Laboratory for Manufacturing and Productivity

The Laboratory for Manufacturing and Productivity (LMP) is an interdepartmental laboratory in the School of Engineering with three major goals: (1) development of the fundamental principles of manufacturing systems, processes, and machines; (2) application of those principles to the manufacturing enterprise; and (3) education of engineering leaders.

With 12 faculty and senior research staff and 70 students, the laboratory conducts research in innovation, design, analysis, and control of manufacturing processes and systems.

Research is conducted through industrial consortia, sponsored research projects, and government grants. LMP's major areas of interest include production system design, precision engineering, three-dimensional printing, rapid autonomous machining, droplet-based manufacturing, automatic identification, machine elements and systems design, complexity and system design, information technology, microelectromechanical systems (MEMS), nanomanufacturing, renewable energy, and environmentally benign manufacturing. In addition, LMP works closely with many other departments, laboratories, and programs at MIT, including the Departments of Biological Engineering, Chemical Engineering, Electrical Engineering and Computer Science (EECS), and Mechanical Engineering (ME); the Singapore–MIT Alliance (SMA); the Research Laboratory of Electronics; and the Leaders for Manufacturing Program. Many of our research projects collaborate with industrial companies, including General Motors Corporation and EPCglobal. Our government support, which is often coordinated with industrial support, comes from the National Science Foundation (NSF). We also maintain a strong international presence: our research sponsors include the University of Singapore, the Korean Institute of Machinery and Materials, and LG CNS.

LMP's total research volume was $3,570,000 for 2005–2006, an increase of more than 85 percent from the previous year, and it is expected to grow further in the coming year. This research volume was bolstered by the active programs of Professors Jung-Hoon Chun, Martin L. Culpepper, Timothy G. Gutowski, Stephen C. Graves, David E. Hardt, Emanuel M. Sachs, Sanjay E. Sarma, David L. Trumper, and John R. Williams, and Doctors David L. Brock and Stanley B. Gershwin.

Research and Education Highlights and Awards

In past years, we have seen significant new trends within the laboratory, including the following three new research thrust areas:

- Micro- and nanoscale manufacturing processes: Professors Chun, Culpepper, Hardt, Sang-Gook Kim, and Trumper are now actively engaged in this research thrust area. An SMA flagship research project on microfluidic device manufacturing is being led by Professor Hardt, who is joined by Professor Chun and other ME and EECS faculty members. Professor Kim focuses on MEMS, whereas Professors Culpepper and Trumper apply precision engineering to micro- and nanoscale technologies. The third International Symposium on

Nanomanufacturing (ISNM) was held in Cyprus in 2006, with the strong leadership and participation of MIT faculty; the fourth symposium, which will be held at MIT, is currently being organized by Professor Culpepper.

- Manufacturing systems and information technologies: the Auto-ID Laboratory, led by Professor Williams, puts radio-frequency identification (RFID) at the centerpiece of an effort to create an intelligent infrastructure to connect physical objects to the Internet and to each other, while Dr. Brock expanded the MIT Data Center to develop the languages, protocols, and technologies required to integrate data and models across global networks. Dr. Gershwin is active in factory-level manufacturing systems design and control, whereas Professor Graves focuses his research on supply-chain design and management. Professor Nam P. Suh continued his quest to develop a complexity theory.
- Renewable energy and environmentally benign manufacturing: Professor Sachs is now researching photovoltaics. Professors Chun and Suh continued their work on a fuel cell design and manufacturing project for mobile devices. Professor Gutowski is engaged in research projects for environmentally benign manufacturing.

Beyond research, there are significant educational activities in the laboratory. Last year Professor Hardt, along with LMP, ME, and EECS colleagues Chun, Kamal Youcef-Toumi, Lallit Anand, Gershwin, Graves, and Duane Boning, launched the first manufacturing degree program at MIT. The new Master of Engineering in Manufacturing commenced in September 2005. This highly focused one-year professional degree program is intended to prepare students to assume a role of technical leadership in the manufacturing industry.

In the first year, we received 50 applications and selected a final class of 11, 8 of whom are funded by the SMA fellowship. This truly global education program now has three industry-based team projects under way in Singapore and one in Cambridge. The projects run from factory system and supply-chain issues in a major shipyard to novel process development for soft lithography. In our second round of admissions, we had even stronger applications and expect a class of 16 for our second year.

Professor Kim developed and taught a new graduate/undergraduate subject in micro- and nanoscale engineering (2.76 Multi-scale Systems Design and Manufacturing) together with Professor Culpepper. Professor Kim is developing a new laboratory subject for 2-A Nanotrack students that will encourage creative thinking through hands-on experience with building, observing, and manipulating micro- and nanostructures. The lab subjects will take advantage of the newly constructed Pappalardo Micro and Nano Engineering Teaching Laboratory, which Professor Kim has also been involved in establishing.

Professor Culpepper has started educational outreach activities with the purpose of teaching young engineers the fundamentals of equipment design for nanoscale manufacturing. He created a student design project in which freshman MIT students design, fabricate, and integrate the subsystems of a nanopositioner: actuators, electronics, controls, a fixture for precision assembly of the nanopositioner, and a

compliant positioner stage/mechanism. At the end of the term, students "raced" their nano-manipulators through a virtual 30 × 30 micron racetrack that emulates a factory work-handling layout. The curriculum for this course project was turned into a design project kit for use by students outside of MIT. At the 2005 ISNM, the kit was used in a design competition by four undergraduates from underrepresented groups and from different colleges (MIT, George Washington University, University of Arkansas, York College). This student design project will be repeated at subsequent ISNM events. This kit is also under consideration for use in another undergraduate program in ME: 2.004 Modeling Dynamics and Control.

Dr. Brock expanded the MIT Data Center, an initiative focused on developing languages, protocols, and technologies to integrate data and analytic models across the internet. The Center is developing infrastructure, proposing solutions, and building prototypes that enable the practical interoperation of data and analytic models within and across the enterprise. The Center currently has six sponsors and has hosted numerous international conferences and workshops in applications from manufacturing, petroleum, consumer goods, healthcare, and marketing science. The Center has a number of publications, including a book to be published this fall by Springer-Verlag. Finally, a prototype system developed by the Center is now in operation and in field trials by half the sponsors.

This past year, Professor Chun continued to play an important leadership role in bringing together many of the world experts in nanoscale technology to develop a vision for nanomanufacturing. This work included organizing the third ISNM, held in Cyprus. The fourth symposium will be held at MIT this fall. In addition, Professor Chun continued the research initiative on manufacturing portable fuel cells under the auspices of the Korean Institute of Machinery and Materials. He was also actively involved in an SMA flagship research project on the manufacture of microscale fluidic devices.

Professor Culpepper's research focuses on designing equipment and instruments for small-scale manufacturing and manipulation. His group has started an effort to engineer and manufacture mechanical devices at the fundamental barriers of miniaturization. They are tackling the challenges associated with creating nanomechanical devices that use molecules as functional mechanical elements. The end goal is to miniaturize mechanical devices to the nanometer level, or approximately 30 times smaller than can currently be obtained by state-of-the-art approaches. Professor Culpepper has also started an effort aimed at creating miniature precision optical systems that may be used to noninvasively scan internal tissues for cancer detection. This new approach eliminates the need for physical biopsy, which saves money and time. This combination makes treatment more accessible to a larger number of people and therefore may affect the survival rate for several types of cancer.

Dr. Gershwin continues his high level of activity with the SMA and his research, which is focused on complex manufacturing systems models and analysis. Recently, his group initiated a quantitative analysis of the interaction between quality and quantity measures in production systems. General Motors provided corporate support for Dr. Gershwin's research on manufacturing systems. Dr. Gershwin presented a keynote talk on his group's advances at INCOM 2006 (the 12th IFAC Symposium on Control Problems in Manufacturing), in Sainte-Etienne, France.

Professor Graves has continued to work on a number of projects related to modeling supply chains and production/inventory systems. With Professors Rohit Bhatnagar of Nanyang Technical University (NTU) and Michelle Cheong of Singapore Management University, he has completed research developing a model and solution method for logistics network design. With Professors Bhatnagar and Chong (NTU), he has completed research on the development of a tactical planning model for setting production and inventory levels in a make-to-order environment. Another major project examined a variety of tactical issues that arise in order fulfillment and inventory planning in an online retailing system; this is collaborative work with Russell Algor and Ping Xu (amazon.com). With support from SMA, he initiated research on capacity planning for supply chains for new products, as would arise with emerging industries. The intent of this project is to develop a decision support system that would help supply-chain planners decide on the best capacity options across their supply chain as they launch a new product family.

Professor Gutowski's research focuses on the environmental aspects of manufacturing and the role of manufacturing and product design in a sustainable society. His current work is supported by NSF in the areas of manufacturing process analysis (for eight processes: electrical discharge machining, abrasive water jet machining, grinding, milling, sand and die casting, injection molding, and chemical vapor deposition) and product design for recycling. This last area includes modeling the recycling system and analyzing alternative product designs. Other work focuses on system level effects such as the "rebound effect" and various policy-level interactions such as mandated efficiency requirements and tradable permits. He received an NSF MUSES grant this year to study the materials flows for iron sand casting. Two of his students received best paper awards at this year's IEEE International Symposium on Electronics and the Environment.

Professor Hardt and a group of eight LMP faculty members launched the Manufacturing Systems and Technology (MST) program between LMP and NTU in Singapore. This effort is part of the five-year second phase of the SMA. MST includes a focused research effort to develop a fundamental basis for the polymer processes used to create microfluidic devices. LMP participants include Professors Chun, Hardt, Anand, Youcef-Toumi, Boning, and Todd Thorsen. The MST program also has a component aimed at exploring systems issues related to emerging industries such as biomicrofluidic devices. This research will involve three LMP participants (Professors Graves and Jeremie Gallien and Dr. Gershwin) and three from NTU.

Professor Kim's research has continued to address the issues of design and manufacturing at micro- and nanoscales, where the traditional make-and-see approach does not work. His research aims to establish a product development tool for MEMS and nanoscale technology, such as carbon-nanotube-tipped nanoscanning platforms for biomedical diagnostics.

Professor Sachs, the Fred Fort Flowers '41 and Daniel Fort Flowers '41 professor of mechanical engineering, focused his research on photovoltaics (PV)—solar panels that convert sunlight directly into electricity using semiconductor devices. PV is already the energy source of choice for remote telecommunications and for rural electrification.

Professor Sachs's goal is to contribute to the realization of PV, which is cost competitive with electricity from fossil fuels. He invented the "string ribbon" process for manufacturing crystalline silicon substrates for solar cells. In this technology, flat, thin silicon sheets are grown directly from a melt of silicon, thereby obviating the need to slice and polish wafers from boules or blocks. Several PV-related projects are under way, including high-performance metallization for solar cells, light trapping, optical concentration, and module tracking.

Professor Suh, the Ralph E. and Eloise F. Cross professor of mechanical engineering, has continued his work in the area of complexity theory. Professor Suh's group at the Park Center for Complex Systems has been undertaking a number of design and development projects in diverse technical disciplines; these projects include a customizable automotive suspension system with no energy input, portable fuel cells for mobile devices, and a novel process for water desalination. The customizable automotive suspension system design project has resulted in two US patents, and the latest concept of using auxiliary volumes for air springs is being implemented on an actual vehicle to demonstrate the technology by the end of summer 2006. The project for designing and manufacturing portable fuel cells is being conducted in collaboration with Professor Chun's group. Developing a novel, power-efficient desalination process is a new project initiated in early 2006, and a partnership with collaborators from NTU has been established. Professor Suh's group has also continued to work in the area of large systems design, including collaboration with Draper Laboratory on their concept exploration and refinement study for NASA.

Professor Trumper's research efforts center on the design of novel precision electromechanical systems. His group has recently completed projects studying the properties of elastomeric bearings for precision positioning systems and the use of electromagnetic actuators as precision nanopositioners. His group has also experimentally demonstrated the world's highest performance fast tool servos for use in diamond turning of contoured surfaces. In a continuing collaboration with Professor Linda Griffith's research group from the Department of Biological Engineering, Professor Trumper is investigating pumping and instrumentation systems for liver bioreactors. He also is engaged in active collaboration with Professor Robert Hocken and Professor Stuart Smith of the University of North Carolina–Charlotte (UNC–Charlotte) in projects for precision motion systems in support of accurate measurement devices for use in semiconductor fabrication and in support of nanotechnology. Professor Trumper is also involved with a project with Dr. Mark Schattenburg of the Center for Space Research and Professor Robert Hocken of UNC–Charlotte for investigating the fabrication of extreme accuracy gratings for use as reference artifacts in nanometrology systems. As part of this effort, his group is creating accurate atomic force microscopes utilizing novel capacitive metrology configurations. In a collaboration with Lincoln Laboratory, Professor Trumper's group is designing and testing new configurations of fast steering mirrors for optical communications. Professor Trumper's group is now embarking on new projects in the areas of active vibration control and precision stage systems.

Professor Williams has led the Auto-ID Laboratory over the last year and was named by *Network World Magazine* as one of only two academics in their list of the 50 most powerful people in computer networking. The Auto-ID Laboratory has held two academic convocations bringing together the 100 top researchers in RFID from around the world to identify and coordinate research in the area. As a result, the Chinese Academy of Arts and Sciences invited the lab to cohost with them a third convocation in Beijing in October this year. Stephen Miles is leading discussions with the Broad Institute and W3C on the use of identifiers in the life sciences.

There have been several changes in LMP over the past year. Professor Culpepper became the assistant director of LMP as of January 2006. Professor Williams of Civil Engineering became director of the Auto-ID Laboratory while Professor Sarma is on leave. Professor Kim was awarded tenure. Professor Graves of the Sloan School of Management joined LMP to work in the manufacturing systems area, and Professor Nafeh left the Institute.

Professor Sachs was elected as a fellow of the Society of Manufacturing Engineers. Professor Suh was honored with two awards: The Academy Gold Medal of Honor from the Academy of Transdisciplinary Learning and Advanced Studies (Society for Design and Process Science) on June 26, 2006, and the General Nicolau Award, the highest award of the Collège International pour l'Etude Scientifique des Techniques de Production Mécanique (also known as the International Academy for Production Engineering). In June 2006, he was selected to be the next president of the Korea Advanced Institute of Science and Technology and will be on leave.

New Initiatives

We have continued the renewal campaign of LMP that we began last spring. The Manufacturing and Productivity Seminar Series at MIT was held through fall 2005 and spring 2006 as an intellectual forum within the MIT community to present and exchange emerging ideas on manufacturing and productivity developed at LMP, at MIT, and in industry.

We continued with our physical space upgrades as part of the renewal as well. The renovation to create a common students' office space was completed with great success. The room currently holds 22 personal office areas and also features a group study and lounge area. This spring the room saw full occupancy by students and visitors and hosted a number of LMP social gatherings. To support this physical upgrade, we initiated a fundraising effort aimed at LMP alumni with the support of the School of Engineering Dean's Office and the Office of the Alumni Association. We will continue these fundraising efforts to support renewal projects.

The first MIT Manufacturing Summit, "Manufacturing Research and Education in the Global Economy," was held this April. We drew 12 speakers and more than 120 registrants, who shared ideas about the future of manufacturing in three sessions: "New Directions for Manufacturing Research and Education," "Manufacturing Systems and Information Technology," and "The Role of Manufacturing in Renewable Energy." Materials from the summit are available online at http://web.mit.edu/lmp/summit.html.

Next year, in preparation for LMP's 30th anniversary, we are planning several important events and projects. Laboratory spaces are being renovated to create a new multimedia conference room for the use of LMP research groups. The new room will be dedicated to the memory of Professor Nate Cook as part of the 30th anniversary commemoration.

More 30th anniversary events are being planned to coordinate with the second MIT Manufacturing Summit, which will take place in the fall. We hope to build on the success of this year's summit by attracting even more MIT, industry, and academic participants.

Jung-Hoon Chun
Director
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More information about the Laboratory for Manufacturing and Productivity can be found at http://web.mit.edu/lmp/.