Transportation Infrastructure Precast Innovation Center (TRANS-IPIC)

University Transportation Center (UTC)

Bio-Inspired Solutions for Roadside Barriers: Exploring 3D Printing as Alternative Precast Technology — Phase II
Project N: (PU-23-RP-03)

Quarterly Progress Report
For the performance period ending [06/30/2025]

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Submitted to:
TRANS-IPIC UTC
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TRANS-IPIC Quarterly Progress Report:

Project Description:

1. Research Plan - Statement of Problem

Phase 2 builds on successful small-scale validation from Phase 1 by scaling up *Bouligand* and *sinusoidal Bouligand* architected bioinspired structures. These designs showed high strength, toughness, and impact resistance and are now being fabricated for roadside barriers using a large robotic arm. We are also preparing these materials for mechanical tests on larger prototypes under quasi-static and dynamic loads. We are optimizing the fabrication process with larger nozzles and longer fibers to enhance performance and ensure feasibility for real-world manufacturing, with the goal of translating these innovations to industry. A few patents are currently in progress based on these findings from year 1, and we are working closely with the *Purdue Office of Technology Commercialization* (OTC) to develop strategies for industry engagement. We are laying the groundwork to engage with companies specializing in roadside barrier systems and precast concrete technology to explore collaborative pathways for deployment. These advancements have effectively created a new class of architected materials with unprecedented strength and energy absorption. This innovation directly addresses the urgent need for safer, more resilient roadside barriers, especially in the era of heavier, differently balanced electric vehicles. We are making history with a game-changing solution for one of infrastructure's most demanding challenges.

2. Research Plan - Summary of Project Activities (Tasks)

<u>Task 1- Architected Material Designs and Fabrication</u>: Task 1 comprises four integrated subtasks aimed at adapting and scaling the 3D concrete printing process for the Large Scale Robotic Arm (LSRA) system. Subtask 1.1 focuses on advancing toolpath design. Subtask 1.2 focuses on a fork-type nozzle to improve flow control, speed, and reliability. This is key for demonstrating feasibility and efficiency industrial translation. Subtask 1.3 centers on adapting the fiber-reinforced concrete mixture for large-scale printing, evaluating long fibers on printability, flowability, and structural performance. Subtask 1.4 is a study of printing parameters, including nozzle size, shape, and the interplay between fiber length and deposition quality, to optimize both process efficiency and mechanical outcomes in large-scale printed structures.

<u>Task 2- Mechanical Testing</u>: We have begun preparing for mechanical testing of large-scale bioinspired architectures under quasi-static and dynamic loading. Current efforts focus on fabricating test specimens and setting up drop-tower impact experiments to evaluate strength, toughness, energy dissipation, and crack resistance. These results will provide critical insights and metrics for guiding final design refinements and commercialization.

Project Progress:

3. Progress for each research task

<u>Task 1 Architected Material Designs and Fabrication (83% Completed- weighted average):</u>

<u>Task 1.1 Toolpath design (100% Completed):</u> During the second quarter, the toolpath generation algorithm was fully developed and validated within the Rhino and Grasshopper environments, advancing the slicing and path-planning workflow for large-scale robotic 3D printing using the LSRA system. This parametric framework is now ready for deployment in physical printing, pending final testing.

The current implementation enables precise control over key architectural and process parameters that influence both the filament geometry and print quality. These include the amplitude-to-wavelength ratio (A/λ), which determines the degree of undulation in the sinusoidal trajectory and contributes to mechanical anisotropy. The layer height can be adjusted to optimize the interlayer bond strength and printing speed. Filament width is controlled based on deposition rate and nozzle geometry, while the filament overlap can be modulated to improve cohesion between adjacent paths. Nozzle diameter is explicitly integrated into the slicing logic, influencing the minimum printable curvature and overall resolution of the printed layers. Figure 1(a) presents the Grasshopper definition, where all parameters are incorporated into a modular, scalable slicing routine. This parametric control allows adaptation to different nozzle sizes, material systems, and printing scales without rewriting the underlying geometry logic. The surface slicing is handled by discretizing the sinusoidal geometry into point sets, from which interpolated curves are created to define the filament paths. These curves are then stacked vertically to generate a multi-layer deposition sequence.

A major improvement introduced this quarter is the connection of adjacent sine wave curves at their endpoints. In the earlier version, curves were not joined, which led to unnecessary travel moves that disrupted the continuity of the extrusion process. This issue has been resolved, enabling uninterrupted, continuous filament deposition within each layer—an essential requirement for defect-free printing. Figure 1(b) illustrates the generated toolpath in Rhino, showing continuous deposition curves that closely follow the sinusoidal geometry. Following toolpath generation, the geometry is exported to the RhinoRobot plugin, where it is translated into RAPID code for the ABB IRB6700 robotic arm. Figure 1(c) shows the toolpath in the RhinoRobot simulation environment. This step confirms the print's feasibility with respect to the robotic arm's kinematic limits, reachability, and tool orientation, providing a final layer of validation before proceeding with physical printing.

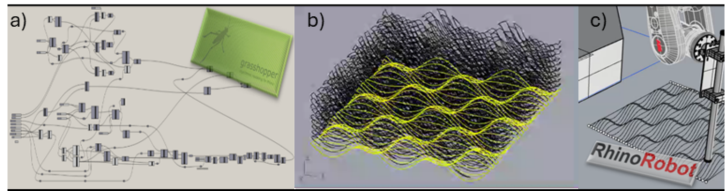

Figure 1. Finalized Grasshopper definition showing parametric control blocks for slicing the sinusoidal geometry (a); Toolpath generated in Rhino illustrating continuous, connected filament trajectories (b); RhinoRobot simulation of the toolpath within the workspace of the ABB IRB6700 robotic arm (c).

<u>Task 1.2 Nozzle development (86% Completed)</u>:

To ensure fabrication efficiency and industrial feasibility, <u>we have completed the concept design of a multi-nozzle extrusion system</u>. This design, which is now being prepared for patenting, will be shared with industry partners to explore co-development of the detailed design and eventual fabrication. We consider this task largely completed, as the conceptual development was the most technically demanding step. We will still proceed with testing to validate performance. Building on initial design considerations and literature insights, the finalized model features a custom multi-extrusion manifold for the LSRA system, replacing previous flow control mechanisms with iris-style diaphragm valves—offering a compact and precise solution for localized control of cementitious material flow. As shown in Figure 2 (a), the designed manifold connects to the existing LSRA extruder and redistributes material to multiple outlets through a central distribution block. Each outlet is equipped with a dedicated iris diaphragm valve, allowing the flow area to be modulated during printing. These iris mechanisms dynamically adjust the opening diameter by rotating interlocking blades, providing continuous and responsive control over the flow rate. This configuration supports selective filament activation, enabling spatially variable deposition patterns and tailoring of material placement across the print.

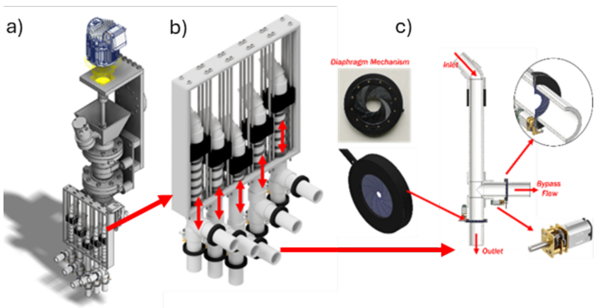

Figure 2. Multi-extrusion Manifold connected to the LSRA printing System (a); Manifold Shape-Shifting Branches Profile (b); Flow control system. bypass flowline and valve (c).

A major innovation in the design is the inclusion of a bypass flow path for each outlet. In addition to the primary extrusion channel, a bypass line is included to relieve internal pressure when an outlet is closed. This prevents pressure buildup in the manifold, which could otherwise result in flow instability or material backflow, especially under varying flow conditions. Figure 2(b) illustrates the assembly and functional layout of the manifold. The full system includes a series of parallel outlet branches arranged beneath the extruder, moving axially to allow the TCP (Tool center point) at each nozzle to align with the sinusoidal toolpath. Figure 2(c) highlights the use of iris-style diaphragm valves, each controlling flow to one outlet. The schematic shows the flow control architecture, including the main inlet, active extrusion outlet, and bypass flow line. The iris mechanism is also shown in detail, emphasizing its precision and suitability for controlling flow of viscous materials without introducing sharp obstructions that may promote clogging.

This quarter's efforts focused on the mechanical design and CAD modeling of the nozzle manifold, integration of diaphragm mechanisms, and overall flow path layout. Materials and actuators for the diaphragm system were selected based on durability, response speed, and compatibility with cementitious paste rheology. The conceptual design is now complete and is in preparation for patent registration. The remaining time allocated to this task will be dedicated to refining specific details—particularly the connection interfaces between the piping and the valve assemblies. The design, in its current form, is suitable for implementation and fabrication by potential industry partners, providing a practical and scalable solution for multi-nozzle cementitious extrusion in large-scale additive manufacturing.

Task 1.3 Mixture development (75% completed):

In the second quarter, significant progress was made in advancing the mixture development work for 3D printed concrete. Building on the first quarter's optimization of fiber dosage ranges and pumping requirements, the team finalized the mix design for ongoing experimental and production-scale evaluations. The selected formulation is an optimized mixture of Portland Limestone Cement (PLC), Limestone filler (LF), Cellulose Nanofiber (CNF) and aggregates, chosen from the mixtures developed and characterized in earlier phases, as shown in Table 1.

Table 1. Mixture Design

Mixture design	PLC (kg/m^3)	LF (kg/m^3)	Water (kg/m^3)	CNF (kg/m^3)	Sand (kg/m^3)
PLC-LF-CNF0.30	601.02	288.98	356.00	2.67	890.00

In addition to finalizing the base mixture, the second quarter focused on planning exploratory work to investigate fiber reinforcement strategies aimed at improving interlayer bonding and mechanical properties of 3D printed elements. To this end, three distinct fiber length ranges—10 mm, and 12 mm—were defined for further testing. These lengths were chosen to capture a representative range that could meaningfully impact extrusion behavior, alignment within layers, and the overall reinforcement effect, thereby enabling a robust parametric study of fiber dimensions at a later stage.

As part of the material selection process, Basalt fibers and Polyvinyl Alcohol (PVA) fibers were identified as the most promising candidates for incorporation into the finalized mixture. Basalt fibers are valued for their high tensile strength, chemical stability, and resistance to alkali environments, making them well-suited for cementitious systems. PVA fibers, meanwhile, offer excellent dispersion, bonding with the cement matrix, and ductility-enhancing characteristics that have been widely documented in advanced concrete technologies. Planned next steps include systematic testing of the finalized PLC-LF-CNF0.30 mixture with these fiber types and lengths, evaluating fresh-state properties such as flowability, buildability, and pumpability, as well as hardened-state performance including compressive strength, tensile behavior, and interlayer bonding. This approach aims to ensure the developed mix design is not only suitable for laboratory-scale printing but also capable of reliable translation to full-scale additive manufacturing with optimized reinforcement strategies.

Task 1.4 Printing parameter study progress (63% completed):

During the second quarter, we investigated how key parameters affect filament geometry in 3D concrete printing, including nozzle height, printing direction (up/down), and surface inclination. This supported the development of optimized printing strategies for sinusoidal ligand structures and laid the foundation for upcoming large-scale printing using a 25 mm extrusion nozzle. To evaluate the interaction between these parameters, the main goal was to determine the minimum nozzle height required to achieve the desired filament geometry. Filament geometry was evaluated using aspect ratio (width/thickness), which is a key indicator of shape stability, Figure 3 shows the effect of nozzle height at different inclinations on 3D printed filament geometry. Based on geometric collision analysis, we used a theoretical model from Year 1 to determine the minimum safe nozzle height for large-scale printing, which is expressed in Equations (1)-(3), we can calculate the minimum height for large-scale printing, as shown in table 2.

Collision check:

$$H_{min} = R \times tan\ (\alpha) \quad (1)$$

Printing downward:

$$H_{min} = \frac{T}{cos\ (\alpha)} + R \times tan\ (\alpha) \quad (2)$$

Printing upward:

$$H_{min} = \frac{T}{cos\ (\alpha)} - R \times tan\ (\alpha) \quad (3)$$

Where: R-Radius of the nozzle;
T-Thickness of the designed layer;
α- Incline angle of the support base;
H-height of the nozzle relative to support base;

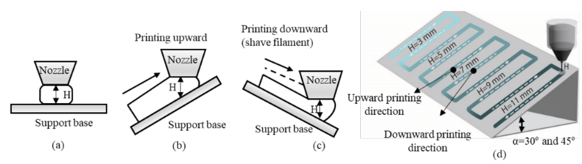

Figure 3. Illustration of the influence of nozzle height on filament geometry for 3D printing on (a) flat surfaces, (b) inclined surfaces when printing upward, and (c) inclined surfaces when printing downward; (d) Toolpath design to evaluate the influence of nozzle height, printing direction, and surface incline angle on printed filament geometry; examination of filament shape when printed on inclined surfaces with angles of 30° and 45°

H_{min}- Minimum height of the nozzle relative to support base to obtain designed filament geometry.

However, excessive nozzle height can result in inaccurate placement and inconsistent filament shape. also be problematic. At very high heights, material instability was observed due to excessive free-fall, Therefore, nozzle height must be carefully optimized to be just above the minimum height to prevent pressing, but still close enough to the surface to allow controlled and accurate material deposition. Moreover, nozzle height alone does not guarantee print quality. It must be coordinated with extrusion speed and printing speed, both of which are affected by the fluidity of the concrete mixture. Higher fluidity allows for higher extrusion rates but may compromise buildability if not properly managed. Different mixture designs will require individual tuning of speed and nozzle parameters to maintain both filament shape and structural integrity during printing.

Printed on inclined surfaces with angles	Printing downward		Printing upward	
	Thickness of the designed layer	Minimum height of the nozzle	Thickness of the designed layer	Minimum height of the nozzle
30°	50	43.3	50	43.3
	40	37.5	40	31.8
	25	72.2	25	14.4
	20	60.6	20	8.7
45°	50	95.7	50	45.7
	40	81.6	40	31.6
	25	60.4	25	10.4
	20	53.3	20	3.3

Table 2. Minimum nozzle height for upward and downward printing

Task 2 Mechanical Testing (7% completed - weighted average):

Task 2.1 Flexural and compressive tests (14% Completed)

Significant progress has been made in preparing the foundational support system required for the concrete 3D printing of Bouligand-inspired sinusoidal structures, a critical prerequisite for fabricating testable samples. Due to the inherent limitations of concrete extrusion—particularly its inability to self-support complex geometries—a reusable base was designed and manufactured to serve as temporary formwork. The support structure was machined from stacked and bonded Foamular insulating sheets using a Haas gantry system, with toolpaths generated in Autodesk Fusion 360 to precisely match the sinusoidal Bouligand pattern. The Fusion 360 model was parametrically designed, allowing key geometric parameters such as amplitude, wavelength, and layer offsets to be modified, ensuring adaptability for future design iterations or performance-driven adjustments. This approach not only ensures geometric accuracy and compatibility with the concrete printer's deposition path but also streamlines the rapid prototyping of alternative configurations. The foam material was selected for its lightweight properties, ease of machining, and minimal interference with the curing concrete. Without this support system, producing viable samples for mechanical testing (e.g., flexural and compressive evaluations) would be impossible, as the overhangs and intricate layer alignments of the Bouligand design would collapse during printing. The successful implementation of this method enables the fabrication of test specimens with controlled layer interfaces and fiber alignment, which are essential for validating the structural performance of these bio-inspired architectures under quasi-static and dynamic loading conditions. Next steps include printing concrete prototypes with the extrusion system currently implemented in the LSRA using this base.

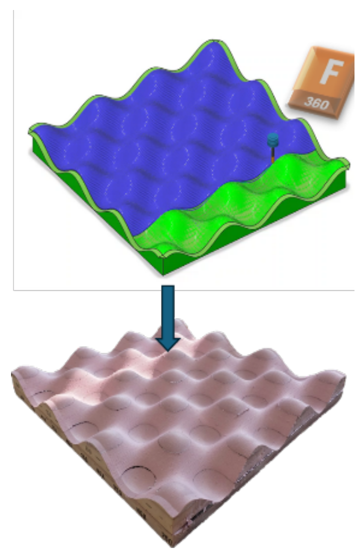

Figure 4. CAM representation of base manufacturing (top); picture of finalized printing base (Bottom).

In response to feedback from the TRANS-IPIC management team regarding our Quarterly report 1, we acknowledge the importance of aligning our drop-tower impact testing with AASHTO/FHWA specifications to evaluate whether 3D printed barriers can withstand realistic vehicular impact loads. Our mechanical testing strategy is explicitly designed to extract large-scale structural properties such as strength and energy absorption (toughness), which are critical for assessing overall performance. These metrics will be directly mapped to relevant performance thresholds outlined in AASHTO/FHWA guidelines by the end of Year 2. The propose technology also go beyond current standards by addressing needs not yet fully captured by existing specifications. Specifically, we are extending the application of concrete to vehicle types that demand not only rigidity but also enhanced flexibility and energy absorption. This is particularly important in light of the rising use of electric vehicles, which are not only heavier than traditional vehicles but also exhibit different weight distributions due to battery placement. These factors introduce fundamentally different impact conditions. Therefore, instead of making concrete better for existing applications, we are making it viable for entirely new applications, a shift that represents a major advancement in roadside barrier design.

4. Percent of research project completed

Project Milestones		2025-2026											
		1	2	3	4	5	6	7	8	9	10	11	12
Task1	Task 1.1 Toolpath design (100%)												
	Task 1.2 Nozzle development (86%)												
	Task 1.3 Mixture development (75%)												
	Task 1.4 Printing parameter study (63%)												
Task 2	Task 2.1 Flexural and compressive tests(14%)												
	Task 2.2 Drop-tower impact tests												
	Task 2.3 Repetitive impact tests												
	PI Submits Final DRAFT report to TRANS-IPIC for editing and publication												
	Report Posted to TRANS-IPIC website												

5. Expected progress for next quarter

Next quarter's work will focus on the fabrication of test samples, now that printing is enabled by the availability of the supporting base. The first third of the period will be dedicated to fabricating specimens for flexural and compressive strength testing. During the second third, fabrication will shift to impact test specimens, allowing the previously printed flexural and compressive specimens to develop their mechanical properties over the 28-day curing period.

During the fabrication phase, tasks 1.3 and 1.4 will involve adjusting the mix proportions and printing parameters to optimize printing quality. These refinements aim to ensure consistent layer formation, promote fiber alignment, and enhance anisotropic behavior.

6. Educational outreach and workforce development

- ASU – Swinburne Workshop on Advances in Concrete 3D Printing
  Melbourne, Australia, June 11-13 /2025.

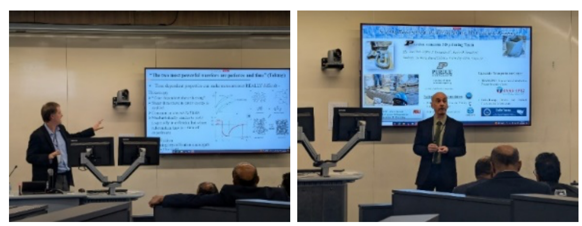

Figure 5. Faculty Presentation at ASU – Swinburne Workshop on Advances in Concrete 3D Printing.

7. Technology Transfer - Provisional Patent Applications submitted (Purdue Office of Technology Commercialization)
   1. *Youngblood, J. P., Olek, J., Zavattieri, P. D., Wang, Y., Douba, E. A., Low Carbon, Low Cost Cement Mix Containing Cellulose Nano Fiber and Limestone Filler For 3D Concrete Printing, (Available for License)*
   2. *Zavattieri, P. D., Youngblood, J. P., Olek, J., Wang, Y., Energy-Absorbing Roadside Barriers Using Bio-Inspired Architecture and 3D Concrete Printing (Available for License)*
   3. *Zavattieri, P. D., Youngblood, J. P., Olek, J., Wang, Y., Cubillos, L. David, Reconfigurable acoustic metamaterials for traffic noise reduction (Available for License)*
   4. *Zavattieri, P. D., Olek, J., Marika Santagata, Youngblood, J. P., Wang, Y., Hygrolock - reinforcement for building blocks made of earth materials (Available for License)*
   5. *Cubillos, L. David, Zavattieri, P. D., Youngblood, J. P., Olek, Multi-Nozzle Extrusion System for Large-Scale Concrete Printing (Disclosure in preparation).*

Research Contribution:

8. Papers that include TRANS-IPIC UTC in the acknowledgments section:

   - *Y. Wang, A.E. Douba, J. Olek, P. D. Zavattieri,J.P. Youngblood, Better, Cheaper, Greener: A high-performance Cementitious Composite for Sustainable Concrete 3D Printing, to be submitted to Nature Communications.*
   - *Y. Wang, L. Shyamsunder J. Olek, P. D. Zavattieri, J.P. Youngblood, Impact resistant sinusoidally-architected Bouligand 3DPC materials inspired by the mantis shrimp, to be submitted to Advanced Materials.*

9. Presentations and Posters of TRANS-IPIC funded research:
   [List any presentations or posters presenting TRANS-IPIC research

   For each presentation or poster provide citation]

   - Delivered the talk titled 'Bio-Inspired Solutions for Roadside Barriers: Exploring 3D Printing as an Alternative Precast Technology' at the TRANS-IPIC Research Highlights Webinar on February 19, 2025, as part of the project's dissemination efforts.
   - Professor Zavattieri's research, "Bio-Inspired Solutions for Roadside Barriers: Exploring 3D Printing as Alternative Precast Technology" leverages 3D concrete printing and bioinspired material design to develop innovative roadside barriers for impact energy absorption. 2025 TRANS-IPIC UTC Workshop April 22-23

   - Presented the poster "Bio-inspired solutions for roadside barriers: exploring 3d printing as alternative precast technology" at 2025 TRANS-IPIC UTC Workshop.

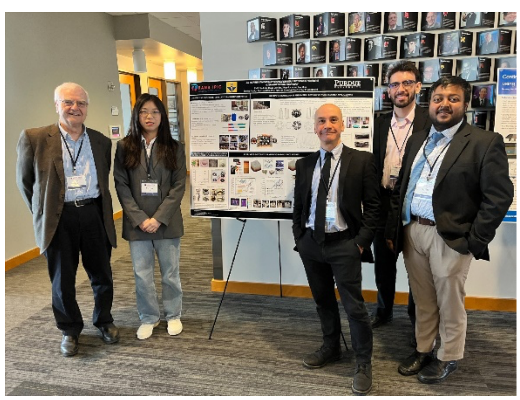

Figure 6. Poster presentation at 2025 TRANS-IPIC UTC Workshop.

- Presented the poster *“Large-Scale Additive Manufacturing of Bioinspired Bouligand Structures via Controlled Flow, Multi-Axis Printing, and Mix Design Optimization” at* ASU – Swinburne Workshop on Advances in Concrete 3D Printing.

Figure 7. Poster presentation at ASU – Swinburne Workshop on Advances in Concrete 3D Printing.

10. Please list any other events or activities that highlights the work of TRANS-IPIC occurring at your university (please include any pictures or figures you may have). Similarly, please list any references to TRANS-IPIC in the news or interviews from your research.

Purdue CCE Impact Magazine: Purdue University's recent research highlights significant advancements in 3D-printed construction. Collaborating with Terran Robotics, Purdue engineers are developing sustainable and affordable housing solutions by integrating artificial intelligence with 3D printing technologies. The team is experimenting with 'cob,' a low-carbon material composed of clay, sand, water, and straw, aiming to optimize its strength and resilience for construction applications. This initiative not only addresses environmental concerns but also offers innovative approaches to modern housing challenges.

https://engineering.purdue.edu/CCE/Media/Impact/2025-Spring/building-the-future

Purdue Engineering Distinguished Lecture Series – (September 12th 2024) Description: The Concrete 3D Printing Team presented a poster featuring their latest work, in which research from TRANS-IPIC was highlighted. The poster emphasized Purdue’s efforts to advance sustainable and resilient infrastructure through innovative 3D printing technologies.

Figure 8. Poster presentation at Purdue Engineering Distinguished Lecture Series research showcase.

6th Annual CEGSAC Research Symposium - – (April 25^{th}, 2025) Description: The symposium brought together students, faculty, and industry leaders to showcase cutting-edge research in civil and construction engineering. Graduate and undergraduate researchers presented their work during the poster session, highlighting advancements in sustainable infrastructure, materials innovation, and smart construction technologies. The event also featured networking opportunities with industry partners, fostering collaboration between academia and the professional sector, The Concrete 3D

Printing Team presented a poster featuring their latest work, in which research from TRANS-IPIC was highlighted.

Figure 9. Poster presentation at 6th Annual CEGSAC Research Symposium.

Appendix 1: Research Activities, leadership, and awards (cumulative, since the start of the project)

A. Number of presentations at academic and industry conferences and workshops of UTC findings
  - No. = 4 (in 2025, for phase II)

B. Number of peer-reviewed publications submitted based on outcomes of UTC funded projects
    - No. = 2 papers to be submitted that include an acknowledgement of TRAN-IPIC.

C. Number of peer-reviewed journal articles published by faculty.
    - No. = 2 papers to be submitted that include an acknowledgement of TRAN-IPIC.

D. Number of peer-reviewed conference papers published by faculty.
  - No. =

E. Number of TRANS-IPIC sponsored thesis or dissertations at the MS and PhD levels.
  - No. MS thesis = 0
  - No. PhD dissertations = 1 (Dec. 2024)
  - No. citations of each of the above = 0 (the PhD thesis has not been published yet)

F. Number of research tools (lab equipment, models, software, test processes, etc.) developed as part of TRANS-IPIC sponsored research
    - Research Tool #1 (Toolpath development) = Parametric Toolpath Generation Model for Non-Planar 3D Printing, a computational model developed in Grasshopper for generating toolpaths tailored to non-planar, multi-axis 3D concrete printing. The model allows users to define sinusoidal surface geometries, discretize them into point sets, and create interpolated curves that serve as custom toolpaths for robotic extrusion. This tool supports real-time geometry adjustments and can be adapted to different nozzle configurations and print parameters. Link available upon request.

G. Number of transportation-related professional and service organization committees that TRANS-IPIC faculty researchers participate in or lead.
  - Professional societies
    - No. participated in = 6
    - No. lead = 1
  - Advisory committees (No. participated in & No. led)
    - No. participated in = 1
    - No. lead = 0
  - Conference Organizing Committees (No. participated in & No. led)
    - No. participated in = 1
    - No. lead = 0
  - Editorial board of journals (No. participated in & No. led)
    - No. participated in = 2
    - No. lead = 0
  - TRB committees (No. participated in & No. led)
    - No. participated in =2
    - No. lead = 0

H. Number of relevant awards received during the grant year
- No. awards received = 4

I. Number of transportation related classes developed or modified as a result of TRANS-IPIC funding.
  - No. Undergraduate = 1
  - No. Graduate = 1

J. Number of internships and full-time positions secured in the industry and government during the grant year.
    - No. of internships = 0
    - No. of full-time positions = 1

References:

[1] L. Morita, A. Asad, X. Sun, M. Ali, and D. Sameoto, “Integration of a needle valve mechanism with cura slicing software for improved retraction in pellet-based material extrusion,” *Addit. Manuf.*, vol. 82, p. 104045, Feb. 2024, doi: 10.1016/j.addma.2024.104045.

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[3] M. K. Mohan, A. V. Rahul, K. Van Tittelboom, and G. De Schutter, “Evaluating the Influence of Aggregate Content on Pumpability of 3D Printable Concrete,” in *Second RILEM International Conference on Concrete and Digital Fabrication*, F. P. Bos, S. S. Lucas, R. J. M. Wolfs, and T. A. M. Salet, Eds., Cham: Springer International Publishing, 2020, pp. 333–341. doi: 10.1007/978-3-030-49916-7_34.

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[6] M. David, N. Freund, K. Dröder, and D. Lowke, “The effects of nozzle diameter and length on the resulting strand properties for shotcrete 3D printing,” *Mater. Struct.*, vol. 56, no. 8, p. 157, Oct. 2023, doi: 10.1617/s11527-023-02246-1.

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[8] A. V. Rahul, M. Santhanam, H. Meena, and Z. Ghani, “3D printable concrete: Mixture design and test methods,” *Cem. Concr. Compos.*, vol. 97, pp. 13–23, Mar. 2019, doi: 10.1016/j.cemconcomp.2018.12.014.

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[10] T. T. Le, S. A. Austin, S. Lim, R. A. Buswell, A. G. F. Gibb, and T. Thorpe, “Mix design and fresh properties for high-performance printing concrete,” *Mater. Struct.*, vol. 45, no. 8, pp. 1221–1232, Aug. 2012, doi: 10.1617/s11527-012-9828-z.

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