

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) the education of engineering leaders. With 14 faculty and senior research staff members and 60 students, LMP conducts research in the areas of design, analysis, and control of manufacturing processes and systems.

This 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, reconfigurable tooling, droplet-based manufacturing, automatic identification, machine elements and systems design, complexity and system design, information technology, micro-electromechanical systems (MEMS), nanomanufacturing, biological systems, renewable energy, and environmentally benign manufacturing. In addition, LMP works closely with many other departments, labs, and programs at MIT, including the Singapore–MIT Alliance (SMA), the Biological Engineering Division, and the Leaders for Manufacturing Program. Many of our research projects are conducted in collaboration with individual companies, including General Motors Corporation and Bally Ribbon Mills. In total, LMP works with about 50 different companies worldwide. Our government support, which is often coordinated with industrial support, comes from a variety of agencies, including the Department of Defense, Department of Energy, and National Science Foundation (NSF). We also maintain a strong international presence: our research sponsors abroad include the University of Singapore and the Korean Institute of Machinery and Materials.

The total research volume for the Laboratory for Manufacturing and Productivity was \$1,915,000 for the 2004–2005 academic year. This research volume was bolstered by the active programs of Professors Chun, Gutowski, Hardt, Nayfeh, Sachs, and Trumper and Dr. Gershwin.

Research and Education Highlights, Awards

In the past year, LMP has seen significant new research trends, including three new research thrust areas:

—*Micro- and nanoscale manufacturing processes.* Professors Jung-Hoon Chun, Kimberly Hamad-Shifferli, David E. Hardt, Sang-Gook Kim, Alexander H. Slocum, Nam P. Suh, and David L. Trumper are now actively engaged in this area. An SMA flagship research project on microfluidic device manufacturing will be led by Professor Hardt, joined by Professor Chun and other faculty members from the Departments of Mechanical Engineering and Electrical Engineering and Computer Science. Professor Hamad-Schifferli researches nanoscale interfaces to biological molecules, while Professor Kim focuses on MEMS. Professors Culpepper, Nayfeh, Slocum, and Trumper apply precision engineering to micro- and nanoscale technologies. Professor Suh's group

investigated surfaces with nanoscale features. The 2nd International Symposium on Nanomanufacturing was held in Korea with the strong leadership and participation of MIT faculty, following the successful first-ever International Symposium on Nanomanufacturing held at MIT under the guidance of Professor Chun.

—*Manufacturing systems and information technologies.* The Auto-ID Center, led by Professor Sanjay E. Sarma, put 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. David Brock launched the MIT Data Center (see below). Dr. Stanley B. Gershwin is active in factory-level manufacturing systems design and control. Professor Nam P. Suh continued his quest to develop a complexity theory.

—*Renewable energy and environmentally benign manufacturing.* Professor Ely Sachs is now researching photovoltaics. Professors Jung-Hoon Chun and Nam P. Suh also initiated a fuel cell design and manufacturing project for mobile devices. Professor Timothy G. Gutowski is engaged in research projects for environmentally benign manufacturing.

Beyond research, there are significant educational activities in the laboratory. Professor Hardt led an effort to introduce a Master of Engineering in Manufacturing program in the Department of Mechanical Engineering; the program was approved and will welcome its first batch of students this fall. Professor Sachs devoted his teaching time to the development of undergraduates' hands-on exploration projects and will continue his efforts to spread his pedagogical methodology to a wider collection of undergraduate core courses.

Dr. Brock launched the MIT Data Center on January 1, 2005, after 18 months of research and preparation. The Data Center is a new initiative charged with researching and developing the languages, protocols, and technologies to integrate data and models across global networks. The center will develop the infrastructure, recommend the standards, and build the prototype applications that enable the interoperation of data and mathematical models commonly used in engineering and management within and across enterprises. The technologies and standards created by the center will be open and freely distributed. Current focus is in three industrial areas: (1) health care, including genetic data; (2) heavy industries, including automotive, construction equipment, and energy; and (3) food, consumer goods, retailing, agriculture, and pharmaceutical industries.

The main event of AY2005 was Smart World 2004, sponsored by the MIT Industrial Liaison Program. The program drew 300 attendees and featured speeches relating to interoperable modeling by leading companies such as Intel, IBM, Microsoft, Proctor & Gamble, SAP, and Johnson & Johnson. During the early part of the academic year, several authors from the Data Center published an article entitled "An Introduction to Semantic Modeling for Logistical Systems." This article won the E. Grosvenor Plowman Award, presented at the Council of Logistics Management Logistics Educators Conference.

This past year, Professor Jung-Hoon Chun continued to play an important leadership role in bringing together many of the world experts in nanoscale technology to develop

a new vision for nanomanufacturing. This work included the organization of the 2nd International Symposium on Nanomanufacturing held in Korea. The 3rd symposium will be held in Cyprus this fall before the 4th symposium returns to MIT in 2006. In addition, Professor Chun launched a new research initiative on manufacturing portable fuel cells under the auspices of the Korean Institute of Machinery and Materials. As already noted, he will also be actively involved in an SMA flagship research project on microscale fluidic device manufacturing.

Professor Culpepper received a 2004 Presidential Early Career Award for Scientists and Engineers for his research and education activities in nanopositioning equipment. Professor Culpepper served on the NSF World Technology Evaluation Center panel to assess the worldwide state of the art in design of parts and products manufactured by nonlithography-based processes. The results of the panel's findings were reported to the House Science Committee in Washington, DC, in May 2005. Professor Culpepper will also play a leading role in organizing the 4th International Symposium on Nanomanufacturing, which will be held at MIT in 2006, along with Professor George Barbastathis of Mechanical Engineering and Professor Chun.

Dr. Gershwin continues his high level of activity with the Singapore–MIT Alliance and his research 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. Corporate support for Dr. Gershwin's manufacturing systems research has been provided by Xerox, Peugeot, and General Motors. He has also collaborated with the Auto–ID Center to evaluate Auto–ID technology in inventory management.

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 the modeling of the recycling system and an analysis of 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 a new NSF MUSES grant this year to study the material flows for iron sand casting.

Professor Hamad-Schifferli's research is on nanoscale interfaces to biological molecules, investigating how structure and function of biomolecules are impacted by nanoparticles. She has been expanding her interdisciplinary research program to study proteins and is now developing tools to study cellular processes. Professor Hamad-Schifferli was on family leave for spring 2005. She was awarded the Esther and Harold E. Edgerton career development chair. In addition, she received the Ruth and Joel Spira Award for Distinguished Teaching from the School of Engineering.

Professor Hardt led a group of eight LMP faculty members in establishing the Manufacturing Systems and Technology (MST) program between LMP and Nanyang Technological University (NTU) in Singapore. This effort is part of the five-year second

phase of the Singapore–MIT Alliance (SMA 2). MST will include a focused research effort to develop a fundamental basis for the polymer processes used to create microfluidic devices. It includes 6 faculty members, 4 postdoctoral associates, and 10 graduate students, along with a similar number of collaborators from NTU. LMP participants include professors Chun, Hardt, Anand, Youcef-Toumi, Boning, and 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 Gallien and Dr. Gershwin) and three from NTU.

Professor Hardt's work on Cycle-to-Cycle or Run-by-Run control reached a milestone this year, when the basic results were successfully extended to a general multivariable case. This extension was made difficult by the large dimensions considered (hundreds of states) and the challenge of creating fully accurate models, whether linear or nonlinear. A novel approach to using sparse experimental data with a preexisting distributions function was found to be robust to significant model errors when used in an optimal control framework. This approach was verified with extensive experiments on the LMP discrete die-forming facility, where more than 100 input-output pairs were considered.

Professor Hardt's group has also begun an effort aimed at establishing the process control needs for microembossing of polymers. They have created a test facility that will afford complete control over the process environment in a maximum bandwidth fashion, allowing full exploration of the feasible processing window. The work is currently focusing on relating passive process capability to variables such as forming temperature, cycle time, and cooling rates. Features of 10–100 μm are being used in the current test parts. In addition, advanced methods for evaluating product performance in process are under investigation.

Professor Hardt, along with LMP colleagues Chun, Youcef-Toumi, Anand, Gershwin, Graves and Boning, have launched the first manufacturing degree program at MIT. The new Master of Engineering in Manufacturing program will commence in September 2005. This highly focused one-year professional degree program is intended to prepare the student to assume a role of technical leadership in the manufacturing industries. It comprises a highly integrated set of subjects and projects that cover the process, product, system, and business aspects of manufacturing. The degree is aimed at practitioners who will use this knowledge to become leaders in existing as well as emerging manufacturing companies. While centered in engineering and firmly grounded in the engineering sciences, these degree programs are centered on the enterprise of manufacturing. Students will gain both a broad understanding of the many facets of manufacturing and the knowledge of manufacturing fundamentals from which to build new technologies and businesses.

Professor Kim's research has continued to address the product realization issues of multiscale systems by bridging the gaps across design and manufacturing processes and developing adequate manufacturing processes for newly developed nano- and microscale materials. Recently his group has set important milestones in direct-contact MEMS switches, tunable optical microphotonic devices, and energy-harvesting MEMS devices for autonomous wireless sensors. He invented a transplantation assembly

process for carbon nanotubes that can be broadly applied to the manufacture of many nanoscale structures in addition to carbon nanotubes. New material processes have been developed during his research and are made available to general users at MIT: carbon nanotube growth PECVD machine, XeF₂ dry-etching machine, and thin-film piezoelectric processes.

Professor Nayfeh has developed a new approach to damping structural vibration using low-density, low-wave-speed media, and he is currently working to design these into vehicle drive shafts with the Ford Motor Company. He is also developing applications for his three-dimensional integrally woven structures with bias yarns, the first delamination-free fiber-reinforced structures with multiple-axis (shear and extensional) reinforcement in three dimensions. Finally, he is developing a radical approach to textile production that eliminates time- and labor-intensive setup operations from the weaving process in order to rapidly respond to fluctuating demands, enabling production to be carried out in high-wage countries.

Professor Sachs, the Fred Fort Flowers '41 and Daniel Fort Flowers '41 professor of mechanical engineering, graduated his last student on the 3-D Printing project and will now rely on the success of MIT's licensees in this area to carry on. Professor Sachs' research is now committed to 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' goal is to contribute to the realization of PV, which is cost competitive with electricity from fossil fuels. He is the inventor of the "String Ribbon" process for the manufacture of 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 underway, including high-performance metallization for solar cells, light trapping, optical concentration, and module tracking.

Professor Sarma commenced a two-year leave of absence from MIT to begin the commercialization of RFID technologies that he helped create at the Auto-ID Center. The Auto-ID Center, which he cofounded with his colleague Dr. David Brock, put RFID at the centerpiece of an effort to create an intelligent infrastructure to connect physical objects to the internet and to each other. The efforts of the center led to the creation of a worldwide RFID movement and a set of global standards called the Electronic Product Code standards. With over a hundred sponsors, the center split into two entities: a global not-for-profit standards organization called EPCglobal and a set of university labs, headquartered at MIT, called the Auto-ID Labs. EPCglobal has taken on all the commercial activities of the center. Professor Sarma sits on the board of EPCglobal and is helping to expand its technology. While on leave, Professor Sarma also serves as the chief technology officer of OATSystems.

Professor Slocum worked on various research projects on precision engineering such as Nanogate and Silicon Insert Molded Plastics. These concepts will allow the dimensional control in molecular scales. Professor Slocum's group will complete its project this fall on growing carbon nanotubes using a porous "showerhead." This work, funded by the

Deshpande Center for Technical Innovation, will result in the technology to grow the world's longest nanotubes for a fraction of current costs.

Professor Suh, the Ralph E. and Eloise F. Cross professor of mechanical engineering, transformed the Manufacturing Institute into the Park Center for Complex Systems, which will continue to focus on developing a complexity theory. The Park Center appointed Dr. Taesik Lee, a research associate of the department, as an assistant director to help develop various research programs for the center. The Park Center has been developing research activities in three major thrust areas: (1) design of complex engineering systems, (2) understanding of natural systems, and (3) understanding/design of socioeconomic systems. Specific research topics include the architecture design for NASA's space exploration program, the application of engineering principles to systems biology, design of a nanoprecision motion stage, cost estimation for large systems, and the application of complexity theory to health-care system design. His new book, *Complexity: Theory and Applications*, was published by Oxford University Press in 2004. He also coauthored the book *Axiomatic Design and Fabrication of Composites* with Professor Dai Gil Lee of the Korea Advanced Institute of Science and Technology (Oxford University Press, 2005).

Professor Trumper's research efforts center on the design of novel precision electromechanical systems. Most recently, in 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 has also recently started 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.

Professor Trumper's group is now completing several projects studying fast tool servos for use in diamond-turning machines. These fast tool servos are used to rapidly move a diamond tool during a lathe turning operation in order to allow the creation of controlled features on a turned surface. Such fast tool servos can be used in the production of spectacle lenses, contact lenses, off-axis optics, optical films, and other applications requiring precisely contoured surfaces. Another project in this area is a collaborative effort with Lawrence Livermore National Laboratory to develop fast tool servos for use in the fabrication of target spheres for use in the National Ignition Facility in the study of laser-induced fusion reactions. Professor Trumper is now completing a project for the creation of accurate atomic force microscopes utilizing novel capacitive metrology configurations.

Changes in LMP over the last year include the following: Professor Chun became LMP's director in January 2005; Professor Nayfeh was promoted to associate professor without tenure and will be on sabbatical leave this year; and Professor Sarma will be on leave

for another year to develop his Auto-ID technology full time. While Professor Sarma is on leave, Professor John Williams of Civil Engineering will direct the Auto-ID Center. Professor Stephen C. Graves of the Sloan School of Management will join LMP and work with LMP colleagues in the manufacturing systems thrust area. Professor Gutowski stepped down as associate head of the Department of Mechanical Engineering and will be on sabbatical leave this year. Dr. Nannaji Saka retired.

New Initiatives

We initiated a renewal campaign of LMP this spring. Several initiatives were launched, including a new seminar series in manufacturing, a headquarters area upgrade, a new student office, and planning for a symposium, Manufacturing Summit at MIT, this fall.

The Manufacturing and Productivity Seminar Series at MIT was held in spring 2005 as an intellectual forum within the MIT community to present and exchange emerging ideas on manufacturing and productivity developed at LMP, MIT, and in industry. This well-attended seminar series covered a wide breadth of topics along our new research thrust areas. The series will continue in coming years.

The hallway around the headquarters received a cosmetic upgrade to project an image of our renewal process. A room is being renovated to create a common student office space. This will not only give students a sense of community but also facilitate their learning from each other. To support this physical upgrade, we initiated a fundraising effort with the support the Dean's Office, the Department of Mechanical Engineering, and the Office of the Alumni/Alumnae Association. We will solicit donations from LMP alumni.

We initiated a planning process for the Manufacturing Summit at MIT to chart our future directions on research and education in the global economy. The summit will be held in November 2005, and we will solicit a broader participation within MIT as well as industry leaders and LMP alumni.

Jung-Hoon Chun

Director

Professor of Mechanical Engineering

More information about the Laboratory for Manufacturing and Productivity can be found online at <http://web.mit.edu/lmp/>.