NATIONAL SCIENCE FOUNDATION

Summer Institute on Nanomechanics and Nanomaterials and Micro/Nanomanufacturing

in collaboration with

University of Texas, Austin

A Short Course on:

Additive Manufacturing

May 29-31, 2013

Hilton Garden Inn, 1818 Maple Avenue, Evanston, Illinois, 60201
Organized by
Prof. David Bourell (UT Austin) and Prof. Jian Cao (NU)

Course Objectives:

Additive Manufacturing (AM) is a collection of advanced manufacturing technologies which produce objects from 3D model data, usually layer upon layer, as opposed to subtractive manufacturing methodologies. Effectively, AM fabricators are 3D printers which allow the user to "print" a 3D object from a computer solid model of the part. The first AM processes were developed and commercialized in the mid to late 1980s. The industry today is valued at almost $2B, with international activity and interest. AM fabricators span from do-it-yourself, download-and-build machines costing less than $500 to advanced material fabricators costing over $1M. The objective of this summer institute short course on additive manufacture is to provide attendees the opportunity to learn about various important aspects of AM technologies from leaders in the field. The course will include an introduction to AM, computational aspects, physical modeling of part creation, feedstock materials, AM part properties, machine design, simulation, design for AM, and applications of AM technologies and parts. Additionally, lab tours will be organized. The activities of the recently federally-funded $30M National Additive Manufacturing Innovations Institute matched with over $40M non-federal funds will also be presented by the NAMII executive leadership.

Course Organization

Day 1, May 29, Wednesday

8:00 AM – 8:30 AM Welcome from NSF Program Director

8:30 AM – 10 AM Rapid Manufacturing 101 and Roadmap David Rosen

This talk will set the stage for subsequent presentations by introducing the range of additive manufacturing (AM) processes and technologies, then by offering a roadmap of research issues and directions. Processes will be categorized based on whether they deposit material or deliver energy as their primary method of part fabrication and by whether material is processed using 1D vector scanning, parallel 1D raster scanning, or area filling approaches. Mechanisms of material processing will be summarized. Applications will be surveyed. Differences between prototyping, tooling, and production manufacturing will be highlighted. In the second part of the talk, results from the 2009 NSF/ONR Roadmap for Additive Manufacturing Workshop will be presented. Technologies and capabilities of commercial AM machine will be summarized. A research roadmap will be offered in the areas of materials, processes, and machines; processing modeling and control; design for AM; applications; and education.

10:00 AM – 10:30 AM Break

10:30 AM – 12 PM CAD Yong Chen

The benefits of using unique capabilities of additive manufacturing (AM) such as unlimited geometric capability and heterogeneous material property for better design performance are mainly untapped. There is limited knowledge regarding the use of such capabilities in achieving improved design performance. Current computer-aided design (CAD) tools (e.g. Pro-Engineer and SolidWorks) are developed for traditional manufacturing processes, which pose severe limitations on the designed shapes and materials. Product designs with simple shape and limited material complexity, in another hand, limit the wide adoption of AM. This presentation discusses some research issues on developing new CAD systems for additive manufacturing including topology and conceptual design, human-centered design, and system interaction with designers. Some applications including designing customized orthodontic braces will also be given as examples.

Noon – 1:00 pm Lunch

1:00 – 2:30 pm Lab Tour

2:30 – 3:00 pm Break

3:00 – 5:00 PM **Bio Applications** **Wei Sun**

Bio-additive manufacturing encompasses a broad application to tissue-engineered substitutes, medical devices, orthopedic implants and cell/tissue-on-a-chip micro-fluidic systems. Computer-aided tissue engineering technology, including bio-modeling, biomimetic design and SFF fabrication of cell/biomaterials based building blocks has facilitated the development of the field of bio-additive manufacturing. This presentation will report some salient advances on Bio-additive manufacturing, covering computer-aided tissue engineering, design and fabrication of 3-dimensional tissue scaffolds, and cell/organ printing. Selected bio-modeling and additive manufacturing techniques for design and fabrication of advanced tissue scaffolds and customized tissue replacements will be presented. Printing/assembling living cells for constructing *in vitro* biological models and the applications to regenerative medicine, disease study, drug testing and micro-tissue/organ systems will be introduced. Challenges and opportunities of Bio-additive manufacturing as an interdisciplinary field of engineering and life sciences will also be discussed.

Day 2, May 30, Thursday

8:30 AM – 10 AM **Design** **David Rosen**

Additive Manufacturing enables parts to be designed with complex geometries, customized shapes, complex material compositions and distributions, and even functional mechanisms without assembly. These capabilities enable designers to have unprecedented freedoms in their approach to product design. Rather than focusing on the limitations imposed by manufacturing processes, designers can explore new design spaces of concepts, configurations, and shapes. In this talk, a wide array of examples will be presented to illustrate the range of design principles and approaches that others have taken. Medical device shapes can be customized for individual patients (e.g., hearing aid shells, clear orthodontic braces). For small production volumes, AM can be used effectively to replace assemblies of conventionally fabricated parts with part designs of complex shapes and integrated designs. Working devices can be fabricated in AM with moving parts, energy sources, actuator, sensors, and electrical circuitry, enabling a wide variety of novel, integrated designs. In the future, the concept of digital materials opens up an even broader array of possibilities that are enabled by AM. The presentation will conclude with an introduction to an effort to standardize design guidelines, as part of the larger ASTM F-42 AM standardization work.

10:30 AM – 12 PM **Physical Modeling** **Yong Chen**

Physical and geometric modeling and computation are essential for computer-aided design and manufacturing. Additive manufacturing (AM) can cost-effectively fabricate complex three-dimensional (3D) shapes. However, to design and fabricate future product components whose shapes would be orders of magnitude more complex than those of current product design, new modeling and computing methods are required that have superb robustness and efficiency for complex geometries. Currently the Boundary-representation (B-rep) is the most dominant geometric representation; however the B-rep based geometric operations fall short of robustness and simplicity in handling special cases. This presentation discusses some of the challenges on modeling and computation. A geometric modeling and computation method based on discrete digital samples will be presented. The geometric operations based on such discrete representations are shown to have the desired robustness and efficiency. Various applications related to AM including mesh regulation, auto-filleting of internal structures, and identifying additive manufacturing constraints will be presented to demonstrate the discussed approaches.

1 PM – 2:30 PM **Simulation** **Jack Beuth**

Numerical simulation is an important tool in reducing the number of experiments needed to characterize an AM process. Because of the complexity of AM processes, testing alone is not a practical approach, particularly in characterizing microstructure (which involves time-consuming sectioning and microscopy). Another important role for simulation is its use in the development of effective process control strategies. This presentation covers current thermomechanical modeling approaches applied to AM. They range from detailed thermal fluid modeling of temperature fields at the scale of the melt pool to coarse modeling of thermal fields and residual stress at the scale of a growing part. Attention will be given to "process map" approaches developed by the speaker that model AM processes at a scale between these two extremes. These methods have led to a unique approach of integrated melt pool geometry and microstructure control, where microstructure (which is not easily monitored in real time) can be indirectly controlled via direct control of melt pool geometry (which can be monitored in real time). Other simulation-derived insights and manufacturing strategies will be discussed, including how the approach can be applied across a wide variety of direct metal AM processes.

3:00 PM – 4:00 PM **Thinking Outside of the CAD Box** **Hod Lipson**

Additive manufacturing technology is giving designers unprecedented control over the shape and composition of matter. High-end 3-D printers today can combine multiple materials into arbitrary patterns at a resolution nearing ten microns, leading to the ability to create geometry with fidelity and complexity that rivals that of the natural world. Yet CAD systems today offer limited access to this vast new space of geometric complexity. As printers become more capable, consumers and designers will expect CAD systems to keep pace. This talk will discuss future design and modeling paradigms, including generative designs, matter compilers, dynamical blueprints, feedback based designs, scan reparameterization, and more.

4:00 PM – 5:00 PM **Societal Aspects of AM** **Hod Lipson**

Today, additive manufacturing is largely unregulated, but this will change as the technology is increasingly adopted by both companies and individuals. One such issue is intellectual property (IP) of parts. How can a creator of a part protect their design? With AM, the IP battleground may not so much be a small company or individual against a large corporation as much as a fight between two object makers. The concept of a "micro-patent" will be presented and applied to AM IP. Another aspect is liability issues. Numerous diverse entities potentially bear responsibility, including a potentially remote and unaware designer, part purveyor, part manufacturer and distributor. If a part fails and causes damage, who is responsible? Security issues also bear on AM. How can innovation be maintained while simultaneously keeping the technology from being used to advance antisocial ends? Finally, there are environmental and sustainability issues associated with AM.

Day 3, May 31, Friday

8:30 – 10:00 AM **Feedstock Materials and Part Properties (1)** **Dave Bourell**
10:00 – 10:30 AM **Break**
10:30 – 12:00 PM **Feedstock Materials and Part Properties (2)** **Dave Bourell**

The range of materials used for additive manufacturing (AM) includes virtually all materials. Materials must be suitable for processing in the specific AM technology including possible post-processing, and they must satisfy the service performance requirements. This presentation deals with materials for AM. First is consideration of materials that are best suited for specific common AM processes. Applications deemphasizing mechanical properties are used as an example of the impact of service performance on materials selection. A review of the mechanical properties of AM parts is given for polymer, metal and ceramic systems. Broad categorization of the microstructural factors impacting service mechanical properties will be presented. Finally, a case study will be described based on commercial production runs: development of mechanical properties in laser sintered polyamide. This represents a common material and AM process. The development of mechanical properties depends strongly on the residual porosity in the polymer which is driven by the manufacturing practice.

1 – 2:30 PM **Negative Stiffness** **Carolyn Seepersad**

Additive Manufacturing (AM) is a powerful tool for compressing the product development cycle by rapidly building and testing intermediate designs. This presentation will describe the use of selective laser sintering (SLS) for building prototypes of structural assemblies for passive vibration and shock isolation. These assemblies include negative stiffness elements that are designed to simultaneously provide high levels of stiffness and damping for structural applications. SLS is used to build prototypes of these assemblies and test their behavior rapidly, so that the results can be used to update and validate analytical and numerical models of their performance. Results include patentable proof-of-concept prototypes.

2:30 – 3 PM **DoD Applications** **Khershed Cooper**

Navy/DoD is exploring additive manufacturing to produce new parts and replacement parts and to repair worn and broken parts when there is no available inventory of spare parts or when restarting production lines is unaffordable and impractical. Navy/DoD requires certification and accreditation for critical components. This is a critical hurdle for the additive manufacturing industry and its wider adoption by

Navy/DoD and industry in general. Additive manufacturing by its nature is flexible and agile. Moreover, additive manufacturing continues to advance in usable materials, energy sources, and process control. The technology of additive manufacturing may, however, offer an innovative approach to certification using the continuous real-time data from its in-situ monitoring, the same data that its process control could use to build a part from the micro-scale up. Additive manufacturing is data and computation intensive but it has not fully exploited those characteristics. This view opens new fundamental challenges for the field and opportunities to leverage advances in network and information technologies, sensing and control, and materials models. The practical need for certification will change the system architectures in additive manufacturing to be more accountable. This direction is the focus of a new basic research program, known as cyber-enabled manufacturing systems (CeMS). It is the latest step in the long history of support for basic research in additive manufacturing to meet future naval and defense needs.

3:00 – 4:00 PM NAMII Institute Talk Ralph Resnick

Speaker Biographies

Dr. **Jack L. Beuth** is Professor of Mechanical Engineering at Carnegie Mellon University. Jack Beuth received his Ph.D. in Engineering Sciences from Harvard in 1992. He has been on the Carnegie Mellon faculty since that time. Dr. Beuth's research is in the areas of solid mechanics, heat transfer and manufacturing, with over 75 publications across the areas of additive manufacturing, interfacial mechanics, thin film mechanics and fracture mechanics. His current research includes not only modeling of additive manufacturing processes, but also micro-scale testing and the study of strength size effects in MEMS materials. His latest educational research is in collaboration with the CMU Human-Computer Interaction Institute, developing software agent-monitored collaborative projects for undergraduate courses. Dr. Beuth was a recipient of the 1998 Ralph R. Teetor Educational Award. In 2000, he was awarded George Tallman and Florence Barrett Ladd Development Professorship in Mechanical Engineering. In 2005 Dr. Beuth was co-recipient of the ASME Curriculum Innovation Award. In 2009 Dr. Beuth received the Benjamin Richard Teare Teaching Award from the Carnegie Mellon Engineering College. Dr. Beuth's modeling research in additive manufacturing has led to the development of "process map" approaches for mapping out the role of principal process variables on process characteristics such as melt pool geometry, microstructure and residual stress. By characterizing AM processes over their full process variable range, Dr. Beuth's research is allowing unique insights into process control, expansion of process operating ranges, and unique comparisons of AM processes operating in very different regions of processing space.

Dave Bourrell is the Temple Foundation Professor of Mechanical Engineering at The University of Texas at Austin. He is currently Director of the Laboratory for Freeform Fabrication. Dr. Bourell's areas of research include particulate processing with emphasis on sintering kinetics and densification, and materials issues associated with Laser Sintering (LS). He holds 9 primary patents dealing with materials innovations in LS dating back to 1990 and has published over 200 papers in journals, conference proceedings and book chapters. Dr. Bourell is a Fellow of ASM International and TMS, and he is also a lifetime member of TMS. In 2009, he received the TMS Materials Processing and Manufacturing Division Distinguished Scientist/Engineer Award. He has received two major conference career awards in additive manufacturing: the SFF Symposium FAME Award and the Portuguese VRAP Career Educator Award. Professor Bourell is a leading expert in advanced materials for Laser Sintering, having worked in this area since 1988. Dave was the lead author on the original materials patent for LS technology. Issuing in 1990, this patent has been cited by 150 other patents, and it represents the original intellectual property for mixed and coated powders for LS, including binders.

Yong Chen is an assistant professor in the Epstein Department of Industrial and Systems Engineering at University of Southern California (USC). He received his Ph.D. degree in Mechanical Engineering from the Georgia Institute of Technology in 2001. Prior to joining the USC in 2006, he was a senior engineer at 3D Systems Inc. His research focuses on direct digital manufacturing (or 3D printing) and related novel applications. Dr. Chen has published more than 75 publications in refereed journals and conferences. Among them, he received eight Best/Outstanding Paper Awards in major design and manufacturing journals and conferences. Other major awards include the National Science Foundation CAREER Award and Outstanding Young Manufacturing Engineer Award from the Society of Manufacturing Engineers. Dr. Chen is an active member of the American Society of Mechanical Engineers, the Society of Manufacturing Engineers, and the Institute of Industrial Engineers.

Khershed Cooper is a Senior Materials Scientist in the Materials Science and Technology Division of the Naval Research Laboratory and a Program Officer for the Manufacturing Science and Technology Program at the Office of Naval Research. His research and programmatic interests are advanced materials processing and manufacturing, specifically additive-, micro- and nano-manufacturing. He has nearly 140 publications, nearly 150 invited talks and nearly 70 contributed presentations. He is a Fellow of ASM International, a recipient of ASM Burgess Memorial Award, Best Paper awards and several professional society citations. He is a member of TMS and ASM International. He serves on ASM's Awards Committee. He is an advisor to the Rapid Prototyping Journal, Solid Freeform Fabrication Symposium and Penn State-ARL's Center for Innovative Materials Processing. He is involved with the DoD JDMTP AME and Electronics sub-committees and Reliance 21 Community of Interest for Materials and Processes. He is a member of NSTC's NSET sub-committee, where he co-chairs the Nano-manufacturing, Industry Liaison and Innovation (NILI) working group. He has organized and/or participated in several workshops and symposia in additive- and nano-manufacturing.

Hod Lipson is a professor of engineering at Cornell University in Ithaca, NY, and a co-author of the recent book "Fabricated: The new world of 3D printing". His work on automatic design and manufacture of robotic life forms, self-replicating robots, food printing and bio printing has received widespread media coverage including NY Times, Wall Street Journal, Newsweek, Time Magazine and NPR. Lipson has co-authored hundreds of papers and speaks frequently at high profile venues such as TED and the National Academies. Hod directs the Creative Machines Lab, which pioneers new ways to make machines that create, and machines that are creative. http://www.mae.cornell.edu/lipson.

Ralph Resnick joined NCDMM in September 2008 as Vice President, Chief Technology Officer and Director Corporate Development with over 30 years of manufacturing experience. He assumed President & Executive Director in May 2011. The NCDMM is a not-for-profit 501(c)3 company whose mission is to proactively engage with all branches of the U.S. military and its industrial base to control cost and improve productivity and performance of manufactured parts and assemblies. Upon NCDMM organizing and winning the competitive National Additive Manufacturing Innovation Institute (NAMII) contract in August 2012, Mr. Resnick also assumed Acting Director of NAMII. Mr. Resnick serves on numerous Boards, including the Louisiana Center for Manufacturing Sciences (LCMS); former Chairman and longtime member of the Board of Directors for the National Center for Manufacturing Sciences (NCMS); the NIST Smart Machining Consortium; the Navy Metalworking Center's (NMC) Industry Advisory Board; former Board member of the Navy's Electro Optic Center (EOC); member of the Board of the MTConnectSM Institute; a member of DoD's JDMTP Metals Subpanel and Advanced Manufacturing Enterprise (AME) subpanel; participates actively in National Science Foundation (NSF) proposal reviews and technical events; past Chairman of the AMT's Technology Issues Committee, member of AMT's Global Advisory Board and Coalition for Manufacturing Infrastructure; active member of the NDIA Manufacturing Division; Industry Advisor for the Eastern Westmoreland Career and Technology Center; founder of the recently formed Mission Ready Sustainability Initiative (MRSI); and is an associate member of the prestigious International Institution for Production Engineering Research (CIRP). He is a Fellow of SME, Past President of the NAMRI/SME, and the Chairman of SME's International Awards and Recognition Committee. In 2010, Mr. Resnick received the NAMRI/SME "Outstanding Lifetime Service Award."

David Rosen is a Professor and Associate Chair for Administration in the School of Mechanical Engineering at the Georgia Institute of Technology. He is Director of the Rapid Prototyping & Manufacturing Institute at Georgia Tech. His research interests include computer-aided design, additive manufacturing, and design methodology. He has over 250 journal and conference papers and is a co-author of a popular additive manufacturing textbook entitled "Additive Manufacturing Technologies: Rapid Prototyping to Direct Digital Manufacturing," published in 2010. During his graduate school years, he was a software engineer at Computervision Corp. and a Visiting Research Scientist at Ford Research Laboratories. He is a Fellow of ASME, recently served on the ASME Computers and Information in Engineering Division Executive Committee, and received the 2012 ASME CIE Division Excellence in Research award.

Carolyn Seepersad is an Associate Professor and General Dynamics Faculty Fellow in the Mechanical Engineering Department at the University of Texas at Austin. She received a PhD in Mechanical Engineering from Georgia Tech, an MA/BA in Philosophy, Politics and Economics from Oxford University as a Rhodes Scholar, and a BS in Mechanical Engineering from West Virginia University. Dr. Seepersad's research involves the development of methods and computational tools for engineering design and additive manufacturing. Her research interests include simulation-based design of complex systems and materials, design for additive manufacturing, innovation, and environmentally conscious design of products and energy systems. In 2009, Dr. Seepersad was the inaugural recipient of the International Outstanding Young Researcher Award in Freeform and Additive Manufacturing from the additive manufacturing community. She received the 2010 Outstanding Young Investigator Award from the Design Automation Committee within ASME's Design Engineering Division. In 2010, she received the University of Texas Regents' and Dean's Awards for Outstanding Teaching by an Assistant Professor; the Regents' award is the highest teaching award for faculty in The University of Texas System. Dr. Seepersad is the recipient of a Best Paper Award for the 2009 ASME Design Theory and Methodology Conference and two best paper awards for the 2010 ASEE Annual Conference and Exposition. She is also the author of more than 70 peer-reviewed conference and journal publications and one book. She co-organizes the annual Solid Freeform Fabrication Symposium and attended and co-organized the 2010 and 2011 NAE Frontiers of Engineering Symposia. She teaches courses on product design, additive manufacturing, and design of complex engineered systems.

Wei Sun

Dr. Wei Sun is appointed Albert Soffa Chair Professor of Mechanical Engineering, Drexel University; 1000plan Chair Professor and Director of Biomanufacturing Engineering Research Institute, Tsinghua University, Beijing, China. He is currently an elected President for International Society of Biofabrication and Editor-in-Chief for journal Biofabrication. Dr. Sun's research interest has been on Biofabrication, Computer-Aided Tissue Engineering, CAD/CAM and Additive Manufacturing. His research has been sponsored by National Scienece Foundation (NSF), Defense Advanced Research Projects Agency (DARPA), National Aeronautics and Space Administration (NASA), National Institute of Standard and Technology (NIST), Johnson & Johnson (J&J), Chinese Natural Science Foundation (CNSF) and Chinese Ministry of Science and Technology. He has over 300 journal and conference papers/abstracts and conducted over 150 invited presentations in the field of his research.

Fees

The registration fee for the short course is: $2,200. An additional $220 fee will be added to late registrations received after **May 1, 2013**. Register by **March 31, 2013** and receive a 20% discount that the reduced registration fee is $1,760. The fee includes coffee breaks, and lunches each day as well as all presentation materials, lecture notes and appropriate review papers.

NSF fellowships are available to faculty members, high-school science teachers, post-docs and Ph.D. candidates from the US. The fellowship consists of full registration fee plus an accommodation allowance. A limited number of fellowships are also available for faculty and postdoctoral fellows outside the US. Download the application form from http://tam.northwestern.edu/summerinstitute/Home.htm. The deadline for fellowship application is **March 15, 2013**.

Location

The course will be held at Hilton Garden Inn, 1818 Maple Avenue, Evanston, Illinois, 60201.

Accommodation

A block of rooms has been reserved at special rates for short course attendees at the **Hilton Garden Inn**. Attendees should contact the hotel directly to make reservations by calling 847-475-6400 or through 1-877-STAY HGI or 1-800-HILTONS, or www.evanston.hgi.com. To qualify for special rates guests **must** mention "**Additive Manufacturing**". The rooms at the **special rate of $119 single and $129 double will only be held until May 1, 2013.**

Registration

For additional information, contact:
http://summerinstitute.mech.northwestern.edu/
email: summerinstitute@mail.mech.northwestern.edu