Multi-Robotic 3D Printing Wood-Based Slurry on Construction Scale

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ABSTRACT: In response to the escalating demand for rapid urbanization, the construction industry is compelled to shift towards sustainable alternatives, aiming to overcome various challenges, including shortages in skilled labor, material scarcity, and environmental degradation stemming from conventional and inefficient construction methods. 3D Printing (3DP) offers a transformative solution by digitizing construction processes and enabling the investigation of novel, sustainable materials that are biodegradable, reusable, and recyclable. Among these materials are wood-based slurry materials, which have the potential to divert 3 million tons of wood waste directed annually to landfills in the United States and recycle it in the production of various construction elements, making a step towards circular construction practices. This research investigates MR-3DP using wood-based slurry to manufacture ultra-lightweight, large-scale building components. This paper presents research that aims to investigate and understand the process parameters associated with the success and failure of printing construction scale objects using Multi-Robotic 3D Printing (MR-3DP) with wood-based slurry material. This is investigated through the design and fabrication of two non-load-bearing cavity wall prototypes.

KEYWORDS: Multi-Robotic 3D Printing, Wood-based material, Sustainable construction practices, Circular economy in construction, Large-scale additive manufacturing

INTRODUCTION

The construction industry has to respond to the rising need for rapid urbanization (Cohen 2006), yet it is hindered by challenges, including low productivity, a shortage of skilled labor, construction materials scarcity, and the negative environmental impacts resulting from inefficient traditional construction methods (Crawford and Vogl 2006; Klemmt et al. 2022). Given these issues, there is a pressing need for alternative sustainable construction methods. 3D Printing (3DP) emerges as a promising solution capable of addressing these challenges by digitizing the construction industry and fostering the development of novel material explorations that are fully biodegradable, reusable, and recyclable, thus paving the way for more sustainable construction practices. 3DP only deposits material where needed, facilitating the creation of optimized, lightweight structures that significantly reduce waste compared to conventional construction methods. Particularly, Robotic 3D Printing (R-3DP) enhances the capabilities of 3DP, enabling the fabrication of more complex structural elements with extraordinary multifunction on a large scale (Kamhawi et al., 2024a, Kamhawi et al., 2024b, Aghaei Meibodi et al., 2024).

In recent years, 3DP with wood-based slurry has captivated significant attention and was investigated in multiple research, as it offers the potential for recycling 3 million tons of sawdust produced annually in the United States (Batool et al. 2021), paving the way for circular construction practices. The presented paper expands upon the existing body of research by exploring the potential applications of multi-robotic 3DP (MR-3DP) with wood-based slurry for the construction of large-scale building elements. By leveraging the opportunities of multiple robots working together, MR-3DP can significantly accelerate the construction process, allowing for the fabrication of complex, large-scale structures, which not only enhances productivity but also enables the realization of intricate architectural features that were previously difficult or impossible to achieve with a gantry-based 3D printer or single robot 3D printing system. While the application of multi-robotic strategies has been extensively investigated within the context of assembly tasks in research groups such as Gramazio Kohler Research, Block Research Group, and Digital Building Technologies at ETH Zurich or ICD at the University of Stuttgart (Thoma et al. 2019; Leder et al. 2019; Wang et al. 2023; Wagner et al. 2020), very limited research has been conducted on MR-3DP. Stands out as one of the few, if not the only, research efforts in this area is the work at Nanyang Technological University (Zhang et al. 2018) on developing a MR-3DP system that utilizes a team of mobile robots to cooperatively print a single concrete structure aiming to address the challenge of scalability associated with 3DP in construction scale.

1.0 RESEARCH METHOD: MULTI-ROBOTIC 3D PRINTING WITH WOOD-BASED SLURRY

This research investigates the use of MR-3DP with wood-based slurry to produce ultra-lightweight building components on a large scale. The study is conducted through the design and fabrication of a construction-scale prototype of two non-load-bearing cavity walls (Figure 1). The first prototype is manufactured using a R-3DP, and the second utilizes a MR-3DP fabrication system. The prototype has a square base plan that measures 1.3m x 1.3m and depicts the design of a double wall conventionally used in 3D concrete printed houses. The cavity in the double wall hosts a series of ribs that provide structural stability for the element, while the voids in between the ribs can host thermal insulation. The presented paper aims to experimentally understand the various parameters contributing to the success and failure of the fabrication of the designed prototype. This paper presents preliminary research into the application of MR-3DP with wood-based slurry at a construction scale. It identifies the challenges and opportunities associated with this method and presents tentative preliminary data that helps focus and refine future research questions in this field. MR-3DP with wood-based slurry entails the development of several interconnected areas:

1. **Material Design:** Exploring and refining the formulation of wood-based slurry materials for 3D printing purposes, particularly focusing on developing and recycling wood-based slurry materials. The paper highlights the importance of finding the right material ratios for successful pumpability, extrudability, and buildability. Additionally, the material buildability is evaluated using single-robot printing to understand how changes in material viscosity related to various material designs impact the 3DP process.
2. **MR-3DP Process Parameters Control and Fine-Tuning:** Understanding and fine-tuning process parameters within MR-3DP when working with wood-based slurry that influences precise material deposition, buildability, and geometric fidelity. The goal is to understand and identify various process-related parameters, such as material pumping rate, nozzle printing speed, and nozzle diameter, alongside the coordination of multiple robots that impact consistent and reliable material deposition. The aim is to derive relationships to enable future fine-tuning of parameters.
3. **Task Division, Path Planning, and Motion Planning:** The objective is aimed at maximizing the efficiency and effectiveness of the collaborative printing process, ensuring that each robot's path is optimized to minimize overlap and interference while also enhancing the overall speed and quality of the 3DP process.

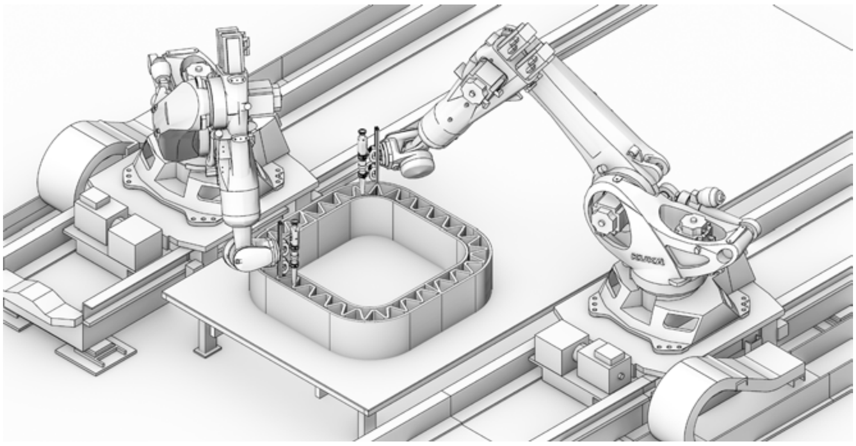

Figure 1: The developed construction scale prototype. Source: (Created by the authors 2024)

2.0 WOOD-BASED SLURRY MATERIAL DESIGN AND BEHAVIOUR IN RELATION TO THE 3DP PROCESS

2.1. State of the art in wood printing

In the pursuit of eco-friendly and sustainable practices within the construction industry, this research has extensively investigated material compositions for 3DP. The environmental footprint of wood-based materials, especially in the context of additive manufacturing, is aimed to be enhanced. The ingredients chosen for the formulations are entirely organic and renewable, ensuring recyclability without compromising the material's inherent characteristics. This approach aligns with the research’s commitment to promoting sustainable, environmentally friendly construction practices and contributing to a circular economy.

Two additive manufacturing techniques have been commonly used to investigate 3DP with wood: Hot extrusion, which entails heating the material before extruding it from the printing toolhead, and cold extrusion, which involves pushing the material out of the toolhead at ambient temperature. In contrast to hot extrusion techniques, which demand high temperatures, cold extrusion enables the shaping and molding of construction materials at room temperature or slightly elevated temperatures (Materiability Research Group 2020). The hot extrusion method involves using a filament feedstock composed of 70% plastic and only 10 to 30% wood. The elevated temperature during hot extrusion also presents a potential hazard of burning the wood filaments in the process (Krapež Tomec and Kariž 2022; Das et al. 2021). The cold extrusion approach offers several advantages for the construction sector, including the ability to work with heat-sensitive materials like wood and a reduction in energy consumption. However, achieving precise dimensional accuracy to align with the digital twin model presents a challenging task. Consequently, this research builds on previous research presented by DART Laboratory (Muhammad Dayyem Khan et al. 2023) and will concentrate on cold extrusion for a newly developed wood-based material for 3D printing.

Most research in 3DP wood focuses on developing wood-based slurry to overcome challenges related to scalability, deformation, and mechanical strength. Most material compositions investigated in 3DP with bio-based material still constitute a modest proportion of wood-based content and are often supplemented by synthetic resins or thermoplastics like High-Density Polyethylene (HDPE).

(Wei et al. 2022) in their work successfully presented a bio-material that did not include any wood-based content by combining chitosan and cellulose with essential ingredients: xanthan gum to improve viscosity, dimensional stability, printability, and uniformity and flour and paper fiber to reduce shrinkage and enhance mechanical strength. Other researchers (Bierach et al. 2023) were successful in developing a new material derived from both biobased and wood sources. However, it was observed that the mechanical properties of the material underperform in comparison to those of wood, carbon fiber-reinforced polymers, and thermoplastic. ‘BioHome3D’ is a research project presented by researchers from the University of Maine (Ward Taylor 2022); the research presented a 600-square-foot prototype house built with wood fiber and bio-resin-based material using FFF 3DP. For optimized printability, researchers use a blend of high-grade biopolymers and pine fibers. Including wood fibers improves the rheology’s cooling properties, reducing both setting time and challenges related to deformation. Using non-biodegradable bio-resins or thermoplastics in 3D printing wood-based slurry materials poses challenges in recycling and lacks eco-friendliness compared to biodegradable alternatives. This obstacle impedes the advancement of environmentally friendly construction practices. Despite wood's traditional role in building construction, there has been little research in exploring 3D-printed wood-based materials for construction. This study is committed to developing a scalable, easily recyclable, biodegradable wood-based slurry material specifically designed for MR-3DP.

2.2. Wood-based slurry processing and recycling

A comprehensive approach was taken to achieve a material design for a 3D-printable wood-based slurry, prioritizing printability, 100% recyclability, and biodegradability. The wood-based material consists of a blend of bio-polymers, additives, and solvents. Bio-polymers, sourced from natural origins like chitosan, flour, and xanthan gum, act as renewable binders. Additives, including sawdust, cellulose, paper pulp, magnesium oxide, calcium chloride, and calcium carbonate, enhance strength and regulate moisture. Solvents such as water and acetic acid optimize viscosity, creating a sustainable and versatile material for 3D printing.

To attain optimal viscosity, a set of 20 tests was carried out using a manual syringe extrusion technique, emphasizing considerations of stability and extrudability. Systematic experimentation encompassed a range of material compositions, with a specific focus on elevating concentrations of strengthening additives to induce an increase in viscosity, thereby aiming to achieve favorable material extrudability and buildability. Following a comprehensive assessment, a conclusive composition featuring 42.5% sawdust and 13.9% paper pulp was identified as optimal, satisfying criteria related to buildability, printability, and extrudability. Additionally, the ongoing monitoring of setting time remains imperative to facilitate expedited solidification processes. (Figure 2) showcases the most significant viscosity tests, highlighting the ease with which they were extruded, as well as curing time and measured shrinkage after curing. The material mix for these tests and the final material mixes are included in (Table 1).

Figure 2: Different material compositions employed in experiments for material research. Source: (Created by the authors.)

Table 1: Different material compositions employed in experiments for material research. Source: (Created by the authors 2024)

	Xanthan Gum	Wood Dust	Cellulose	All Purpose Flour	Paper Fiber	Chitosan	Calcium Carbonate	Magnesium Oxide	Acetic Acid	Calcium Chloride	Water
T6	2g	8g	16g	2g	8g	2g	1.5g	N/A	4g	1.5g	70g
T7	2g	N/A	8g	2g	8g	2g	4g	5g	4g	1.5g	80g
T8	2g	8g	16g	2g	8g	2g	N/A	10g	4g	1.5g	80g
T12	4g	16g	8g	4g	12g	2g	4g	15g	4g	1.5g	90g
T15	4g	8g	16g	4g	8g	2g	4g	10g	4g	1.5g	120g
T16	4g	8g	N/A	4g	16g	2g	4g	10g	4g	1.5g	110g
F1	**152g**	**610g**	**304g**	**152g**	**457g**	**75g**	**100g**	**578g**	**152g**	**61g**	**4500g**
F2	**152g**	**610g**	**304g**	**152g**	**457g**	**75g**	**100g**	**578g**	**152g**	**61g**	**5750g**

This research delineates a four-stage method for preparing wood-based material for R-3DP. In the initial stage, sawdust is ground to achieve a millimeter to sub-millimeter particle size, ensuring dimensional stability. The second stage involves mixing 42.5% sawdust and 13.9% paper pulp with water to attain a mache consistency. Subsequently, cellulose (9.3%), calcium carbonate (4.7%), and magnesium oxide (11.6%) are added to provide strength and mold resistance. Binding agents, including flour (4.7%), xanthan gum (4.7%), and chitosan (4.7%), contribute to viscosity and adhesion. Activation with solvents like water and acetic acid results in a slurry. The addition of calcium chloride acts as an accelerating agent and reduces settling time. A commercial mixer is employed to create a cohesive material suitable for 3D printing (Figure 3). After material preparation, a slump test ensures a slurry-based paste for continuous extrusion by the robot systems' pumps.

Figure 3: Material mixing process. Left to right: Paper pulp, saw-dust, hydrated mix of paper and saw-dust, dry mix of other ingredients, and final slurry. Source: (Created by the authors.)

The recycling process is closely linked to the moisture content retained by the material. When the material holds 50%-60% moisture, it is introduced into the mixer and hydrated to reach the required consistency. Throughout this hydration phase, ingredients such as flour, chitosan, and xanthan gum are reactivated, thereby preserving the material's structural and chemical integrity. Conversely, if the material is completely dry, it is first pulverized to a submillimetre granularity before being added to the mixer. Water is then incrementally introduced until the target consistency is obtained. Once the desired texture is achieved, the material becomes suitable for the printing process. Remarkably, this material can undergo multiple recycling rounds without a decline in its inherent properties and quality (Figure 4).

Figure 4: Material recycling process from bone dry to slurry. Source: (Created by the authors 2024)

3.0 MULTI-ROBOTIC WOOD 3D PRINTING FOR CONSTRUCTION

3.1. Multi-robotic 3D printing fabrication system architecture

The multi-robotic 3D Printing fabrication system in this research entails material pumps, 3D printing end effectors, and robotic arms. The setup for MR-3DP with wood-based slurry in this study involves:

1. **Two industrial robotic arms** KUKA KR-120s were specifically chosen for their robust payload capacity. This ensures they can comfortably handle the weight of the 3D printing nozzles and the hose filled with material. At the same time, their extensive motion range enables complete coverage of the printing area measuring 1.3m x 1.3m.
2. **Two cold extrusion 3D printing end effectors** with a nozzle of a diameter of 2.5 cm.
3. **Two pumps with digital variable rates** the MAI 2PUMP-PICTOR and a custom in-house designed pump. The latter is powered by a Beckhoff servo motor, providing a continuous torque output of 2.7 Nm with an operational speed range of 0 to 1000 rpm. To ensure a uniform and synchronized material flow using these two distinct pumps, the pumping parameters were fine-tuned according to their respective volume capacities.
4. **A robotic control system** designed to ensure seamless synchronization between the two robotic 3DP processes—pump flow rates and the robot's motions, which include the speed of material deposition along the print path. This coordination is achieved through Beckhoff PLC, with distinct logical I/O control for each pump aligned with its respective robot and 3D printing end-effectors.
5. The MR-3DP system's infrastructure is further supported by two 5m hoses, each connected to the cold extrusion 3DP end effectors. The operation is overseen by three human operators. Two were responsible for initiating the print programs and continuously monitoring the process to ensure continuous material flow, precise material deposition, and structural integrity of the part being 3D printed (Figure 5). The third person was responsible for supplying the feedstock material, ensuring an adequate supply to the pumps, and manually assisting in pushing the material from the hopper to the pump. While pumping the highly viscous wood-based slurry, the viscosity itself remained consistent with our pump. The major challenge

arose in manually pushing the material into the pump, as there was no automated system for this phase, requiring manual intervention.

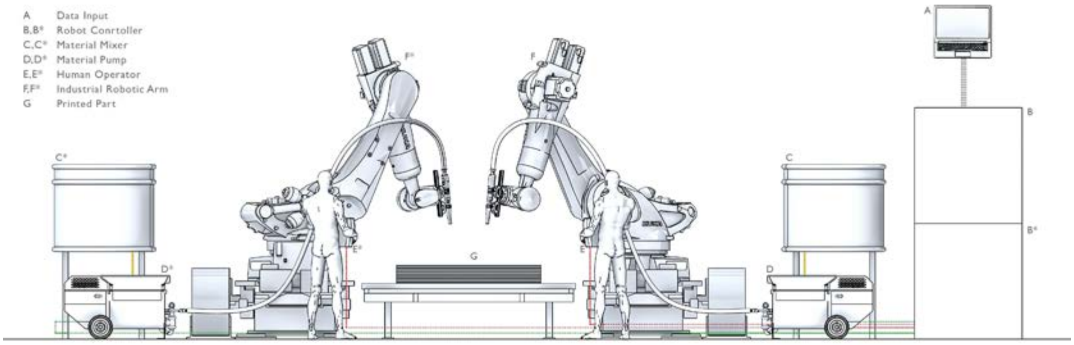

Figure 5: Multi-Robotic 3D Printing for Wood-Based Slurry Fabrication System Architecture. Source: (Created by the authors 2024)

3.2. Print path slicing and motion planning

The control of both robotic 3DP systems is achieved by loading and running two KUKA SRC files on two separate robot controllers. SRC files are source code files used by KUKA robotic arms; the SRC file contains plain text written in KUKA Robot Language (KRL). KRL is used for defining robot movements, handling inputs and outputs, data manipulation, and integration with external devices. A multi-step software workflow was developed to generate the two SRC files to optimize the processes-related parameters in the two-robotic 3D Printing with wood slurry (Figure 6):

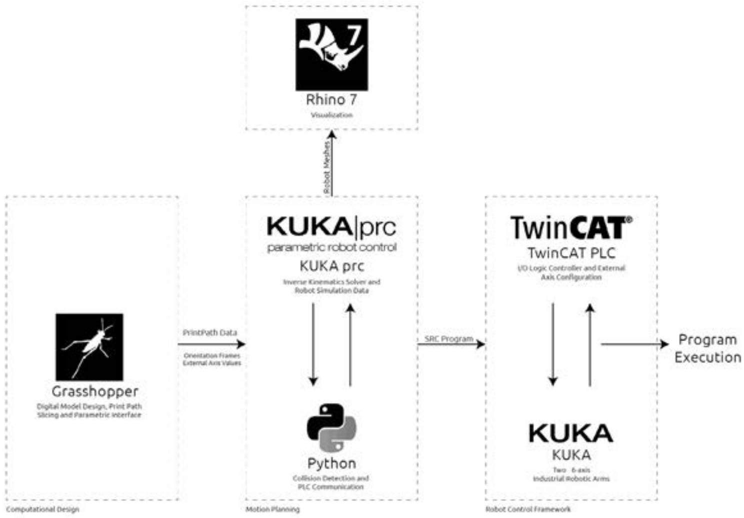

Figure 6: Software Workflow Demonstrating the Digital Design to Fabrication Process. Source: (Created by the authors 2024)

1. Grasshopper plugin to Rhinoceros modelling software was utilized to develop the computational design model of the prototype, slicing the resulting geometry into print path and generating the orientation frames for each robot based on their respective print path. The orientation frames are pivotal in determining how the robots would navigate and coordinate their actions within the shared work cell. This aspect of the workflow was strategically designed to maximize the efficiency and effectiveness of the collaborative 3D printing process. The print paths and orientation frames were optimized to minimize possible overlap between both robots while performing the 3DP, ensuring a harmonious operation where the robots can work side by side without disrupting each other's tasks (Figure 7).
2. The orientation frames are used as input for KUKA PRC to solve the inverse kinematics of the robots. This step results in the determination of the final joint positions for each robot, ensuring they move accurately and efficiently in the designated printing area.
3. The robot joint positions are used as input for a custom Python script developed to detect collisions between all states of the MR-3DP system. To minimize computational time, the Python script starts by wrapping a simple convex hull around each robot, followed by the application of the GJK (Gilbert-Johnson-Keerthi) algorithm (Lindemann 2009), an algorithm that runs an iterative search for the smallest distance between two convex sets and is capable of determining if an overlap has occurred between them (Figure 7).
4. Rhinoceros 3D acts as the visualization platform for the collision detection simulation, offering a detailed view of the two robotic 3d printing process along the generated print path, and allowing for adjustments of print path in areas of collision before final execution.
5. Finally, the resulting configurations are compiled in an SRC program file. This file not only includes the detailed joint states of each robot but also integrates the operation of external axes, like those controlling

the material pumps, ensuring seamless synchronization between the movement of the robots and the delivery of the wood-based slurry.

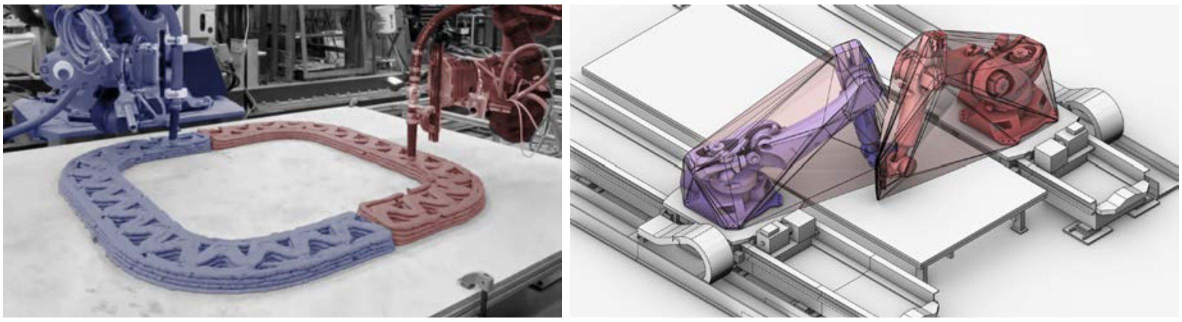

Figure 7: Left image: Task division and coordination in the multi-robotic 3D printing process, Right image: Collision detection using a simple convex hull and Gilbert-Johnson-Keerthi algorithm for faster collision computation. Source: (Created by the authors 2024)

This integrated software and hardware approach facilitates a highly coordinated and efficient MR-3DP process, which was employed in the fabrication of a construction scale wall (Figure 8). The printing process for the wall case study was planned to synchronize the nozzle printing speed and pumping flow rates, ensuring a consistent flow of material from the pump to the end effector in a way that matches the movement speed of the robots. To achieve a layer height of 13 mm, the pumping rate was set at 0.25 liters per minute, a robot speed of 0.015m/s. For this prototype, the lower viscosity material composition (F2) was used. This material was modified based on the final material design (F1) achieved by (Muhammad Dayyem Khan et al. 2023). This modification was a result of the pumping limitations of the MAI 2PUMP-PICTOR, which is not capable of handling the high viscosity of material (F1).

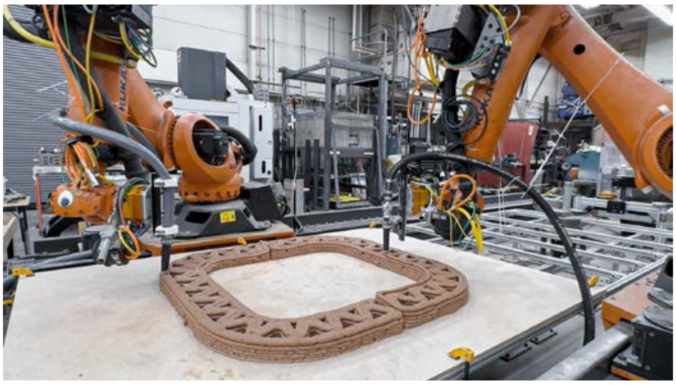

Figure 8: Resulting construction scale prototype from the MR-3DP process with wood-based slurry material using material (F2). Source: (Created by the authors 2024)

4.0 WOOD 3D PRINTING OF SLURRY WITH A SINGLE ROBOT

The aim of this prototype is to measure the effect of the material viscosity and layer cycle time on the buildability of the printed object; thus, the more viscous material (F1) was used in this case study in addition to printing with a single robotic arm. As described in the previous section, the MAI 2PUMP-PICTOR pump posed a limitation on the viscosity of the material that can be printed. In contrast, the custom in-house designed pump, therefore it was utilized in this experiment, can handle more viscous materials. To get an accurate evaluation, all the printing parameters for the MR-3DP experiment were replicated in this experiment. Consequently, the pumping rate was set at 0.25 liters per minute. The robot speed was set at 0.015m/s to achieve a layer height of 13 mm. (Figure 9) showcases the resulting prototype from the experiment. The experiment was conducted over two days, 9 layers were printed over the course of the first day, followed by the printing of 8 layers on the second day.

Figure 9: Resulting construction scale prototype from the R-3DP process with wood-based slurry material using material (F1). Source: (Created by the authors 2024)

5.0 RESULTS AND DISCUSSION

1. The developed MR-3DP system enabled the production of a prototype that is 78 mm high and 1.3 m x 1.3 m in length and width. The 3DP process took 45 mins, and each print layer took between 7-8 mins. In comparison, the prototype resulting from the R-3DP process has the same footprint but achieved a height of 221 mm. The 3DP process took 289 mins, and each print layer took between 15-18 mins. Both cases required similar material preparation time of about 5-6 hrs.
2. The 3DP experiment conducted with a single robotic arm was able to successfully print 17 layers, while the one with the MR-3DP system only achieved 6 layers before layer deformation occurred. This disparity in the construct's performance can be traced back to the difference in the layer cycle time, where the R-3DP scenario is approximately double that of the MR-3DP, which allows the material more time to set before the deposition of fresh material.
3. The 3D printed construct produced by both setups ultimately experienced a plastic failure. The lower layers failed to support the weight of the newly deposited material above, leading to the structure's collapse (Figure 10).
4. Rheological properties significantly impact the performance of 3D-printed constructs. Previous prototypes using low-viscosity wood-based slurry faced severe delamination due to high water content causing uneven shrinkage across layers (Figure 10). This issue highlights the need for further research into the slurry's rheological characteristics. Uneven water loss during various stages of MR-3D printing, especially during pumping, contributes to this problem. The goal is to keep the slurry fluid during pumping while ensuring it retains its form upon extrusion. Future advancements should focus on developing inorganic accelerators for wood-based slurry and integrating these accelerators at the end effector to control setting time, optimizing the process for better structural integrity and precision.

Figure 10: Left image: Deformation resulting from the plastic failure in the prototype printed through the R-3DP, Right image: Demonstrates the delamination of the object manufactured using the MR-3DP process using material (F2). Source: (Created by the authors 2024)

5. The division of 3D printing tasks was strategically managed by bisecting the object down the center to create two distinct print paths for each robotic arm. This minimized the possible areas of overlap, thus reducing the chances of collision between the two robotic arms. This approach also resulted in two continuous seams throughout the object, which can result in reduced mechanical and structural performance. To address this, future research should explore alternative seam positioning across multiple layers to eliminate division across the object and evaluate its impact on overall performance. This investigation may encompass an analysis of how seam placement influences structural strength, durability, and aesthetic attributes.
6. The need for a third operator to supply material stock and continuously agitate the material to ensure continuous feeding to the pump represents a major bottleneck in the automation and scalability of the whole process; not only that, but it also introduces the potential for inconsistent material extrusion, Addressing this by integrating a fully automated feedstock supply system could significantly enhance the overall efficiency and reliability of the MR-3DP process.
7. While the 3DP process was monitored by two operators in MR-3DP, there were multiple challenges that arouse while attempting to real-time modify and synchronize the robot 3DP settings, such as robot motion speed and material flow rate, between both robots. This highlighted a need for a more intelligent robot control system that would facilitate an enhanced level of collaboration between both robotic printing setups.

CONCLUSION

The presented research showcased the opportunities and challenges of MR-3DP with wood-based slurry for construction applications. This was achieved through a comparative analysis between two prototypical construction walls; the first was manufactured using R-3DP and the second MR-3DP. Significant insights into the various process parameters and material-related parameters were gained from these comparisons such as the effect of layer cycle time and material viscosity on the structural integrity and buildability of printed objects. Additionally, these experiments revealed the need for further research into the thixotropic properties of wood-based slurry and the benefits of developing a set on-demand process for this material.

Key process-related parameters critical for successful buildability were identified, which include, Material mixing time, the time interval between material mix and feeding the material into the material pump, material feeding rate, material flow rate through the pump, material travel time from pump to 3D printing nozzle, 3D printing nozzle diameter relative to the material carrying hose diameter, ambient temperature, layer cycle time relative to the material setting time, robot motion speed as well as the synchronization between both robots. This paper laid the groundwork for future research by understanding the various effects and relations some of these parameters have on the MR-3DP process. Further data collection needs to be conducted in order to accurately identify the correlation between these parameters in order to optimize them for a more streamlined and efficient MR-3DP.

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