Laboratory for Manufacturing and Productivity

The Laboratory for Manufacturing and Productivity (LMP) is an interdepartmental laboratory in the School of Engineering (SOE) devoted to exploring new frontiers in manufacturing. It has three major goals: (1) to develop the fundamental principles of manufacturing processes, machines, and systems; (2) to apply those principles to the innovation of manufacturing enterprises; and (3) to educate engineering leaders.

With 21 faculty and senior research staff and 85 students participating, the laboratory conducts research in the areas of innovation, design, analysis, and control of manufacturing processes, machines, and systems.

Research is conducted through industrial consortia, sponsored research projects, government grants, and international collaborations. LMP's major areas of interest include polymer microfabrication, chemical-mechanical polishing, precision engineering, machine elements and systems, micro-electromechanical systems (MEMS), nanomanufacturing, production system design, supply chain management, radio frequency automatic identification, information technology, photovoltaics, portable fuel cells, and environmentally benign manufacturing. In addition, LMP works closely with many other departments, laboratories, and programs at MIT including the departments of Biological Engineering, Chemistry, Electrical Engineering and Computer Science (EECS), Civil and Environmental Engineering, Mechanical Engineering (ME), the Singapore-MIT Alliance (SMA), the Center for Transportation and Logistics, the Research Laboratory of Electronics, the Leaders for Manufacturing program, and the Sloan School of Management. Many of our research projects collaborate with industrial companies, including the Semiconductor Research Corporation, Raytheon, Procter and Gamble, the SKF Group, and EPCglobal. Our government support, which is often coordinated with industrial support, comes from the National Science Foundation (NSF) and the National Institutes of Health (NIH). We also maintain a strong international presence: our research sponsors include the University of Singapore, Samsung Electronics Co. Ltd., and LG CNS.

LMP's total research volume was $5,960,000 for 2006–2007, an increase of more than 65% 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 Jung-Hoon Chun, Martin L. Culpepper, Timothy G. Gutowski, Stephen C. Graves, David E. Hardt, Alexander M. Klibanov, Emanuel M. Sachs, Sanjay E. Sarma, David L. Trumper, John R. Williams, David L. Brock, Joseph Coughlin, and Stanley B. Gershwin.

Research and Education Highlights, Awards

In the past year, we continued to develop our research programs in three major thrust areas:

Micro- and nanoscale manufacturing processes: Jung-Hoon Chun, Martin Culpepper, David Hardt, Sang-Gook Kim, Alexander Slocum, and David Trumper are now actively engaged in this research thrust area. David Hardt, joined by ME and EECS faculty members in the new Center for Polymer Microfabrication, is leading an SMA flagship research project on microfluidic device manufacturing. Sang-Gook Kim focuses on MEMS. Martin Culpepper, David Trumper, and Alexander Slocum and Mark Schattenburg of the Kavli Institute at MIT established the Precision Engineering Center, which focuses on micro- and nanoscale technologies.

Manufacturing systems and information technologies: The Auto-ID Laboratory, led by John Williams, develops radio frequency identification (RFID) technologies for supply chain management. Sanjay Sarma contributes to RFID research and also works on wireless sensors and complex systems. David Brock continued the expansion of the MIT Data Center Program to develop the languages, protocols, and technologies required to integrate data and models across global networks. Stanley Gershwin is active in factory-level manufacturing systems design and control, while Stephen Graves focuses his research on supply chain design and management.

Renewable energy and environmentally benign manufacturing: Emanuel Sachs has been joined by James Bredt in his photovoltaics research. Jung-Hoon Chun continues his work on a fuel cell design and manufacturing project for mobile devices. Timothy Gutowski is engaged in research projects for environmentally benign manufacturing.

Significant developments have been made in research this year at LMP. We have established the new Center for Polymer Microfabrication (CPM) to focus attention on the activities of faculty in LMP and our collaborators at Nanyang Technological University (NTU) Singapore. This center covers a broad spectrum of research related to the science and engineering of creating commercially viable methods for manufacturing micro- and nanoscale products from polymers. We currently focus on microfluidic products in both the biomedical and computational fields.

Participants in the CPM include David Hardt, Jung-Hoon Chun, Lallit Anand, Kamal Youcef-Toumi, Todd Thorsen, and Duane Boning. Our collaborators in Singapore include Professors Yue, Tor, Sivakumar, Lam, Yoon, and Bhatnagar at NTU along with Professors Nee and Subramanian at National University of Singapore.

This group has developed a three-pronged approach to the manufacturing science of polymer microdevices, with thrusts in materials and mechanics, equipment and automation, and metrology and process control. We have recently met milestones in our work in each of these areas, including the first fully coupled constitutive models for PMMA and COP polymers, along with initial fully coupled (thermal and mechanical) simulations of the process of microembossing. We have discovered that the whole field of tooling for such processes has not been explored sufficiently, and we have launched a number of projects in that area, including the use of metal deposition, amorphous metal embossing, and embossed high-temperature polymers. We have begun a comprehensive study of the demolding problems for embossing and casting elastomers. Finally, we are exploring the use of data fusion techniques to combine the outputs of sensors of different resolution for the purpose of inspecting polymer microdevices. Sources include scanners, interferometers, and atomic force microscopes. We have also begun to characterize the spatial and temporal variations that can be expected in a number of processes as the starting point for overall process control strategies.

David Hardt's work within the CPM has focused on several problems in the area of equipment and automation. A basic study of tooling design has been launched to determine the forces present during the demolding process and then to find methods to minimize such forces. The former include surface adhesion effects as well as thermally induced shear forces. In response, his group is looking at the use of materials with low surface energy, such as high-temperature polymers, and also at the effect of high-temperature demolding. The use of coatings and alternative metals is also being pursued. In another project, the development of a single-step process to produce surface profiles (e.g., channels) and through holes for fluid communication has been explored. With careful design of the tooling, thermal cycle, and mechanical cycle, acceptable parts have been made, and we will conduct a functional test on such a part in the near future. Finally, his group is looking at the issues of scale up and commercial viability of castable elastomers (such as PDMS). In particular, the focus is on minimizing variation and maximizing rate and reliability.

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

Jung-Hoon Chun continued to lead the copper chemical mechanical polishing (CMP) research program under the auspices of Semiconductor Research Corporation, a semiconductor industry consortium. The program's foci are process innovation, modeling, and validation. Since the circuit size in ultra-large-scale integrated electronics decreases while the wafer size increases, his current research involves the development of a novel CMP architecture and a comprehensive, multiscale tribological process model, as well as an investigation of nanoscale scratching. In addition, he has been participating in the Center for Polymer Microfabrication focusing on assembling compliant parts containing microscale features and he led fuel-cell reliability research in collaboration with Nam P. Suh. Professor Chun was also instrumental in establishing the Samsung-MIT LMP Collaborative Research Program, which supports precision engineering activities, and the DGIST-MIT Collaborative Research Program, which supports cognition research on drivers in an aging society for the automotive industry.

Martin 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 design, modeling, and manufacturing challenges associated with engineering nanomechanical devices that use molecules as functional mechanical elements. They have generalized the design of these molecular machines and are now working to solve the problems associated with the mass manufacturing and measurement of these machines. The goal of this work is to miniaturize mechanical devices to the nanometer level—approximately 30 times smaller than can currently be obtained using state-of-the-art approaches—for consumer electronics and nanoinstrumentation. Professor Culpepper continues to work on solving problems that are associated with the design and manufacturing of miniature precision optical scanning systems that may be used for noninvasive scanning of internal tissues for cancer detection. NIH has funded this effort and preliminary results have demonstrated that the new approach to a small-scale precision machine design will work. This new approach eliminates the need for physical biopsy, which in turn saves cost and time. This combination makes treatment more accessible to a larger number of people and therefore will affect the survival rate for several types of cancer. Professor Culpepper received a 3M innovation grant for his work on small-scale equipment and instruments and a Karl Chang innovation grant for his work on molecular machines. He organized the 4th International Symposium on Nanomanufacturing, which was held at MIT, and the 1st International Conference on Micromanufacturing, both in fall 2007.

Stanley Gershwin continues his research on complex manufacturing systems models and analysis. He also continues to teach and do research in the SMA, and he has begun to participate in the MIT Portugal program, both in course development and in research collaboration. Specific research areas include a quantitative analysis of the interaction between quality and quantity measures in production systems, mathematical modeling and analysis of systems with loops (for material control information or for pallets/fixtures), mathematical modeling and analysis of systems with multiple part types, and analytical solutions of single-buffer systems with general arrivals and service. The latter is of considerable interest both because it is a long-standing problem in queuing theory and because such systems are used in the decomposition analysis of complex flow systems. General Motors and Hitachi have provided corporate support for Dr. Gershwin's manufacturing systems research. He coauthored with Yun Kang (MIT PhD 2004) "Information inaccuracy in inventory systems: stock loss and stockout," which was selected for the Best Paper of the Year in IIE Transactions on Design & Manufacturing. Dr. Gershwin was an author of four papers presented at the Analysis of Manufacturing Systems Conference in Lunteren, The Netherlands, 11–16 May 2007. He gave a keynote talk at the Conference on Systems and Control, held in Marrakesh, Morocco, from May 16–18, 2007.

Stephen Graves has conducted a number of projects related to the modeling of supply chains and production and inventory systems. With colleagues from NTU he has completed research on two projects: development of a tactical planning model for setting production and inventory levels in a made-to-order environment and optimization of a vendor-buyer system accounting for nonlinear transportation costs. Another major project examines the inventory management of low-demand items at an online retailing system; this is collaborative work with Russell Algor and Ping Xu (amazon.com). With support from SMA, he has extended earlier work on the optimal placement of safety stocks in a supply chain, subject to an evolving forecast; a Teradyne supply chain has been used to validate and test the research outputs. Another project entails capacity planning for supply chains for new products, as would arise with emerging industries.

Over the past year, effective solution methods have been developed and tested for this capacity planning problem.

Timothy 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 the NSF in the areas of manufacturing process analysis and product design for recycling. The latter 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 a NSF MUSES grant last year to study the materials flows for iron sand casting. He also has a new project on energy efficiency with the Swedish company SKF. Two of his students received best paper awards at the IEEE International Symposium on Electronics and the Environment in 2006. One student received a best paper award at the European recycling conference Eco-X in 2007.

Sang-Gook Kim has been working on the new manufacturing and assembly processes for micro- and nanosystems and design of devices with nanoenabled functionalities. Recent research progress includes transplanting assembly of individual carbon nanotube, muscle inspired MEMS actuators, and digital printing of piezoelectric MEMS. "Digital printing of piezoelectric MEMS" is a part of the Defense Advanced Research Projects Agency $5 million funding to MIT's Focus Center on Non-Lithographic Technologies for MEMS/NEMS. He served on the program committee of Solid State Sensors and Actuators Workshop on Hilton Head Island 2006, and co-organized the first American Society of Mechanical Engineers Society-wide Micro and Nanotechnology Forum at the International Mechanical Engineering Congress & Exposition 2006.

Emanuel 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 the manufacture of crystalline silicon substrates for solar cells, the core technology of Evergreen Solar, Inc. In this technology, flat, thin silicon sheets are grown directly from a melt of silicon, obviating the need to slice and polish wafers from boules or blocks. Professor Sachs is now building a PV research group at MIT and has projects in all three areas of the manufacture of PV: making modules, making wafers, making a cell on wafers. In module making, the project involves improved light capture at the module level using an idea called the light trapping bus wire. At the cell level, a new cell architecture is being developed that seeks to achieve efficiency parity between low-cost multiwafers and single crystal wafers. The third project seeks to develop a new method of manufacturing wafers that achieves the economics of ribbon growth with the efficiency of single crystal growth.

David Trumper's research efforts center on the design of novel precision electromechanical systems. He is actively collaborating with Robert Hocken of the

University of North Carolina, Charlotte, and Mark Schattenburg of the Kavli Institute at MIT in projects for precision motion systems in support of accurate measurement devices for use in semiconductor fabrication and nanotechnology. These projects are also investigating the fabrication of extreme accuracy gratings for use as reference artifacts in nanometrology systems. In a project supported by Philips Corporation, Professor Trumper's group is investigating techniques for active vibration control in ultraprecision machines and instruments. In collaboration with the Air Traffic Control Systems group at MIT Lincoln Laboratory, Professor Trumper and his students have designed advanced fast-steering mirrors for optical communications, such as might be used in high-speed data links from spacecraft to earth or between aircraft. These fast-steering mirrors are used to maintain tracking of the tightly focused optical beams used for such communications. Their experimentally demonstrated prototype has the highest performance of any reported beam steering mirror system and is the subject of a current patent filing. Most recently, his group is studying novel approaches for high-speed, high-accuracy scanned probe microscopes for nanometrology, such as might be used in semiconductor fabrication.

The Auto-ID Laboratory, led by John Williams and Sanjay Sarma, puts RFID at the center of an effort to create an intelligent infrastructure, "The Internet of Things," to connect physical objects to the Internet and to each other. The lab has developed a supply chain simulator capable of modeling the pharmaceutical supply chain that is being used to develop techniques to eliminate counterfeit drugs from entering the United States. (In 2003, 18 million tablets of the cholesterol-lowering drug Lipitor were recalled in the United States after fake pills were found in pharmacies and data indicate that the scale and sophistication of counterfeiting is growing.)

John Williams has led a collaboration between MIT, SAP, and Microsoft to develop a supply chain network simulator that is being applied in the health and life science area to the problem of eliminating counterfeit drugs. Sanjay Sarma has continued his leadership of RFID data security through his work on predicate logic for secure data exchange. Abel Sanchez and Christian Floerkemeier cofounded the Auto-ID Laboratory Open Source initiative that allows other universities and researchers access to the latest developments in RFID and EPC standards, such as e-Pedigree and EPC Information Services. Stephen Miles has organized the third, fourth, and fifth RFID Academic Convocations in China, Europe, and the United States that brought together the lead international researchers and has led to continuing collaboration between the Chinese Academy of Sciences and the Auto-ID Laboratory.

Professor Sarma's research has focused on three areas: wireless sensors, RFID, and complex systems. In RFID, he has worked on new protocol concepts for RF security and on the network layer. He is also working on applying RFID with robots and in warehouses, which can be mapped automatically by wandering "RFID-bots." Professor Sarma continues to serve on the board of EPCglobal, which is the premier RFID standards body worldwide. He recently started a research program in wireless sensing, focusing particularly on sampling theory as related to multiple mobile sensors. The applications of this research range from unmanned aerial vehicles sampling chemical fields to pinpoint a chemical leak to unmanned buoys in the ocean detecting tidal waves.

Finally, Professor Sarma has worked on using visibility data in the supply chain and in other complex systems like warehouses to (a) improve performance using techniques like statistical process control, and (b) invent new ways to design systems for better performance. For example, his group is currently studying the concept of randomized—as opposed to organized—warehouses.

This year, we continued with our significant educational activities in the laboratory. We have completed the second year of our master of engineering in manufacturing degree program, which, although not a LMP activity, occurs largely through the efforts of our faculty and staff. This highly focused one-year professional degree program is intended to prepare the student to assume a role of technical leadership in the manufacturing industry. As of August 2007, we will have 30 alumni, and the entering class for 2007–2008 will number 19. Students have been engaged in industry-based group projects for their project theses in companies including IBM, BD Medical, Philips Domestic Products, and Merck in Singapore and Nanoterra and Varian Semiconductor Associates in Massachusetts. We are also initiating a Corporate Education Affiliate program to seek more active involvement of these and other companies in our new degree program.

Sang-Gook Kim developed and taught a new graduate/undergraduate subject in micro- and nanoscale engineering (2.76 Multiscale Systems Design and Manufacturing) together with Martin Culpepper. Professor Kim is currently developing a new laboratory subject for 2-A Nanotrack students that will encourage creative thinking through hands-on experience via 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 he was involved in establishing.

Professor Culpepper established a new 2A undergraduate track in precision engineering. This track builds on the core mechanical engineering curriculum by adding specialized knowledge that is required to synthesize/invent, model, fabricate, and measure next-generation precision devices. This track will enable our undergraduates to be prepared to take on the new design and manufacturing challenges that are associated with small-scale devices that are beginning to work their way into consumer products, instruments, and equipment and into scientific apparatus for nano- and biological research.

David Trumper continues his active involvement in teaching and curriculum development. This year he created a new version of 2.171 Computer Control Systems, which includes a significant laboratory component allowing students to design and test computer control systems. Professor Trumper also taught for the first time the combined 2.14/2.140 course Analysis and Design of Feedback Control Systems. This course is taught to both undergraduate students (2.14) and graduate students (2.140) and includes laboratory experiences centered on the design of control systems. Professor Trumper will be on sabbatical during academic year 2007–2008 and plans to work on writing a text on the control of precision mechatronic systems, which will support his teaching efforts in such courses.

There have been several changes in the laboratory over the past year. Sanjay Sarma returned from leave, while Nam P. Suh is now on leave. Tonio Buonassisi joined LMP as a visiting assistant professor.

New Initiatives

We have continued the renewal campaign of LMP that we began in spring 2005. The Manufacturing and Productivity Seminar Series at MIT continued this year and was held through fall 2006 and spring 2007 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.

We continued with our physical space upgrades as part of the renewal. Planned upgrades include a reorganization of laboratory and office spaces to accommodate new staff and faculty. Laboratory spaces are being renovated to accommodate precision engineering, the Center for Polymer Microfabrication, and photovoltaics. Office spaces are being renovated to create a new multimedia conference room. The new room will be dedicated to the memory of Professor Nate Cook as part of the 30th anniversary commemoration. To support these physical upgrades, we continued to build our fund-raising efforts aimed at LMP alumni with the support of the SOE Dean's Office and the MIT Alumni Association.

In June 2007, LMP soft-launched a new website. It will help us publicize upcoming events, create an alumni community, and communicate with students and research sponsors.

In conjunction with LMP's 30th anniversary, we are planning several important events and projects. The second MIT Manufacturing Summit will take place in September. We hope to build on the success of last year's summit by attracting even more MIT, industry, and academic participants.

Jung-Hoon Chun
Director
Professor of Mechanical Engineering

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