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 the advancement of the fundamental principles of manufacturing processes, machines, and systems; the application of those principles to the technological innovation of manufacturing enterprises; and the education of engineering leaders. With 17 faculty and senior research staff and more than 90 students, the laboratory conducts research in the areas of design, analysis, control, and innovation 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, precision machine elements and systems, nanomanufacturing, nanoengineered surface and coating technologies, modeling and design of supply chain and production systems, radio-frequency automatic identification, sensor networks, information technology, robotics, photovoltaics, 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, and Mechanical Engineering, the Singapore-MIT Alliance (SMA), the Deshpande Center for Technological Innovation, the DuPont-MIT Alliance, Leaders for Global Operations, the MIT Energy Initiative, the Novartis-MIT Center for Continuous Manufacturing, Lincoln Laboratory, and the MIT Sloan School of Management. Many LMP research projects collaborate with industrial companies, including Boston-Power, 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 (DOE), the Department of Transportation, the National Aeronautics and Space Administration (NASA), and the National Science Foundation (NSF). LMP also maintains a strong international presence—research sponsors include ASML, Ferrovial S.A., GS1 AISBL, King Fahd University of Petroleum and Minerals (KFUPM), the National University of Singapore, Nissan Motor Company, and Samsung Electronics Company, Ltd.

LMP's total research volume was $8.8 million for AY2013. The active programs of professors George Barbastathis, Tonio Buonassisi, Jung-Hoon Chun, Martin Culpepper, Nicholas Fang, Sylvija Gradecak, Stephen Graves, Jeffrey Grossman, Timothy Gutowski, David Hardt, Sanjay Sarma, David Trumper, and Kripa Varanasi, and research scientists Brian Anthony, Stanley Gershwin, and Karl Iagnemma, 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 Barbastathis, Chun, Culpepper, Fang, Hardt, Trumper, and Varanasi are now 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 Mechanical Engineering and EECS faculty members in the Center for Polymer Microfabrication. Professor Hardt has also begun a new project on micro-contact printing sponsored by the Center for Clean Water and Clean Energy, in collaboration with Dr. Anthony. Professor Chun works in the area of CMP, while Professors Barbastathis, Culpepper, Trumper, and Fang 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 Sarma, develops identification technologies, including radio-frequency identification (RFID), to enable "the internet of things." Professor Sarma works on wireless sensors and complex systems as well. 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 to work in photovoltaics research in collaboration with Professors Gradecak and Grossman. Professor Gutowski is engaged in research projects focusing on issues of sustainability for the manufacturing industry. Professors Buonassisi and Gutowski and Dr. Gershwin have initiated informal collaborations to identify the most environmentally sustainable paths toward scaling photovoltaics to the terawatt level.

Brian Anthony

Dr. Anthony and his group created instruments, algorithms, and devices to sense and control physical systems. His research combines multiple approaches, including mathematical modeling, simulation, optimization, and experimental observations, to develop instruments and measurement solutions for problems that are otherwise intractable. The focus of his research can therefore be described as "computational instrumentation."

Active areas of research in Dr. Anthony's group include medical ultrasound imaging and the high-speed inspection of three-dimensional (3D) micro-manufactured parts. Research in freehand ultrasound, supported by the MIT Medical Electronics Device Realization Center (MEDRC), is directed towards expanding the productivity and diagnostic capability of ultrasound imaging. MEDRC works to transform the medical electronic devices industries and to revolutionize medical diagnostics and treatments by bringing healthcare directly to the individual and by creating enabling technology for future information-driven healthcare systems. His group has developed an ultrasound probe that measures and controls the user's applied force and measures the orientation of the probe. This probe is used to acquire ultrasound image sequences as a function of applied force. Newly developed algorithms use the image vs. force sequences to estimate un-deformed 2D tissue structures and elastic properties. In addition, a newly developed probe that combines accelerometers, gyros, and cameras is used to estimate the position and orientation of the probe with respect to the patient's body and to acquire 3D ultrasound scans.

Dr. Anthony's research in optical and photogrammetric metrology focuses on creating production-ready instruments capable of measuring 3D micron-scale features distributed over a meters-scale area. His group has developed a high-speed 3D profilometer for the inspection of micro-manufactured transparent parts, and is now developing high-throughput inspection techniques for the monitoring and control of roll-to-roll manufacturing processes for continuous high-rate production of flexible electronic systems. His research is funded by General Electric, NSF, KFUPM, and SMA.

George Barbastathis

With support from Samsung Electronics, the project conducted by Professor Barbastathis focuses on the detection of defects at hundreds nanometer scale on a fourth-generation thin-film transistor (TFT) glass panel. Defects as small as 100nm on an initial glass plate may grow as big as several micrometers during the multilayer-deposit process of TFT glass fabrication. He has proposed a detection method based on an off-axis holography with an attenuated reference field. With the proposed method, the optical fields scattered from defects are projected to a charge-coupled device camera to make a hologram with a reference field the intensity of which is attenuated comparable to that of the scattered field. Simulations over particles as small as 100nm in diameter have been performed under experimental noises such as shot and Gaussian noises, and they show the validity of the scheme. Further experimental verification is in progress.

Antonio Buonassisi

The mission of Professor Buonassisi's Photovoltaic Research Laboratory is to develop the next generation of photovoltaic materials and processes by focusing on core strengths of defect engineering, characterization, and simulation.

Professor Buonassisi and professor Karen Gleason were awarded a new project in collaboration with Eni to develop a hybrid organic-silicon solar cell (combining the stability and performance of crystalline silicon with high-rate manufacturing of organic materials for contacts, coatings, and encapsulants). In collaboration with professor Mariana Bertoni (Arizona State University), a former LMP postdoctoral fellow, Professor Buonassisi was awarded a DOE BRIDGE grant to develop an in-situ sample stage for a scanning nanoprobe X-ray fluorescence beamline at the Advanced Photon Source synchrotron, Argonne National Laboratory. With this tool, they aspire to probe defects in thin-film chalcogenide solar cells under simulated processing conditions to reveal governing defect kinetics and thermodynamics. Ongoing collaborative research center activities include an NSF-sponsored Engineering Research Center (Professor Buonassisi is Thrust 1 co-lead) with Professors Gradecak and professor Alexie Kolpak, DOE-sponsored projects with professor Roy Gordon (Harvard University) and Dr. Steven Hegedus (University of Delaware), and a KFUPM-MIT Center for Clean Water and Energy project with professors Grossman and Kolpak—all focused on utilityscale photovoltaics. Other collaborative activities include a Singapore-MIT Alliance for Research and Technology activity (the Low Energy Electronics Systems Interdisciplinary Research Group) focused on developing high-efficiency photovoltaics for mobile devices.

Professor Buonassisi and his group generated several newsworthy research highlights, including achieving record thin-film solar cell efficiencies in two novel material classes (tin sulfide and cuprous oxide) via "interface engineering" with carrier-selective contacts; demonstrating efficient organic passivation of silicon via chemical vapor deposition, in collaboration with Professor Gleason; challenging the "textbook" value of nickel diffusivity in silicon, demonstrating a value order of magnitude higher than previously believed; developing a model to predict the efficiency limit of integrated photovoltaic/electrochemical devices (artificial leaf), in collaboration with professor Daniel Nocera; and engaging in translational research with "kerfless" silicon wafer manufacturers (wafer fabrication approaches that use an order of magnitude less silicon), which resulted in improvements to one company's electronic quality by roughly an order of magnitude, enabling solar-cell efficiency improvements of nearly 33%.

Jung-Hoon Chun

Professor Chun continued to lead the copper (Cu) CMP research program in collaboration with Dr. Nannaji Saka under the auspices of Samsung Electronics. Since various low-*k* dielectric materials (mechanically softer than SiO2) are introduced into ultra large-scale integrated electronics replacing SiO2 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 to maintain optimum topologized properties of CMP pads, which will reduce the use of consumables during conditioning. In addition, he 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. He became co-convener of the Smart Green Buildings research project under the Hong Kong University of Science and Technology–MIT Research Alliance Consortium.

Martin Culpepper

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

Nicholas Fang

Professor Fang's research focuses on the development of innovative micro-/nanomanufacturing technologies to overcome current limitations of existing manufacturing methods and to explore new engineering applications. His group has developed a novel micro 3D printing technology called projection micro-stereolithography (PμSL). PμSL is a rapid, additive, and scalable stereolithography technique that uses a state-of-the-art digital micro display array as a dynamically reconfigurable digital photomask. Therefore, PμSL is capable of rapidly fabricating complex 3D microstructures consisting of multiple materials in a bottom-up, layer-by-layer fashion via photo-polymerization. Professor Fang's group uses PμSL to manufacture various types of functional materials, including soft active gels, biomaterials, shape memory polymers, and metallic/ceramic materials. This versatile manufacturing tool played a pivotal role in the recent development of new engineering applications in Fang's group, such as 3D tissue engineering scaffolds, soft robotic micro-devices, and shape-transforming active microstructures, some of which were recently highlighted in *MIT News*, *Physics*, and *Science Daily*.

Professor Fang also invented a solid-state electrochemical nano-imprint process for direct patterning of metallic nanostructures, called solid-state super-ionic stamping (S4). S4 uses a patterned solid electrolyte as a stamp and etches a metallic film by an electrochemical reaction to directly reproduce metallic features as small as 10 nm. This single-step, high-throughput, high-resolution, large-area manufacturing technology for metallic nanostructures may potentially lead to groundbreaking solutions for the semiconductor industry. Such innovations in manufacturing have a transformative impact on a broad range of disciplines, including material science, mechanics, photonics, and biomedical engineering. Much of the research is supported by various funding agencies, including NSF, DARPA, the Office of Naval Research, the Air Force Office of Scientific Research, and Samsung Electronics.

Stanley Gershwin

Dr. Gershwin continued his research on complex manufacturing systems models and analysis. 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, real-time scheduling and material flow control, and the design of separation systems for recycling. He has maintained a longstanding collaboration with colleagues at the Politecno di Milano with support from the Rocca Foundation, and he will join the MIT Skoltech Initiative to develop a manufacturing system course for the Skolkovo Institute of Science and Technology.

Stephen Graves

Professor Graves continued to do research on the modeling of supply chains and production/inventory systems. With support from SMA, he examined inventory management and order fulfillment in an online retail setting. The supply chain for an online retailer presented many new challenges because the online retailer would stock each item in multiple warehouses and then dynamically decide how to assign inventory to orders and what shipment modes to use. Professor Graves's research focused 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 of manufacturing systems and supply chains. One current project entails the examination of how best to utilize operational flexibility in a complex serial manufacturing system in which jobs can be moved from one line to another to achieve a more balanced workflow. Another project analyzes a closed-loop supply chain for the support of warrantee exchanges for electronic devices. When a customer's device fails, the customer can exchange it for a refurbished device; failed units are then repaired, if possible, and returned to inventory. The research considers how to forecast the inventory requirements and best manage the inventory over the lifecycle of a product. Professor Graves also continues research on tactical planning in supply chains in which he develops planning models 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.

Timothy Gutowski

Professor Gutowski's research group, Environmentally Benign Manufacturing (EBM), continued to do research on the interaction between manufacturing and the environment, with special attention to energy usage and carbon emissions. Current research efforts by EBM exist at all levels of the manufacturing enterprise, including the development of new processing technologies, design methods, factory-level energy improvements, and an environmental assessment of the manufacturing sector at the global level. This year, the EBM group was part of a successful team that won a $7.6 million research contract from the Department of Energy. The group included Boeing, Ford, Northwestern University, Pennsylvania State University, and MIT. The project will focus on the development of flexible sheet metal forming technologies for low energy.

David Hardt

Professor Hardt's work focuses on novel equipment and control systems for micron-scale polymer processing. In the past year, his group has developed novel equipment for automated tape bonding of microfluidic device covers and for rapid automatic inspection and functional testing. In addition, the micro-contact printing group has completed design and construction of a roll-to-roll printing system with a unique measurement capability that allows for in-process visualization of the contact region to micro level resolution. His group is also continuing the refinement of a unique centrifugal casting of cylindrical printing tools with micron scale features written continuously on the mold master. In 2013, Professor Hardt was named an American Society of Mechanical Engineers Fellow.

Karl Iagnemma

Dr. Iagnemma's research focuses on modeling, design, and algorithm development for mobile robotic systems. Much of his work was supported by the Department of Defense 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 will lead 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 the jamming of granular materials.

Sanjay Sarma

Professor Sarma's research has focused on three areas: wireless sensors, city scanning, and cloud computing. He has continued his work in RFID in the sensors arena, leveraging physical changes to the antenna in a regular, inexpensive RFID tag 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 to enable large-scale mapping and "hot spot" detection (e.g., of the source of a pollutant leak) using large numbers of fixed or mobile sensors. Separately, Professor Sarma's group has developed a range of technologies for scanning cities and environments. One technology utilizes longwave infrared images to analyze the thermal efficiency of buildings. The output of this system 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 Sarma's group has also established a new research front called "CloudThink," with over 100 vehicles around the world now being tested with new hardware developed for a subproject focused on a CloudThink-connected car.

David Trumper

Professor Trumper's research has led to new designs for a new type of electromagnetic nano-imager. 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 the MIT Energy Initiative, the group has been studying novel types of motors and magnetic suspensions for high-speed machinery and flywheel energy storage.

Kripa Varanasi

The mission of Professor Varanasi's research group is to bring about transformational efficiency enhancements in various industries, including energy (power generation, oil and gas, and renewables), water, agriculture, transportation, and electronics cooling, by fundamentally altering thermal-fluid-surface interactions across multiple length- and timescales. 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 CO_2 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.

Research accomplishments over the past year include development of lubricant-impregnated slippery surfaces (also LiquiGlide), hydrophobic ceramics, enhanced condensation, anti-icing surfaces, fundamental understanding of contact line interactions and droplet mobility on various types of surfaces, and scalable manufacturing techniques of nanoengineered surfaces. These results were disseminated in various journals, including *Nature Materials*, *Nature Communications*, and *ACS [American Chemical Society] Nano*. The super-slippery coating technology LiquiGlide, developed in the laboratory, has received significant attention and has been selected as one of the best inventions of the year by *Time* and *Forbes* magazines for 2012. The LiquiGlide technology has been spun off into the startup company LiquiGlide, Inc. (based in Kendall Square) to commercialize the technology for various applications. Professor Varanasi was awarded the Outstanding Young Manufacturing Engineer Award by the Society of Manufacturing Engineers.

John Hart

Professor John Hart will join the Laboratory for Manufacturing and Productivity effective July 1, 2013. Prior to coming to MIT, he was assistant professor of mechanical engineering at the University of Michigan. His research group focuses on the realization of novel machines and manufacturing processes for nanostructured materials and their applications in composites, electronics, energy systems, and biointerfaces.

Initiatives

This year, LMP continued significant educational activities, including the graduation of the seventh class of the Master of Engineering in Manufacturing (MEngM) degree program, which, while not an LMP activity, occurs largely through the efforts of the laboratory's 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 2013, the program will have over 130 alumni, and the AY2014 entering class numbers 18 students who will engage in industry-based group projects for their project theses in companies that include Daktari, Medtronic, Synqor, Ultrasource, Waters Corp, Leneze Corp, and Varian Semiconductor.

Also this year, a group of LMP students, staff, and faculty received training for a 5-Axis Control Vertical Machining Center, loaned by the Machine Tools Technology Research Foundation. The machine resides in the machine shop, Room 35-125, and will be used for education and research.

Jung-Hoon Chun
Director
Professor of Mechanical Engineering