

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 (1) advancing the fundamental principles of manufacturing processes, machines, and systems; (2) applying those principles to the innovation of manufacturing enterprises; and (3) educating engineering leaders.

With 16 faculty and senior research staff and 102 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, microelectromechanical systems, nanomanufacturing, production system design, radio frequency automatic identification, sensor networks, information technology, photovoltaics, fuel cells, and environmentally benign manufacturing. In addition, LMP works closely with many other departments, laboratories, and programs at MIT including the Departments of Chemical Engineering, Civil and Environmental Engineering, Electrical Engineering and Computer Science (EECS), Materials Science and Engineering, and Mechanical Engineering; the Singapore-MIT Alliance (SMA); the Center for Transportation & Logistics; the Deshpande Center; Leaders for Manufacturing; MIT Lincoln Laboratory; MIT Energy Initiative (MITEI); and the Sloan School of Management. Many of our research projects collaborate with industrial companies, including the Semiconductor Research Corporation, Raytheon, Soliant Energy, Prior Scientific, EPCglobal, and ASML. Our government support, often coordinated with industrial support, comes from the National Science Foundation (NSF), Defense Advanced Research Projects Agency, and the Department of Energy (DOE). We also maintain a strong international presence: our research sponsors include the National University of Singapore (NUS), Daegu-Gyeongbuk Institute of Science and Technology, King Fahd University of Petroleum and Minerals, GS1, Orta Anadolu, Samsung Electronics Co. Ltd., and SAP AG.

LMP's total research volume was \$5.15 million for 2008–2009. The active programs of professors George Barbastathis, Tonio Buonassisi, Jung-Hoon Chun, Martin L. Culpepper, Timothy G. Gutowski, Stephen C. Graves, David E. Hardt, Emanuel M. Sachs, Sanjay E. Sarma, David L. Trumper, John R. Williams, and Kamal Youcef-Toumi, and of Dr. Brian Anthony, Dr. David L. Brock, Dr. Joseph Coughlin, and Dr. Stanley B. Gershwin contributed to this research volume.

Research and Education Highlights and Awards

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

- Micro- and nanoscale manufacturing processes: Professors Chun, Culpepper, Hardt, Trumper, and Youcef-Toumi 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 Mechanical Engineering and EECS faculty members in the new Center for Polymer Microfabrication (CPM). Professor Chun works in the area of chemical-mechanical polishing and Professors Culpepper, Trumper, and Youcef-Toumi work in the area of precision engineering, which focuses in part on equipment and instruments for micro- and nanoscale technologies.
- Manufacturing systems and information technologies: The Auto-ID Laboratory, led by Professor Williams, develops identification technologies, including radio frequency identification (RFID), to enable “The Internet of Things.” Professor Sarma contributes to RFID research and works on wireless sensors and complex systems. Dr. Brock continued expansion of 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, and Professor Graves focuses his research on supply-chain design and management.
- Renewable energy and environmentally benign manufacturing: Professor Sachs has been joined by Professor Buonassisi in his photovoltaics research. Professor Chun continues his work on fuel cells for mobile devices and, along with Professor Culpepper, has launched an effort to enable energy-efficient, mass manufacturing of carbon nanotubes (CNTs) for energy storage and conversion devices. Professor Gutowski is engaged in research projects focusing on thermodynamic analysis of manufacturing processes and analysis of recycling and remanufacturing to save energy.

CPM comprises a broad spectrum of research related to the science and engineering of creating commercially viable methods for manufacturing 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 NUS.

Research in CPM is currently focused on a basic understanding of the processes of embossing, reaction casting, and thermal bonding, along with implementation in a manufacturing system. For the former, the group has developed basic constitutive models for the polymers involved and created numerical tools for full thermomechanical simulation of the embossing process as well as reaction-distortion models of elastomer reaction casting. The emphasis of these analyses is to establish limits to the production rate and quality of microdevices. The group has also worked on novel hardware for these processes, including fast-embossing equipment; novel centrifugal degassing

equipment; and high-speed high-resolution, large-range metrology systems. Finally, the group recently launched a “research factory” to achieve fully automated, high-volume production of functional microfluidic devices as a testbed for our component research.

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; all data indicate that the scale and sophistication of counterfeiting is growing.)

Dr. Anthony is growing a research group to develop computational instrumentation. He creates computational systems to sense and control physical systems. He uses computation and computer science as a methodology for attacking complex instrumentation problems. His research combines mathematical modeling, simulation, optimization, and experimental observations to develop instruments and measurement solutions for problems that are otherwise intractable. Two research projects are funded by SMA. His research in freehand ultrasound instrumentation is directed to expand the usability and functionality of freehand ultrasound instruments. His research in optical and photogrammetric metrology is focused on creating production-ready instruments capable of measuring three-dimensional micrometer-scale features distributed over a meter-scale area.

Dr. 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 integrating free-form natural language with structured data, yielding a comprehensive solution for knowledge management and discovery. 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 and commercial organizations including United States Joint Forces Command, Air Force Cyber Command, Joint Improvised Explosive Device Defeat Organization, Department of Homeland Security, Raytheon, and Volkswagen.

Professor 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. This past year, he presented 13 invited talks on his work, which is supported by grants from DOE, MITEI, the Chesonis Foundation’s Solar Revolution Project, and numerous other private benefactors. Professor Buonassisi is a founder of the nascent Fraunhofer Center for Sustainable Energy Systems and serves as its scientific director. He is also a participant in the MITEI Future of Solar Energy

Study and serves as scientific advisory board member for a new synchrotron nanoprobe beamline at Brookhaven National Laboratory.

Professor 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 various low-k dielectric materials are introduced into ultra-large-scale integrated electronics replacing SiO₂ as the insulator, his current research involves investigating and mitigating nanoscale scratching during copper CMP. In addition, Professor Chun has been participating in CPM, focusing on developing a polymerization-distortion model for the casting process, and led portable fuel-cell research in collaboration with professor emeritus Nam P. Suh. Recently, Professor Chun started work on a supply-chain issue in manufacturing of photovoltaic panels in collaboration with Professor Graves. He also participates in the Novartis–MIT Center for Continuous Manufacturing in developing a new manufacturing paradigm and enabling technologies for the pharmaceutical industry.

Professor Culpepper's research focuses on the design of mechanisms, equipment, and instruments that are required to make, manipulate, and measure parts for small-scale manufacturing. Professor Culpepper's group is tackling the challenges associated with designing and manufacturing (1) 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 high-performance and low-energy consumption sensors and electronics), (2) miniature precision optical scanning systems that may be used for noninvasive scanning of internal tissues for cancer detection, and (3) equipment and tooling that enables the directed printing of CNTs. The end goal of this work is to enable mass manufacturing of textured surfaces with aligned CNTs and CNT-based interconnects that enable mass manufacture of devices that leverage the unique properties of CNTs (surface area-to-volume ratio, electrical conductivity, thermal conductivity, elasticity) in devices that store, convert, and transport energy.

Dr. Gershwin continues his research on complex manufacturing systems models and analysis. He continues to teach and do research in the SMA and 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), and mathematical modeling and analysis of systems with multiple part types, analytic solutions of single-buffer systems with general arrivals and service, and real-time scheduling and material flow control.

Professor Graves has continued to do research on modeling supply chains and production and inventory systems. With support from SMA and MITEI, he has collaborated with Professor Gutowski to study the effects of remanufacturing on energy use and carbon emissions. He also continues work on supply-chain modeling and optimization with focused projects examining the supply chains for photovoltaic

panels and for wood pellets. Another focused project studies the scheduling of work at the Broad Institute sequencing facility. In a continuing project, he has examined inventory management in a retail setting with the objective of identifying how to allocate inventories to reduce out-of-stocks and maximize revenues. In the coming year, he plans to consider similar issues in an e-retailing setting.

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 and product design for recycling. The latter area includes modeling the recycling system and analyzing alternative product designs. He received an MITEI grant with professor Steve Graves of the Sloan School and Dr. Elsa Olivetti of Materials Science and Engineering. They are studying 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 Sachs was on leave.

Professor Sarma's research has focused on three areas: wireless sensors, RFID, and sustainable water and energy. 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 that can be mapped automatically by wandering "RFID-bots." Professor Sarma continues to serve on the board of EPCglobal, the premier RFID standards body worldwide. Professor Sarma recently started a research program in wireless sensing, focusing 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 detection of water leaks and on energy efficiency with techniques ranging from robots to infrared thermography.

Professor Trumper's research efforts center on the design of 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 ASML, Professor Trumper's group is investigating novel actuation and control approaches for high-accuracy motion in lithography systems. Professor Trumper's group is also collaborating with professor Christopher Love of Chemical Engineering to design new instruments and processes for rapid cell assays. These assay techniques hold promise in identifying rare cells that secrete compounds of interest in treating diseases such as HIV and malaria.

Professor Kripa Varanasi was a new faculty hire.

Professor Williams is leading a new collaboration between MIT, the University of Colorado at Boulder, the National Renewable Energy Laboratory, and SAP Research on smart grid technology. Professor Sarma has continued his leadership of RFID data security through his work on predicate logic for secure data exchange. A book by Professors Sarma and Williams on RFID technology was published by Cambridge University Press. 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.

This year, the laboratory continued significant educational activities. This year saw graduation of the third class of the new master of engineering in manufacturing degree program, which, although 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 students to assume a role of technical leadership in the manufacturing industry. As of August of 2009, we will have 78 alumni, and the entering class for 2009–10 will number 24. Students have been engaged in industry-based group projects for their project theses in companies that include BD Medical, Philips Domestic Products, Tetra Pak, Schlumberger, and Merck in Singapore, and Nano-Terra and Instron Corporation in the United States. It is important to note, however, that this year's entering class will be the last to have access to the fellowship program for this degree from SMA.

Katy Hartman received an NSF fellowship, Bonna Newman received the Claire Booth Luce Postdoctoral Fellowship, Sarah Bernardis was nominated for best poster award at the Fall Materials Research Society Meeting in Boston, and the LMP best student presentation was awarded to Steve Hudelson.

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 2008 and spring 2009 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. Renovations to laboratory spaces for Precision Engineering, CPM, and Photovoltaics have been completed. Space renovation to create a new multimedia conference room was completed and was 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 April, LMP held the 2009 Manufacturing Summit at MIT in conjunction with dedication of the Professor Nate Cook Room. The summit included presentations from all research areas within the lab, a keynote by professor Nam P. Suh, and the first meeting of the LMP Industrial Advisory Board. The event was a success, with more than 100 participants, and continued to build relationships with alumni and industry. The laboratory is in the process of planning 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/>.