changes in response to global economic forces. Industry trends are shaping a new future for U.S. manufacturers – one where high-value, knowledge-intensive, highly-customized products and processes will be the new cornerstones for growth and prosperity. In labor-intensive commodity sectors, U.S. manufacturers currently face substantial competitive and cost disadvantages. To remain competitive and promote growth, manufacturers must adapt to new challenges and market demands that require more complex and individually customized products with improved quality, functionality, and performance. Such rapidly changing market demands necessitate shorter innovation cycles, more flexible and rapidly reconfigurable manufacturing systems, integrated and streamlined communications and supply chains, reduced environmental impacts, and improved energy efficiencies. In the future, U.S. manufacturing processes must be accurate, agile, automated, flexible, intelligent, interoperable, reconfigurable, and sustainable. For this vision to come about, an underlying foundation and infrastructure must be developed and implemented so that U.S. manufacturers can quickly capitalize on future game-changing opportunities and technological innovations.

This program considers three themes as the fundamental areas of contribution:

1. Knowledge generation and improvement related to manufacturing processes and equipment
2. Unambiguous representation and communication of such knowledge and information
3. Methods and tools that can combine and integrate knowledge and information in order to make possible cost-effective decisions in response to changing conditions in manufacturing environment (including customer demand, operating conditions, and other economic and technical drivers)

Specific projects address technical challenges in one or more of these themes.

Key Accomplishments and Impacts:

- Developed a prototype robust optimizer for process parameters that incorporates modeling uncertainties, and demonstrated its use for a contoured turned part, resulting in 50% cycle time improvement.
- Completed development of a model-based, real-time error compensation system for machines in a typical shop environment at both NIST and U.S. Army Picatinny Arsenal, resulting in a 65% reduction of geometric and thermal machine errors.
- Achieved the first-ever harmonization of U.S. national and ISO standards for machine tool performance evaluation, giving U.S. industry a new ability to unambiguously compare and specify machine tools, establish mutual obligations between buyers and sellers, and improve manufacturing productivity and product quality.
- Completed development of a pulse-heated Kolsky bar facility to measure material properties during rapid heating and rapid increase of strain. Data obtained for AISI 1045 steel improved the ability of finite element-based machining simulations to predict process phenomena such as cutting forces and temperatures observed during machining experiments.
- Completed development of a high-speed, dual-spectrum (visible and infrared) micro-videography system to measure material flow and temperature distribution during orthogonal cutting. Collaborators, including Los Alamos National Laboratory and Third Wave Systems, are using data obtained in this way to validate and improve models and simulations of machining processes.
- Initiated and led a new standards activity that developed the IEEE 1588 standard, the highest-precision clock synchronization protocol for networked measurement and control.

Future Directions and Plans:

The measurements and standards scope of this program is in transition – from a prior MEL emphasis on smart machining systems to a focus on high-priority, advanced manufacturing systems needed by U.S. industry in the global economy. Industry needs and priorities will be a primary driver for future programmatic choices.

Awards and Recognition

- Alkan Donmez and Hans Soons received the 2006 Department of Commerce Silver Medal Award for Exceptional Federal Service for outstanding leadership and achievements leading to the first-ever harmonization of national and international standards for machine tool performance.
- Kang Lee received the 2006 NIST Equal Employment Opportunity / Diversity Award for 25 years (e.g., 1,500 Saturdays) of dedication to education and inspiration of middle and early high school students through hands-on science with the "Adventures in Science" program.
- Michael McGlauflin received the 2007 NIST Bronze Medal Award for Superior Federal Service for sustained achievements and excellence in providing outstanding technical support for machine tool metrology and performance standards.

- Hans Soons received a Certificate of Appreciation from the ASME Council on Codes and Standards for his major contributions to the work of the ASME B5/TC52 Standards Committee on machine tool performance evaluation. [February 2005]
- Kang Lee was profiled in a special issue of the EE Times publication on "Great Minds, Great Ideas" about people and technologies that change marketplaces and open new opportunities. The issue profiled 29 innovators in the world who make a difference in their field, transform markets, and change the way people work, live, and play.

  The story "Paving the Road to Ubiquitous Computing" recognized Kang as an innovator in that area. [December 2005]
- Kang Lee received the 2006 Society Award from the IEEE Instrumentation and Measurement Society for his dedicated contribution and services as Chair of the Technical Committee on Sensor Technology. Under Kang's leadership, this committee developed the IEEE 1451 smart transducer interface standards and IEEE 1588 standard for precision clock synchronization. [April 2006]
- Kang Lee was selected by the IEEE Instrumentation and Measurement Society as an IEEE Distinguished Lecturer on the topics of smart sensors and distributed measurement and control systems. [June 2007]
- Kang Lee was recognized in the preface of a book written by Dr. John Eidson of Agilent Technologies about the IEEE 1588 standard for precision clock synchronization. Kang chairs the IEEE Committee on Sensor Technology that was responsible for developing this standard. According to Dr. Eidson, "Everyone using IEEE 1588, including myself, owes special thanks to Kang Lee of NIST not only for his work as the IEEE sponsor of the standard, but also for his tireless efforts in its promotion."
- Program activities and results were highlighted in several trade magazines, including Industrial Engineering (July 2005), Fabrication and Metalworking Magazine (October 2006), Manufacturing Engineering (November 2006), and Mechanical Engineering (upcoming in 2008).

Projects

Advanced Manufacturing Systems Program

Physics-based Modeling of Machining

(Status: to be completed in FY2010)

Challenge/Problem Addressed:

Machining models have not yet reached their full potential as robust tools for process planners and tool designers, despite many academic studies and commercially available (finite element) simulation tools that predict machining performance. Existing models suffer from a lack of constitutive models to describe material behavior during the rapid increase of strain and rapid heating encountered in (high-speed) machining. Commercial modeling packages provide proprietary solutions to compensate for this missing information, but with variable success. Furthermore, there are no reliable methods to assess the performance of these models for generic applications. Fine-tuning such models for specific applications defeats the original purpose of using models to predict machining performance. One specific challenge related to assessment of machining models is to obtain an accurate measure of material flow and temperature distribution at the tool-workpiece interface. Although significant efforts have been pursued to measure cutting temperatures, the uncertainties associated with such measurements (reported or unreported) make the assessment of machining models very difficult.

Objective

Develop measurement methods and reference data to assess and improve the uncertainty of state-of-the-art physics-based machining models.

Accomplishments:

- Completed development of a pulse-heated Kolsky bar facility to measure material properties during rapid heating and rapid increase of strain. Capabilities include: strain rates up to 10^4 s^{-1}; a rapid heating capability of 1000 °C in 0.5 s; network-based database and data processing; and finite element models of sample behavior. Recent advances include compensation for the behavior of the graphite layer between the sample and the instrument, measurement and improvement of sample temperature uniformity, and heating rate control.
- Applied Kolsky bar data obtained for AISI 1045 steel to finite element machining simulations and improved the ability to predict cutting forces and temperatures observed during machining experiments.
- Developed a new orthogonal machining setup to validate physics-based machining models. Completed development of a high-speed, dual-spectrum (infrared and visible) micro-videography system to measure material flow and temperature distribution.
- Characterized and improved the uncertainties of thermal measurements during orthogonal cutting (e.g., camera calibration, stray reflections, emissivity changes during machining).

- Demonstrated the applicability of digital image correlation analysis in estimating the velocity and strain field during orthogonal cutting. Developed automated data acquisition system for chip segmentation frequency. Obtained micro-videography data for interrupted cutting.
- Collaborators such as Los Alamos National Laboratories and Third Wave Systems are using the data from these tests to validate and improve predictions of physics-based machining models.

Planned Future Accomplishments:

- Conduct Kolsky bar and orthogonal machining experiments to improve process parameter recommendations and cutting inserts for challenging alloys with high economic importance, such as titanium (planned collaboration with Kennametal).
- Perform further reduction and characterization of thermal measurement uncertainties (e.g., effects of the oxide layer on emissivity).
- Publish a guide on uncertainty assessment during thermal imaging of machining processes to improve machining process research by academia and industry.
- Lead international comparison of thermal measurements sponsored by the International Academy of Production Sciences (CIRP) to improve agreement of measurements and uncertainty statements.
- Develop strain measurement capability for the cutting shear zone to improve predictive models of machining phenomena.
- Develop new measurement method for material properties at higher strain rates than currently achieved with the Kolsky bar to better approximate conditions during high-speed machining.
- Develop a visual and thermal micro-videography measurement capability for other machining processes important to industry, such as milling.

Customers and Collaborators:

- Kennametal
- Los Alamos National Laboratory
- Third Wave Systems
- University of North Carolina at Charlotte

We provide regular updates to many companies and universities interested in our work through e.g., the annual Third Wave Systems User Conference.

Advanced Manufacturing Systems Program

Robust Optimization of Machining

(Status: to be completed in FY2009)

Challenge/Problem Addressed:

Although methods to optimize machining exist in the research community and in practical use, there is no unified methodology that combines all the information available related to process capability, machine capability, cutting tool characteristics, material properties, and other factors. Furthermore, the available knowledge and information suffers from significant uncertainties since the underlying data are often incomplete and ill-defined. Optimization that accounts for such uncertainties, providing "robust" optimum machining conditions, may require novel mathematical tools. Existing optimization tools are developed using certain objective functions and sets of constraints, but in a typical manufacturing environment requirements and conditions change frequently. Any generic optimization system should be able to adapt to these changes by allowing modifications to constraints and objective functions. Such flexibility would require all information to be represented in an unambiguous standard form, which currently does not exist.

Objective

Develop and test a prototype of a flexible and robust optimization framework that integrates all available process, machine performance, part design specifications, and associated time and cost information. This framework would help identify needs and opportunities for proper representation of knowledge and information to make possible construction of autonomous decision making tools in manufacturing.

Accomplishments

- Developed a prototype robust optimizer incorporating empirical modeling uncertainties and used the system to demonstrate 50% cycle time improvement for turning contoured production parts.
- Demonstrated integration of the robust optimizer with the STEP-NC standard, opening up possibilities for STEP-NC to deliver the much-promised capabilities surpassing those of the current RS-274 machine control language.
- Demonstrated a flexible capability for constructing optimization objectives and constraints based on business priorities, economic or technical considerations, or design specifications.
- Developed genetic algorithms to overcome difficulties in handling highly non-linear characteristics of process and equipment models in robust optimization, and obtained promising preliminary results.
- Developed preliminary interface specification for exchanging data between process planning and process optimization, paving the way for future standardization efforts.
- Developed a multi-layered framework for generalized machining optimization which includes facilities for strategic analysis (of preliminary process plans), translation of the analysis results to a set of objective functions and constraints, as well as the actual robust optimization based on these objective functions and constraints.

Planned Future Accomplishments:

- Test the interface specifications with a commercial computer-aided manufacturing system to demonstrate the validation of knowledge integration capabilities.
- Adapt the existing system to the newly acquired turning center.
- Investigate other methods of integrating machine and process information for modeling and decision making in follow-up projects.

Customers and Collaborators:

- Caterpillar
- United Technologies Corp.
- Agilent Technologies
- Techsolve
- Association for Manufacturing Technology
- Remmele Engineering
- Sikorsky Aircraft
- General Electric
- U.S. Army
- Los Alamos National Laboratory
- Oak Ridge National Laboratories
- Alcoa
- Third Wave Systems
- General Motors
- Ford Motor
- Cincinnati Lamb
- Hurco
- Hardinge Brothers
- Automated Precision Inc.
- Lion Precision
- VulcanCraft
- University of North Carolina at Charlotte
- University of Florida
- University of Maryland
- DP Technologies

Model-Based Control of Turning

(Status: completed in 2006)

Challenge/Problem Addressed:

The U.S. Army Armament Research, Development, and Engineering Center (ARDEC) located at Picatinny Arsenal required an improved machining capability to increase the accuracy of turned parts for Army products. Army personnel desired a science-based solution using adaptive machine control that incorporated sensor feedback and models of the machining process. A testbed was needed to support the integration, demonstration, and validation of prototype smart machine concepts for realistic applications on actual machine tools. Prior NIST work developed and implemented methods and software to improve the accuracy of machine tools and coordinate measuring machines. Candidate types of machines for effective error compensation generally have highly repeatable motions and are located in stable environments. This project applied and extended prior concepts to address the more common low-cost machine tools operating in a regular machine shop environment. The project's success demanded the demonstration of a functional, real-time model-based control system that improved machining performance in the real production environment.

Objective

Improve the efficiency of turning operations at the U.S. Army Picatinny Arsenal and its supplier base through the application of open-architecture model-based machine control.

Accomplishments:

- Completed real-time error compensation on two separate but similar machine tools (one at NIST, one at Picatinny Arsenal) resulting in 65% reduction of machine errors.
- Fully integrated the model-based software into the machine's open architecture controller to compensate for geometric and thermal errors, using real-time data from seven temperature sensors.
- Demonstrated machining process optimization using machining models and machine performance data, yielding a 50% improvement in productivity.
- Improved the efficiency and performance of turning operations for the manufacture of Army products through an upgraded machine tool and machining capability.

Customers and Collaborators:

- U.S. Army Armament Research Development, and Engineering Center (ARDEC)
- U.S. Army Picatinny Arsenal
- Fryer Machine Tools

Advanced Manufacturing Systems Program

Machine Tool Performance Characterization and Communication

(Status: to be completed in FY2010)

Challenge/Problem Addressed:

Performance characterization of machine tools and other manufacturing equipment is difficult due to the many geometric, dynamic, and thermal sources of errors that change over time and have complex impacts on part accuracy. Existing national and international standards address various aspects of machine performance testing, but can provide ambiguous and sometimes inconsistent guidance. U.S. manufacturers and users of machine tools urgently need harmonization of the standards for performance parameters and testing methods. Since machine performance data is difficult to obtain and analyze, full-scale performance characterization is not a common practice in industry. Instead, machine vendors and users typically rely on a limited set of tests to characterize their machines. A challenge is to identify and develop ways to maximize the information obtained by the limited tests. A further complication is the need for unambiguous and comprehensive measurement methods that have an intuitive relation to the capability of a machine. Current established performance tests are designed for "unloaded" conditions when the machine tool is not cutting the workpiece. Performance tests under operating conditions must be developed such that the loads can be applied during measurement while not influencing the measurement setup or methods. Once the machine performance information is obtained, no standards exist to communicate a machine's capability throughout the manufacturing enterprise. Standardized data models and specifications to represent machine performance information would have enormous utility in resource allocation, process planning, maintenance planning, supplier selection, and business decisions. The ultimate challenge is development and validation of procedures to translate generic performance parameters into machined tolerances of specific parts, so that knowledge about machine capabilities can be used for improved product design, diagnosis of product errors, and product quality assurance in agile manufacturing environments.

Objectives:

- Harmonize national and international standards for machine tool performance testing and characterization
- Develop updated test methods and standards that address technological advances of machine tools and testing equipment
- Develop standards for representing and communicating machine tool performance and machine tool specifications
- Develop in-situ measurement systems for characterization of cutting tools and workpieces
- Develop test methods, models, and standards to characterize the performance of machine tools under operating conditions
- Develop virtual machining algorithms to evaluate machine tool capability for machining parts to specification
- Create statistical machine performance models that incorporate uncertainties about machine performance and operating conditions typical of industrial environments

Accomplishments:

- Achieved the first-ever harmonization of U.S. national and ISO standards for machine tool performance evaluation, resulting in new capabilities for U.S. industry to unambiguously compare and specify machine tools, establish mutual obligations between buyers and sellers, and improve manufacturing productivity and product quality.
- Completed ISO 230-7:2006 "Test code for machine tools – Part 7: Geometric accuracy of axes of rotation," the first-ever international (ISO) standard for evaluating the accuracy of machine tool rotary axes and spindles. This standard makes possible consistent comparison and assessment of these most critical contributors of machine tool performance.
- Completed ISO 230-2:2006 "Test code for machine tools – Part 2: Determination of accuracy and repeatability of positioning of numerically controlled machine tool axes," introducing the concepts of measurement uncertainty associated with instruments and providing guidance for how to estimate and deal with such uncertainties in assessing machine positioning performance.

- Completed ISO 230-3:2007 "Test code for machine tools – Part 3: Determination of thermal effects," introducing test methods to assess structure deformations due to thermal gradients and other operating characteristics beyond just spindle drift and linear axis growth to make possible more comprehensive assessment of machine thermal behavior.
- Contributed to development of the draft ISO/TR 230-8 "Test code for machine tools – Part 8: Vibrations," first-ever ISO technical report outlining the theoretical basis for testing machine tool dynamic characteristics, applications, and test methods. Publication by ISO is expected in the first half of 2008.
- Contributed to development of the draft ISO 230-10 "Test code for machine tools – Part 10: Determination of the measuring performance of machine tools," providing tools to assess the validity and uncertainty of on-machine touch-trigger probe-based coordinate measurements, eventually leading toward minimization of costly post-process part inspections. Publication by ISO is expected by the end of 2009.
- Developed a new automated in-situ measurement system to characterize the dynamic properties of cutting tools for chatter avoidance, reducing the need for experienced test technicians and overcoming a key barrier for widespread use of dynamic testing.
- Completed a detailed analytical study on the properties of the proposed step-diagonal test for machine tool performance evaluation and presented the results at the International Lamdamap Conference, This study provides a scientific and neutral basis for competing instrument vendors to resolve their differences.
- Designed, fabricated, and integrated an invar metrology frame to a meso-scale machine tool to permit direct measurement of cutting tool position with respect to the workpiece, eliminating Abbe offsets and thermal influences on machine performance.
- Completed the draft ANSI/ASME B5.59-1 "Data specification for machine performance tests," and obtained ASME committee approval for initiating the ballot process. This standard will be the first-ever data specification standard for the properties and results of machine tool performance tests. It will facilitate the specification, exchange, and archiving of machine tool performance data, improving manufacturing applications ranging from resource allocation decisions to performance tracking, maintenance planning, and quality control.
- Completed the draft ANSI/ASME B5.59-2 "Data specification for properties of machine tools for milling and turning," and obtained ASME committee approval for initiating the ballot process. This standard will be the first-ever data specification standard describing the properties and performance of machine tools for unambiguous communication of machine capabilities among manufacturing applications. It will facilitate better resource allocation decisions, integration of design and manufacturing, and e-commerce for more efficient supply chains.

- Developed and implemented virtual machining software algorithms to analyze the effects of machine tool and setup errors on the accuracy of hemispherical parts at Los Alamos National Laboratory. Results are used to establish selection criteria and test procedures for machine tools.

Planned Future Accomplishments:

- Develop test methods and standards to characterize 5-axis machining centers and multi-tasking turning centers.
- Finalize test methods to assess the measuring capability of machine tools using touch-trigger probes and other measuring instruments.
- Develop measuring instruments and methods to enable machine tools to self-assess their errors.
- Develop statistical tools to estimate part quality based on a small set of machine tool performance data and associated uncertainties.
- Implement and validate an in-situ measuring system for tool dynamics in high-speed machining applications.
- Validate the effectiveness of the metrology frame on the meso-scale milling machine by demonstrating improvement in machined part accuracy.
- Develop new measuring systems to enable on-machine part inspection and verification.

Customers and Collaborators:

- Caterpillar
- United Technologies Corp.
- Agilent Technologies
- Techsolve
- Association for Manufacturing Technology
- Remmele Engineering
- Sikorsky Aircraft
- General Electric
- U.S. Army
- Los Alamos National Laboratory
- Oak Ridge National Laboratories
- General Motors
- Ford Motor
- MAG Cincinnati Machine
- Hurco
- Hardinge Brothers
- Automated Precision Inc.
- Lion Precision
- VulcanCraft
- University of North Carolina at Charlotte
- University of Florida

Advanced Manufacturing Systems Program

Condition Monitoring of Machine Tools (Status: to be completed in FY2009)

Challenge/Problem Addressed:

Machine tools are complex structures with many potential sources of failure. Incompleteness of data and a low signal-to-noise ratio make it difficult to identify and diagnose the conditions of machine components in "noisy" machining environments, often leading to expensive false alarms. Data obtained from multiple sensors that monitor different aspects of the system or operation must be integrated and continuously correlated with expected signatures from the properly functioning operation.

Objectives

Develop measurement, sensing, and analysis methods and associated data specifications and metrics to verify that machine tools and machining processes are operating within expected design limits and to optimize maintenance tasks. Specifically:

- Develop optimal sensor placement methodology for condition monitoring of machine spindles
- Develop wavelet-based envelope algorithm to process sensor data for diagnostics
- Develop output-only modal analysis method for testing spindle condition
- Demonstrate remote monitoring to detect and analyze abnormal machine conditions
- Develop a framework to integrate information related to machine condition and maintenance planning
- Develop standards for smart sensor interfaces and networks

Accomplishments:

- Developed a structural dynamics-based approach for optimization of sensor placement on machine spindles using the Effective Independence (EfI) method, providing the capability to minimize the number of sensors needed to obtain all critical information for a given spindle design.
- Developed and verified a new signal processing technique using an analytic wavelet transform to extract the envelope of the defect-related vibration for diagnosis of spindle condition, increasing sensitivity to small systematic variations in bearing signatures and leading to early fault detection capabilities that prevent costly spindle failures.
- Demonstrated a method of testing spindle condition using the output-only modal analysis technique, enabling modal analysis to be a fast, non-intrusive, and cost-effective fault detection tool.
- Developed a framework to organize the cause-and-effect relationships of potential machine failures and remedial actions, leading towards more comprehensive systematic analysis, planning, and optimization of machine maintenance operations.
- Led the development and completion of two parts of the IEEE 1451 series of standards for smart sensor interfaces and networks, enabling interoperability among a variety of sensors and sensor networks.
- Initiated and led a new standards activity leading to release of the first version of the IEEE 1588 standard for precision clock synchronization for networked measurement and control.

Planned Future Accomplishments:

- Develop a suite of parameters based on combinations of waveform analysis techniques optimized for spindle condition monitoring.
- Validate optimal parameters by correlating them with metrics of spindle condition throughout its useful life.
- Expand the IEEE 1588 standard to extend precision clock synchronization to applications for industries such as aerospace, industrial automation and control, power and utility, and telecommunication.

Customers and Collaborators:

- University of Massachusetts-Amherst
- Timken
- Boeing Commercial Airplane
- Caterpillar
- United Technologies Corp.
- Agilent Technologies
- Techsolve
- Association for Manufacturing Technology
- Remmele Engineering
- Sikorsky Aircraft
- General Electric
- U.S. Army
- General Motors
- Ford Motor Company
- MAG Cincinnati Machine
- Hurco; Hardinge Brothers
- VulcanCraft
- University of Florida
- University of Maryland

Manufacturability of Fuel Cells

(Status: to be completed in FY2008)

Challenge/Problem Addressed:

Manufacturers of fuel cells are under tremendous pressure to increase production rates and improve fuel cell performance while significantly reducing the cost of production. For automotive applications, fuel cell manufacturers must be able to produce a high-performing bipolar plate every few seconds. No data exists on the influence of fabrication variations on fuel cell performance. As a result, fuel cell manufacturers and their second tier suppliers are continually searching for better fabrication methods to increase production rates and improve cell performance.

Objective

Generate a knowledge base providing the relationship between fabrication variations in bipolar plate production and single cell performance.

Accomplishments:

- Designed statistical factorial experiments (4 factors, 2 levels) for conducting and analyzing test results in order to identify relationships between fabrication variations and fuel cell performance.
- Machined a set of graphite bipolar plates with simulated errors in the flow field geometry and performed detailed dimensional inspection.
- Assembled the NIST-fabricated plates with original Teledyne plates (on anode side) and successfully completed leak testing in accordance with U.S. Fuel Cell Council test protocols.
- Conducted electrical testing of single cells according to the factorial design to identify relationships to fuel cell performance.

Customers and collaborators:

- U.S. Fuel Cell Council (USFCC)
- Los Alamos National Laboratory
- National Renewable Energy Laboratory
- Department of Energy
- General Motors
- Teledyne Corporation
- Rensselear Polytechnic Institute
- Japanese Automobile Research Institute (JARI)
- Korean Institute for Energy Research (KIER)