MSEC | Virtual Conference, Hosted by the University of Cincinnati
June 21, 2021 - June 25, 2021

# Doctoral Symposium

Welcome to the Doctoral Symposium of MSEC 2021!

The Doctoral Symposium will be an opportunity for doctoral students who will graduate soon (within a year) or a recently graduated doctoral student to showcase their doctoral dissertation research in various advanced manufacturing research areas. The symposium will also provide universities and industrial companies an opportunity to identify excellent candidates for job openings targeting Ph.D. graduates in advanced manufacturing.

In the first Doctoral Symposium of ASME Manufacturing Science and Engineering Conference, 16 students will present their work on Friday (June 25). They are assigned to three sessions, and each session will be 90 minutes. Each presentation will be 12 minutes with 3 minutes of Q&A.

The students' email addresses are given in this booklet. Please feel free to follow up with the students on their work before/after the Doctoral Symposium.

**Organizers**

Dr. Yong Chen, *University of Southern California, Los Angeles, CA, USA*
Dr. Karl Haapala, *Oregon State University, Corvallis, OR, USA*

# Doctoral Symposium

## 13-01 Process planning and modeling (Friday, June 25 – 12 – 1:30 pm)

| | | | |
|---|---|---|---|
| Karl | Schuchard | kgschuch@ncsu.edu | North Carolina State University |
| Rishi | Malhan | rmalhan@usc.edu | University of Southern California |
| Donghua | Zhao | dongdong5212a@163.com | Shanghai Jiao Tong University |
| Joseph | Kubalak | josephk7@vt.edu | Virginia Tech |
| Ankit | Agarwal | agarwal.3@iitj.ac.in | Indian Institute of Technology Jodhpur |
| Muhammad-Ali | Ablat | amaimaitiaili@ucmerced.edu | University of California Merced |

## 13-02 Processes and materials (Friday, June 25 – 1:30 – 3:00 pm)

| | | | |
|---|---|---|---|
| Yizhou | Jiang | yizhouj@usc.edu | University of Southern California |
| Daniel | Franke | dfranke2@wisc.edu | University of Wisconsin-Madison |
| Padmalatha | Kakanuru | padmalathakakanuru@gmail.com | Stevens Institute of Technology |
| Yang | Xu | yxu195@usc.edu | University of Southern California |
| Hemant | Agiwal | agiwal@wisc.edu | University of Wisconsin-Madison |

## 13-03 Design, simulation, and optimization (Friday, June 25 – 3:00 – 4:30 pm)

| | | | |
|---|---|---|---|
| Nathan | Hertlein | hertlenj@mail.uc.edu | University of Cincinnati |
| Zhuo | Wang | zwg@umich.edu | University of Michigan-Dearborn |
| Vysakh | Venugopal | venugovh@mail.uc.edu | University of Cincinnati |
| Matthew | Krugh | mkrugh@gmail.com | Clemson University |
| Lun | Li | li2l6@mail.uc.edu | University of Cincinnati |

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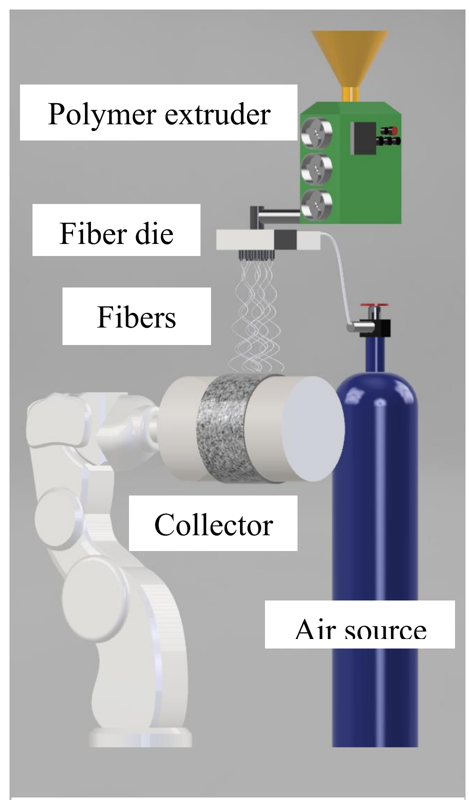
## Doctoral Symposium

# Computational and Experimental Characterization of 3D-Melt blowing Process-Structure-Function Interrelationships for Tissue Engineering

Karl G. Schuchard
North Carolina State University
Dr. Rohan Shirwaiker

Biofabrication processes enable the manufacturing of tissue and organ substitutes. Applications of these substitutes range from novel therapeutics, regenerative implants, drug and disease screening platforms, and microphysiological systems. Scaffolds that mimic the macro-geometry, microarchitecture, and biofunctional properties of native tissue matrices are central to this field. With the right cues, cells adhere to a scaffold, proliferate, and secrete newly formed tissue, mimicking native mammalian tissue analogs. There is a need for biofabrication processes that can fabricate scaffolds that capture both the macrogeometry and microarchitecture of tissues as these modulate cellular response and govern tissue maturation. Towards this, we have engineered a new process, 3D-Melt blowing (3DMB), that can fabricate scaffolds with preferential multiscale architectures suitable for fibrous tissue engineering.

3DMB synergistically combines a nonwoven fiber formation process and an additive-manufacturing-inspired collection system to manufacture next-generation fibrous scaffolds. Fiber formation is accomplished in 3DMB using melt blowing, a high throughput and scalable fiber fabrication process wherein high-temperature air jets elongate coaxial streams of molten polymer via drag forces to form biomimetic nano- and microfibers. The fibers travel towards a high-speed rotating collector, positioned by a computer-numerically-controlled industrial 6-axis robotic arm. The rotation of the collector can elongate and align the fibers, governing the scaffold architecture. Fibers aggregate on the collector, forming an organized scaffold




**3DMB process schematic**

that recapitulates native fibrous musculoskeletal tissue microarchitecture, macrogeometry, and mechanical properties. Comprehensive characterization of 3DMB is needed to engineer scaffolds with specific critical quality attributes. The overarching goal of this dissertation comprises three objectives:

**O1.** Elucidate the fundamental physical mechanisms governing 3DMB fiber formation and collection by using 2D computational fluid dynamic (CFD) models to characterize the interrelationships between:

- melt blowing process parameters, fiber diameter, and fiber motion using a multiphase CFD model
- 3DMB fiber collection process parameters and scaffold fiber alignment using a single-phase model with rotating boundary condition

**O2.** Experimentally characterize the 3DMB process-structure design space for poly(caprolactone) using factorial design of experiments and critical process variables to quantify their effects on:

- fiber and pore morphology and fiber alignment using ImageJ and Matlab scripts
- tensile, compressive, and cyclic fatigue properties using standardized test methods

**O3.** Evaluate biofunctionalization aspects of 3DMB scaffolds, especially relationships between scaffold morphology and:

- cellular adhesion and metabolic activity of human adipose-derived stem cells
- tissue maturation and biomechanical properties after 10-week culture

This dissertation's systematic process-based approach comprises a holistic investigation of the fundamental relationships between key process parameters, scaffold morphological and mechanical properties, and responses of cells to scaffolds *in vitro*. The primary contributions of this work include: 1) comprehensive process models of the 3DMB fiber formation and collection, which can be used to study the 3DMB parameter design space *in silico*, 2) Empirical process-structure relationships that can be utilized in the generative design of tissue scaffolds and lay the groundwork for enhanced process control systems, and 3) biofunctionalization schema for 3DMB scaffolds and comparison with other additively manufactured scaffolds.

# Doctoral Symposium

## Biography – Karl G. Schuchard

Karl Schuchard is a doctoral candidate and Edward P. Fitts Fellow at North Carolina State University, supervised by Dr. Rohan Shirwaiker in the Edward P. Fitts Department of Industrial and Systems Engineering. Karl's work focuses on characterizing fundamental process-structure-function interrelationships for a new manufacturing process, 3D-Melt blowing, with applications in tissue engineering. Specifically, his work utilizes computational fluid dynamics to study nonwoven nano- and microfiber formation and empirical process characterization using SEM and nanoCT to study scaffold morphology alongside standardized mechanical test methods to characterize scaffold mechanical and fatigue properties. Karl also uses aseptic cell culture techniques in a BSL-2 environment to study human stem cell responses to 3D-Melt blown tissue scaffolds, including cellular adhesion, viability, and metabolic activity, and tissue maturation and biomechanical properties. In the future, Karl's interests lie in the continued application of his applied mathematics and engineering background to bring a systematic and data-driven approach to solving complex and technical cross-functional problems in the biomedical and pharmaceutical domains.

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# Doctoral Symposium

# Manipulator Trajectory Planning Under Motion Constraints

Rishi Malhan
University of Southern California
Advisor: Dr. Satyandra K. Gupta

**Background**

Serial-link industrial manipulators or robots are being widely used for manufacturing automation. The robots are required to trace a set of complex toolpaths using a tool attached to the end-effector for robotic cutting, additive manufacturing, finishing, composite layup, and similar applications. Traditionally, a human operator manually localizes the workpiece and programs the path constrained robot trajectories. Workpiece localization is a cumbersome task involving several trial and errors since robot has a limited workspace. Localization inaccuracies are high in the manual process. Robot has limited reachability and kinodynamic variations lead to infeasibility in manual programming. Process constraints like force, velocity, collision avoidance, and path continuity and smoothness over complex geometries lead to more challenges in high-mix production lines. Smart manufacturing cells of the future will be characterized by automated workpiece placement, accurate localization using RGB-D cameras and trajectory generation. The objective of this work is to make algorithmic advances in the aforementioned areas.

**Research Questions**

- Can we characterize the complex robot workspace in an efficient data structure?
- What is the best way to formalize process constraints in smooth differentiable constraint violation functions to be used by the non-linear optimization algorithm?
- How can we improve localization accuracy of workpiece placement to sub-millimeters using inexpensive depth sensors?
- Can we develop a path constrained trajectory planner that takes multiple tool center points and tolerances defined by the process into account?

**Problem Statement**

Given the model of the robot used, a task consisting of set of toolpaths, process constraints, set of tool center points (TCP) over tool surface, toolpath tolerances, and other general constraints, we want to determine a suitable workpiece placement, perform accurate localize, and find path constrained trajectory to be executed by the robot to successfully complete the task.

**Hypothesis**

- Robot workspace is fairly complex but can be captured in a capability map using a discrete representation. The map can be used with smooth and differentiable constraint violation functions to improve efficiency of a workpiece placement algorithm.
- Workpiece localization uncertainty can be reduced to sub-millimeters using a continuous set of diverse pointclouds captured from optimized camera configurations.
- A graph and sampling based method can be used to incorporate TCP and tolerances to find optimal path constraint trajectories over constraint manifolds.

**Contributions**

***Workpiece Placement:*** We developed an approach to characterize the robot workspace in a capability map that encodes robot singularities and reachability. High quality initial guesses are generated for a non-linear optimization algorithm to find promising placements. We developed smooth and differentiable constraint violation functions for the placement algorithm that capture motion constraints like velocity, force, continuity, collision, and singularity.

***Workpiece Localization:*** We made advances in 3D reconstruction technology. We proposed a multi-stage optimization-based camera calibration method that outperforms conventional calibration. Optimal camera configurations are generated using set-cover algorithm and a traveling salesman algorithm finds a minimum cycle time robot path constrained trajectory. Pointclouds are captured while executing the trajectory and merged using our algorithm. We obtained a sub-millimeter accuracy in localization and also a realtime uncertainty quantification.

***Path Constrained Trajectory Planning:*** Advanced manufacturing applications use multiple TCPs on the tool surface and also assign position and orientation tolerances along toolpath. Redundancy is introduced as degrees of freedom of the robot are more than what the process requires. We developed a framework to incorporate the redundancy and plan robot configuration space trajectories using a graph-based approach. We provide theoretical insights into the problem and propose an iterative approach to construct a reduced graph using sequential progression and workspace heuristics. A sampling-based approach is used to select root nodes in the graph that leads to low-cost paths.

# Doctoral Symposium

## Biography – Rishi Malhan

Rishi Malhan works at the intersection of Robotics and Artificial intelligence as a third-year Ph.D. student under Dr. Satyandra K. Gupta at the University of Southern California. He believes that we as humans are progressing towards a front where smarter machines will revolutionize our lives' quality. He is doing his part by contributing to robotics in advanced manufacturing by developing planning and learning algorithms to solve complex real-world problems. He is primarily involved in developing algorithms (a) to find planning solutions to computationally challenging problems (b) process parameter estimation for improving productivity under process constraints. His research interests include reinforcement learning, deep learning, numerical optimization, manipulator motion planning, machine learning, manufacturing, and automation.

He has a publication record of 5 journal papers in journals like International Journal of Robotics Research (IJRR), Robotics and Computer Integrated Manufacturing (RCIM), and Additive Manufacturing. He is actively involved in publishing in conferences like International Conference on Robotics and Automation (ICRA), Manufacturing Science and Engineering Conference (MSEC), and Conference on Automation Science and Engineering (CASE). He has a record of 16 published papers in these conferences with best paper award (third place) in MSEC 2018, judge's choice award for poster (MSEC 2018), and first and runner up poster awards (Aerodef 2019). University of Southern California awarded him the best academic performance as a Masters student in 2018. His research has been showcased in various media platforms like Forbes, Hexagon magazine, and NBC Bay area. In the past, he has worked with Lockheed Martin and UTRC to develop multi-arm cells for the layup of viscoelastic composite sheets.

## Doctoral Symposium

# Research on Design Methodology and Key Technology of Rotary 3D Printer for Curved Layer Slicing

Donghua Zhao
Shanghai Jiao Tong University
Prof. Weizhong Guo

3D printing, formally known as additive manufacturing, creates complex parts with layer-by-layer material addition. In recent years, with the rapid development of 3D printing technology, 3D printing has become a research hotspot, leading to tremendous aerospace, military, and robotics applications. However, there still exist some limitations in the current 3D printing technology, such as: **stair-step error caused by step effect, the anisotropy of printed parts resulted from 2.5D manufacturing principle, time-consuming and energy-consuming issues brought by printing and post-processing of supporting structures**. Advanced design for additive manufacturing (ADfAM) is widely emphasized to obtain the desired components. **On the one hand, 3D slicing and path planning, which are the critical steps of ADfAM, directly determine manufacturing process variables, shape, and printed parts performance.** Curved layer fused deposition modeling (CLFDM) has been proposed by researchers to alleviate or even solve these problems. However, to the best of our knowledge, available CLFDM mainly focuses on filling with the uniform extruded filament in the same layer. While intricate parts usually possess small and critical features, as well as manufacturing error and assembling error. **On the other hand, with the aid of robotic AM manufacturing technologies, it is possible to manufacture components with intricate geometry and high-performance with fewer supports or even no supports, which is a step toward solid freeform fabrication (SFF).**

It is significant to get **a comprehensive understanding of the current status and challenges of ADfAM**. This paper reviews available slicing and path planning methods based on the demand for shape and performance-controlled additive manufacturing for complex parts. Then, **CLFDM with variable extruded filament (VEF)** has been researched. This paper carries out type synthesis for the rotary 3D printer with GF sets theory and dimensional design based on manufacturing's motion requirement. Meanwhile, this paper **proposes the mixed-layer adaptive slicing method** for robot AM innovatively and **several curved-layer slicing methods** for CLFDM. Finally, **a prototype of the rotary and multi-mode 3D printer** has been proposed. At the same time, **the structure design and preliminary experiments have been carried out**. The new 3D printer could be applied into flat layer FDM and CLFDM, owning broad application prospects in the field of shape and performance controlled additive manufacturing for complex parts. The key issues and specific research contents in this paper are as follows:

(1) **The 3D printing principle and critical technology of manufacturing complex parts**. The principle and critical technology of complex curved layer printing are the theoretical premises and technical guarantee for developing 3D printing equipment with curved layer printing capabilities. On this basis, 3D printing equipment has efficient building speed and superior printing performance. This paper analyzes the CLFMD with VEF to improve the shape and performance-controlled technology's theoretical connotation for components.

(2) **Innovative design for the collaborative 3D printers (type synthesis and dimensional design)**. 3D printing equipment is the prerequisite for realizing controlling components' shape and performance. This paper profoundly studies the basic principle of robotic additive manufacturing to obtain the motion characteristics of collaborative 3D printers. Based on the GF sets theory, this article synthesizes the mechanisms for 3D printers. Then, the dimensional design is carried out step by step based on the PCbDM (Performance Chart based Design Methodology).

(3) **Curved layer slicing and filling patterns for shape and performance controlled AM for complex parts**. Process planning is a critical link in implementing the 3D printing process. Establishing the curved layer slicing model for the control of the components' shape and performance requires a more reasonable filling strategy. Therefore, this research plans the printing path and generates the control data based on the bio-inspiration of 3D printing to establish 3D surface printing theory and methods for shape and performance-controlled AM for complex parts.

(4) **Prototype development and experimental research of the novel rotary 3D printer**. The author carried out the structural design, control system construction of the prototype, and analyzed its performance; developed the upper computer software; and carried out experimental research.

# Doctoral Symposium

## Biography – Donghua Zhao

Donghua Zhao received his B.S. degree in Mechanical Engineering from Nanjing Normal University in 2013. He is currently working toward his Ph.D. in Mechanical Engineering at the Shanghai Jiao Tong University. His research is in sand mold printing, a novel 3D printer designing, type synthesis of parallel mechanism, 3D slicing and path planning, curved layer fused deposition modeling and mixed-layer adaptive slicing for robotic additive manufacturing.

He has published one international conference paper in IDETC/CIE and eight SCI papers in the journals, including Rapid Prototyping Journal, Journal of Intelligent Manufacturing, Journal of Manufacturing Science and Engineering， Journal of Computing and Information Science in Engineering and Mechanism and Machine Theory. He has eleven national invention patents (seven granted) and one granted software copyright; Meanwhile, he serves as International SCI journal reviewer of 3D Printing and Additive Manufacturing, Part B: Journal of Engineering Manufacture and IEEE Access; Besides, he won the national scholarship for doctoral students, Shanghai Jiao Tong University's ‘Three Good Student’ and outstanding graduates; as the student leader, the project ‘research on shape and performance controlled curved layer 3D printer for complex parts’ won the Innovation Award of Good Design launched by IDAC Innovation Design Alliance of China & China Knowledge Center for Engineering Sciences and Technology.

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# Topology and Toolpath Optimization via Layer-Less Multi-Axis Material Extrusion

Joseph Kubalak
Virginia Tech
Christopher B. Williams, Alfred L. Wicks

Although material extrusion (ME) additive manufacturing technologies impart significant geometric freedom in part design, the mechanical properties resulting from the typical layer-by-layer deposition process (Figure 1d) are unsuitable for end-use application. Specifically, the thermal characteristics of the process create weak inter- and intra-layer bonds that reduce mechanical performance in those directions. However, this same deposition process offers control over the orientation of material anisotropy (e.g., the direction of a composite reinforcement) through toolpath customization; by specifically aligning depositions to the load paths acting on the structure (Figure 1b), mechanical performance can be improved. While conventional (i.e., XY-planar) ME deposition platforms can only leverage this capability within the deposition plane, recent advances in multi-axis deposition have demonstrated the ability to deposit material aligned to any 3D (i.e., non-planar) vector. In this work, the goal is to improve the mechanical properties of printed parts by simultaneously optimizing the part geometry and the toolpath used to fabricate it through a combination of topology optimization (TO) and multi-axis deposition (Figure 1e).

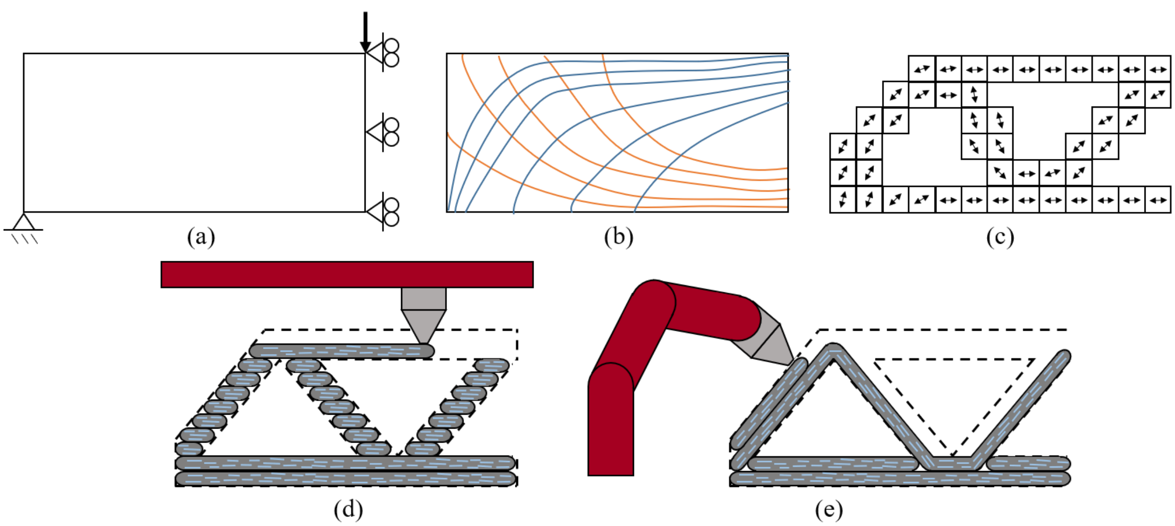



Figure 1. Defining and aligning deposition paths to load paths within a structure. (a) load case, (b) load paths, (c) discretized orientation field, (d) XY-planar deposition does not result in good alignment with the load paths, whereas (e) multi-axis deposition enables strong alignment with the load paths.

While the utility of multi-axis deposition has been demonstrated in literature, toolpath planning capabilities are limited; geometries and load paths are restricted to surface-based entities, rather than fully 3D load paths. This restriction is imposed to i) prevent collisions between the deposition head and the part being printed and ii) allow the use of existing toolpath planners for XY-planar and curved-layer slicing. To enable the deposition of arbitrary geometries with deposition paths aligned to the anticipated load paths, the author presents a novel design and process planning workflow that simultaneously optimizes the topology of the part and the toolpath used to fabricate it. The workflow i) identifies the optimal structure and road directions using TO, ii) plans roads aligned to those optimal directions, and iii) translates those roads to a collision-free, robot-interpretable toolpath.

The workflow is presented and demonstrated in the context of 2D and 3D load cases. A planar multi-load case was simultaneously optimized for tensile and bending, and the resulting topology and orientation field was propagated with i) the custom alignment-focused deposition path planner and ii) conventional toolpath planners. The alignment-focused method resulted in a 97% correlation between the road directions and the orientation field, while the conventional methods only achieved a maximum of 77%. Mechanical testing of the printed samples demonstrated a 108.24% and 29.25% improvement in each load case, respectively, using the alignment-focused method. To evaluate the methodology in a multi-axis context, a 3D inverted Wheel problem was optimized and processed by the workflow. The resulting toolpath was then fabricated on a multi-axis deposition platform and mechanically evaluated relative to geometrically similar structures using a conventional toolpath planner. Although the multi-axis toolpath had a 93.13% correlation to the optimized orientation field compared to 54.99% in the conventional toolpath, the multi-axis samples only withstood 7% additional load. This muted improvement is hypothesized to be due to the physical limitations of the multi-axis deposition platform.

# Doctoral Symposium

## Biography – Joseph Kubalak

Joseph joined the Design, Research, and Education for Additive Manufacturing Systems (DREAMS) Lab in 2013 as a senior design student working on the DreamVendor 2.0 and continued in the lab as a PhD candidate. Joseph's research has contributed to three journal publications, six conference papers, and one patent, and he has presented in five talks and six poster presentations. Additionally, he has presented at the SXSW Conference (2016) and the ACCelerate Festival (2017) and won the America Makes Innovation Sprint for Smart Structures (2016). Throughout most of his graduate program, Joseph worked as a research assistant for the Institute for Creativity, Arts, and Technology (ICAT) in the Create Studio. Currently, Joseph works as a post-doctoral researcher in the DREAMS lab and is continuing his research in optimized multi-axis deposition.

## Doctoral Symposium

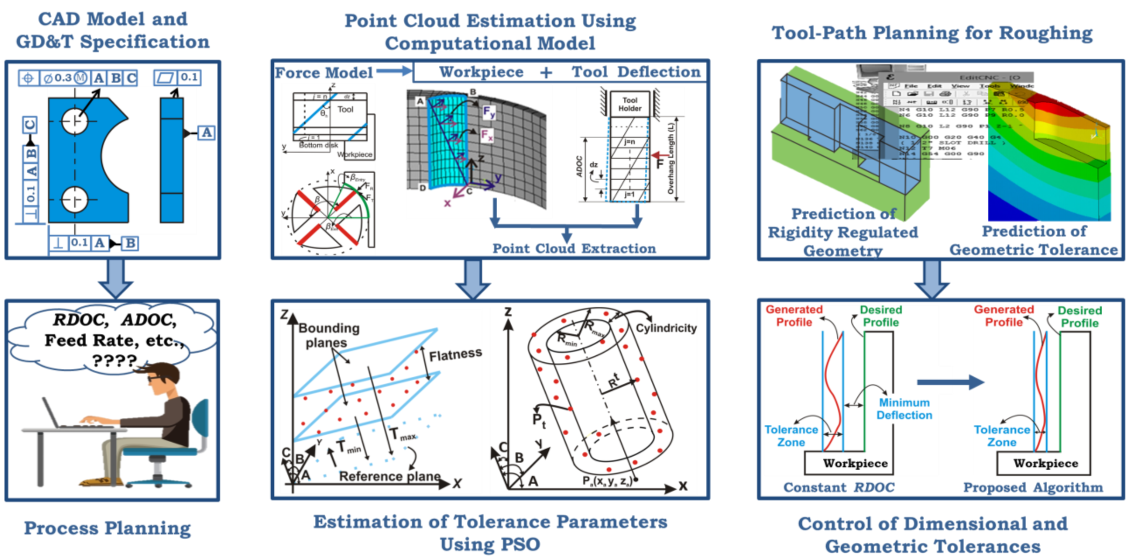
# Modeling and Control of Geometric Tolerances in End Milling of Thin-walled Components

Ankit Agarwal
Indian Institute of Technology Jodhpur, Rajasthan, India
Dr. Kaushal A. Desai

High-precision manufacturing of thin-walled components in a monolithic form is vital for products having complex functional requirements typically employed in aerospace, automobile, die/mold making, and power generation industries. End milling is preferred for manufacturing thin-walled components due to its versatility to generate complex shapes in various materials with high quality and productivity. End milling is an intermittent material removal operation with periodically varying cutting forces causing static deflections of thin-walled components. The static deflections are a primary source for the deviation of manufactured components from the design features resulting in rejection and scrap work. The designer specifies allowable deviations as per the Geometric Dimensioning and Tolerancing (*GD&T*) principles (ASME Y14.5-2009, ISO 1101:2017) to transfer designer intent to the manufacturer. According to *GD&T* principles, the deviation of manufactured components is specified using basic dimensions and geometric parameters such as size, form, and orientation. **It is essential to develop a computational framework that aids manufacturers in selecting process parameters (depths of cut, feed, etc.) and devising an appropriate strategy to control geometric tolerances within the design limits.**

The doctoral work develops a comprehensive computational framework to estimate static deflection-induced flatness and cylindricity tolerances during the end milling of thin-walled planar and curved components (Fig.1). The framework consists of a cutting force model, tool and workpiece deflection models, and geometric tolerance estimation algorithm. The flank and bottom cutting edges are two primary contributors to cutting forces during the end milling operation. **A comparative assessment of three different analytical approaches is conducted in the doctoral work to highlight the importance of incorporating bottom and flank cutting edges in cutting force models for the end milling operation.** The limitations of the classical physics-based cutting force model in dealing with random process variations can be addressed by Machine

Learning (ML) techniques. **The doctoral work explores developing a hybrid cutting force model that amalgamates strengths of physics and ML-based models for improved prediction accuracy**.




(a) Inputs (b) Tolerance Prediction (c) Control Strategy

Fig.1: Framework for Estimation and Control of Geometric Tolerances

The cutting force model is integrated with the finite element-based workpiece deflection model and cantilever beam-based tool deflection model to estimate distorted machined coordinates for straight and curved components. Particle Swarm Optimization (PSO) technique-based flatness and cylindricity parameter estimation algorithm is developed to extract the relevant geometric error parameters from the distorted coordinates. **The overall framework is implemented in the form of computational models to determine geometric tolerance parameters for thin-walled planar and curved components, as depicted in Fig. 1(b).**

**A Rigidity Regulation Approach (RRA) is devised in the doctoral work** to determine the semi-finished workpiece geometry that optimizes geometric tolerances attainable during the final machining pass (Fig. 1(c)). The model regularizes the rigidity of the thin-walled component to manufacture it within the given tolerance limits. A set of machining experiments are conducted, and an assessment of geometric tolerance parameters is carried out on representative geometries to examine the efficacy of the proposed framework. **The doctoral work provides meaningful information to *CAD/CAM* software users and process planners in selecting appropriate machining conditions for producing *first-time-right* thin-walled components.**

# Doctoral Symposium

## Biography – Ankit Agarwal

Ankit Agarwal is a Postdoctoral Researcher at International Center for Automotive Research Clemson University. He is a recent Ph.D. graduate from the Department of Mechanical Engineering, Indian Institute of Technology Jodhpur, Rajasthan, India. He received his Master of Technology in Production Engineering from the Delhi Technological University, Delhi, in 2015 and Bachelor of Technology in Mechanical and Automation Engineering from the Guru Gobind Singh Indraprastha University, Delhi, in 2013. His research interests are; CAD/CAM, mechanics of machining, GD&T, and machine learning application in manufacturing.

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## Doctoral Symposium

# Mechanics of Origami-based Sheet Metal Bending

Muhammad-Ali Ablat Nuryar
Mechanical Engineering
University of California Merced
Advisors: Ala Qattawi, Jian-Qiao Sun

The increased use of sheet metal products in the automotive, construction, and aerospace industries demands the need for a more precise, economic, and sustainable sheet metal forming techniques that are die free and able to accommodate design changes easily. The conventional sheet metal bending processes such as wiping die bending, U bending, air bending and roller bending often require costly shape-dedicated die/mold set and special high tonnage machinery. Origami-based sheet metal (OSM) bending can overcome the challenge and achieve precision, simplicity, and minimum machinery/equipment requirement by implementing the origami sequential folding principle to form a final three-dimensional (3-D) structure. The core idea of OSM bending is based on constructing 3-D structures by fold forming a two-dimensional (2-D) metal sheet. In order to determine the bending line, the forming process of OSM is achieved with the aid of induced material discontinuities (MD) in the 2-D sheet metal. MD can be created using laser slitting or progressive die stamping with predetermined shapes. Figure 1 shows the OSM bending configuration.

To date, there are very limited attempts to understand and explore OSM bending in the manufacturing research community. The bottleneck that hinders OSM bending from wide usage is due to a lack of understanding of the OSM bending mechanics in metal sheets with the presence of MDs. The dissertation focuses on expanding the knowledge about OSM bending from a mechanics point of view. The dissertation research objective is to fundamentally understand the OSM bending process mechanics and contribute to the development of a precise, economic and sustainable sheet metal bending technique.

This work relies on computational, experimental, and analytical approaches to present investigations on fundamentals of OSM bending mechanics in terms of bending accuracy, required bending force, deformation occurred, and failure due to ductile fracture. Particularly, this works conceptualizes the OSM bending process and pave the way for future research work in studying the topological analysis of MDs and their corresponding influence on sheet metal folding performance and accuracy. Then the parameters associated with both OSM bending process are determined. The dissertation lays out a selection methodology based on the folding mechanics that manufacturer can apply based on the thickness of the sheet, the MDs topology used and the kerf-to-thickness ratio. In addition, the dissertation also offers an experimental and analytical modeling for the required bending force for OSM approach with respect to the sheet metal type and thickness. Further, the deformation behavior of OSM under tension and shear loading is investigated where the dissertation work provides a developed technique to apply standard tensile and shear stress to sheet metal samples with various MD geometries. Finally, fracture prediction in OSM bending is explored considering the effect of MD scale (i.e. the ratio between the kerf and thickness of the sheet) and sheet thickness.

The results showcased that OSM bending is feasible without using a die, and that the OSM bending requires less amount of bending force. This work also presented a prediction model for the required OSM bending force, which concluded that each MD type has a unique shape factor impacting the magnitude of the OSM bending force. It is discovered that the topology of the MD has significant importance in OSM bending process. The topology of MD is relevant to bending stress, required bending force, and the possibility of fracture. Hence, identifying better MD topology or improving the existing MD topologies can advance the OSM bending technique to the next level.

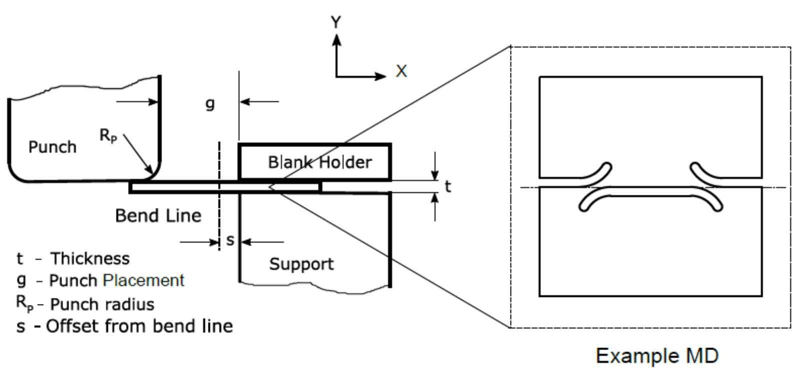


Figure 1. OSM bending Configuration.

# Doctoral Symposium

## Biography – Muhammad-Ali Ablat Nuryar

Dr. Muhammad-Ali Ablat Nuryar is currently a lecturer at the University of California Merced. He received his Ph.D. from the University of California Merced in Fall 2020 in Mechanical Engineering. His dissertation work focuses on the mechanics of origami-based sheet metal bending. He also holds a master's degree in computational mechanical engineering and a bachelor's degree in mechanical engineering. With the specialization in computational mechanics and manufacturing, his research interest centers on the mechanics of manufacturing with an emphasis on numerical simulation. Dr. Nuryar worked as a research intern at Zimmer Biomet Holdings Inc in 2018 and also worked as a research intern at Rosen Technology and Research Center (GmbH) at Germany from 2014-2015. Dr. Nuryar published a total of 8 articles between journals and conference proceedings. He was awarded the North Rhine-Westphalian Scholarship at Germany and the Bobcat Fellowship from the University of California Merced in 2016 and 2018.

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# Doctoral Symposium: Direct Ink Writing of Functional Fiber Composites

Yizhou Jiang
The University of Illinois at Chicago
Advisor: Yayue Pan

**PROBLEM STATEMENT** Fiber-polymer composites show tremendous promise due to their unique mechanical/electrical/thermal properties. Such composites usually consist of polymer matrix embedded with high-strength synthetic/natural fibers. By printing fiber-polymer composites using additive manufacturing (AM) techniques, the three-dimensional models can be fabricated with arbitrary free-form geometry, improved mechanical properties, and even multiple functionalities. Yet grand challenges such as limited material choices, weak fiber-matrix interface, and little control over filler distributions within the matrix still exist in the major additive manufacturing processes for fiber-polymer composites.

**BACKGROUND** Among the many additive manufacturing techniques that have been investigated for the productions of fiber-polymer composites, direct ink writing (DIW) is an extrusion-based AM approach. It has a relatively diverse choice of printable filler and matrix materials for the composite structure. Applications, including energy storage, mechanical reinforcements, medical implants, and biomimetic materials, have been presented through the DIW of fiber composites. However, challenges, including the complicated process planning, low geometrical accuracy, filament shape instabilities, and minimal fiber extrusion capability, are still existing in the DIW of fiber composites.

**RESEARCH QUESTIONS** My dissertation aims to address these challenges in DIW of fiber-polymer composites and to develop a fundamental understanding of the complex interplay of ink properties, printing process, and functionalities by answering the following research questions:

**Q1** How does the incorporation of an electric field between the printing nozzle and the substrate affect the shape-stability and the geometrical accuracy of the printed filament?
**Q2** Can the addition of hydrogel change the storage modulus and loss modulus of the synthetic fiber suspensions to suit the extrusion-based additive manufacturing process?
**Q3** What are the influence of the probe sonication process on the natural fiber structure and their dimensional variations under a polymer-based composite configuration?

**CONTRIBUTIONS** Following the research questions, I conducted fundamental studies in material printability evaluation and process/design enhancement. A DIW setup equipped with an electric field is developed. The DIW process assisted with the electric field is modeled analytically and validated experimentally. Synthetic-fiber-polymer composite inks and natural-fiber-polymer composite inks are prepared and characterized for DIW printing. Functional devices are printed using the formulated composite inks, and the printed structures are characterized. The scientific contributions can be summarized in the following perspectives:

**C1** Developing generalized mappings between feature geometries and process parameters

**C2** Understanding the influence of liquid rheological properties on printing stability

**C3** Establishing approaches for modifying synthetic/natural fiber for printable composites

**C4** Incorporating field-assisted and temperature-controlled process planning strategies

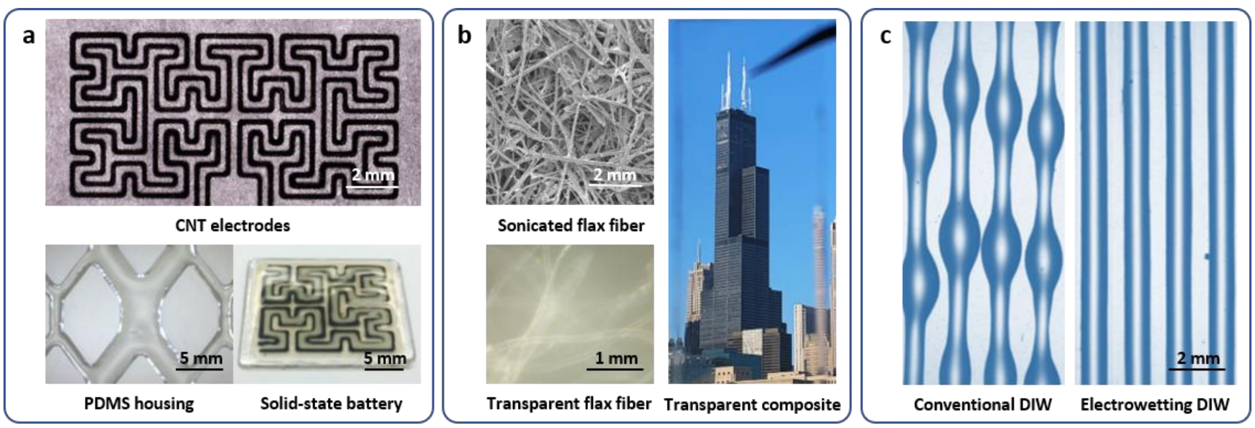


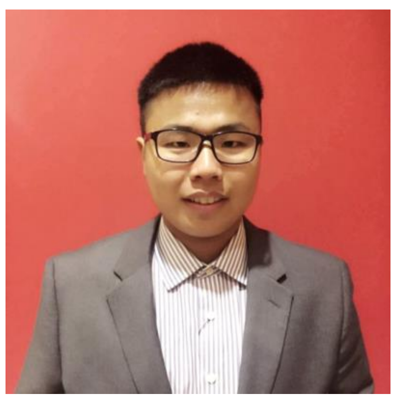

**Fig.1 Research summary. a)** Fabricated energy storage devices using synthetic fiber composites. **b)** High-performance structural materials using natural fiber reinforcement. **c)** Printed filament controlled by the electric field to prevent defect formation.

These findings enable significant improvements in applied techniques for fabricating next-generation energy storage devices (**Fig.1a**), high-performance structural materials (**Fig.1b**), real-time optimizations in manufacturing, and novel liquid/droplet control approaches (**Fig.1c**). The outcomes serve as one of the first efforts that advance the processes, materials, and designs in future manufacturing technologies.

# Doctoral Symposium

## Biography – Yizhou Jiang

Dr. Yizhou Jiang joined the Epstein Department of Industrial and Systems Engineering and Center for Advanced Manufacturing at the University of Southern California as a Postdoctoral Research Associate in January 2021. He received his Ph.D. degree in Industrial Engineering and Operations Research from the University of Illinois at Chicago in 2020. He obtained his M.S. in Electrical and Computer Engineering from the University of Illinois at Chicago in 2016 and his B.E. in Automation Engineering from Jilin University in 2015. His research interests are additive manufacturing process development/optimization and novel applications in various areas, including energy harvest, structural materials, robotics, and bio-inspired designs. He has authored and co-authored more than 15 research papers in peer-reviewed journals in manufacturing processes and printable material developments.



MSEC
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## Doctoral Symposium

# Sub-Surface Void Formation and Detection during Friction Stir Welding of Aluminum Alloys

Daniel Franke
University of Wisconsin Madison
Prof. Frank Pfefferkorn

The formation of sub-surface defects during friction stir welding has limited the adoption of the transformative joining process in high-reliability applications and high-volume production. This is due to the need for costly post-process non-destructive evaluation (NDE) of welds in high-reliability applications, and a greater tendency for sub-surface void formation at greater process speeds. Process adoption can be increased by developing robust methods of in-process defect monitoring, along with designing the process for higher travel speeds while avoiding sub-surface defect formation. The **objective** of my research is to develop a fundamental understanding of how sub-surface voids form, as well as develop a fundamental understanding of how void formation alters measured process outputs. A fundamental physical understanding must be developed in order to advance the state of the art in these two areas. The fundamental understanding will form the basis for more robust methods of defect monitoring that are transferable across changes in process settings and will help drive improved numerical simulation of the sub-surface void formation process.

The void formation process has been examined through multiple experimental techniques. The first of which was through an improved examination of process force transients during void interaction. Prior literature had shown that process forces oscillate at the tool rotational frequency and that material flow and void formation occur at the periodicity of each tool revolution. It was hypothesized that the eccentric motion of the tool (tool runout) was the primary driver of process force oscillations. A novel experimental setup was used to measure process forces in combination with the angular position of the eccentric points of the tool, which produced the observation that the eccentric motion of the tool applies the oscillatory force to the workpiece and thus appears to be the driver of the flow of material per revolution. Additionally, when features of the tool probe (flats) interact with void volumes there is a momentary reduction in the oscillatory force that the tool applies to the workpiece. The fundamental understanding of the force transients holds the potential to form the basis of a more robust force-based void monitoring method.

The hypothesizes derived from force observations were examined further by experimentally measuring the real-time motion of the tool during friction stir welding via a laser vibrometer. The results showed that the runout of the tool is constrained by the workpiece during welding, which supports the hypothesis that the eccentric motion of the tool drives force oscillations. Additionally, the motion measurements showed that the tool is momentarily deflected into void volumes during feature interaction. This suggests that a motion-based method of void monitoring has potential for application, which would provide the option of using an accelerometer instrumented toolholder. A simple mass-spring-damper model was developed in order to describe the dynamic properties of the welding system that will govern tool motion during void interaction. This will provide a fundamental understanding of how the dynamics of a welding system will affect a motion-based method.

Lastly, I am working on the realization of *in situ* imaging of the sub-surface void formation process. This will be achieved through the utilization of the high-speed X-ray imaging capabilities at Argonne National Laboratory's Advanced Photon Source. Static imaging performed at the beamline has proven the feasibility of imaging sub-surface friction stir welding voids within thin sections of aluminum alloys. Subsequent dynamic imaging will be performed in order to capture the evolution of sub-surface voids within the material during welding. This will be achieved by friction stir welding thin sections of aluminum within the beamline. The resultant radiographic images will be used to test prior hypotheses on material flow and void formation physics. Additionally, it will inform the numerical simulation of the sub-surface void formation process. The fundamental knowledge gained as a result of my research will advance the state of the art in friction stir welding, allowing for increased adoption of the novel process in various U.S. manufacturing sectors.

# Doctoral Symposium

## Biography – Daniel Franke

I am a doctoral candidate in the Department of Mechanical Engineering at the University of Wisconsin Madison and will be defending my dissertation in August 2021. Over the past six years, I have researched friction stir welding of aluminum alloys. My Master's thesis focused on using friction stir welding to join very dissimilar materials and my Ph.D. work has focused on understanding sub-surface void formation as well as developing methods of real-time monitoring of void formation through process force and tool motion measurements. Between my master's degree and starting my Ph.D. program, I worked at the Naval Surface Warfare Center Carderock Division examining friction stir processing of additively manufacturing materials. The highlights of my academic career including winning the MSEC Best Paper Award in 2016, receiving the Graduate School Physical Sciences Fellowship from the Department of Mechanical Engineering at UW-Madison in 2016, receiving the F.M. Young Distinguished Teaching Award in 2017, and playing an instrumental role in writing a successful funding proposal that was awarded by the National Science Foundation.  I am currently looking for employment opportunities starting August 2021.

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## Doctoral Symposium

# Process Science for Additively Manufacturing Silicon Carbide Composites

Padmalatha Kakanuru
Stevens Institute of Technology
Dr. Kishore Pochiraju

Silicon Carbide (SiC) is extensively used in aerospace, nuclear and biomedical applications due to its thermal stability, higher thermal conductivity, low coefficient of thermal expansion, chemical inertness, and excellent oxidation resistance. The traditional shaping methods such as pressing, injection molding, and casting are developed to produce SiC ceramic with improved density, performance, and dimensional stability. However, these methods are highly challenging to make complex geometric ceramic parts due to SiC ceramic's high hardness and melting point. Recently ceramic components are being shaped with additive manufacturing (3D-printing) techniques without mold needs. In addition, SiC ceramics are densified by heating the green parts in an inert atmosphere. Due to the highly covalent character of the Si-C bonds, high sintering temperatures of ≥ 1800°C are required to achieve enough neck growth between particles. Hence manufacturing high quality and dimensionally predictable SiC ceramic parts at low process temperatures is quite challenging. Among the available additive manufacturing techniques, printing a polymer-derived ceramics green body and densifying in an inert atmosphere at temperatures about 1100ºC has become a popular technique for Si-based ceramics due to low processing temperatures. However, they undergo about 30% volumetric shrinkage during pyrolysis to become densified ceramic parts. **Hence in this research, a new approach called Oxidation-Bonding is chosen for densification**. In Oxidation-Bonding, the SiC particles are bonded with oxidation-derived silica.

Here, SiC ceramic parts were fabricated by additive manufacturing and the Oxidation-Bonding technique. **UV- light Stereolithography technique was used to print the SiC green parts. The formulation and SLA printing of a high percentage SiC loaded photopolymer resin mixture is a challenge.** The green parts were then heat-treated in the air at temperatures up to 1200°C for polymer burn out, Oxidation-Bonding, and sintering. Cracking was observed in the heat-treated parts. Hence it is essential to understand the oxidation mechanics and the associated effects in the entire manufacturing process to make high-performance damage-free SiC/Silica composites. Thus, **a high-fidelity thermo-chemo-mechanics numerical model was developed to predict the oxide (Silica) thickness/ behavior and sintering of oxide and the associated stress state.** The thermal oxidation was modeled using coupled diffusion-reaction kinetics. The volumetric expansion and relaxation of silica were implemented using Pilling-BedWorth ratio and viscoelasticity, respectively. Then the sintering process was simulated to quantify the shrinkage and relative density of the consolidated oxide. Sintering was modeled using viscoelastic thermal-induced creep deformation. Sintering stress was treated as an equivalent hydrostatic pressure that links the surface energy and grain growth. The temperature-dependent Arrhenius viscosity parameters required for sintering simulation were identified using the optimization technique available in Python SciPy. This research paves the way to design the process parameters and material composition for additively manufacturing of high-performance SiC composites.

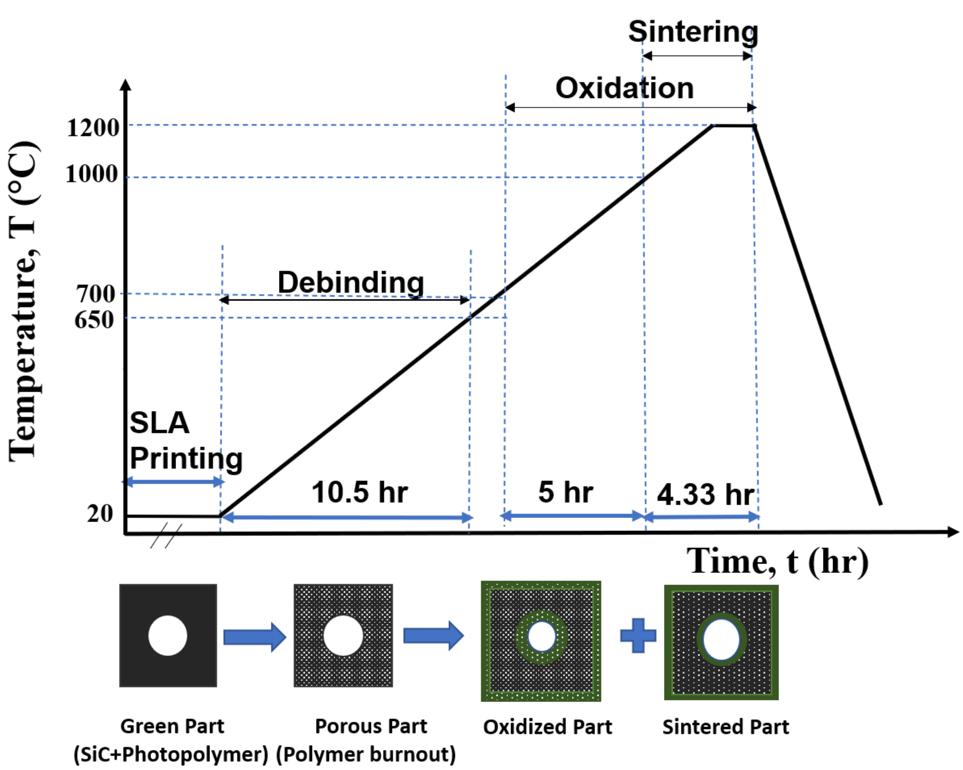


Fig.1 Process chart for Additively manufacturing SiC/Silica composites

# Doctoral Symposium

## Biography – Padmalatha Kakanuru

Padmalatha Kakanuru is a Ph.D. candidate in the Department of Mechanical Engineering at Stevens Institute of Technology, Hoboken. She received her Bachelor's in Mechanical Engineering from Sri Krishnadevaraya University, India, in 2000 and her Master's in Machine Design from Visweswaraiah Technological University, India, in 2002. She worked as a Scientist at Aeronautical Development Agency, Bangalore, India, from 2003-2008 in system safety, reliability analysis, quality assurance, and configuration control management for India's design and development of indigenous Light Combat Aircraft. Then she worked as a scientist at National Aerospace Laboratories from 2008 to 2011 in the areas of structural testing and evaluation of static, fatigue, and fracture behavior in fiber-reinforced polymer composite materials under environmental aging and high-temperature conditions. She also ventured into nanocomposites by researching the effects of nano-silica and micron rubber particles on fatigue and fracture behavior of GFRP composites. She is the author of 4 journal papers and 17 conference proceedings papers. Her research interests include design, computational modeling, and simulation of process science for additively manufactured Silicon Carbide ceramic composites.

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## Doctoral Symposium

# Direct Droplet Writing – A Novel Droplet-punching Capillary-splitting 3D Printing Method for Highly Viscous Materials

Yang Xu, University of Southern California, Advisor: Yong Chen

As one of the most popular additive manufacturing (AM) processes, **material jetting** has demonstrated excellent ability in multi-material (MM) fabrication. Rather than a continuous flow of liquid material, a sequence of discrete droplets is ejected out of small nozzles by micro piezo. This drop-on-demand (DOD) approach is capable of controlling a three-dimensional (3D) object's property voxel by voxel. Despite the superiority, there exist several **key bottlenecks** in material jetting. **Firstly**, current material jetting suffers from low-viscosity material restriction. Only the materials of viscosity lower than 40 mPa·s can be successfully printed, which dramatically reduces the material options. **Secondly**, the contactless mode also brings troubles. Satellite droplets between primary droplets and splashing during droplet impact often occur without optimizing material surface tension and rheological properties and fine-tuning process parameters, including pulse waveform and stand-off distance. **Thirdly**, additional support structures are always required for overhang features in material jetting, increasing material waste and fabrication time. **On the other side, direct ink writing (DIW)** is a simple 3D printing technique with access to materials over a wide range of viscosity (from 1 to over 1,000,000 mPa·s). The continuous material filament keeps contact with the build platform or previously built layers once extruded so that the process is more robust. However, this analog deposition approach loses the ability to define an object's property point-by-point. Similar to material jetting, printing additional supports will slow down fabrication speed and increase material consumption.

In comparison, material jetting is more promising in terms of MM fabrication. At the same time, DIW has advantages in handling viscous materials and robustness. My dissertation aims to address this dilemma by developing a **novel droplet-based process called direct droplet writing (DDW) that can reliably 3D print objects using highly viscous materials meanwhile with minimum support consumption**. The methodology is to inherit both methods' merits, as shown in Fig. 1. This goal involves three **research questions**: **Q1** How to apply more powerful shear stress in DOD approaches to overcome the resistance of high viscosity? **Q2** How to realize droplet deposition without adverse effects from satellite droplets, droplet splashing, and deflection? **Q3**

How to minimize 3D-printed support to cut down material waste and printing time in droplet-based 3D printing methods?

Aiming at the above problems, I formulated these **hypotheses**: **H1** A new DOD approach suitable for viscous materials can be achieved relying on mechanical force; **H2** A contact-based approach can be applied to DOD to increase reliability; **H3** Metal pins can be utilized as automatic and reusable support to reduce material waste and fabrication time;

Following the research questions, I conducted fundamental studies regarding support structure design and material printability in various jetting approaches. A 3D printer setup equipped with reusable supports and novel printer heads based on the DDW process was developed to verify the hypotheses. The corresponding **contributions and achievements** are summarized as below:

**C1** The innovative printer head based on droplet-punching and capillary splitting principles enables the printing materials to have a **viscosity up to 190,000 mPa·s**, which is the **highest record in current droplet-based approaches**; **C2** The reusable support strategy in the developed process shows an average of **~40% saving** on the printing time and material with increased reliability and robustness, **compared with all present support designs**; **C3** The contact-based method can avoid issues resulting from satellite droplets, droplet splashing, and deflection completely, **demonstrating the best positional accuracy compared with other jetting approaches**. These research findings solved the barriers that hinder the droplet-based process in printing viscous materials and large-area 3D printing. The outcomes will drastically broaden the range of 3D printable materials and significantly advance the droplet-based printing methods in fabricating multi-material objects for various functional applications.

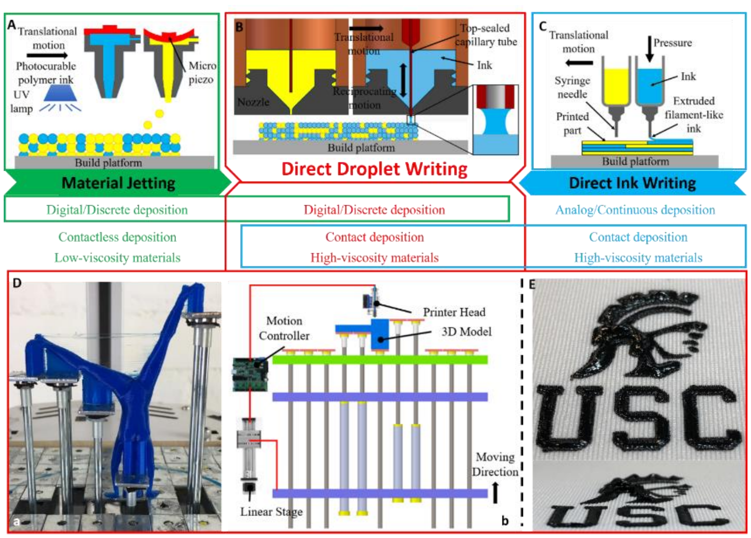


Fig. 1. The methodology of DDW and verification of corresponding primary hypotheses. (**A**) Schematic illustrating the principle of material jetting. (**B**) Schematic showing the principle for DDW. (**C**) Schematic illustrating the principle of DIW. (**D**) Automatic and reusable support to minimize material waste and fabrication time. (a) Fabrication result with reusable support. (b) Schematic diagram of reusable support. (**E**) 3D USC logo printed on fabric via DDW using polyurethane (PU) leather ink with a viscosity of 190,000 mPa·s.

## Doctoral Symposium

## Biography – Yang Xu

Yang Xu is a Ph.D. candidate in industrial and systems engineering at the University of Southern California. He received a B.E. and an M.E. in mechanical engineering from Beihang University in 2013 and 2016, an M.S. in Computer Science from the University of Southern California in 2021. His current research interests are novel multi-material/multi-scale additive manufacturing processes development, including vat photopolymerization, material jetting, and fused filament fabrication. His recent publications include “Reusable Supports for Additive Manufacturing” (Additive Manufacturing, 2021) and “A Vibration-assisted Separation Method for Constrained-surface-based Sterelithography” (ASME Journal of Manufacturing Science and Engineering, 2021.) which was given the Best Paper Award (2nd Place) in MSEC2020.

## Doctoral Symposium

# Low Force Friction Surfacing for Crack Repair in 304l Austenitic Stainless Steels

Hemant Agiwal
University of Wisconsin-Madison, USA
Dr. Frank Pfefferkorn

The objective of this research is to generate a fundamental understanding of the friction surfacing process and evaluate the efficacy of the process to perform crack repair on simulated and stress corrosion cracks in 304L stainless steels while reducing process forces. The motivation for this work arises from the problem of stress corrosion cracking in stainless steel canisters used for dry cask storage of used nuclear fuel. Traditionally, fusion overlay welding methods have been employed however the introduction of detrimental segregated solidification microstructure and shrinkage in harsh environments has led to the need for solid-state repair processes.

Friction surfacing is an emerging solid-state technology that produces fine-grained coatings with superior surface and corrosion properties by pressing a rotating rod against the substrate under an applied axial load. Frictional heat generated viscoplastic boundary layer at the rod tip creates pressure and temperature conditions leading to an interdiffusion process that results in a metallic bond between the plasticized material and the substrate.

The research aims at evaluating friction surfacing using a 304L consumable rod on a substrate of the same material and investigates a novel regimen of high-spindle speeds during friction surfacing (up to 40,000 RPM). The motivation for high spindle speeds is to reduce process forces to help enable the portability of the process for in-field repair applications. Friction surfacing has been performed using a CNC machine tool in position control mode while observing the process forces. Several combinations of consumable rod diameters feed rates, and spindle speeds have been used. Axial pressures measured during the process reduced from 60 MPa at 4,000 RPM to 12 MPa at 20,000 RPM. Acceptable coatings were produced at forces of 200N while using a 3/16” diameter consumable rod at 20,000 RPM.

Initial attempts have been made to understand the physics of this process by using analytical equations and regression analyses on the processing parameters and measured performance i.e., force, deposition morphology, bond strength, and microstructure. The influence of process conditions on bonding characteristics and thermomechanical properties during the process has also been studied. The self-limiting nature of the friction surfacing process combined with a change in stick-slip conditions has been found as the reason for force reduction at higher spindle speeds.

Friction surfacing was performed on simulated cracks of width ~50µm followed by helium leak testing to evaluate the ability to create a gas-tight repair. Cleaned and oxidized substrate conditions were tested for repair. Closing of cracks up to 200 µm below the interface of the substrate and coating was observed after microstructural analyses. Helium leak tests were used to evaluate the efficacy of the repair and tests revealed a leak-proof coating. Conditions resulting in leak-proof coatings were characterized for mechanical properties via microhardness, bending, and tensile tests. Coatings did not fail under bending loads and had a high ultimate tensile strength of 560 MPa before failure. The tensile failure occurred outside the coated region.

The proposed future work involves completing a robust microstructural characterization of coatings to understand the thermomechanical events. Friction surfacing and crack repair will be performed up to 40,000 RPM spindle speed to further reduce process forces. Friction surfacing will also be performed on chloride-induced stress corrosion cracking to mimic cracks found in canisters for storage of used nuclear fuel. These stress corrosion cracks will be fabricated in-house using a boiling MgCl2 setup according to ASTM G36-94 standard. Since canister breach will also lead to gas leakage, friction surfacing will be performed on simulated and stress corrosion cracks while gas is leaking through them.

This study explores various novel areas in the field of friction surfacing technology including the material combination, high-speed regimen, low process forces, and application towards repair and mitigation of cracks. The results will allow for use of low-force friction surfacing for applications across transportation and nuclear industries. It will also lead pathways for discussions about understanding material flow and thermo-mechanical events during friction surfacing.

# Doctoral Symposium

## Biography – Hemant Agiwal

Hemant Agiwal is a Ph.D. candidate at the University of Wisconsin-Madison in Mechanical Engineering, where he also completed an M.S degree in Manufacturing Systems Engineering. His ambition, expertise, and focus for research lie in the areas of non-conventional manufacturing technologies, solid-state additive manufacturing, smart and quick response manufacturing; with an overall aim at designing and implementing greener, safer and efficient solutions to engineering problems. Hemant is currently working as a research assistant at the Multi-Scale Metal Manufacturing Lab at UW-Madison, under the guidance of Prof. Frank Pfefferkorn. His area of study is the mitigation and repair of stainless steel canisters using friction surfacing. Previously, he worked on discontinuity detection and material flow analysis in Friction Stir Welding of Aluminum Alloys. He completed his undergraduate degree in Mechanical Engineering from MNNIT-Allahabad, India, and has more than 3 years of automotive/ manufacturing industry experience. Having been exposed to the manufacturing of a wide range of materials from metals, plastics, composites, and fabrics, Hemant has established a working knowledge of component design, development, and process optimization techniques.

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## Doctoral Symposium

# Optimal Design and Processing for Additive Manufacturing Using Machine Learning

Nathan Hertlein
University of Cincinnati
Sam Anand, PhD

Additive manufacturing has significantly expanded the achievable geometric design space for components to be built from a wide set of materials. At the same time, it has come with complex process parameters that must be chosen carefully to ensure optimal build quality, often on a part-by-part basis. This has created the need for methods to take full advantage of the new design freedom in a manner that is compatible with the capabilities of additive processes, and a need for intelligently selecting the interrelated build parameters of the process. Meanwhile, mechanical engineers routinely face **a range of design scenarios**, each with its own level of complexity. Optimal engineering efforts in these scenarios would each suffer from considerable compromises if addressed by some single computational approach. Therefore, a **series** of design optimization approaches is required, with differences where necessary and similarities where possible. There is a corresponding need to computationally optimize the AM processes themselves. Collectively, these efforts are motivated by the goal of fully utilizing AM's design freedom to achieve complex parts with the exact desired behavior, which ranges from lightweight strength to tunable secondary stable configurations. An ensemble of approaches to this end has been emerging in the literature. **However, the following challenges persist, which the present work is intended to address, through the careful integration of machine learning with traditional design and manufacturing principles.**

- High **computational expense**, even associated with optimization with linear materials.
    - We employ a generative adversarial network (GAN) to reduce iterative finite element analysis (FEA) requirements.
    - Dimensionality reduction, such as uniform manifold and projection (UMAP), enables the development recommendations for further efficiency improvements in future work.

- Scarcity of considerations for **strain rate effects**.
  - We exploit Bayesian optimization's abilities in non-convex, gradient-free conditions.
- Limited ability to handle **nonlinear materials**—especially in **multi-stable structures**.
  - We propose objective and optimization formulations to ensure multi-stable optima while maintaining computational efficiency.
- **Uncertainty quantification** in process-driven quality prediction.
  - We develop a Bayesian network-driven predictive framework of an AM process, including a first-order approximation of the process window.

As illustrated in Fig. 1, addressing the above points requires work spanning the product development process, from initial physics-based design to manufacturing process setup.

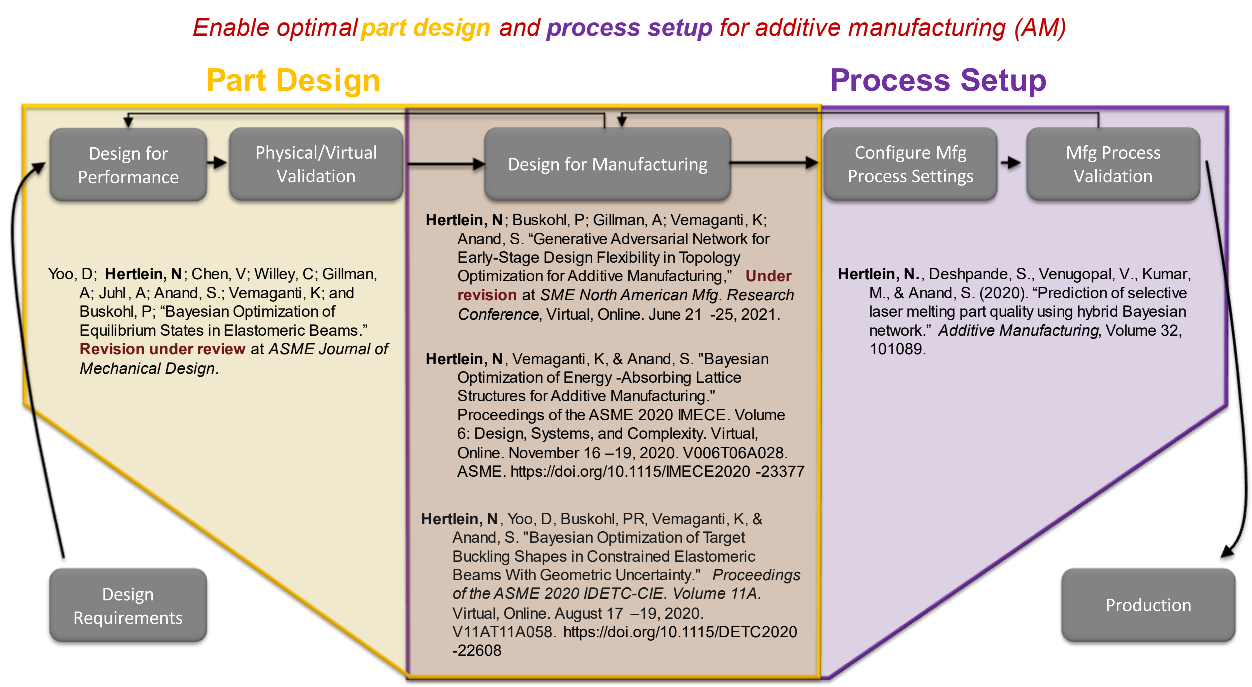



***Figure 1:*** *An overview of this thesis, including all the publications to date. The overall contribution lies in filling important gaps in the emerging body of literature aimed at taking full advantage of the geometric freedom provided by AM, in a consistent manner. Because these areas of opportunity have spanned the product development process, this thesis has done so as well.*

# Doctoral Symposium

## Biography – Nathan Hertlein

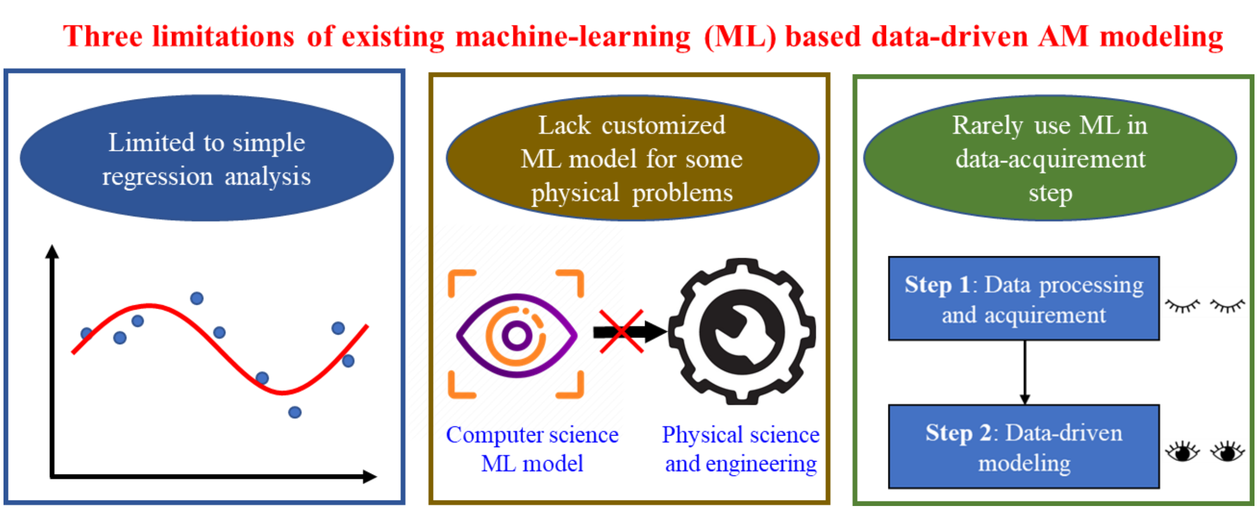
After being awarded his university's Herman Schneider Medal for Excellence in Co-op and graduating from an accelerated Master of Engineering program, Nathan Hertlein worked as a product development engineer for Fiat Chrysler Automobiles in Auburn Hills, MI, where he helped release occupant restraint systems for the Jeep Wrangler and Wrangler PHEV programs. There he acted as a connection between Tier 1 suppliers and various teams within the OEM, while ensuring proper prototyping, design validation, and design for assembly activities. Since 2018, he has been pursuing doctoral studies in mechanical engineering at the University of Cincinnati's Center for Global Design and Manufacturing with Professor Sam Anand, where his research focuses on the optimal adoption of additive manufacturing. Conducted in close collaboration with the Air Force Research Laboratory's Materials and Manufacturing Directorate since 2019, his work meeting both design and processing challenges in additive manufacturing using a variety of machine learning techniques has resulted in 7 refereed conference and journal publications, with more in the pipeline.

## Doctoral Symposium

# Machine learning boosted modeling and simulation of additive manufacturing: process, structure and property

Zhuo Wang
University of Michigan-Dearborn
Lei Chen

Additive manufacturing (AM), which build a single part directly from a 3D CAD model in a layer-by-layer manner, can fabricate complex component with intricate geometry in a time- and cost-saving manner, thus making it potent and increasingly popular in many industries. However, accompanied with its unique building manner and benefits thereof are the significantly complicated physics behind the AM process. This fact poses great challenges in modeling and understanding the underlying process-structure-property (P-S-P) relationship that, however, is vital to efficient AM process optimization and quality control. With the advancement of machine learning (ML) models and increasing availability of AM-related digital data, ML-based data-driven modeling has recently emerged as a promising approach towards exhaustively exploring and fully understanding AM P-S-P relationship. Nonetheless, most of existing ML-based AM modeling severely under-utilize the powerful ML models by using them as simple regression tools, while largely neglecting their distinct advantage in handling complex-data (e.g., image or field) involved data-driven modeling problems and other versatilities.



To overcome those limitations, the current research aims to explore the full potential of ML in data-driven AM modeling by addressing three associated research questions:

1) In addition to engaging in simple curve-fitting things or alike, can we take more real advantage of various ML techniques to build data-driven models that can act as a full (or at least maximum) substitute of physics-based models for **high-level AM modeling and even realistic AM simulation**?
2) Can we **develop customized physical-problem-oriented ML models** for solving those data-driven AM modeling problems intractable by existing ML models and thus further unlocking the full potential of ML techniques?
3) Can we enhance data-driven AM modeling by using ML techniques as more than a data-driven AM modeling tool and, for example, from the pre-data-driven-modeling aspect of **improving data itself** via ML-assisted data collection, processing and/or acquirement?

To adequately answer the above questions, the current research presents a ML-intensive data-driven AM modeling framework and attempts to provide an ultimate ML-based solution to data-driven modeling and simulation of various physical events throughout the AM lifecycle, from process to structure and property. A variety of ML models, including Gaussian process (GP), multilayer perceptron (MLP), convolutional neural network (CNN), recurrent neural network (RNN) and/or their variants, are leveraged to handle representative data-driven modeling problems with different quantities of interest across three phases of AM lifecycle, namely process modeling (melt pool, temperature field), structure modeling (porosity structure, bulky shape) and property modeling (stress-strain curve, stress hotspot). The results show that this research can break current limitations of data-driven AM modeling and, therefore, well address the three raised questions. Although this research uses six representative physical events in AM as examples, the key components developed and data-driven methodologies presented can be broadly expanded to data-driven modeling of many other physical events in AM and beyond, and thus may significantly advance data-driven modeling and simulation across many domains.

# Doctoral Symposium

## Biography – Zhuo Wang

Zhuo Wang is a 5th-year Ph.D. student in Mechanical Engineering at University of Michigan-Dearborn (expected graduation: 2021 Fall). He received his BS degree from Huazhong University of Science and Technology in 2015. His research interests include: 1) multi-scale multi-physical simulation of additive manufacturing (AM); 2) "small data" based on high-throughput AM simulation and 3) machine learning based data-driven modeling and simulation for material&manufacturing researches. He has published over 15 peer-reviewed papers in top journals including npj Computational Materials, Additive Manufacturing, Journal of Manufacturing Science and Engineering - ASME, etc. Zhuo has received a number of awards, including travel grants from Mississippi State University and University of Michigan-Dearborn, third place in poster competition in 2017 MSU Graduate Student Research Symposium and first place in 2020 ASME-CIE Hackathon.

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## Doctoral Symposium

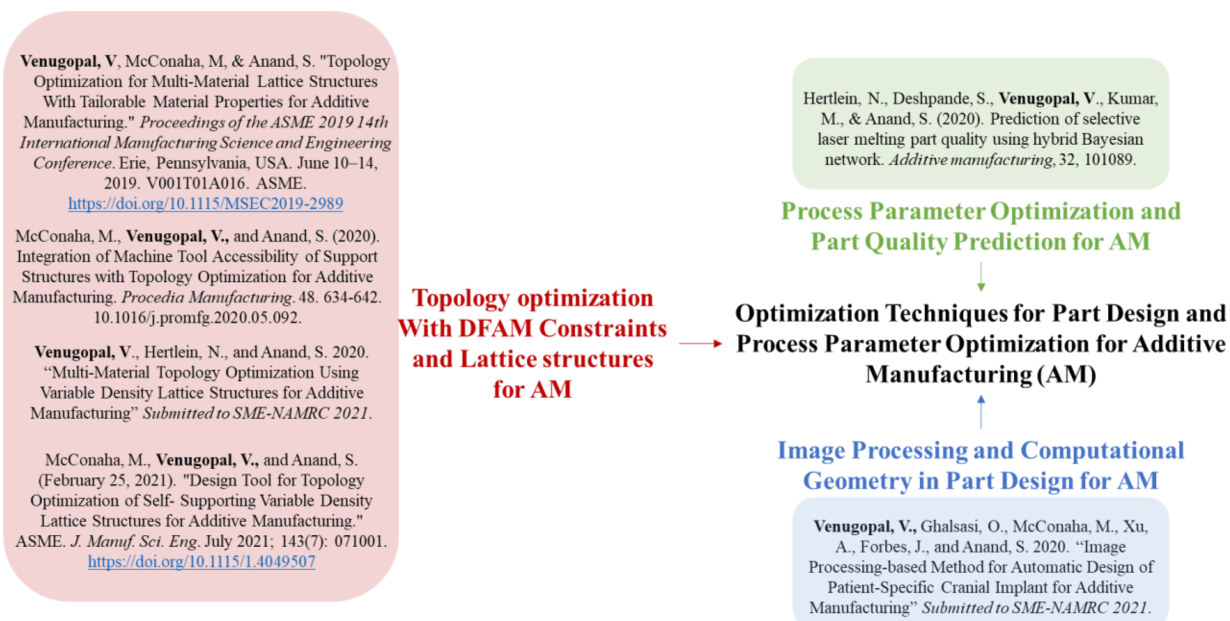
# Numerical Optimization and Machine Learning Techniques for Part Design and Process Parameters for Additive Manufacturing

Vysakh Venugopal
University of Cincinnati
Prof. Sam Anand

Additive manufacturing (AM) has gained a significant amount of traction over the past decade due to its capability to produce parts of complex geometries. Various methodologies such as topology optimization, image processing, and computational geometry principles are being constantly harnessed to tackle challenges in part design that is specific to AM. From the perspective of AM process parameter optimization, machine learning algorithms are used in conjunction with large datasets to create a mapping of different process parameters to the final part quality. Eventually, **the main objective is the development of an intelligent approach for a part and process design for AM that results in high-quality parts in less time and less cost**. In this dissertation, a collection of AM part design and process parameter optimization methods have been presented, all of which works towards the main objective stated before.

**The part design side of the dissertation consists of topology optimization for mechanical and thermal load-bearing capabilities using multi-material lattice structures and the inclusion of DFAM (Design for Additive Manufacturing) guidelines in topology optimization. An image processing-based method for automatic design of cranial implants from digital DICOM data is also presented as a viable approach to design patient-specific cranial implants of high precision that are to be manufactured using AM. Following that, a hybrid Bayesian network is used to map the different AM process parameters from a Selective Laser Melting process to the final build quality parameters and this forms the process parameter optimization side of the dissertation**. Together, the proposed method will serve as a complete package of smart algorithms for high efficiency and cost-effective part design and process parameter settings for additive manufacturing. The methods of part design in AM using topology optimization, lattice structures, image processing, and process parameter optimization for a part build quality as presented in this dissertation are as follows and the figure shows the publications associated with each algorithm.

1. Topology optimization of multi-material lattice structures with low coefficient of thermal expansion, low thermal conductivity, and high stiffness with DFAM constraints.
2. Multi-material topology optimization with variable density lattice structures for low compliance and high heat transfer capability.
3. Topology optimization of self-supporting variable-density lattice structures for additive manufacturing.
4. Integration of machine tool accessibility of support structures within density-based topology optimization for additive manufacturing.
5. Image processing-based method for automatic generation of patient-specific cranial implants using DICOM data for additive manufacturing.
6. Prediction of part quality of parts made using Selective Laser Melting using a hybrid Bayesian network.




With the use of topology optimization integrated with DFAM constraints and lattice structures, one can manufacture high-precision lightweight parts with less material and post-processing time. Additionally, image processing and computational geometry algorithms can be leveraged to design and manufacture customized implants. The build quality prediction techniques suggested here can be used to optimize the process parameters to get optimum part quality.

# Doctoral Symposium

## Biography – Vysakh Venugopal

My name is Vysakh Venugopal. I am a Ph.D. student specializing in the application of computational geometry and computational structural mechanics for Metal Additive Manufacturing. The crux of my research consists of topology optimization with the design for Additive Manufacturing constraints, multi-material lattice structures, application of image processing and computational geometry algorithms for biomedical implant design, and hybrid Bayesian networks for AM process parameter prediction.

I graduated with a Masters in Mechanical Engineering from the University of Cincinnati in 2019 under the guidance of Prof. Sam Anand. My master's thesis was based on the design of topologically optimized multi-material lattice structure-unit cells for low coefficient of thermal expansion and low thermal conductivity using homogenization methods. In 2014, I graduated with a Bachelor’s degree in Mechanical Engineering from the Visversaraya National Institute of Technology in Nagpur, India. My senior project was based on the design and finite element analysis of femur-bone implants.

I am currently in the process of my Ph.D. proposal defense based on the topology optimization methods presented here. After my Ph.D., I aspire to work in industries that specialize in developing algorithms and software products that aid in the advanced CAD/CAM and additive manufacturing domain.

MSEC
Virtual Conference, Hosted by the University of Cincinnati
June 21, 2021 - June 25, 2021

## Doctoral Symposium

# Evaluation of Product Quality Through Technologically Augmented Workers in Industry 4.0 Assembly

Matthew Krugh, Ph.D.
Clemson University
Laine Mears, Ph.D.

Manual assembly processes under the Industry 4.0 framework will blend together data from many disparate sources, including to and from the worker. This fusion of cyber-data and real-world influence holds the potential to improve productivity, quality, and production costs; however, the essential element of the worker influence has largely remained undefined.

This research's objective was to test whether a stochastic representation of worker-generated data can reliably predict product quality using local characterization systems in manual mixed-model automotive assembly and investigate whether providing feedback on process state to the assembly worker affects product quality.

This work intended to explore the role of worker data in assembly and quality characterization possible through the consideration of worker signals in manufacturing. Considering worker signals together with process signals should generate new information about process performance, ultimately leading to a better understanding and control of process output.

This work significantly captured worker-generated data where limited or lack of data existed prior, capture such data within an active production environment, and establish a database of sensor output signatures for manual assembly process tasks.

This work is the first classification for product quality, using human-activity-recognition through worn sound and motion sensors for manual assembly. The classifier was trained from and validated on data from an active production environment with uncontrolled background noise and motion across multiple users.

This work achieved a user-independent, online, stateless, continuous classification to detect short-time sporadic automotive electrical connection events. The resulting classifier evaluated product quality by segmenting the continuous data using time boundaries to estimate success and demonstrated providing feedback to the worker before the completion of the process.

User performance and preference of color-based, haptic, textual, and symbolic wearable feedback methods were evaluated using two Lego-based assembly tasks. Finally, the cost of waiting to repair a generalized electrical connection defect for five locations throughout an automotive assembly line demonstrated the increasing cost of rework as a defect moves through assembly. Also described was the need for a generalized cost of rework model through the use of design complexity, manufacturing complexity, and worker complexity-based factors.

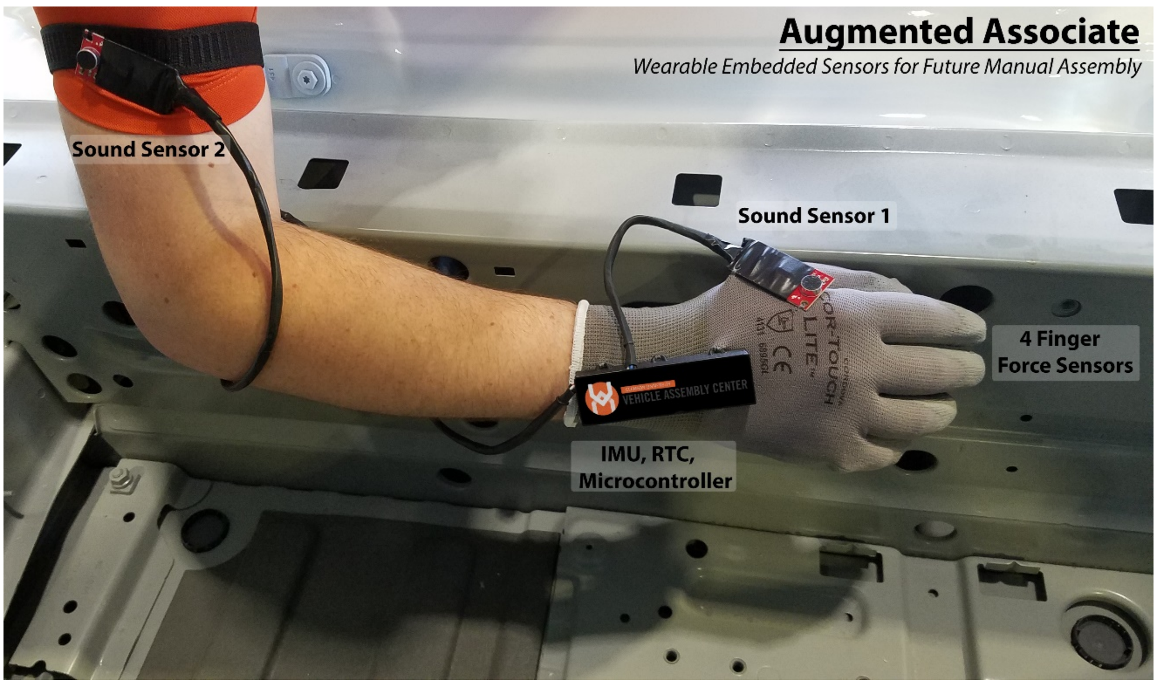



*Figure 1. Wearable sound, motion, and microcontroller glove prototype*

# Doctoral Symposium

## Biography – Matthew Krugh

Matthew Krugh is a Postdoctoral Research Fellow with Clemson University, where he teaches the class Digital Manufacturing, and Lab Manager with the Clemson Vehicle Assembly Center. He graduated from Clemson University with his Ph.D. in Automotive Engineering specializing in manufacturing and assembly in August 2020, MS in Automotive Engineering from Clemson University, and BS in Mechanical Engineering from Penn State Erie, The Behrend College. While with Clemson, he spent two years as a guest researcher with the National Institute of Standards and Technology Center for Automotive Lightweighting, characterizing advanced high-strength steels and metallic alloys before transitioning to explore embedded systems and wearable technologies to support production line workers for companies including BMW Group, BMW Manufacturing Co., Robert Bosch LLC., and Samsung Electronics. During his Ph.D. studies, he contributed to and managed over $1M in projects and the creation of the Clemson Vehicle Assembly Center. Project topics include areas of manual/semi-automated assembly; process improvement; prototyping wearable sensing and feedback mechanisms; measuring and modeling human behaviors in assembly systems; sensing, edge computing, and state estimation strategies for downtime reduction and maintenance strategy planning; and the use of pervasive sensors for machine health and process quality evaluation.

# Doctoral Symposium

## Fast Additive Manufacturing Simulation and Optimization

Lun Li
University of Cincinnati
Dr. Sam Anand

The Powder Bed Fusion Additive Manufacturing process has emerged as an important industrial process that is capable of manufacturing complex part features, such as hollow, lattice structure and other unique design structures. On the other hand, the part distortion caused by repeatedly heating and cooling is the main drawback. Predicting the distortion and optimizing the process for distortion mitigation within practical time frame are the priorities of metal AM research. In this work, a novel workflow of metal AM process, which includes support structure optimization and hatch pattern optimization, is created based on inherent prediction through neural network and distortion prediction through big layer simulation and a novel Backward Interpolation.

First, a neural network based method is presented to predict inherent strain for any given hatch pattern that is adopted during the part build. The neural network was trained by the inherent strain calculated through thermo-mechanical simulation. The results show that the trained neural network can predict the inherent strain of any arbitrary hatch pattern within an acceptable error.

Then, a novel Backward Interpolation (BI) model is presented for fast estimation of part distortion based on inherent strain and distortion factor. The as-built distortion before cutoff from the substrate is calculated based on distortion factors and the internal forces generated by inherent strain. After that, the spring back distortion is calculated based on the releasing of interfacial reaction force caused by the as-built distortion. The total part distortion is then finally calculated as the summation of as-built distortion and the spring back distortion. Experimental validations were conducted, and the predicted distortion results appeared to agree well with the distortion of sample part and published data.

Furthermore, a hatch pattern optimization is presented to decrease GD&T callouts with the combination of artificial neural network (ANN), backward interpolation (BI) and genetical algorithm (GA). The hatch angle of each layer was selected as the optimization variable while the flatness of sample part was chosen as the fitness variable in the GA process. The results showed that increasing islands number is good for achieving better flatness. Furthermore, the flatness error of four benchmark hatch patterns were calculated to make comparison with the optimization results. The comparison showed that the flatness error of the sample part with optimized hatch pattern is better than the results of benchmark hatch patterns.

Finally, a SPO based support structure optimization is presented to decrease the part GD&T errors. The support structure is simplified as beam element and connected to the solid part with MPC in ANSYS. The distortion is calculated by larger layer method with the nodal force derived from inherent strain.

Keywords: Additive Manufacturing, Hatch Pattern, Inherent Strain, Distortion Prediction, GD&T, Support Structure

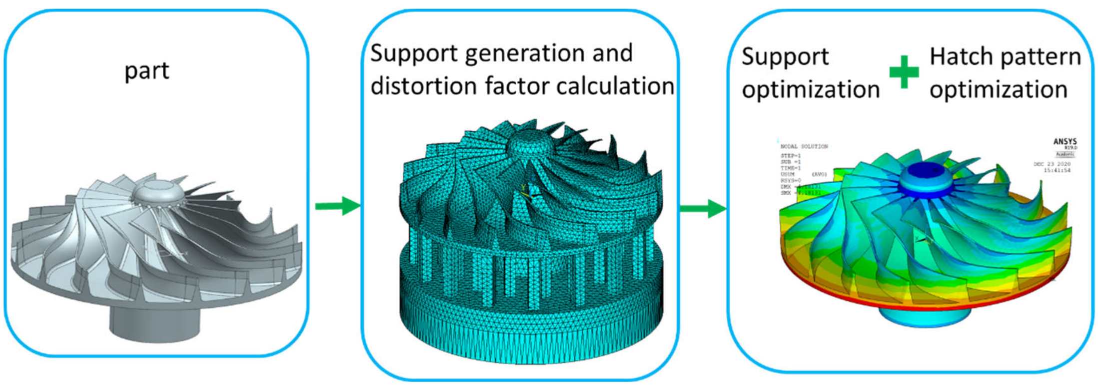



Fig. 1. Workflow of metal AM process optimization

# Doctoral Symposium

## Biography – Lun Li

Lun Li is a fourth year Ph. D student in Mechanical Engineering at University of Cincinnati. He has a B.S degree (Harbin Engineering University, 2009) and M.S degree (China Ship Design Academy, 2012) in Ship and Ocean Structure Engineering. He worked in Shanghai Volkswagen as crash simulation engineer between 2012-2015. Under the mentorship of Dr. Sam Anand, he is currently working on fast metal additive manufacturing simulation and optimization, includes inherent strain estimation, distortion prediction, powder coating collision prediction, hatch pattern, support structure and build orientation optimization to mitigate GD&T errors. He also works on computational geometry, includes primitive shape recognition through neural network, automatic segregation and reconstruction.