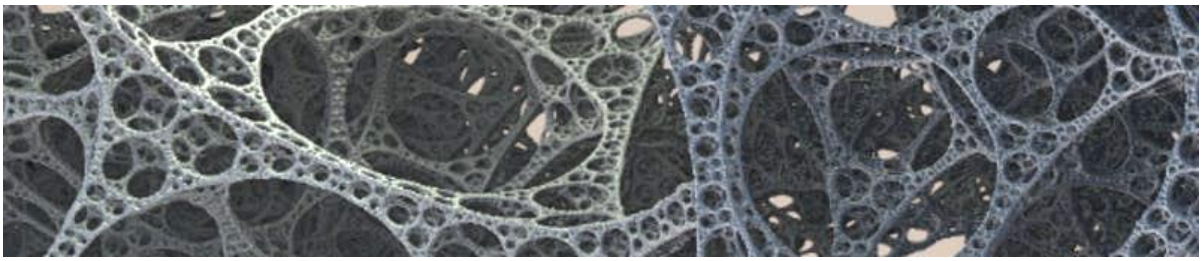
Workshop on Exploiting Advanced Manufacturing Capabilities:

Topology Optimization in Design



November 19, 2019

National Academy of Sciences Building, Room 125
2101 Constitution Ave., N.W., Washington, D.C 20418

8:00 Breakfast available in the Cafeteria

8:30 Welcome, Objectives, Introductions all around – CHAIR **Haydn Wadley**

Introduction by: Dianne Chong

8:45 Keynote Speaker **Ole Sigmund**, DTU Technical University of Denmark
Presentation Title: Recent development in large-scale, multi-scale and multi-physics topology optimization

Topic 1: Topology Optimization and Advanced Manufacturing Technologies
Introductions by: Angus Kingon Q&A by: Katherine Faber

Topology optimization focuses on the function of a material or structure, but the manufacture of the material or structure is rarely considered as part of the optimization. In practice, this results in designs that are theoretically optimal but that could never be realized. This topic considers how topology optimization can incorporate manufacturability along with functional design. We ask: What new methods are required to simultaneously optimize a design and its manufacture; What new manufacturing technologies are enabled by doing so; and What are the step change improvements that can be created in the underlying manufacturing technologies?

9:35 Speaker **James Guest**, Johns Hopkins University
Presentation Title: Topology Optimization with Embedded Manufacturing Constraints and Considerations

10:05 Break

10:25 Speaker **Chris Spadaccini**, Lawrence Livermore National Laboratory
Presentation Title: Optimal Design, Architected Materials, and Advanced Manufacturing Processes

10:55 Speaker **Matt Begley**, UC Santa Barbara
Presentation Title: Process-informed Simulations of Printed Components for Optimization Frameworks

11:25 Lunch

12:25 Panel Discussion on *The Emerging Synergy between Topology Optimization, Manufacturing, and Materials*

Introductions by: Katherine Faber Q&A by: Angus Kingon

Panelists: **Claus Pedersen**, Dassault Systèmes Simulia Corp

Panelists: **David Chapin**, GE

Panelists: **Jonathan Berger**, Nama Development, LLC

Topic 2: Topology Optimization and Multi-Physics

Introductions by: Carlos Levi Q&A by: Bill King

Most topology optimizers consider a single physical domain, for example stress-strain analysis for structural design, or electromagnetic analysis for photonic crystal design. This topic considers challenges and opportunities that combine multiple physical processes. For example: How might we create an optimal design for both mechanical properties along with fluid-structure interactions; or how might we create an optimal design for a chemically reacting flow in the presence of a distributed catalyst? The session will discuss the methods required for multi-functional topology optimization and the software intelligence required to search these design spaces.

1:45 Speaker **Graeme Milton**, University of Utah

Presentation Title: The role of bounds in topology optimization

2:15 Speaker **Ryan Watkins**, NASA Jet Propulsion Laboratory (JPL)

Presentation Title: Designing optical instruments for space applications: Multiphysics topology optimization

2:45 Break

3:00 Speaker **Reinhard Radermacher**, University of Maryland
Presentation Title: Topology Optimized Heat Exchangers: Their Potential, Design and Manufacturing Challenges

3:30 Panel Discussion on *Topology Optimization and Multi-Materials*

Introductions by: Bill King Q&A by: Carlos Levi

Panelists: **Kimberly Saviers**, United Technologies Research Center (UTRC)

Panelists: **Alicia Kim**, University of California San Diego

Panelists: **Rebecca Dylla-Spears**, Lawrence Livermore National Laboratory

4:50 Wrap up and final comments

5:00 Adjourn meeting day 1

November 20, 2019

National Academy of Sciences Building, Room 125
2101 Constitution Ave., N.W., Washington, D.C 20418

8:00 Breakfast in the Cafeteria

8:30 Welcome, plans for today – CHAIR Haydn Wadley

Introduction by: Ned Thomas

8:45 Keynote Speaker Joe DeSimone, Carbon
Presentation Title: Digital design and manufacturing with tunable, high-performance elastomeric materials

Topic 3: Topology Optimization of Soft Materials and Deformable Structures
Introductions by: Frank Zok Q&A by: Ned Thomas

Soft and compliant structures could unlock new applications in medicine and bioengineering, wearable structures and devices, and human-machine interfaces. While topology optimization for rigid materials and structures is quite mature, there are a lack of tools and methods for topology optimization of soft or compliant structures, and structures that undergo large deformations as part of their intended function. This topic considers: What are the fundamental challenges for topology optimization of soft structures and how might these be overcome; and for what applications and domains would there transformational new opportunities.

9:35 Speaker **Brett Compton**, University of Tennessee, Knoxville
Presentation Title: Multi-Material Hybrid Structures

10:05 Break

10:25 Speaker **Mark O'Masta**, HRL Laboratories
Presentation Title: Structure and Material Optimization for Additive Manufacturing

10:55 Speaker **Xiaoyu (Rayne) Zheng**, UCLA
Presentation Title: Design and Additive Manufacturing of Micro-Architectures with Encoded Functionalities and Mechanical Behaviors

11:25 Lunch

12:25 Panel Discussion on *Emerging Materials and Efforts*
Introductions by: Ned Thomas Q&A by: Frank Zok

Panelists: **Hardik Kabaria**, Carbon

Panelists: **Chris Spadaccini**, Livermore Lab

Panelists: **Ole Sigmund**, DTU Technical University of Denmark

1:45 Wrap up discussion for the full workshop, Haydn

2:30 Adjourn meeting

Speaker Bios

Jonathan Berger

Dr. Jonathan Berger is founder and President of Nama Development Corporation. Nama uses its expert knowledge, and a proprietary material geometry that has been rigorously demonstrated to achieve the theoretical upper limit in specific stiffness and strength of a lattice material, to enable novel performance through new ultralight materials. Nama leverages a deep knowledge of lattice design, optimization, solid mechanics, and materials processing to design fabricable materials for emerging applications. Dr. Berger's recent efforts have focused on optimization algorithms for composite sandwich panels using a new generation of stiff core materials. Dr. Berger is a recent graduate of the UCSB Materials program, where his research focused on the design and modeling of multifunctional mechanical metamaterials, as well as the constitutive and finite element modeling of the extreme dynamic behavior of brittle materials. His research and development work primarily rely on solid mechanics, finite element modeling, experimental design, and their execution. His research has been published in the leading journals Nature, Journal of the American Ceramics Society, and Extreme Mechanics Letters. Nama is a part of the NSF I-corps national, and NASA Early Stage Innovation programs.

Matthew R. Begley

Matthew R. Begley is currently a Professor of Mechanical Engineering and Professor of Materials at UCSB, having served previously on the faculty at the University of Connecticut (1997-2001) and the University of Virginia (2001-2009). Professor Begley's research focus is on theoretical mechanics and advanced simulations to guide materials development, with an emphasis on multilayered systems, interfaces and composites. He has more than 100 archival publications, with topics including: thermal barrier coatings, environmental barrier coatings, the mechanical integrity of microelectronics, advanced simulations of virtual tests, bio-inspired composites and adhesives, novel 3D printing strategies for two-phase materials, acoustic assembly of colloidal particles, the structural integrity of microelectronics, nano-porous gold, and the performance of microfabricated devices for biochemical diagnostics. Prof. Begley has also served as a consultant regarding material behavior and structural performance, for industries including nuclear energy (Areva), fuel cell energy (FCE), solar power (Sunpower), biomedical implants (legal consulting, 4WEB), and thin films/coatings (Intel, Pratt & Whitney, Raytheon).

David Chapin

Dave Chapin has the privilege to lead GE Additive's AddWorks design consulting team. His team works daily to drive the additive epiphany with customers. A 15-year GE veteran, Dave has focused on bringing new technology and innovation to commercial products spanning roles at Global Research, Environmental Services, Aviation and Additive. Prior to joining GE

Additive, Dave most recently spent 5 years developing additive aerospace parts for production. Dave's AddWorks design team brings its additive expertise, disruptive design process, along with GE's deep additive technology expertise to partner with clients and accelerate their additive journey. Dave graduated from Union College with his BSME and from Georgia Tech with his MSME. He resides in Cincinnati, OH with his family.

Brett Compton

Dr. Brett Compton is an Assistant Professor in the Department of Mechanical Engineering at the University of Tennessee, Knoxville. He earned his Ph.D. in 2012 from the University of California, Santa Barbara. Before joining the University of Tennessee, Dr. Compton did his post-doctoral research at the Wyss Institute for Biologically Inspired Materials at Harvard University, and was a Materials Scientist in Additive manufacturing for the Manufacturing Demonstration Facility at Oak Ridge National Laboratory. Currently, his work involves developing new high-performance materials for additive manufacturing (AM) technologies and developing the necessary fundamental understanding of AM processes to enable the application of rigorous engineering principles to AM components. This requires establishing the link between feedstock processing parameters, deposition parameters, and the mechanical and functional properties of the resulting materials through mechanical testing, numerical simulation, and modeling. Of particular interest for his research are printable fiber-reinforced polymer and ceramic matrix composites (PMC's and CMC's) and multi-material hybrid structures. These represent a huge area of untapped potential now accessible via additive manufacturing techniques. Potential areas of application include aerospace, nuclear power, armor, wear materials, and lightweight, highly efficient structures for the transportation sector.

Joe DeSimone

Dr. Joseph M. DeSimone brings a unique perspective to Silicon Valley as CEO and co-founder of Carbon. As a professor at the University of North Carolina for over 20 years before launching Carbon in 2013, Joe made scientific breakthroughs in areas including green chemistry, medical devices, and nanotechnology, also co-founding several companies based on his research. When Joe took on 3D printing, he brought together insights from diverse fields to co-invent the core technology that now drives the Carbon Platform. Powered by Digital Light Synthesis™ (DLS™) technology, the Carbon Platform is enabling companies to break free of traditional polymer manufacturing methods to advance product innovation. Carbon has cracked the code on 3D printing at scale and is now a 400+ person global company defining the digital revolution in manufacturing. Joe studied chemistry at Ursinus College, a small liberal arts school in his hometown. A first-generation college student, he was inspired by chemistry and went on to earn his Ph.D. at Virginia Tech in 1990, joining the faculty at UNC that same year. He quickly achieved international recognition as a scientist, inventor, and entrepreneur, earning major accolades including the U.S. Presidential Green Chemistry Challenge Award and the Lemelson-MIT Prize. In 2016 President Obama awarded him the National Medal of Technology and

Innovation, the highest honor in the U.S. for achievement and leadership in advancing technological progress. At UNC, Joe built a strong culture in his research group centered on the notion that diversity is a fundamental tenet of innovation. He mentored 80 students through Ph.D. completion, half of whom are women and other members of underrepresented groups in STEM. He credits much of his laboratory's success to this approach, frequently emphasizing how both human and disciplinary diversity accelerate progress in team problem-solving. Joe now brings this perspective to Carbon and considers it crucial for Carbon's position as a world-leading digital manufacturing company operating at the intersection of software, hardware, and material science. An author of over 350 scientific publications and a named inventor on nearly 200 issued patents, Joe maintains academic appointments at both UNC and North Carolina State University. He is one of only roughly 20 individuals elected to all three U.S. National Academies—the National Academy of Sciences, the National Academy of Medicine, and the National Academy of Engineering.

Rebecca Dylla-Spears

Rebecca Dylla-Spears received her PhD in Chemical Engineering at the University of California, Berkeley in 2009. She is currently a group leader in Advanced Optical Materials & Processing Science and Technology at Lawrence Livermore National Laboratory (LLNL), managing efforts to support LLNL's laser programs. Rebecca leads a research program to additively manufacture glass and optics that contain functional gradients in material properties. Previously, Rebecca has served as a subject matter expert for growing cryogenic, single-crystalline deuterium-tritium fuel layers for fusion experiments on the National Ignition Facility. She helped develop processes for fabrication of specialized laser optics used in the High-repetition-rate Advanced Petawatt Laser program and was part of an R&D100 Award winning team for her work on polishing slurry stabilization and filtration. Rebecca was recognized in 2018 with an Early-Mid Career Award at LLNL.

James K. Guest

James K. Guest, an associate professor in the Department of Civil Engineering, is an internationally recognized leader in the field of topology optimization. He holds a secondary appointment in the Department of Materials Science and Engineering. Guest leads the Topology Optimization Group at Johns Hopkins, which focuses exclusively on the development and application of topology optimization algorithms to the design of materials, devices, components, and systems in structural, mechanical, biomedical, and aerospace applications. He also serves as the associate director of the Johns Hopkins Center for Additive Manufacturing and Architected Materials (JAM2) and the Center for Integrated Structure-Materials Modeling and Simulation (CISMMS). Guest is secretary-general for the International Society for Structural and Multidisciplinary Optimization, and chair of the technical committee on Optimal Structural Design for the American Society of Civil Engineers (ASCE) Structural Engineering Institute. He also is a member of the Computational Mechanics Committee of the ASCE Engineering

Mechanics Institute (EMI), and member of the Design Automation Committee of the American Society of Mechanical Engineers (ASME). He is an associate editor of the journals Structural and Multidisciplinary Optimization and ASME Journal of Mechanical Design, and a reviewer for over 30 technical journals. In 2017, Guest received the ASCE Walter L. Huber Civil Engineering Research Prize for his overall impact on the field of topology optimization and engineering mechanics. He also is a recipient of the 2015 EMI Leonardo da Vinci Award from ASCE.Guest received his bachelor's degree in Civil Engineering systems from the University of Pennsylvania in 1998. He then studied at Princeton University, where he received a master's degree in Civil Engineering and Operations Research in 2001, a master's degree in Civil and Environmental Engineering in 2002, and a PhD in Civil and Environmental Engineering in 2005. He joined the Whiting School of Engineering faculty in 2005.

Hardik Kabaria

Dr. Hardik Kabaria serves in the role of Computational Geometry Lead at Carbon. He earned his Ph.D. in Mechanics and Computation from Stanford University under the guidance of Prof. Adrian Lew. His doctoral research focused on the development of an efficient and robust algorithm for geometric discretization in two and three dimensions, where the shape of the geometry is changing over the course of physical simulations of topology optimization. Partially funded by the Army High-Performance Computing Research Center at Stanford, Dr. Kabaria also earned a Stanford Graduate Fellowship to support his research. The algorithm "Universal meshes" developed during Dr. Kabaria's doctoral research has now been implemented in Carbon's codebase to aid the development of Carbon's process simulation and automated texture application software modules. At Carbon, Dr. Kabaria currently leads the development of the company's computational design software tools that help customers take full advantage of the Carbon Digital Light SynthesisTM (DLSTM) technology. These software tools have helped enable the design and production various products including Riddell football helmet liners, specialized bike saddles, and a J&J medical device.

Alicia Kim

Dr. H Alicia Kim is Jacobs Scholar Chair Professor in the Structural Engineering Department of the University of California San Diego. She leads the Multiscale Multi-physics Design Optimization (M2DO) lab. Her interests are in level set topology optimization, multiscale and multi-physics optimization, modeling and optimization of composite materials and multifunctional structures. She has published over 200 journal and conference papers in these fields including award winning papers at the AIAA conferences and World Congresses on Structural and Multidisciplinary Optimization. She is a prestigious EPSRC Fellow for Growth. Her research in topology optimization began in the 90's at the University of Sydney, Australia where she developed one of the first boundary based topology optimization methods. She continued her research at the University of Warwick and the University of Bath, UK for 15 years before moving to the current position in 2015.

Mark O'Masta

Mark R. O'Masta is a research staff scientist in the Architected Materials group at HRL Laboratories, LLC. He earned his Ph.D. in Material Science and Engineering from the University of Virginia in 2014. Prior to joining HRL in 2017, Mark was as Research Associate in the Centre for Micromechanics at the University of Cambridge. His research focuses on developing new materials for additive manufacturing, mechanics of materials, architected materials and composites.

Graeme Milton

Graeme W. Milton received B.Sc. and M.Sc. degrees in Physics from the University of Sydney in 1980 and 1982 respectively. He received a Ph.D. degree in Physics from Cornell University in 1985, after which he joined the Caltech Physics Department as a Weingart Fellow from 1984 to 1986. He then joined the Courant Institute of Mathematical Sciences where he stayed until 1994 when he joined the faculty at the University of Utah as a full professor. He has received numerous honors and awards, including an Alfred P. Sloan Fellowship and a Packard Fellowship, both in 1988. He was an Invited Speaker for the 1998 International Congress of Mathematicians. He was awarded the Ralph E. Kleinman Prize in 2003 by the Society for Industrial and Applied Mathematics for "his many deep contributions to the modeling and analysis of composite materials." He also received the 2007 Prager Medal from the Society for Engineering Science, "in recognition of his groundbreaking mathematical analyses of heterogeneous media," the 2012 Landauer Medal from the ETOPIM association for "excellence in the field of composite science", and the 2015 Levi-Civita Prize for the Mathematical and Mechanical Sciences.

Claus Pedersen

Claus is Optimization Technology Director at the CTO Office of R&D SIMULIA, Dassault Systèmes where he has the job role of defining R&D strategies, inventing and examining the technology of new optimization methodologies, coding of CAE and optimization kernels, competitive intelligence, technical due diligence, coaching and knowledge sharing for core optimization technologies, research projects and numerical implementation with different commercial research partners, worldwide presale for customers and presenting at conferences, and corporations with leading international universities. Additionally, his role is highly interdisciplinary working with different teams and organizations involving crossover brand activities from R&D, marketing to international sales on latest technology. He has continued to have a strong connection to applied science and research since he received his Ph.D. at Department of Mechanical Engineering, Solid Mechanics, Technical University of Denmark in 2002 and his work the following 2 years as a Research Associate at the Department of Engineering, Cambridge University, UK. He is reviewing for thirteen international journals,

external examiner at several technical universities and supervisor of interns. He has published 12 articles in reviewed international journals and held more than 50 presentations at international conferences. He has been working 20 years in the field of optimization and initially, he worked with some of the pioneers in structural optimization with many whom he is still interacting. The last 15 years his work has been focused on industrial sensitivity based optimization and developing solutions and apps for function-driven generative design and digital continuity on the 3DEXPERIENCE® Platform, non-linear adjoint solver technology in the Abaqus framework and other multi-physics solver as well as mathematical programming and industrial traditional and additive manufacturing constraints. Thus, he is daily working on technologies in industrial design workflows applied in many sectors as aerospace, transportation & mobility, industrial equipment, high tech, life sciences, consumer goods and construction. Here he is especially contributing on assigning theoretical optimization research into an industrial framework, on leading technologies in industrial design workflows, on industrial optimization issues as motivation for theoretical research and on interaction between academia and industry.

Reinhard Radermacher

Reinhard Radermacher holds a PhD in physics and conducts research in heat transfer and working fluids for energy conversion systems — in particular heat pumps, air-conditioners, refrigeration systems, and integrated cooling heating and power systems. His work resulted in more than 530 publications, numerous invention records and 14 patents. He has co-authored three books. His research includes the development of software for the design and optimization of heat pumps and air-conditioners, which is now in use at more than 80 companies worldwide. He has raised $40 million in research funding from government and industrial sponsors over the years. Dr. Radermacher is Minta Martin professor of Mechanical Engineering and director and co-founder of the Center for Environmental Energy Engineering. He was awarded the Institute of Refrigeration J&E Hall Gold Medal and the IIR Gustav Lorentzen Medal for his innovation in the field of refrigeration. He is co-operating agent of International Energy Agency's (IEA) HPT Annex 53 project. He is Fellow ASHRAE and holds memberships in ASME, SAE, DKV and IIR. He is a lifetime member of IJR and ASHRAE, and is CEO of Optimized Thermal Systems. For 17 years was the editor of the ASHRAE journal, Science and Technology for the Built Environment and currently is leading the strategic planning committee for ASHRAE Research.

Kimberly Saviers

Dr. Kimberly Saviers is currently a Senior Engineer at United Technologies Research Center, located in Connecticut. She contributes in the area of Thermal and Fluid Sciences including topology optimization and electronics cooling. UTRC supports research and innovation for United Technologies Corporation, a large multinational aerospace company. Prior to joining UTRC, Dr. Saviers earned a PhD in Mechanical Engineering at Purdue University in the area of thermal transport in graphene-based materials. She has authored 9 peer-reviewed journal

publications, has 1 issued US patent, and was awarded the Best Aerospace Systems Student Paper at an AIAA conference.

Ole Sigmund

Ole Sigmund is a Professor and Villum Investigator at the Department of Mechanical Engineering, Technical University of Denmark (DTU). He obtained his Ph.D.-degree 1994 and Habilitation in 2001 and has held research positions at University of Essen and Princeton University. He is a member of the Danish Academy of Technical Sciences and the Royal Academy of Science and Letters (Denmark) and is the former President (2011-15, now EC member) of ISSMO (International Society of Structural and Multidisciplinary Optimization) and former Chairman of DCAMM (Danish Center for Applied Mathematics and Mechanics, 2004-2010). Together with Noboru Kikuchi and Martin Bendsøe, Ole Sigmund is one of the founders and main contributors to the development of topology optimization methods in academia and industry. Present research interests include theoretical extensions and applications of topology optimization methods to mechanics and multi-physics problems under the consideration of manufacturing constraints and multiple length scales. Ole Sigmund has authored more than 260 international journal papers which are cited more than 15,300 times in the ISI Science Citation Index and his H-index is 59.

Christopher M Spadaccini

Christopher M. Spadaccini, Ph.D., is currently the Director of the Additive Manufacturing Initiative at the Lawrence Livermore National Laboratory (LLNL) as well as the leader of the Center for Engineered Materials and Manufacturing. He has been working in advanced additive manufacturing process development and architected materials for the last decade and has over 55 journal publications, four book chapters, ~60 invited presentations, and ~35 patents awarded or pending. Dr. Spadaccini founded several new fabrication laboratories at LLNL for process development focused on micro and nano-scale features and mixed material printing. He received his B.S., M.S., and Ph.D. degrees from the Department of Aeronautics and Astronautics at the Massachusetts Institute of Technology (MIT) in 1997, 1999, and 2004 respectively and has been a member of the LLNL technical staff for over 15 years. He has also been a lecturer in the Chemical, Materials, and Biomedical Engineering Department at the San Jose State University where he taught graduate courses in heat, mass, and momentum transfer. He is currently also an adjunct faculty member at the University of California, Davis in the Chemical Engineering Department.

Ryan Watkins

Ryan Watkins is a Mechanical Engineer/Technologist at NASA’s Jet Propulsion Laboratory in Pasadena, CA. His background is in the experimental characterization and theoretical modeling of shape memory alloys, having received his Ph.D. in Aerospace Engineering from the University of Michigan in 2015. In Ryan’s time at JPL, he has worked on flight projects as a

Structural Analyst and, more recently, as a Cognizant Engineer, leading the design, build, test, and integration of launch restraint hardware for the SWOT and NISAR missions. In conjunction with his flight work, Ryan has worked to develop and foster JPL's topology optimization capabilities over the past four years, mentoring new practitioners, integrating the work flow into flight project practices, and engaging with the broader topology optimization community

Xiaoyu (Rayne) Zheng

Xiaoyu (Rayne) Zheng, is an Assistant Professor of Civil and Environmental Engineering and Mechanical and Aerospace Engineering at the University of California, Los Angeles. His group draws principles from mechanics, optics and material science to develop additive manufacturing (3D printing) processes, architected material design and synthesis approaches to create multi-functional materials and all-in-one devices with controlled topologies, encoded compositions and multi-scale features. His group actively transfers these materials to a wide array of applications for electronics, structures, robotics, energy storage and transduction, to biology and health care. Their work on architected metamaterials and additive manufacturing was featured on numerous media outlets including MIT Technology Review Top 10 Innovations, R&D 100 Magazine, the Cover on Science Magazine and Nature Materials. Professor Zheng has over 40 publications and 4 patents. Zheng has been recognized by various organizations for outstanding research production, including a DARPA Young Faculty Award (2019), ONR Young Investigator Award (2018), AFOSR Young Investigator Award (2017), 3M Faculty Award, Freeform Fabrication and Additive Manufacturing Excellence Award (FAME), and Outstanding Assistant Professor Award from Virginia Tech.