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 research and education. Its primary goals are advancement of the fundamental principles of manufacturing processes, machines, and systems; application of those principles to the innovation of manufacturing enterprises; and education of engineering leaders.

With 16 faculty and senior research staff and 97 students, 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, radio frequency automatic identification, sensor networks, information technology, photovoltaics, fuel cells, and environmentally benign manufacturing. LMP works closely with many other departments, laboratories, and programs at MIT including the departments of Chemistry, Electrical Engineering and Computer Science (EECS), Materials Science and Engineering, and Mechanical Engineering (ME); the Singapore–MIT Alliance (SMA); the Center for Transportation and Logistics; Civil and Environmental Engineering; the Deshpande Center; Leaders for Manufacturing; and the Sloan School of Management. Many of our research projects collaborate with industrial companies, including the Semiconductor Research Corporation, Raytheon, Procter and Gamble, Soliant Energy, the SKF Group, Prior Scientific, and EPCglobal. Our government support, which is often coordinated with industrial support, comes from the National Science Foundation (NSF) and the Department of Energy. We also maintain a strong international presence: our research sponsors include the National University of Singapore, Daegu-Gyeongbuk Institute of Science and Technology, Orta Anadolu, Samsung Electronics Co. Ltd., and SAP AG.

LMP's total research volume was $5.8 million for 2007–2008. The active programs of professors George Barbastathis, Tonio Buonassisi, 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, and Kamal Youcef-Toumi and Doctors David L. Brock, Joseph Coughlin, and Stanley B. Gershwin contributed to this research volume.

Research and Education Highlights, Awards

We continued to develop our research programs in three major thrust areas.

Micro- and nanoscale manufacturing processes: Professors Jung-Hoon Chun, Martin Culpepper, David Hardt, Sang-Gook Kim, Alexander Slocum, and David Trumper are actively engaged in this research area. An SMA flagship research project on microfluidic device manufacturing is being led by Professor Hardt, who is joined by ME and EECS faculty members in the new Center for Polymer Microfabrication. Professor Chun works in the area of chemical–mechanical polishing, while Professor Kim focuses on MEMS. Professors Culpepper, Trumper, and Slocum and Dr. Mark Schattenburg established the Precision Engineering Consortium, which focuses in part on micro- and nanoscale technologies.

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

Renewable energy and environmentally benign manufacturing: Professor Emanuel Sachs has been joined by professor Tonio Buonassisi in his photovoltaics research. Professor Jung-Hoon Chun continues his work on fuel cells for mobile devices and, along with professor Martin Culpepper, is initiating a project on the design and manufacture of photovoltaic panels. Professor Timothy Gutowski is engaged in research projects for environmentally benign manufacturing.

Significant research developments continued this year at LMP. The Auto-ID Laboratory, led by professors Williams and Sarma, puts RFID at the centerpiece 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 all data indicate that the scale and sophistication of counterfeiting are growing.)

Professor John Williams is leading a new collaboration between MIT, SAP, and Microsoft to facilitate dynamic pricing of electricity by using information technology. Along with Dr. Abel Sanchez he has developed a supply-chain network simulator that is being applied in the health and life science area to the problem of eliminating counterfeit drugs. Along with Professor Sarma, he has coedited a book on RFID. Professor Sarma has continued his leadership of RFID data security through his work on predicate logic for secure data exchange. Drs. Abel Sanchez and Christian Floerkemeier have continued to lead 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.

Professor Sanjay Sarma’s research has focused on three areas: wireless sensors, RFID, and complex systems. In RFID, Professor Sarma has worked on new protocol concepts for radio frequency security and on the network layer. He is also working on the application of 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. Professor Sarma has 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 the use of visibility data in the supply chain and in other complex systems like warehouses to improve performance by using techniques like statistical process control and to invent ways to design systems for better performance. For example, Professor Sarma's group is studying the concept of randomized, as opposed to organized, warehouses.

The Center for Polymer Microfabrication (CPM) comprises a broad spectrum of research related to the science and engineering of creating commercially viable methods for manufacture of micro- and nanoscale products from polymers. Our current focus is on microfluidic products in the biomedical and computational fields.

Participants in CPM include professors David Hardt, Jung-Hoon Chun, Lallit Anand, Kamal Youcef-Toumi, Todd Thorsen, and Duane Boning and Dr. Brian Anthony. Our collaborators in Singapore include professors Chee Yoon Yue, Shu Beng Tor, Appa Iyer Sivakumar, Yee Cheong Lam, Soon Fatt Yoon, and Rohit Bhatnagar at Nanyang Technological University along with professors Andrew Nee and Velusamy Subramanian at National University of Singapore.

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

Professor David Hardt's work within the CPM has focused on several problems in the equipment and automation area. 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 low surface energy material, 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 functional tests will be conducted on such parts in the near future. Finally, his group is looking at the issues of scale up and commercial viability of castable elastomers (such as polydimethylsiloxane). In particular, the focus is on minimizing variation while maximizing rate and reliability.

Dr. David Brock continues to lead the MIT Data Center Program, building new 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. The program has recently developed theoretic and engineering models for the integration of free-form natural language with structured data yielding a comprehensive solution for data management. The program has also expanded through the deployment and testing of research results on real-world problems in logistics, intelligence, and security. In cooperation with corporate sponsors, the MIT Data Center Program has developed and tested prototypes for government organizations including the Air Force Cyber Command, the Joint Improvised Explosive Device Defeat Organization, the Department of Homeland Security, and the Defense Advanced Research Projects Agency.

Professor Tonio Buonassisi's research is focused on the field of photovoltaics, with projects specifically addressing the areas of defect engineering, next-generation materials, and nanoscale defect characterization. His current work is supported by grants from the US Department of Energy, MIT Energy Initiative, the Chesonis Foundation's Solar Revolution Project, and numerous other private benefactors. Professor Buonassisi is one of the founding board members of the nascent Fraunhofer Center for Sustainable Energy Systems and is serving as its scientific director.

Professor Jung-Hoon Chun continued to lead the copper chemical mechanical polishing (CMP) research program under the auspices of the Semiconductor Research Corporation, a semiconductor industry consortium. The program's foci are process innovation, modeling, and validation. Since the circuit size in ultralarge-scale integrated electronics decreases while the wafer size increases, his current research involves development of a novel CMP architecture and a comprehensive, multiscale tribological process model as well as an investigation of nanoscale scratching. In addition, Professor Chun has been participating in the Center for Polymer Microfabrication, focusing on assembly of compliant parts containing microscale features, and led portable fuel-cell research in collaboration with professor Nam P. Suh. Professor Chun was 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 of drivers for the automotive industry in an aging society. Recently, Professor Chun started work on improving design and manufacturing of photovoltaic panels in collaboration with professor Martin Culpepper.

Professor Martin Culpepper's research focuses on the design of equipment and instruments for small-scale manufacturing and manipulation. Professor Culpepper's group is tackling the design, modeling, and manufacturing challenges that are associated with the engineering of nanomechanical devices that use molecules as functional mechanical elements. The end goal of this work is to miniaturize mechanical devices to the nanometer level—approximately 30 times smaller than can currently be obtained with 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. Two of Professor Culpepper's PhD students received prestigious awards this year:

- Dariusz Golda received the R.V. Jones Memorial Award for his PhD thesis work from the American Society of Precision Engineering.
- Shih-Chi Chen received the inaugural MGH–MIT Career Development Postdoctoral Fellowship in Translational Research.

Dr. Stanley Gershwin continues research on complex manufacturing systems models and analysis. He also continues to teach and research in the SMA, and has begun to participate in the MIT–Portugal Program, 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 and 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 because it is a long-standing problem in queuing theory and because such systems are used in the decomposition analysis of complex flow systems. Corporate support for Dr. Gershwin's manufacturing systems research has been provided by General Motors and Hitachi. Dr. Gershwin was a coauthor with Yun Kang (MIT PhD 2004) of "Information inaccuracy in inventory systems: stock loss and stockout," which was selected Best Paper of theYear in *IIE Transactions on Design & Manufacturing*. Dr. Gershwin was an author of four papers presented at the Analysis of Manufacturing Systems Lunteren, The Netherlands, May 11–16, 2007. He gave a keynote talk at the Conference on Systems and Control, held in Marrakesh, Morocco, from May 16–18, 2007.

Professor Stephen Graves has continued to do research on modeling supply chains and production and inventory systems. With support from SMA, he has extended earlier work on the optimal placement of safety stocks in a supply chain in two major ways. First, the work has been extended to account for a dynamic, evolving forecast process, which is prevalent in most planning systems; the second extension is to include capacity constraints at any stage in the supply chain. In both instances, the research shows how to adapt and apply existing methods to determine the safety stock levels across a supply chain. A second project entails capacity planning for supply chains for new products, as would arise with emerging industries. This research has developed solution methods for decision support for multitime period capacity planning for multiproduct supply chains. One novel aspect of this work is the inclusion of option contracts. A third project is examining inventory management in a retail setting with the objective of identifying how to allocate inventories to reduce out-of-stocks and maximize revenues.

Professor 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 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. He received an MIT Energy Initiative grant last year with professor Steve Graves of the Sloan School and Dr. Elsa Olivetti of Materials Science and Engineering. They will study the effects of remanufacturing on energy use and carbon emissions. He is writing a book with two colleagues on applying thermodynamics to the analysis of resource use and the sustainability of manufacturing systems. In other work, Professor Gutowski and his students developed a method to model the environmental impacts associated with a person's lifestyle in the United States.

Professor Sang-Gook Kim has continued working on how to assemble multiscale systems (from nano- to macroscale) at much reduced complexity and lower production cost. His group demonstrated that sets of cellular microactuators could be assembled en masse by folding them over thin gold hinges that connect piezoelectric MEMS actuators. By assembling a vast number of cellular piezoelectric MEMS actuators, he targets developing muscle-inspired microactuators for applications in microrobots and implantable devices. The most challenging problem he recently solved is the assembly of carbon nanotubes (CNTs). He invented a concept of transplanting assembly, which embeds a single strand of CNT into a microscale polymer block, which then can be transplanted, oriented, and bonded readily. A CNT-tipped atomic force microscope nanoprobe has been made by assembling a single CNT at the end of a MEMS cantilever. To our knowledge, this effort is the first in which an individual CNT is assembled deterministically to a multiscale system

Professor 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, thereby obviating the need to slice and polish wafers from boules or blocks. Professor Sachs is building a PV research group at MIT and has projects in all three areas of the manufacture of PV: making modules, making wafers, and 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 method of manufacturing wafers that achieves the economics of ribbon growth with the efficiency of single-crystal growth.

Professor David Trumper's research efforts center on designing novel precision electromechanical systems. He is engaged in an active collaboration with professor Robert Hocken of the University of North Carolina–Charlotte and Dr. 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 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, Professor Trumper's group is studying novel approaches for high-speed, high-accuracy scanned probe microscopes for nanometrology, such as might be used in semiconductor fabrication.

This year, LMPcontinued significant educational activities. This year saw the graduation of the second class of the new master of engineering in manufacturing degree program, which, while not an 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 2008, we will have 50 alumni, and the entering class for 2008–09 will number 30. 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. A corporate education affiliate program is being developed to seek more active involvement of these and other companies in our new degree program.

Professor Sang-Gook Kim has developed a new laboratory subject for undergraduate students together with professors Carol Livermore and Todd Thorsen (Course 2.674 Micro and Nano Engineering Laboratory), which was first offered in spring 2008. Nine hands-on lab modules, including the use of scanning electron microscope, atomic force microscope, scanning tunneling microscope, fluorescent microscopes, and a CNT-growing chemical vapor deposition machine, were given to six undergraduate students (one freshman, two sophomores, one junior, and two seniors). Continued efforts will be made to encourage more students to cultivate engineering reasoning capability in the field of micro- and nanotechnology. He has also served the ME Department as the 2A program officer, which has grown to an enrollment of 47 freshmen this year.

Professor Martin Culpepper has overhauled a senior-level design course—Course 2.72 Elements of Mechanical Design—so that it better represents a modern approach to the integrated aspects of mechanical design, manufacturing design, and system design. Students learn advanced concepts of mechanical design and link this knowledge to real-world applications via the design of a piece of precision manufacturing equipment—a desktop lathe. In this way, students learn how to design for manufacturing, design a precision system for a manufacturing process, study the issues involved in creating a manufacturing process to turn the lathe into a product, fabricate a prototype product, and then run experiments to quantify the behavior of the machine versus functional requirements. This course brings home the idea of integrated design and manufacturing for advanced mechanical systems.

Professor David Trumper has been on sabbatical during academic year 2007–08 and has devoted efforts to writing a text on the control of precision mechatronic systems, which will support his teaching efforts in courses such as Course 2.737 Mechatronics and Course 2.171 Computer Controlled Systems.

There have been several changes in the Laboratory over the past year. Dr. Tonio Buonassisi was appointed assistant professor and science director of the Fraunhofer Institute for Solar Energy Systems. Professor Sanjay Sarma returned from leave, while professor Nam P. Suh has retired, and professor David Trumper went on leave.

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 2007 and spring 2008 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. Renovations to laboratory spaces for Precision Engineering, the Center for Polymer Microfabrication, and Photovoltaics have been completed. Space renovation to create a new multimedia conference room continues; the new room will be dedicated to the memory of professor Nathan Cook. Planned upgrades include further reorganization of laboratory and office spaces to accommodate new students, staff, and faculty. To support these physical upgrades, we continued to build our fundraising efforts aimed at LMP alumni with the support of the SOE dean's office and the Office of the Alumni Association.

In conjunction with LMP's 30th anniversary, we held the second MIT Manufacturing Summit in September 2007. The event was a success, with more than 100 participants, and continued to build relationships with alumni and industry. The laboratory has begun planning to host the International Academy for Production Engineering General Assembly in August 2009 as well as the next MIT manufacturing summit, scheduled for the upcoming academic year.

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/.