Laboratory for Manufacturing and Productivity

The Laboratory for Manufacturing and Productivity (LMP) is an interdepartmental laboratory in the School of Engineering devoted to exploring new frontiers in manufacturing research and education. Its primary goals are: (1) the advancement of the fundamental principles of manufacturing processes, machines, and systems; (2) the application of those principles to the innovation of manufacturing enterprises; and (3) the education of engineering leaders. With 17 faculty and senior research staff and 93 students, the laboratory conducts research in the areas of innovation, design, analysis, and control of manufacturing processes, machines, and systems.

Research is conducted through sponsored research projects, government grants, industrial consortia, and international collaborations. LMP's major areas of interest include polymer microfabrication, chemical mechanical polishing (CMP), precision engineering, machine elements and systems, nanomanufacturing, nanoengineered surface and coating technologies, production system design, radio-frequency automatic identification, robotics, sensor networks, information technology, photovoltaics, fuel cells, and environmentally benign manufacturing. In addition, LMP works closely with many other departments, laboratories, and programs, including the Departments of Electrical Engineering and Computer Science (EECS), Materials Science and Engineering (MSE), and Mechanical Engineering (MechE); the Singapore–MIT Alliance (SMA); the Center for Transportation and Logistics; the Deshpande Center for Technological Innovation; the DuPont–MIT Alliance; the Leaders for Global Operations; the MIT Energy Initiative (MITEI); the Novartis–MIT Center for Continuous Manufacturing; the Lincoln Laboratory; and the MIT Sloan School of Management. Many LMP research projects collaborate with industrial companies, including Chevron, General Electric, GS1 US, and Quantum Signal. LMP government support, which is often coordinated with industrial support, comes from the Army Research Office, the Defense Advanced Research Projects Agency (DARPA), the Department of Energy, the National Aeronautics and Space Administration (NASA), and the National Science Foundation (NSF). LMP also maintains a strong international presence—research sponsors include the Daegu-Gyeongbuk Institute of Science and Technology (DGIST), King Fahd University of Petroleum and Minerals, the National University of Singapore (NUS), GS1 AISBL, ASML, Ferrovial S.A., and Samsung Electronics.

LMP's total research volume was $7M for AY2012. The active programs of professors George Barbastathis, Tonio Buonassisi, Jung-Hoon Chun, Martin Culpepper, Stephen Graves, Timothy Gutowski, David Hardt, Sanjay Sarma, David Trumper, Kripa Varanasi, John Williams, and Kamal Youcef-Toumi, and research scientists Brian Anthony, David Brock, Joseph Coughlin, Stanley Gershwin, Karl Iagnemma, and Nannaji Saka contributed to this research volume.

Research Highlights and Awards

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

- *Micro- and nanoscale manufacturing processes and equipment.* Professors Chun, Culpepper, Hardt, Trumper, Varanasi, and Youcef-Toumi continue to be actively engaged in this research thrust area. An SMA flagship research project on microfluidic device manufacturing is led by Professor Hardt, who is joined by MechE and EECS faculty members in the Center for Polymer Microfabrication (CPM). Professor Hardt has also begun a new project on microcontact printing, sponsored by the Center for Clean Water and Clean Energy, in collaboration with Dr. Anthony and postdoctoral associate Joseph Petrzelka. Professor Chun works in the area of CMP, while Professors Barbastathis, 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. Professor Varanasi works in the area of nanoengineered surface and coating technologies for transformational efficiency enhancements in energy and water use.
- *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 as well. Dr. Brock continued the expansion of MIT's 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, while Professor Graves focuses on supply chain design and management. Dr. Iagnemma researches mobile robotic systems, and Dr. Anthony researches the application of information technology to improve the productivity of medical imaging systems.
- *Renewable energy and environmentally benign manufacturing.* Professor Buonassisi continues work in photovoltaics research. Professor Gutowski is engaged in research projects focusing on issues of sustainability for the manufacturing industry. Professors Buonassisi and Gutowski, Dr. Gershwin, and visiting scientist Kotaro Kawajiri have initiated informal collaborations to identify the most environmentally sustainable paths toward scaling photovoltaics to the terawatt level.

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. The current focus is on microfluidic products in both the biomedical and computational fields.

Participants in CPM include Professors Hardt, Chun, and Youcef-Toumi; professors Lallit Anand and Duane Boning; and Dr. Anthony and Todd Thorsen. 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 has focused primarily on the 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 has created numerical tools for full thermo-mechanical simulation of the embossing process, as well as reaction-distortion models of elastomer reaction casting. The group continues to build on this base to create novel methods for device manufacture and to realize these methods in an automated production cell. The goal is to produce functional devices in high volumes with consistent quality using the embossing process. This has involved the development of a precision robotic handling system and novel measurement methods capable of large-range, high-resolution measurements.

In addition, CPM continued work on two projects dealing with continuous or roll-to-roll manufacturing of enhanced surfaces. One project deals with the printing of self-assembling molecules using microcontact printing, and the other considers real-time, on-web measurement and control of nanoembossed patterns. The latter project is conducted as a subcontract to the University of Massachusetts Center for Hierarchical Manufacturing.

Dr. Anthony focuses on the design and realization of computational instrumentation, and his group creates computational systems to sense and control physical systems. His research combines mathematical modeling, simulation, optimization, and experimental observations to develop instruments and measurement solutions for problems that are otherwise intractable. Research in freehand ultrasound instrumentation is directed to expand the productivity and diagnostic capability of medical ultrasound. His research in optical and photogrammetric metrology focuses on creating production-ready instruments capable of measuring three-dimensional micron-scale features distributed over a meters-scale area. This research is funded by General Electric and SMA.

In addition, Dr. Anthony, along with professors Charles Sodini of Microsystems Technologies Laboratories and Joel Voldman of Research Laboratory of Electronics, cofounded and codirects the MIT Medical Electronics Device Realization Center (MEDRC). The vision of MEDRC is to transform the medical electronic devices industries, to revolutionize medical diagnostics and treatments by bringing health care directly to the individual, and to create enabling technology for the future information-driven healthcare system.

With support from Samsung Electronics, the project conducted by Professor Barbastathis focuses on methods to further improve spot quality and compensate for the non-uniformity of the ablated spot by creating a beam with a flat-top profile. Such a beam would ensure that the entire ablation area receives the same energy and would improve the material deposition/ablation profile. This can be done primarily by using a holographic optical component, such as a Fresnel/grating or diffractive optical element, designed and optimized to achieve a flat-top beam output generation. As long as the non-uniformity can be assumed to be static in time, a test ablation structure profile without compensation can be used in the design algorithm. Professor Barbastathis has demonstrated that a uniform beam spot with diameters 2–30 μm can be generated by controlling the proposed system, which can be implemented as a static glass element or dynamic spatially tunable system.

The data interoperability technologies developed by MIT's data center program are supported and evaluated by the Department of Defense (DOD) Joint Chiefs of Staff as a means of integrating data, process, and planning within the United States Joint Forces Command. The program, led by Dr. Brock, builds the languages, protocols, and systems to integrate data and analytic models across the internet. With the ability to combine both structured data and unstructured natural language, the infrastructure addresses many real-world problems in planning, logistics, and communications. In cooperation with government and corporate sponsors, the program has developed and tested prototypes for various agencies within the US government.

Professor Buonassisi's Photovoltaic Research Laboratory (PVLab) aims to develop the next generation of photovoltaic materials and processes by focusing on core strengths of defect engineering, characterization, and simulation. The lab designed a materials simulation tool called Impurity-to-Efficiency to predict the evolution of performance-limiting impurities during crystalline silicon solar cell processing. This tool ran thousands of unique process simulations worldwide since its mid-2011 online release and was applied in industrial settings to increase manufacturing throughput. An economic assessment of the domestic competitiveness of crystalline silicon solar cell manufacturing was featured in The Economist and was presented to the participants in two Institute initiatives: the MIT Study of the Future of Solar Energy, and Production in the Innovation Economy. The PVLab built new collaborations, including three Department of Energy research grants, with collaborators at Harvard University, the University of Delaware, and the National Renewable Energy Laboratory (NREL); an NSF engineering research center, which includes Arizona State University, the California Institute of Technology, the Georgia Institute of Technology, and MIT, among other institutions; and a new Singapore–MIT Alliance for Research and Technology Low Energy Electronic Systems interdisciplinary research group.

Professor Buonassisi also chaired the 5th International Workshop on Crystalline Silicon Solar Cells, which hosted 132 scientists from 15 countries in Boston in fall 2011. He participated in an external review panel for the NREL National Center for Photovoltaics, providing guidance to strategically position the nation's largest renewable energy laboratory. Professor Buonassisi serves as spokesman for a proposed synchrotron beamline, *in-situ* nanoprobe, which was ranked highest in its class by a peer review committee and is in initial design phase at the Advanced Photon Source at Argonne National Laboratory. In addition, he actively serves on three conference-organizing committees in photovoltaics.

In the classroom, Professor Buonassisi is in the process of transitioning his course, 2.626/2.627 Fundamentals of Photovoltaics, into an online format to reach a worldwide audience. This transition is being made in conjunction with Academic Media

Production Services and MIT OpenCourseWare, and with Joseph Sullivan, recipient of a MechE graduate student instructor award. Professor Buonassisi received an NSF CAREER Award.

Professor Chun continued to lead the copper (Cu) CMP research program under the auspices of Samsung Electronics. Since various low-*k* dielectric materials (mechanically softer than SiO_2) are introduced into ultra large-scale integrated electronics replacing SiO_2 as the insulator, his current research involves investigation and mitigation of scratching by pad asperity during Cu CMP. Based on a scratching regime map developed by his group, a new pad conditioning protocol was invented, which will reduce the use of consumables during conditioning. In addition, Professor Chun has been a key participant in the Novartis–MIT Center for Continuous Manufacturing in developing a new manufacturing paradigm and enabling technologies for the pharmaceutical industry.

Dr. Coughlin continued his research collaboration with DGIST in the development of an on-road experimental platform to assess visual distraction and the validity of the DGIST driving simulator as a test-bed for the evaluation of visual secondary demands.

Professor Culpepper's research focuses on the design of mechanisms, equipment, and instruments that are required to make, manipulate, and measure parts for precision manufacturing. His group is tackling the challenges associated with the design and manufacturing of equipment and tooling for precision manufacturing—including tooling for nanoscale patterning and CMP. Professor Culpepper has also worked to initiate dedicated fellowships for mechanical engineering and manufacturing research with Draper Laboratory. He has been in discussions with Draper Laboratory regarding the formation of an LMP-wide (multi-faculty) program in advanced design and mass manufacturing of small-scale precision components and systems.

Dr. Gershwin continues his research on complex manufacturing systems models and analysis. He also continues to teach an introductory course in manufacturing systems, which is a requirement for the Master of Engineering in Manufacturing program. His research areas include 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; analytical solutions of single-buffer systems with general arrivals and service; and real-time scheduling and material flow control.

A research project started in 2011, and supported by Samsung Electronics, aims to study the performance of the Control-Point Policy, a real-time factory scheduling policy developed by Dr. Gershwin and his research group. This is being studied in the context of liquid crystal display flat panel fabrication and will be studied in other contexts as well. Dr. Gershwin has been invited to give a keynote talk at the 4th International Conference on Information Systems, Logistics and Supply Chain, to be held in Quebec in August 2012; and a plenary talk at the Operations Research 2012 conference—the International Annual Conference of the German Operations Research Society—in Hannover, Germany, in September 2012.

Professor Graves continues to do research on the modeling of supply chains and production/inventory systems. With support from SMA, he has examined inventory management and order fulfillment in an online retail setting. The supply chain for an online retailer presents many new challenges because the online retailer will stock each item in multiple warehouses and will then dynamically decide how to assign inventory to orders and what shipment modes to use. Professor Graves focuses on how to provide high levels of service with the least amount of inventory and shipping costs. In research supported by industrial sponsors, he has developed tactical models for planning and scheduling different types of supply chains: a serial manufacturing system, an assembly system, and a job shop. In each case, the tactical planning models allow for the optimization of the relevant tactics for each type of supply chain; these tactics include the optimal deployment of safety stocks, the frequency of production setups, and the level of production smoothing.

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 General Motors, Cummins, and NSF in the areas of materials production, manufacturing process analysis, and product design. The latter includes the modeling of the recycling system and an analysis of alternative product designs. In collaboration with Professor Graves of the Sloan School of Management and Dr. Elsa Olivetti of the Department of Materials Science and Engineering(MSE), and under the auspices of MITEI, his group investigated the effects of remanufacturing on energy use and carbon emissions.

Professor Gutowski, along with Dr. Julian Allwood and professor Michael Ashby (both of the University of Cambridge) and Dr. Ernst Worrell (Utrecht University), hosted a discussion meeting at the Royal Society of London on material efficiency. Professor Gutowski and his students are working with macroeconomist Dr. Harry Saunders (Decision Processes Inc.) to develop methods to model the economic rebound effect associated with energy efficiency improvements.

Professor Hardt's work focuses on novel equipment and control systems for micron-scale polymer processing. In the past year, his group has developed a high-precision, low-cost micro-embossing machine, as well as rapid and accurate methods for evaluating microfluidic device quality in a production environment. A related project has established methods for printing of very small conductive lines (~5 micron) on polymer substrates, again in a low-cost precision fashion. Prior work on understanding the mechanics and control of the contact region in microcontact printing has established a new set of criteria for stamp geometry and process control as a function of stamp properties. These results have led to a new project aimed at creating a novel roll-to-roll experimental facility to large-area, high-resolution printing studies.

Dr. Iagnemma's research focuses on modeling, design, and algorithm development for mobile robotic systems. Much of his work is supported by DOD and has an emphasis on developing robotic systems for operation in challenging environments, which include difficult outdoor terrain, planetary surfaces (including the surfaces of the moon and Mars), and inside the human body. Recent Samsung-sponsored research focused on the design and development of miniaturized, articulated manipulators for next-generation minimally invasive surgery. Other NASA-sponsored research into robot-environment interaction is being performed in support of the Mars Science Laboratory rover mission, for which Dr. Iagnemma serves as a collaborating scientist. Other DARPA-sponsored research is leading to the development of passenger vehicle operator assistance algorithms to reduce or eliminate accidents. Dr. Iagnemma is also developing novel robotic systems that rely on the adhesive properties of magnetorheologic fluids, and jamming of granular materials.

Professor Sarma's research has focused on two areas: wireless sensors and sustainable water/energy. He has extended his work in RFID into the sensors arena. By leveraging physical changes to the antenna in a regular, inexpensive RFID tag, it is possible to create wireless sensors that cost only a few cents. Professor Sarma's group has also developed a mathematical framework for incorporating sensor data into a field reconstruction. This enables large-scale mapping and "hot spot" detection—for example, of the source of a pollutant leak—using large numbers of fixed and mobile sensors. Separately, Professor Sarma's group has developed a range of technologies for scanning cities and environments. One technology utilizes long-wave infrared images to analyze buildings using drive-by scanning from the street. The output of this system, which resembles Google Street View, can be used to automatically analyze and recommend repairs to buildings to minimize heat loss. The group is also developing a technology to analyze streetlights for lighting coverage, lighting quality, and light repair.

Professor Trumper's research has led to new designs for a new type of electromagnetic nanoimager. In the area of actuation, his group has been studying the design of high-linearity iron core actuators for precision motion control systems. In collaboration with MITEI, the group has been studying novel types of motors and magnetic suspensions for high-speed machinery and flywheel energy storage has also invented, jointly with professor David Barrett of Olin College, a new type of actuation system for autonomous robotic locomotion.

Professor Varanasi's research group aims to bring about transformational efficiency enhancements in various industries, including energy (from power generation, to oil and gas, to renewables), water, agriculture, transportation, and electronics cooling, by fundamentally altering thermal-fluid-surface interactions across multiple length and time scales. His group has enabled this approach via highly interdisciplinary research focused on nanoengineered surfaces and interfaces, thermal-fluid science, and new materials discovery, combined with scalable nanomanufacturing for significant efficiency gains, reduction in carbon dioxide emissions, and the prevention of catastrophic failures in real industrial applications. Professor Varanasi's work spans various thermal-fluid and interfacial phenomena, including phase transitions (condensation, boiling, and freezing), nanoscale thermal transport, separation, wetting, catalysis, flow assurance in oil and gas, nanofabrication, and synthesis of inorganic bulk and nanoscale materials guided via computational materials design.

Professor Williams continued his research collaboration with Philip Morris International to develop the electronic product code (EPC) network as the standard for tracking and tracing. The project provided a model and testing capability relative to the tracking of items in the tobacco industry, as well as enabling the development of software and a methodology to validate that EPC information services–compliant servers are able to handle the tobacco industry schema.

The achievements toward high-speed atomic force led by Professor Youcef-Toumi can be categorized into: (1) developments in atomic force microscope (AFM) control schemes, and (2) improvements in mechanical design. On the former, Professor Youcef-Toumi's group has designed and implemented several control approaches to high-speed AFM on both commercially available and custom-built AFMs. In recent work, the group demonstrated a new way to characterize the lateral scanner dynamics without the addition of lateral sensors, and to shape the commanded input signals in such a way that disturbing dynamics are not excited. This approach has enabled an order of magnitude increase in the scan rates of unmodified commercial AFMs and has been successfully applied to a custom-built high-speed AFM-enabling imaging at more than 10 frames per second. Furthermore, Professor Youcef-Toumi's group successfully tested an active vibration suppression technique to improve the bandwidth of a new generation of rigid AFMs. A piezo-based, feedforward controlled, counter actuation mechanism is used to compensate for the excited out-of-plane scanner dynamics, the AFM controller output is properly filtered via a linear compensator and then applied to a counter actuating piezo, and an effective algorithm for estimating the compensator parameters is developed. The information required for compensator design is extracted from the cantilever deflection signal, which eliminates the need for any additional sensors. This imperative characteristic of the proposed approach makes it suitable for commercialization, and the group is currently working on preparing a patent disclosure on this invention. In addition to the control approaches, Professor Youcef-Toumi's group has employed novel mechanical design techniques to improve the dynamics and range of the AFM scanners. The group has presented a novel methodology for generating flexure-based topologies that can meet performance requirements leading to the desirable imaging range and speed. Based on this methodology, the group has designed and built a high-speed AFM, successfully imaging dry samples, such as silicon wafers as well as samples in liquid, to monitor biological processes at very high imaging speeds

This year, LMP continued significant educational activities, including the graduation of the sixth class of the Master of Engineering in Manufacturing program, which, while not an LMP activity, occurs largely through the efforts of its faculty and staff. This highly focused one-year professional degree program is intended to prepare students to assume roles of technical leadership in the manufacturing industry. As of August 2011, the program had over 100 alumni, and the AY2013 entering class will total 16. Students engage in industry-based group projects for their project theses in companies that include Daktari, Medtronic, Synqor, Ultrasource, and Varian Semiconductor.

Professor Ely Sachs retired from MIT in 2011, and research scientist David Brock left LMP in early 2012.

New Initiatives

LMP has continued the renewal campaign that began in spring 2005. The Manufacturing and Productivity Seminar Series at MIT continued this year 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.

In October 2011, LMP held its sixth annual Manufacturing Summit, which focused on manufacturing in an innovation economy. The two-day summit, organized by Professors Chun and Hardt and Dr. Anthony, brought together presenters from industry, government, and academia who discussed their perspectives on the business, policy and economics, and educational programs required for continued manufacturing in the US. More specifically, the presentations and subsequent panel discussions focused on how to alter the perception of manufacturing in the US, and the importance of attracting young professionals to careers in manufacturing.

Jung-Hoon Chun
Director
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