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Towards Adaptive Additive Manufacturing with Image-based Monitoring for Binder Jet 3D Printing

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Towards Adaptive Additive Manufacturing with Image-based Monitoring for Binder Jet 3D Printing

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Abstract

In the context of 3D concrete printing, this study explores the possibility of image-based monitoring approaches for on-site quality evaluation and improvement in powder-based binder jetting procedures. The project's main goal is to create an integrated feedback system that integrates a monitoring system based on images into the printing process, allowing for real-time analysis and improvement. The study also investigates how different concrete composite mixing ratios affect the printing process, laying the groundwork for the use of hybrid materials to enhance the mechanical behavior of binder jetted parts in comparison to homogeneous standard materials. By focusing on these goals, we can considerably advance our understanding of image-based monitoring in additive manufacturing, which will ultimately help us create 3D-printed structures that are more dependable and durable. These developments will also significantly impact 3D concrete printing in building applications, encouraging innovation and better performance in the sector.

1. Introduction

1.1. Prologue

Additive manufacturing (AM) boasts a rich history, with techniques such as lost-wax casting and demolding tracing back approximately 6,500 years [1]. AM techniques are broadly classified into seven categories: Vat Photopolymerisation (VPP), Material Jetting (MJT), Binder Jetting (BJT), Material Extrusion (MEX), Powder Bed Fusion (PBF), Sheet Lamination (SHL), and Directed Energy Deposition (DED) [2]. Among these, binder jetting, material jetting, and material extrusion methods show considerable promise for large-scale concrete printing, owing to factors like material viscosity, powder grain size, and solidification reaction lag.

The expiration of the last patent restricting research into fused deposition modeling in 2009 spurred increased investment and interest in the additive manufacturing field [3]. In contrast to traditional manufacturing techniques that involve subtracting material from a template material block, AM emphasizes adding material to form an object, reducing environmental impact and facilitating greater customization [3]. Z Corporation (Z Corp.) commercialized 3D printing technology, which was subsequently adopted in machine design and architecture industries for prototyping purposes [4].

The application of concrete in material jetting and material extrusion technology has fostered innovation in large-scale 3D printing through the development of 3D extrusion-based concrete printing (3DCP). The advantages of 3DCP encompass reduced labor requirements, increased architectural design flexibility, and cost savings during construction [5].

A challenge in cement-based 3D printing is the in situ monitoring of the printing process. Digital image correlation (DIC) has been employed in powder bed fusion printing processes, such as metal powder printing. However, the binder jetting process provides the opportunity to develop Functionally Graded Materials (FGMs) and hybrid materials for enhanced mechanical behavior compared to homogeneous standard materials. Conversely, extrusion-based printing necessitates consistent aggregate properties from start to finish.

Existing research has examined the use of contact image sensors for laser scanning the top surface of printed parts, but the scanned parts can be influenced by sampling density, resulting in compression or stretching of the resulting images. RGB camera sensor-based monitoring, on the other hand, concentrates on the initial and final stages of powder printing, rendering it a more suitable choice for in situ monitoring.

Image-based monitoring in additive manufacturing has gained traction in recent years due to its potential to provide real-time feedback on the printing process. In binder jetting, the monitoring system can be utilized to track the deposition of binder onto the powder bed, assess the powder bed's surface quality, and detect any anomalies or inconsistencies during the process

[6]. Advanced image processing techniques, such as edge detection and feature extraction, can facilitate the identification of defects and guide appropriate corrective actions [7].

By integrating image-based monitoring systems with the printer's control software, it becomes possible to develop real-time feedback loops that enable adjustments to the printing parameters on the fly, ultimately improving the quality and performance of 3D printed structures [8].

In conclusion, this section has provided a brief overview of additive manufacturing and cement-based 3D printing, highlighting the potential of image-based monitoring techniques in enhancing the quality of binder jetting processes. The integration of advanced image processing in monitoring systems can significantly improve the real-time detection and correction of defects, paving the way for the development of more reliable and robust 3D printed structures.

1.2. Research Objectives

The primary objective of this research is to investigate the potential of image-based monitoring techniques in powder-based binder jetting processes for in situ monitoring of the printing process. By employing image-based monitoring and developing Functionally Graded Materials (FGMs), it will be possible to improve the quality and performance of 3D printed structures. Additionally, addressing the limitations of the working envelope in AM systems for architectural construction could pave the way for future exploration of mobile 3D printing, allowing for greater flexibility and scalability in construction projects.

- To achieve this objective, the research will focus on the following aspects:
- Investigate the current state of image-based monitoring techniques in additive manufacturing, specifically in binder jetting processes.
- Evaluate the effectiveness of different image processing techniques in identifying defects and anomalies during the binder jetting process.
- Develop a real-time feedback system that integrates image-based monitoring with the printer's control software, enabling adjustments to the printing parameters on the fly and improving the quality and performance of 3D printed structures.
- Assess the potential of Functionally Graded Materials (FGMs) and hybrid materials in enhancing the mechanical behavior of binder jetted parts compared to homogeneous standard materials.

By addressing these research objectives, this thesis aims to contribute to the body of knowledge on image-based monitoring in additive manufacturing and explore its potential for improving the binder jetting process and the quality of 3D printed structures.

1.3. Methodology

The research methodology for this thesis will be structured as follows:

- Literature Review: Conduct a comprehensive literature review on image-based monitoring techniques in additive manufacturing, with a focus on binder jetting processes. This review will aim to identify the most promising approaches and techniques for in situ monitoring and evaluate their applicability to large-scale concrete printing.
- Image Processing Techniques Evaluation: Investigate different image processing techniques, such as edge detection, thresholding, and feature extraction, to determine their effectiveness in identifying defects and anomalies during the binder jetting process. This step will involve acquiring images of printed parts during the printing process, processing these images using various techniques, and comparing the results to identify the most suitable approach for in situ monitoring.
- Image-based Feedback System Development: Develop a real-time feedback system that integrates image-based monitoring with the printer's control software, allowing for adjustments to the printing parameters on the fly. This system will utilize the most effective image processing techniques identified in the previous step to detect defects and anomalies during the printing process and communicate the necessary adjustments to the printer's control software.
- Functionally Graded Materials (FGMs) and Hybrid Materials Assessment: Investigate the potential of FGMs and hybrid materials in enhancing the mechanical behavior of binder jetted parts compared to homogeneous standard materials. This step will involve designing and printing test specimens with varying material gradients and evaluating their mechanical properties through experimental testing.
- Data Analysis and Optimization: Analyze the data collected from the image-based monitoring, real-time feedback system, and FGM assessments to determine the effectiveness of the proposed techniques in improving the quality and performance of 3D printed structures. Use these findings to optimize the image-based monitoring and real-time feedback system for use in future binder jetting processes.
- Conclusions and Recommendations: Based on the findings of the research, draw conclusions about the applicability and effectiveness of image-based monitoring in binder jetting processes for large-scale concrete printing. Provide recommendations for future research and development in this area, considering possible advancements in image processing techniques, feedback systems, and material properties.

Through this research methodology, the thesis seeks to offer an in-depth insight into the role of image-based monitoring in binder jetting processes and how it can contribute to enhancing the quality and performance of 3D printed structures for large-scale concrete printing applications.

1.4. Outline of Chapter

- Chapter 1: Introduction – Provides an overview of the research problem, objectives, and methodology.

- Chapter 2: Literature Review – Reviews relevant literature on additive manufacturing, cement-based 3D printing, image-based monitoring techniques, and functionally graded materials.
- Chapter 3: Method:
    - Experimental Setup – Describes the design and implementation of the experimental setup for cement-based 3D printing.
    - Image-Based Monitoring System – Presents the development of the image processing algorithms and machine learning techniques for defect detection and classification.
    - Real-Time Feedback and Control – Discusses the integration of the monitoring system with the printer's control software and the development of real-time feedback algorithms.
    - Functionally Graded Materials – Explores the potential of FGMs in cement-based 3D printing and their impact on the mechanical performance of printed structures.
- Chapter 4: Results and Discussion – Presents the results of the experimental evaluations and discusses the implications of the findings.
- Chapter 5: Conclusion and Future Work – Summarizes the main contributions of the research and suggests directions for future work.

2. Background

2.1. 3D Concrete Binder Jetting Printing and Mobile Printing

Binder jetting is a versatile additive manufacturing (AM) technique that offers several advantages over Material Jetting (MJT) and Material Extrusion (MEX) methods, which require premixing materials with activation binders and maintaining a specific viscosity. The MEX and MJT printing processes can suffer from material tearing and need continuous extrusion of concrete mortar, which requires support and is constrained by a maximum vertical overhang of 17.5º degrees [6]. Binder jetting technology, patented by Emanuel Sachs in 1993, initially applied gypsum-based powder and water-based binder for printing tasks at MIT [7]. Subsequent developments by ExOne [8] and innovations like the D-shaped approach [10] and Voxeljet Company’s Binder Jetting technology [11] have enabled large-scale printing with intricate designs and good print quality.

The binder jetting process involves dispensing a binder compound using a printing nozzle onto the top surface of the powder bed, attaching these areas to one another to build the pre-designed workpiece layer by layer. After a certain period of treatment time, the finished product is removed, and unbonded material is vacuumed with an air jet [9]. This method enables the production of Functionally Graded Materials (FGMs) and hybrid materials with improved mechanical behavior compared to homogeneous standard materials. Binder jetting has evolved to

accommodate large-scale printing, with instances such as the D-shaped approach created by Cesaretti et al. [10] and the Voxeljet Company's Binder Jetting technology [11]. These methods can produce intricately formed building components at realistic manufacturing rates and with excellent print quality and geometric flexibility.

Despite the advancements in mobile 3D printing, addressing defects and ensuring print quality remains challenging. Factors such as material properties, process parameters, and the size of the work cell can affect the quality of the printed structures. For instance, the layer thickness in extrusion-based methods constrains resolution, with continuous filaments being positioned through a nozzle resulting in layer thicknesses ranging from 6 mm to 50 mm [13]. The Selective Cement Activation (SCA) approach, however, can achieve higher resolution with thinner layer thicknesses, as low as 5 mm or even less [12]. Moreover, the mixing materials in the SCA method can be reused for later prints since they have not been activated.

Defects in AM can arise from various sources, such as incorrect process parameters, inadequate material properties, or issues related to the monitoring and control systems. In binder jetting, for example, the saturation level has a significant impact on the compressive strength of printed structures [14, 15]. Ensuring an appropriate saturation level during the printing process can lead to better mechanical properties and improved print quality. Additionally, the choice of binder and powder materials, as well as the dispensing method, can influence the quality of the printed parts.

One of the challenges in large-scale concrete printing is the in situ monitoring of the printing process. Digital image correlation (DIC) has been applied to powder bed fusion printing processes, such as metal powder printing. However, this method may not be suitable for binder jetting due to factors such as sampling density and the potential for compression or stretching of the resulting images. RGB camera sensor-based monitoring focuses on the initial and final stages of powder printing, making it a more suitable choice for in situ monitoring.

To achieve defect-free 3D printed structures, it is essential to develop advanced monitoring and control strategies that can detect and correct defects in real-time. This can be achieved through the integration of sensors, machine vision systems, and feedback control mechanisms, which can monitor the printing process and make necessary adjustments to ensure optimal print quality.

In conclusion, mobile 3D printing platforms have the potential to overcome working envelope constraints in additive manufacturing, enabling the construction of large-scale concrete structures with complex geometries. However, addressing defects and ensuring print quality remains a challenge that requires further research and development. By focusing on advanced monitoring techniques and optimizing process parameters, it is possible to improve the performance and reliability of binder jetting and other AM techniques in the construction industry.

2.2. Image-based Monitoring in Adaptive Additive Manufacturing

This literature review focuses on adaptive additive manufacturing in the context of powder-based binder jetting, with an emphasis on image-based real-time monitoring during the printing process. Additionally, we will explore the application of binder jetting in the fabrication of functionally graded materials (FGM).

Adaptive additive manufacturing involves the use of sensors and real-time feedback systems to optimize the printing process, leading to improved print quality and reduced material waste. Researchers have described the benefits and challenges of incorporating real-time feedback into the 3D printing process, discussing various monitoring techniques and their potential applications in enhancing print outcomes [1].

One significant area of research for adaptive AM is digital image correlation (DIC) and real-time control of the system. Most of the current research in adaptive AM focuses on metal powder printing. However, since metal powder printing requires printing in an inert environment, obtaining applicable images for recognition can be challenging [2].

Image-based real-time monitoring during the binder jetting process can be achieved through various sensor technologies, such as optical, acoustic, or thermal sensors. Studies have explored the use of high-speed X-ray imaging and diffraction for real-time monitoring of powder bed fusion, a process similar to binder jetting [3]. Additionally, researchers have proposed machine vision systems for real-time monitoring of the powder bed fusion process, using high-speed cameras to capture images of the melt pool and employing machine learning algorithms to analyze the data, providing real-time feedback for improved print quality [4].

Recent advances in digital image correlation (DIC) have enabled researchers to develop real-time monitoring techniques for image-based adaptive additive manufacturing. DIC is an optical method that measures the deformation, displacement, and strain of materials by comparing images before and after deformation [11]. DIC has been applied in various fields, including materials science, civil engineering, and biomechanics. In the context of additive manufacturing, DIC can help monitor the printing process by identifying defects, measuring residual stress, and evaluating the mechanical properties of the printed material [12].

Khan et al. [13] demonstrated the use of DIC for real-time monitoring of the binder jetting process. They developed an experimental setup that combined high-speed cameras and patterned light sources to capture images during the printing process. The images were then processed and analyzed using DIC algorithms, which enabled the researchers to monitor the quality of the printed layers and detect defects in real-time.

Furthermore, researchers have applied DIC in conjunction with machine learning algorithms for real-time monitoring and defect detection in binder jetting processes. For example, Sasmal et al. [14] used DIC and convolutional neural networks (CNN) to monitor the

layer-wise deposition of powder during the binder jetting process. The CNN was trained to recognize various defects, such as incomplete spreading, clumping, or insufficient material deposition. By combining DIC and machine learning, the researchers were able to achieve real-time defect detection and improve the overall quality of the printed parts.

In another study, Cai et al. [15] employed DIC to monitor and control the binder jetting process by analyzing the strain fields in printed components. By adjusting the printing parameters based on the real-time strain information, the researchers were able to minimize the residual stress in the printed parts and improve their mechanical properties. This study highlights the potential of DIC in optimizing the printing process through real-time feedback and adaptive control.

Image-based monitoring techniques also benefit from advances in imaging technology, such as high-speed cameras, high-resolution sensors, and advanced image processing algorithms. For example, Wang et al. [16] developed a high-speed imaging system for real-time monitoring of the binder jetting process. The system used a high-speed camera and a custom-built illumination system to capture images at high frame rates. The images were then processed using advanced image processing techniques to extract critical information about the printing process, such as powder bed quality, material distribution, and layer thickness. By providing real-time feedback to the printer controller, the researchers were able to optimize the printing process and reduce defects.

In addition to optical imaging techniques, researchers have also explored other sensing modalities for image-based real-time monitoring of binder jetting processes. For instance, thermography has been utilized to monitor temperature distribution during the printing process, which can provide valuable insights into the quality of the printed parts [17]. Similarly, acoustic emission sensors have been employed to detect defects, such as cracks or delamination, by analyzing the acoustic signals generated during the printing process [18].

Despite the advancements in image-based real-time monitoring techniques and the application of DIC in adaptive additive manufacturing, several challenges remain. For example, achieving optimal lighting conditions for capturing valid images during the printing process can be difficult, especially in the case of metal powder printing, which occurs in an inert environment. Researchers have proposed various solutions to overcome this issue, such as using laser-based illumination systems or optimizing the imaging setup to minimize reflections and enhance image contrast [19].

Moreover, the integration of image-based monitoring techniques with the printing process can be complex, as it may require modifications to the printer hardware or software. Furthermore, real-time image processing and analysis can be computationally intensive, necessitating the use of high-performance computing resources or specialized hardware, such as graphics processing units (GPUs) [20].

In conclusion, image-based real-time monitoring techniques, particularly those utilizing digital image correlation, have shown great promise in enhancing the quality and reliability of binder jetting processes. By providing real-time feedback and enabling adaptive control of the printing process, these techniques can help optimize material deposition, reduce defects, and improve the mechanical properties of printed parts. As research in this area continues to advance, it is expected that image-based monitoring techniques will become increasingly integral to the additive manufacturing process, enabling the production of more complex and high-performance components across various industries.

2.3. Multi-material printing and functionally graded materials

Multi-material printing and functionally graded materials have witnessed a rise in popularity in the area of additive manufacturing in recent years (FGMs). By combining many materials in a single print, multi-material printing enables the creation of structures with specialized mechanical, thermal, or aesthetic characteristics. Functionally graded materials can perform better and operate more effectively because of a gradual shift in composition, microstructure, or other qualities. In the context of large-scale concrete printing, this literature review attempts to present an overview of current developments in FGMs and multi-material printing.

Development of multi-material printing techniques

The creation of complex and heterogeneous structures has advanced significantly as a result of the development of multi-material printing processes. Binder jetting, which provides a great degree of freedom in material choice and design, is one of the most promising techniques for multi-material printing [1]. Zhang et al[2] .'s investigation on the viability of multi-material binder jetting for cementitious materials showed that complex multi-material components with a range of mechanical characteristics may be created. Similarly, Le et al. [3] studied the use of multi-material binder jetting for creating complex geometries with varying material properties by controlling the binder saturation level and layer thickness.

Another method used for printing several materials is material extrusion. For large-scale concrete printing in this situation, Gosselin et al. [4] created a multi-material extrusion system that made use of separate extrusion heads for various materials. The authors showed how this method might be used to create components using a combination of strong and light materials, leading to structures with better mechanical performance and less weight.

Functionally graded materials in large-scale concrete printing

The development of functionally graded materials (FGMs) for large-scale concrete printing holds the potential to produce components with tailored performance characteristics. FGMs can provide enhanced performance characteristics, such as improved mechanical behavior, reduced stress concentrations, or tailored thermal expansion [5]. One of the key

challenges in creating FGMs is the development of appropriate material systems and printing methods.

Buswell et al. [6] explored the use of digital material jetting for creating FGMs in cementitious materials, demonstrating the potential for fine control over material composition and properties. The performance of the printed components was evaluated in the study to determine the impacts of altering the binder amount and particle size distribution. Based on their findings, it is possible to improve mechanical qualities like strength and stiffness by carefully controlling these factors.

FGMs have also been employed to improve the mechanical properties of printed structures. Mechtcherine et al. [7] developed a graded concrete material with a gradual transition from a high-strength core to a more ductile outer layer. This approach resulted in improved load-bearing capacity and reduced stress concentrations in the printed components.

Other studies have investigated the use of FGMs in addressing specific challenges associated with concrete printing. For example, Le et al. [8] focused on the development of functionally graded cementitious materials to reduce the risk of cracking in printed concrete structures. They found that a gradual transition from a high-strength core to a more ductile outer layer could effectively redistribute stresses and reduce the risk of cracking.

In addition to improvements in mechanical properties, FGMs can also enhance the durability and sustainability of printed concrete components. Brütting et al. [9] investigated the potential of using FGMs to improve the frost resistance of 3D-printed concrete. By incorporating air-entraining agents into the outer layers of the printed components, they were able to significantly enhance the frost resistance of the material without compromising its mechanical properties.

The potential of FGMs in concrete printing has also been explored in terms of optimizing material usage and reducing environmental impact. In a study by Panda et al. [10], the authors proposed an approach to create FGMs with optimized material distribution, leading to reduced material consumption and associated environmental impacts. Their method relied on a multi-objective optimization algorithm to determine the optimal distribution of materials within the printed structure.

Despite the promising results of these studies, several challenges remain in the development and application of FGMs in large-scale concrete printing. One such challenge is the need for advanced printing techniques that can accurately control material deposition and enable the precise creation of graded structures. Wu et al. [11] addressed this challenge by developing a robotic extrusion system capable of multi-material deposition, allowing for the creation of FGMs with complex geometries and varying material properties.

Another challenge lies in the development of suitable material systems and formulations for FGMs in concrete printing. Adequate material characterization and understanding of the interactions between different material components are essential to ensure the desired performance of the printed components [12]. Furthermore, the development of appropriate testing methods and standards for evaluating the performance of FGMs in concrete printing is crucial to facilitate their widespread adoption in the construction industry [13].

In conclusion, the development of FGMs for large-scale concrete printing holds significant promise for enhancing the performance and sustainability of printed structures. While several challenges remain, ongoing research efforts in this area are expected to yield new insights and drive further advancements in the field.

Integration of multi-material printing and FGMs

The integration of multi-material printing and FGMs has the potential to revolutionize the construction industry by enabling the production of components with tailored performance characteristics. For instance, Wang et al. [8] developed a multi-material printing method for fabricating functionally graded cementitious components with improved mechanical properties and reduced weight. The authors utilized a combination of lightweight aggregate and high-strength cementitious materials to create components with tailored mechanical behavior.

Nematollahi et al. [9] explored the use of multi-material extrusion-based printing for producing functionally graded cementitious components, demonstrating the feasibility of creating structures with tailored mechanical and thermal properties. The authors employed a dual-material extrusion system to achieve a gradual transition between different material compositions, resulting in components with improved performance characteristics.

Smart and responsive structures

Another promising application of multi-material printing and FGMs is the development of smart and responsive structures. Yu et al[10] .'s proposal for producing cementitious components with embedded sensors, actuators, or communication devices was made in this context. This strategy may make it possible to create intelligent infrastructure systems that can keep track of their own performance and adjust to shifting external factors.

Similarly to this, Khoshnevis et al. [11] investigated how to include sensors and actuators into functionally graded structures to enable real-time monitoring and control of printed components. This strategy could make it easier to create adaptive building systems that can react to environmental cues and self-healing buildings.

Challenges and future directions

Although significant progress has been made in multi-material printing and FGMs for large-scale concrete printing, several challenges remain. They include the creation of appropriate

material systems, the optimization of printing settings, and making sure printed components are long-lasting [12]. The development of sustainable material systems and recycling techniques, as well as more study on the possible environmental effects of multi-material printing and FGMs, are also necessary [13].

Future research in this field should concentrate on examining innovative material combinations and printing methods for multi-material printing and FGMs in addition to resolving these issues.For example, incorporating advanced materials such as nanomaterials, phase change materials, or shape memory alloys could further enhance the performance and functionality of printed structures [14]. Additionally, the development of new printing techniques, such as robotic-assisted deposition or multi-nozzle systems, could further expand the possibilities for multi-material printing and FGMs in large-scale concrete printing [15].

In conclusion, multi-material printing and functionally graded materials hold great promise for the future of large-scale concrete printing. Continued research in this area is essential for realizing the full potential of these technologies and addressing the challenges associated with material systems, printing parameters, and environmental sustainability. As the field progresses, it is anticipated that multi-material printing and FGMs will play a critical role in shaping the future of the construction industry.

1. Method

This section will outline the methodology for implementing an image-based monitoring system for powder-based binder jetting printing with functionally graded materials (FGMs). The primary goal of this study is to develop a real-time monitoring system capable of detecting defects and assessing the quality of printed FGM parts during the binder jetting process.

1.1. Experimental Setup

1.1.1. Binder Jetting Printer:

Extruder and Camera Setup:

Design and fabricate a custom binder jetting extruder with an adjustable nozzle holder to be mounted on the IRB-120 robot arm. The adjustable nozzle holder ensures compatibility with the cement-based materials and allows for the accommodation of desired material gradients during the printing process. Alongside the adjustable nozzle holder, I designed an adjustable camera holder that can be securely attached to the nozzle holder assembly. Mount the Intel RealSense D435 camera on the adjustable camera holder, taking care to position it in such a way that it maintains a clear view of the printing surface throughout the printing process. Integrate the extruder, adjustable nozzle holder, adjustable camera holder, and camera setup with the IRB-120 robot arm. This integration will facilitate precise control of the printing process and enable real-time monitoring for defect detection and process optimization.

Robot Arm Control and Path Planning:

The IRB-120 robot arm must be programmed to execute a series of tasks, which include: (1) positioning the extruder at specific locations for binder dispensing, (2) driving the scraper for material spreading, (3) placing the camera at a static location for image capturing before and after printing, (4) relocating the extruder to a designated location for binder refilling, and (5) providing real-time monitoring of the printing process while collecting data during printing.

A path planning algorithm should be developed for the robot arm, consisting of two parts: (1) paths to fixed positions for image capturing and binder refilling, and (2) paths for binder jetting printing. Although the former positions remain constant across different layers, the paths to reach these locations will vary depending on the end position of each printed layer. For each layer, the printing path must be generated based on the required shape and binder droplets' horizontal expansion. This algorithm calculates the minimum number of droplets needed to cover the desired pattern, ensuring smooth and accurate binder deposition.

A ROS-based control system should be implemented for the IRB-120 robot arm. This system allows for seamless communication and synchronization between the robot arm movement, extruder operation, and camera image capturing process. The ROS-based system also enables integration with the image processing algorithm for real-time feedback and adjustment of printing parameters. Safety features should be developed within the ROS-based control system to prevent collisions between the extruder, camera, and other printer components during operation. This may include implementing predefined safety zones within the robot arm's workspace.

Leveling Powder Bed Construction:

The printer must be compatible with cement-based materials and capable of accommodating the desired FGM part dimensions. To facilitate the experiment, a custom printing bed was meticulously designed and constructed. The apparatus consists of two distinct tanks: a material input tank and a printing tank, both crucial for replicating the powder printing process.

A printing tank equipped with an adjustable printing level was developed, utilizing an Arduino-based stepper motor for precise leveling control in both upward and downward directions. This design allows for the maintenance of a consistent printing surface height throughout the process. To guarantee a controllable layer thickness during printing, a sophisticated control system was implemented to synchronize the leveling panel movement with the material feeding tank and the printing tank. This system ensures the seamless transfer of the mixed powder from the feeding tank to the printing tank, thereby maintaining a consistent powder bed thickness throughout the printing process. A scraper, actuated by a robotic arm, was positioned on the printing bed and is responsible for evenly spreading the powder layers across the printing tank.

The tailor-made printer setup was conceived with modularity and scalability in mind, facilitating easy adaptation to various cement-based materials and FGM part dimensions. The construction of the printer components ensures compatibility with the selected materials while considering factors such as material flow characteristics and binding properties. The printer design also accounts for the need for precise control over the printing process, guaranteeing optimal layer thickness and powder bed consistency for the fabrication of FGMs with desired material gradients.

1.1.2. Image Sensor System:

The camera should be positioned at an angle that allows for clear observation of the powder bed and binder deposition.

1.1.3. Illumination:

Implement a suitable lighting system to ensure adequate illumination of the powder bed during the printing process.

1.1.4. Data Acquisition and Storage:

Develop a data acquisition system that synchronizes the camera with the printer and stores the captured images for further analysis.

1.2. Material Selection

Selecting suitable materials for creating FGMs is vital to ensure their desired properties and compatibility with the binder jetting process. In this context, cement-based materials have been chosen as the primary building blocks for FGM development. Concrete is a more complex material compared to traditional industrial powder-based FGM, as it consists of at least three distinct components: cement, sand, and aggregates. To successfully print cement-based FGM, it is crucial to adapt the material composition, which can be achieved by either adjusting the material ratios or altering the aggregate sizes.To effectively optimize the binder jetting process for these materials, it is important to consider the following steps:

Material Selection: Carefully select the cement, sand, and aggregate materials based on the desired properties of the final cement-based FGM, ensuring their compatibility with the binder jetting process.

Material Ratio Adjustment: Experiment with different material ratios to identify the optimal composition that meets the required performance characteristics and is compatible with the printing process.

Aggregate Size Modification: Evaluate the impact of various aggregate sizes on the printing process and final cement-based FGM properties to determine the most appropriate aggregate dimensions for the desired FGM application.

By thoroughly examining and adjusting the material ratios and aggregate sizes, a suitable cement-based FGM composition can be established, resulting in a more efficient binder jetting process and improved performance of the printed cement-based FGM.

1.2.1. Material Characterization:

A comprehensive characterization of the cement-based materials intended for use in the binder jetting process is essential. This characterization involves the analysis of particle size distribution, roundness, horizontal spreading and penetration depth for each specific recipe, which are critical properties for optimizing the powder bed spreading and binder deposition processes. A thorough understanding of these properties will contribute to a more uniform and stable printed part.

Material Characterization Inspection System Setup:

The inspection system will consist of self-developed binder extrusion system, cameras, illumination, and weight scales

Material Recipe and Saturation Rate Determination:

Identifying the optimal material recipe and desired saturation rate for different material compositions is crucial in the binder jetting process. This is because the proportion of cement, sand, and aggregates, along with the binder-to-powder ratio, greatly influences the mechanical properties, surface quality, and overall performance of the printed parts. By exploring various material compositions and their corresponding saturation rates, researchers can determine the most suitable combination for achieving the desired properties in functionally graded concrete parts. Furthermore, understanding the relationships between material recipes and saturation rates can help in optimizing the printing parameters, such as binder flow rate and layer thickness, leading to enhanced print quality and reduced material waste.

Aggregates size and roundness analysis:

Assessing the size and roundness of aggregates is essential for optimizing material flow and binder jetting performance. The size of aggregates directly affects the print resolution, porosity, and mechanical strength of the printed parts. Larger aggregates may lead to coarser surface finishes and lower print resolutions, while smaller aggregates can result in smoother surfaces and improved detail reproduction. On the other hand, the roundness of aggregates plays a significant role in determining the flowability and packing behavior of the powder bed. More rounded aggregates generally exhibit better flow properties and more uniform powder bed formation,

which can enhance binder penetration and adhesion between layers. By analyzing aggregate size and roundness, researchers

Aggregates size measurement:

Pseudocode:

```
def detect_edges(image, threshold):
    gray = cv2.cvtColor(image, cv2.COLOR_BGR2GRAY)
    blurred = cv2.GaussianBlur(gray, (5, 5), 0)
    edges = cv2.Canny(blurred, threshold, threshold * 2)
    return edges
def find_contours(edges):
        contours,_=cv2.findContours(edges,cv2.RETR_EXTERNAL,
cv2.CHAIN_APPROX_SIMPLE)
return contours
```

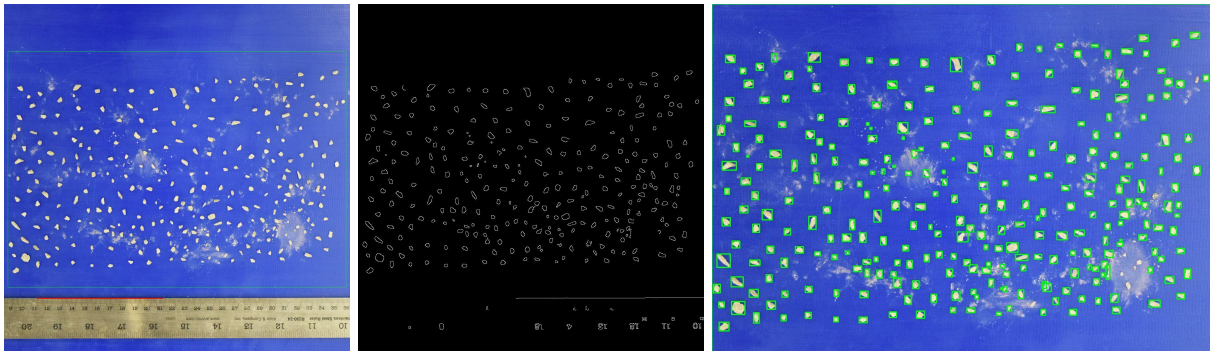
Roundness definition:

Pseudocode:

```
def calculate_roundness(contour):
    area = cv2.contourArea(contour)
    perimeter = cv2.arcLength(contour, True)
    if perimeter == 0:
        return 0
    roundness = 4 * np.pi * area / (perimeter ** 2)
 return roundness
```

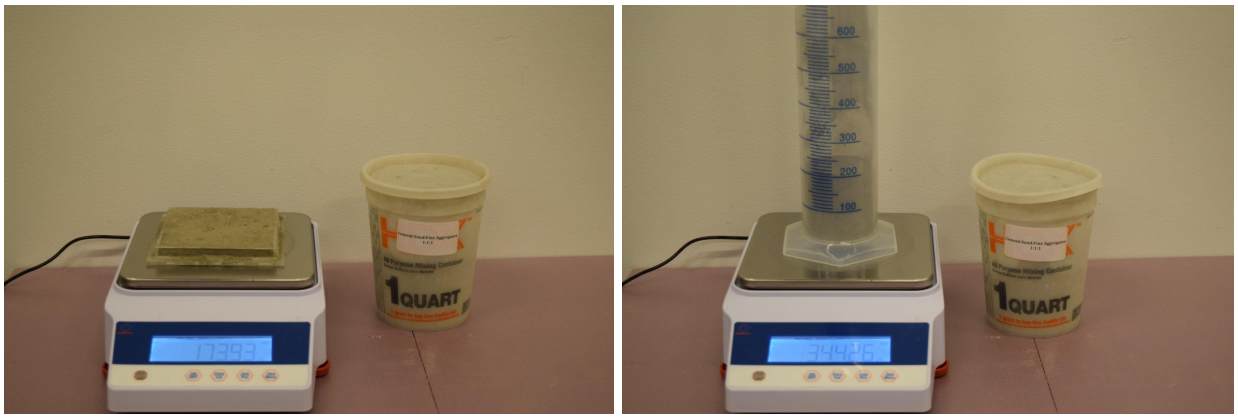
		Sample 1	Sample 2	Sample 3
Aggregate size median	Average (cm)	1.23	1.15	1.20
	Median (cm)	1.20	1.12	1.14

Roundness	Average	0.67	0.69	0.67
	Median	0.75	0.76	0.74



Density of different recipe:

Density measurement setup:



Cement: Sand: Agg	1:1:1	1:1:2	1:1:3
Compact Density (g/cm^3)	1.7393	1.8340	1.9477
Bulk Density (g/cm^3)	1.7212	1.8052	1.8973
Compact Ratio	1.0516%	1.5954%	2.6564%

Material for do not adjust layer thickness, which should use the same size of aggregates as before.

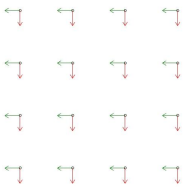
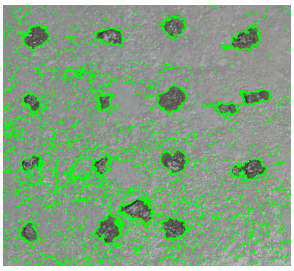
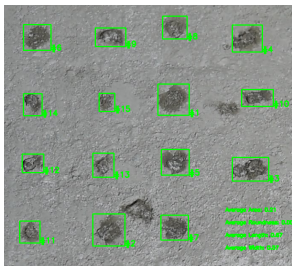
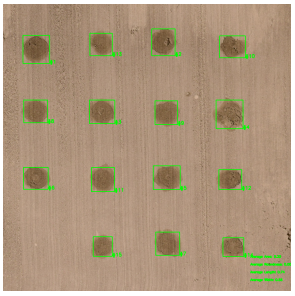
Saturation rate by weight:

water/mixing ratio (weight)

	1:1:1	1:1:2	1:1:3
14%	dry		solidify
18%	solidify		wet
22%	wet	wet	wet

Horizontal expantion:

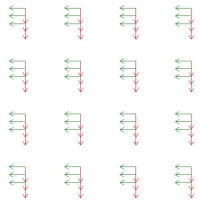
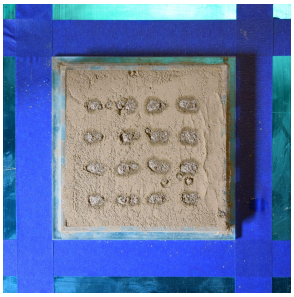
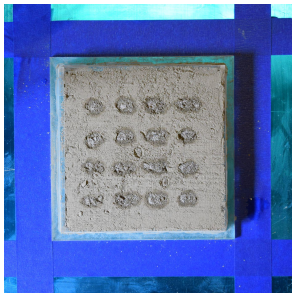
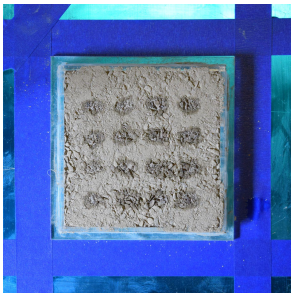
Experiment Setup:

	1:1:1	1:1:2	1:1:3
Horizontal Expansion Area (cm^2)	0.205	0.225	0.300
Horizontal Expansion length (cm)	0.663	0.720	0.790
Horizontal Expansion width (cm)	0.570	0.600	0.670

Penetration depth:

Experiment Setup:

	1:1:1	1:1:2	1:1:3
14%	0.2	0.3	0.5
18%	0.4	0.6	0.8
22%	0.8	1.0	1.0

Concrete Composite Mixing Ratio Selection and Test

Identifying the optimal mixing ratio and layer thickness is crucial for facilitating the printing process and ensuring proper layer adhesion. To achieve the desired pattern printing with varying concrete composite mixing ratios, we have developed mix designs for cement-based materials. This process involves adjusting the proportions of cement, sand, and aggregates according to different binder spacing to achieve shape accuracy and sufficient green body strength for excavation. Additionally, appropriate binder adjustments ensure rapid penetration on the powder mixture's surface.

Oversaturated printing can cause bleeding and shape deviations from the intended pattern, whereas undersaturated printing may result in inadequate green body strength and excavation failures. To address these concerns, we conducted single droplet and short line printing tests using various concrete composite mixing ratios (cement: sand: aggregate = 1:1:1, 1:1:2, and 1:1:3). A 100 mm x 100 mm x 10 mm printing bed was designed and fabricated to hold the concrete composite, and an IRB-120 robot was employed to execute a predefined path for the printing test.

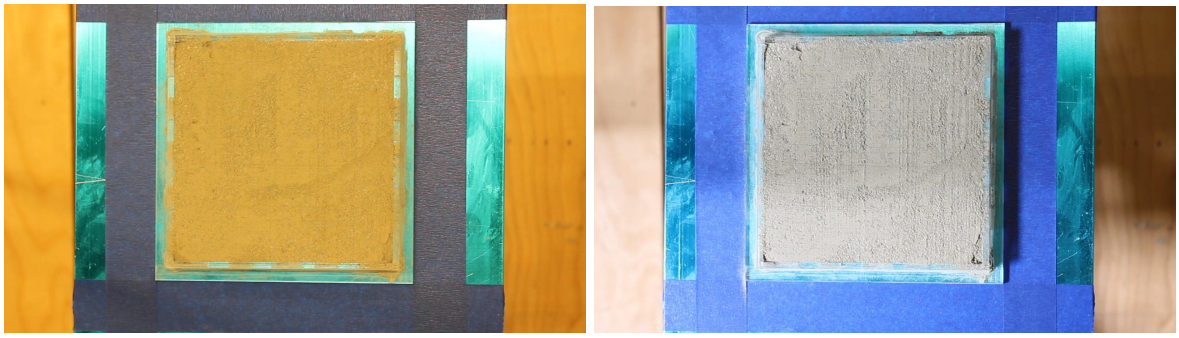


Left: 100 g 1:1:1 Mixing Ratio By Weight; Mid: 100 g 1:1:2 Mixing Ratio By Weight; Right: 100 g 1:1:3 Mixing Ratio By Weight



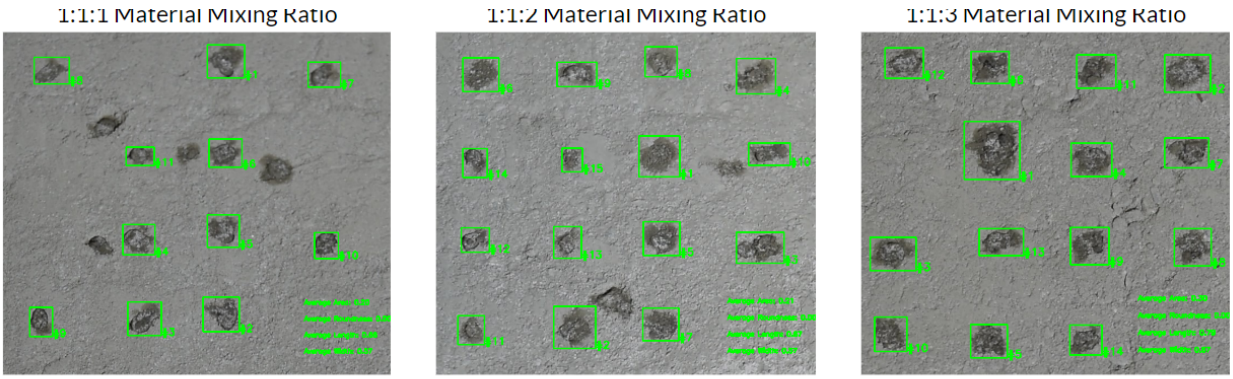
Left: 100 cm^3 1:1:1 Mixing Ratio By Weight; Mid: 100 cm^3 1:1:2 Mixing Ratio By Weight; Right: 100 cm^3 1:1:3 Mixing Ratio By Weight

To minimize the influence of perspective on image capturing and subsequent image processing for analysis, we established an image-based monitoring system equipped with a high-resolution camera. A lifting jack was utilized to adjust the test bed to an appropriate position, circumventing the singularity of the IRB-120. Following multiple tests with the monitoring system, we determined that a lighting system with a higher Kelvin color temperature enhances image-analysis processing, while a high-contrast image facilitates image processing. As a result, the color temperature for the printing setup was set to 6700K.



Left: color temperature 4000K; Right: color temperature 6700 K

The results from the single droplet test prints reveal that as the proportion of aggregates in the concrete composite increases, the horizontal binder expansion becomes more unpredictable, as evidenced by the greater standard deviation observed in the image analysis of droplet expansion. This effect may be attributed to the decreased density and increased compatibility of the concrete composite with a higher aggregate ratio, which can result in increased voidness within a single layer. Greater voidness in the composite leads to enhanced connectivity between the internal voids and the outer space, facilitating binder travel from the surface to a wider range and manifesting as a broader horizontal expansion on the surface.



	1:1:1	1:1:2	1:1:3
Horizontal Expansion Area (cm^2)	0.205	0.225	0.300
Horizontal Expansion Length (cm)	0.663	0.720	0.790
Horizontal Expansion Width (cm)	0.570	0.600	0.670
Standard Deviation	0.0624	0.087	**0.156**

Single droplet printing test results and table

The short-line test prints conducted with different saturation rates demonstrated that the penetration depth of various concrete composite mixing ratios also affects the vertical travel of the binder. Our tests indicated that larger binder spacing in the same mixing ratio of concrete composite material leads to reduced bleeding from the intended pattern and shallower penetration depth. Furthermore, larger binder spacing in concrete composite material with a lower aggregate ratio results in less bleeding from the intended pattern and shallower penetration depth, whereas smaller binder spacing increases the bleeding area for all mixing ratios of aggregates in the concrete composite. However, higher aggregate ratios with smaller binder spacing cause a more significant increase in the bleeding area than larger binder spacing compared to the lower aggregate ratio. Simultaneously, the penetration depth's increase for smaller binder spacing is not as substantial compared to the horizontal spreading pattern.

Based on the selected mixing ratios of concrete composite, the appropriate layer thickness can be determined as follows: 3 mm for a 1:1:1 mixing ratio, 5 mm for a 1:1:2 mixing ratio, and 8 mm for a 1:1:3 mixing ratio.

Image-Based Monitoring System Development

Printed patterns play a vital role in numerous products across the modern manufacturing sector, ranging from textiles and packaging to electronic components and biomedical applications. The quality of these patterns is critical to the overall performance and aesthetic appeal of the final product, as they serve both functional and visual purposes. During the printing process, common issues such as gaps or consistency errors in the printed patterns may arise due to factors such as the printing material, misaligned equipment, or wear and tear.

Quality control is essential in the manufacturing industry for ensuring that products meet expected standards in terms of functionality, aesthetics, and durability. Effective quality control methods can help identify and rectify manufacturing defects, such as gaps in printed patterns before products reach end-users. Addressing these defects can reduce production costs, increase customer satisfaction, and enhance overall product performance. Moreover, effective quality control can bolster a company's reputation and marketability.

Various approaches exist for detecting gaps in printed patterns, including manual inspection and computer vision-based methods. The manual inspection involves human operators visually examining the printed patterns, which can be time-consuming, prone to human error, and less efficient as production scales up. In contrast, computer vision-based methods employ image processing and pattern recognition algorithms to automatically identify and evaluate gaps in printed patterns, offering advantages such as speed, accuracy, and non-destructive testing.

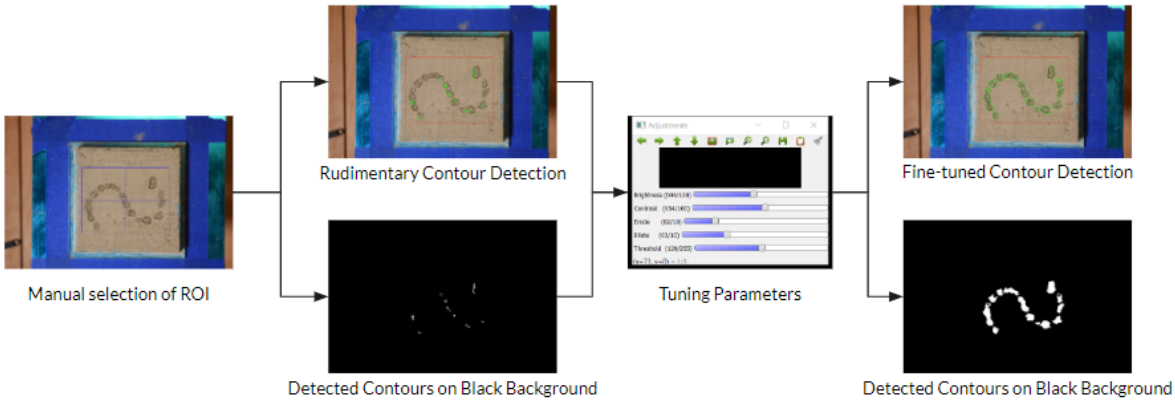
This study presents an image processing pipeline for identifying gaps in binder droplet wetting patterns by comparing predefined patterns to captured images of the printed result for each layer. The pipeline consists of four primary stages: preprocessing, contour identification, similarity comparison, and gap visualization, and is developed using the OpenCV library in Python. This pipeline offers the flexibility to handle various printed patterns and automatically detects and displays gaps. Utilizing this pipeline, the author can achieve higher shape accuracy and reduced binder consumption for concrete printing tasks, enhancing the overall quality and efficiency of the manufacturing process.

Contour Detection

The contours of preprocessed images are identified using the findContours function in OpenCV. Contours represent continuous curves that trace the boundaries of objects in an image. In the context of gap detection, contours serve as the borders of the printed patterns. Upon thresholding, the findContours function examines the binary image and generates contours by connecting adjacent pixels with similar intensity values.

After identifying the contours, they are sorted by area using a custom sort_contours function. Sorting the contours by area allows for focusing on the most significant aspects of the printed pattern while disregarding minor, irrelevant elements that could have been detected due to noise or distortions. The top 10 largest contours are selected for further analysis as they typically represent the primary components of the printed pattern.

The contour area, representing the size of the printed pattern's components, is a crucial aspect of the gap detection technique. By concentrating on the largest contours, the algorithm can effectively identify gaps and inconsistencies in the most critical regions of the pattern. Moreover, selecting contours based on contour area minimizes the influence of noise or artifacts on the gap detection process, thereby enhancing the overall accuracy and consistency of the method in the context of 3D concrete printing applications.

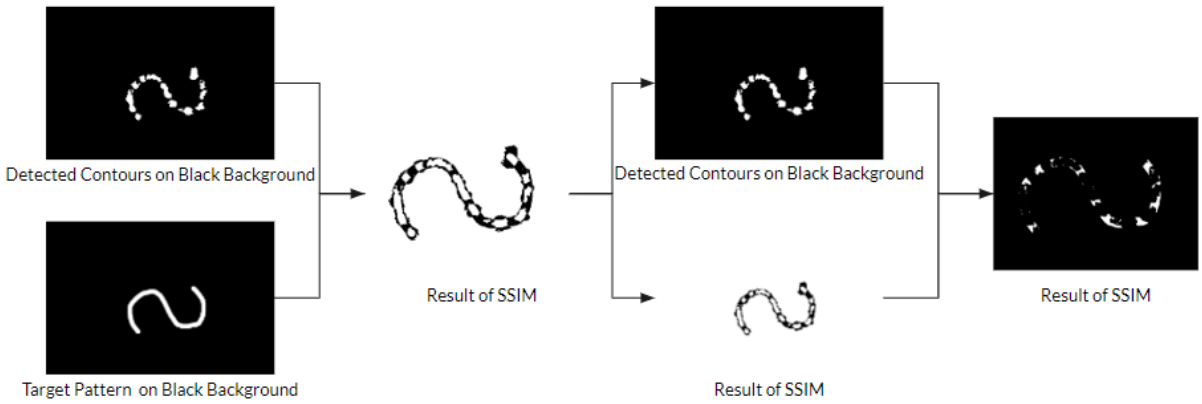


Similarity Comparison

The Structural Similarity Index Measure (SSIM) is a widely-used similarity metric for quantifying visual resemblance between two images. In the gap detection approach, SSIM is employed to compare the contours of the original pattern and the printed output. SSIM offers greater robustness and reliability than other similarity measures, such as Mean Squared Error (MSE) or Peak Signal-to-Noise Ratio (PSNR), as it accounts for brightness, contrast, and structural information within the images.

SSIM incorporates local and global image statistics, which capture brightness, contrast, and structural details, to calculate similarity. SSIM values range between -1 (completely dissimilar) and 1 (identical). During the gap detection process, the SSIM is computed for each pair of corresponding contours in the original pattern and the printed output. Lower SSIM values indicate substantial differences between the original and printed contours, suggesting the presence of gaps or irregularities in the printed pattern.

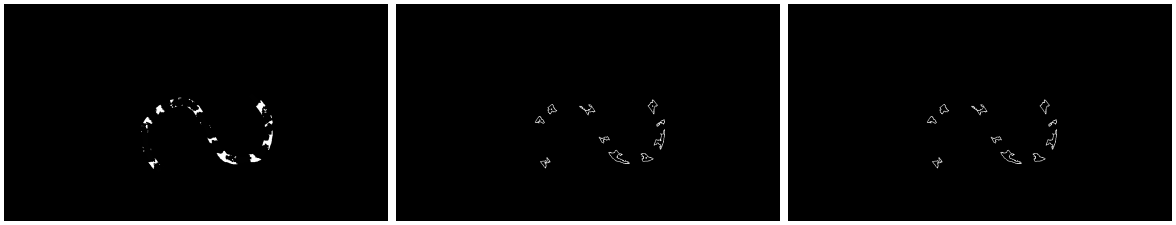
While similarity measures such as MSE and PSNR can also be utilized for image comparison, they may not capture visual resemblance as effectively as SSIM. PSNR evaluates the ratio between the maximum possible power of a signal and the power of the noise, whereas MSE measures the average squared difference between corresponding pixel values in two images. These metrics may provide useful insights for comparing images; however, their focus on pixel-level variations might not fully account for structure, contrast, and brightness information, resulting in a less comprehensive assessment than that offered by SSIM.



Gap Visualization

The gap visualization phase in the pipeline involves highlighting and pinpointing the centroids of detected gaps on a background image. Utilizing OpenCV's drawContours function, the contours of the identified gaps are drawn onto the background image, and the circle function is employed to mark the centroids of the gaps with circles. The resulting image offers a clear and concise representation of the observed gaps, enabling users to quickly identify problematic areas within the printed pattern.

Visualizing the detected gaps is a crucial aspect of the gap identification process, as it allows users to better understand the issues within the printed pattern and determine the most appropriate course of action. By providing a clear visual depiction of the gaps, users can swiftly locate problem areas in the pattern and decide on suitable solutions, such as adjusting the printing process, performing equipment maintenance, or implementing other remedial measures. The gap detection method generates an image file that can be saved as a visual record of the identified gaps or displayed in a graphical user interface for more detailed examination. Utilizing this output, users can analyze the discovered gaps and, if necessary, take further action, such as conducting a more comprehensive analysis of the affected areas or adjusting the algorithm's settings for improved accuracy.



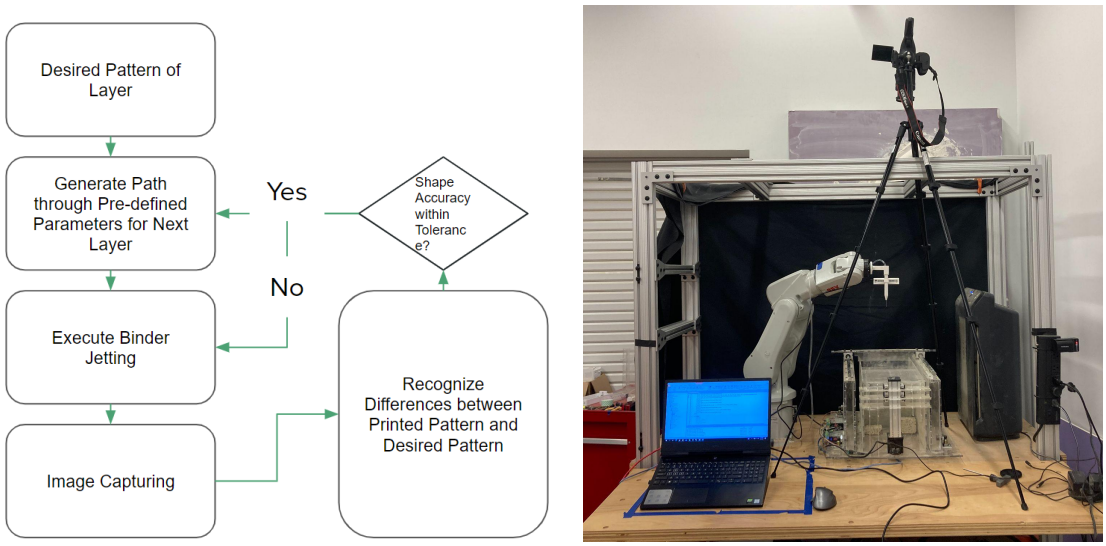
Left:Result of SSIM; Mid: Contours of Gaps within Target Range; Right:Mark Centroid of Gaps Contour Detection

Pipeline and Printing Process



Left: pattern of 3.5 mm spacing pattern printing; Mid: pattern of first-round add binder; Right: pattern of second-round add binder

Through the test prints conducted, this pipeline effectively detected gaps and generated paths based on the missing points. The accompanying images demonstrate the successful execution of gap detection and binder dispensing to fill the missing parts, achieving the desired shape accuracy. It is essential to note that gap detection accuracy highly depends on image resolution, while localization accuracy can be influenced by camera shifting and vibrations during image capture. To ensure precise localization of the generated path for the missing parts, a depth camera was mounted to the print head, which was brought to the same location for image capture before and after the printing process. These images were then used for mapping based on feature points, transferring the missing parts detected in high-resolution images to the coordinate system.



Left: System Pipeline; Right: Printing Setup with IRB-120

The entire procedure can be described as an integrated pipeline consisting of cameras, computers, a printing bed, and robotic arms. This proposed pipeline begins with a predefined path generated according to the desired pattern and printing parameters such as layer thickness and binder spacing. The IRB-120 robot performs the printing process by dispensing the binder onto the concrete composite's top surface. Upon completing each layer, a top-mounted camera

captures a high-resolution image, while the depth camera on the IRB-120 is raised to a higher position by the robotic arm to photograph the entire printed pattern consistently.

The high-resolution images are subsequently processed and analyzed on a computer, comparing the printed parts to the desired pattern generated based on the predefined path and average bleeding width associated with different mixing ratios of the concrete composite. If the printed part's pattern accuracy falls below a certain threshold, the missing areas are mapped onto the low-resolution image taken by the depth camera and localized based on feature points. If the pattern accuracy meets the threshold, the next layer is processed using the same pipeline.

This approach ensures consistent quality control and accurate pattern reproduction throughout the 3D concrete printing process, contributing to the advancement of more reliable and mechanically stable printed structures for construction applications.

3. Results

Preliminary Test Print

Two tests were conducted to validate the proposed pipeline and system. The first test utilized image-based monitoring with a uniform mixing ratio composite and a 5 mm layer thickness. A comparison of binder spacing of 2 mm (continuous pattern) and 3.5 mm (image monitoring to fill gaps) demonstrated enhanced quality and accuracy with image monitoring. The second test examined the effects of different mixing ratios, which influenced layer thickness variations. A comparison of oversaturated printing (maintaining shape consistency) and the correct saturation rate (displaying some gaps) highlighted the advantages of image-based monitoring.

Same Mixing Ratio of Concrete Composite Printing Test:

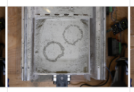
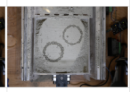
The results of the first test print emphasize the benefits of the image-based monitoring process, leading to reduced binder usage and a lighter product, considering less binder bleeding to react with cement, resulting in fewer aggregates being bound together. The overall shape accuracy revealed that the wall thickness of the image-based monitoring results was approximately 31.82% thinner than the results without image-based monitoring, while the weight decreased by 26.78% for the product incorporating image-based monitoring. Additionally, binder usage decreased from 54 ml to 50.5 ml.

	Without Image Monitoring	With Image Monitoring
Weight (g)	534	391
Dimension (mm)	105 * 100 * 44	90 * 93 * 44
Wall Thickness (mm)	22	15

Hole Depth (mm)	7	13



Table: Dimension of two print products; Left: Without Image Monitoring; Right: With Image Monitoring

	Layer0	Layer1	Layer2	Layer3	Layer4	Layer5	Layer6	Layer7	Layer8
Spacing 2 mm (Bottom-Left)									
Layer Picture									
Total Number of Pts	120	122	132	141	152	137	129	122	120
Initial Read	50	44	38	30	23	15	33	26.5	20
Finish Read	47	41	35	26.5	19.5	12	30	24	17
Total Volume (ml)	3	3	3	3.5	3.5	3	3	2.5	3
Droplet Volume (ml)	0.025	0.02459016393	0.02272727273	0.02482269504	0.02302631579	0.02189781022	0.02325581395	0.02049180328	0.025
Spacing 4 mm (Upper-Right)									
Layer Picture									
Total Number of Pts	60	61	66	71	76	69	65	61	60
Initial Read	47	41	35	26.5	19.5	12	30	24	17
Finish Read	46	40	33.5	25	18	10.5	28.5	22.5	16
Total Volume (ml)	1	1	1.5	1.5	1.5	1.5	1.5	1.5	1
Droplet Volume (ml)	0.01666666667	0.01639344262	0.02272727273	0.02112676056	0.01973684211	0.02173913043	0.02307692308	0.02459016393	0.01666666667

Printing Process for Same Mixing Ratio of Concrete Composite

Different Mixing Ratio of Concrete Composite Printing Test:

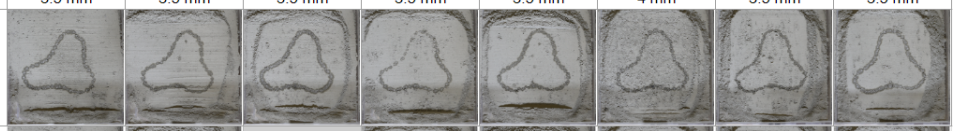
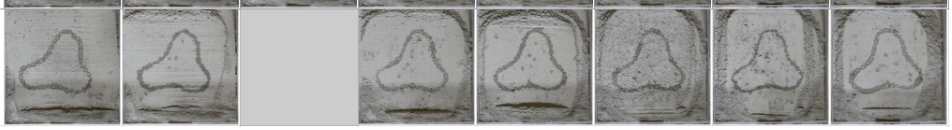
The second test print's results underscore the advantages of the image-based monitoring process across different mixing ratios of concrete composite and varying layer thicknesses

corresponding to the different mixing ratios. Similar to the previous test, the printed product with the image-based monitoring system exhibited lower weight, reduced bleeding, and decreased binder usage. The overall shape accuracy indicated that the wall thickness of the image-based monitoring results was approximately 25.00% thinner than the results without image-based monitoring, while the weight decreased by 31.82% for the product with image-based monitoring. Moreover, binder usage decreased from 48 ml to 39.5 ml.

	Without Image Monitoring	With Image Monitoring
Weight (g)	792	540
Dimension (mm)	150 * 130 * 40	142 * 120 * 40
Wall Thickness (mm)	20	15
Hole Depth (mm)	40	40



Table: Dimension of two print products; Left: Without Image Monitoring; Right: With Image Monitoring

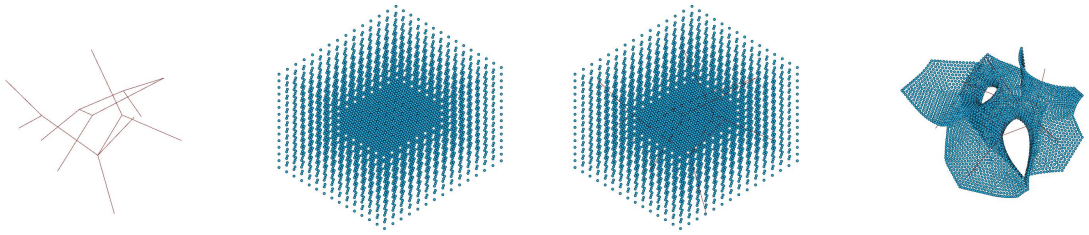
	Layer 0	Layer 1	Layer 2	Layer 3	Layer 4	Layer 5	Layer 6	Layer 7
Layer Thickness	5 mm	3 mm	8 mm	5 mm	3 mm	8 mm	3 mm	5 mm
Mixing Ratio (Cement:Sand:Aggregates)	1 : 1 : 2	1 : 1 : 1	1 : 1 : 3	1 : 1 : 2	1 : 1 : 1	1 : 1 : 3	1 : 1 : 1	1 : 1 : 2
Spacing Between Droplets	3 mm	2 mm	2 mm	2 mm	2 mm	2 mm	2 mm	2 mm
Without Image Monitoring								
Spacing Between Droplets	3.5 mm	3.5 mm	3.5 mm	3.5 mm	3.5 mm	4 mm	3.5 mm	3.5 mm
With Image Monitoring (Before)								
With Image Monitoring (After)								

Printing Process for Different Mixing Ratio of Concrete Composite

Object Design and Test Printing

In this study, the author delved into the intricacies of 3D concrete printing by investigating the printing of partial minimal surface objects. Emphasizing the complexity of the design process and the required modifications involving predefined boundaries and collision components for shape-finding, our research aimed to demonstrate the adaptability of our pipeline and custom system for complex shape printing across various dimensions.

Designing Unique Geometry with Minimal Surface Principles



Shape-finding Process

The utilization of the Kangaroo physics engine, an adjunct to the Grasshopper plug-in within Rhino, permitted the manifestation of complex minimal surface designs through the distinct manipulation of geometry. By establishing boundaries and spheres on a grid composed of 225 (15*15 points grid) points, we facilitated the emergence of minimal surfaces predicated on the computation of spring forces.

```
1: procedure RunScript(Pt, CA, CB, k, A)
2:     A ← newinstanceofMid(Pt, k, CA, CB)
3: end procedure

4: procedure Mid(Pt, k, TargetA, TargetB)
5:     PPos ← arrayofpointsthisgoalactson
6:     Move ← arrayofvectors, oneforeachPPos
7:     Weighting ← arrayofdoublesforhowstronglythegoalaffectseachpoint
8:     Strength ← k
9:     this.TargetA ← TargetA
10:    this.TargetB ← TargetB
11: end procedure

12: procedure Calculate(p)
13:    thisPt ← getcurrentpositionoftheparticle
14:    closestA ← findclosestpointonTargetAtothisPt
15:    closestB ← findclosestpointonTargetBtothisPt
16:    toMidPt ← midpointofclosestAandclosestB
17:    if pointwasfoundonbothTargetAandTargetB then
18:        MoveparticletowardstoMidPt
19:    else
20:        Donotmoveparticle
21:    end if
22: end procedure
```

Pseudocode for 3D Geometry Manipulation

In the process, pivotal components included SphereCollide and SolidPointCollide. The former simulated and calculated interactions between a multitude of identically sized spheres, each of which represented a point within our grid. The latter was responsible for maintaining a group of points outside or inside a predefined mesh, represented by a bounding box. This box encapsulated the designer's vision, intimating the areas where the shape was expected to infiltrate.

Within the custom C# component, it was initiated by defining a novel class, 'Mid', which extended from the 'GoalObject' class supplied by the Kangaroo physics engine. This class was conceptualized to articulate a bespoke goal for the physics simulation. It housed properties including 'Strength', 'TargetA', 'TargetB', and arrays 'PPos', 'Move', and 'Weighting'.

The constructor of the 'Mid' class received input parameters from the 'RunScript' function and initialized the aforementioned properties. These parameters encompassed a 3D point 'Pt', lists of curves 'CA' and 'CB', and a numeric parameter 'k'. The 'RunScript' function was tasked with

the instantiation of the 'Mid' class using these input parameters and subsequently assigned the instance to the output variable 'A'.

However, the linchpin of this class was the 'Calculate' method, which delineated the behavior of the goal. For each particle involved in the physics simulation, this method identified the points on the curves in the 'TargetA' and 'TargetB' lists that were closest to it. It then computed the midpoint between these two points and adjusted the particle's movement in the direction of this midpoint.

The 'Calculate' method commenced by obtaining the particle's current position. For each curve within 'TargetA' and 'TargetB', it ascertained the point on the curve closest to the current particle position. It retained the closest point and its distance from the particle for each list of curves. The method then calculated the vector to the midpoint between the closest points on 'TargetA' and 'TargetB' from the current particle position. If a valid closest point was discovered on both sets of curves, the method modified the particle's movement in the direction of the computed midpoint. If no valid points were identified, the particle's movement remained unaltered.

The degree of modification was contingent on the 'Weighting' factor and the direction from the closest points on 'TargetA' and 'TargetB' to the midpoint. Thus, the custom C# component not only modulated the trajectory of particles within the simulation but also facilitated the customization of the geometry based on the user-specified 'Weighting' factor.

In essence, the integration of the custom C# component significantly bolstered our capability to manipulate geometries. By formulating custom rules and objectives within the Kangaroo physics engine, it was able to materialize intricate and unique minimal surface designs. This methodology offers a potent instrument for prospective design and architectural applications, empowering the generation of exceedingly complex and aesthetically pleasing structures. The final result was a distinctive geometry that combined multiple minimal surfaces seamlessly, showcasing the potential of our custom-developed system for intricate geometric printing.

Optimizing Gap Detection, Mapping, and Binder Dispensing Processes

In order to optimize the gap detection, gap mapping, and binder dispensing processes, an integrated approach was implemented using Grasshopper, specifically incorporating a Python component to call our externally coded gap detection program. By employing the FilePath component, images were able to be accessed by the Canon R6 and Realsense cameras seamlessly. Furthermore, the component devised an input for the target pattern, which was generated based on the predefined path, taking into account offsets on both sides with the average spreading width. The output file, transmitted from the external gap detection program, presents the contours and centroids of the missing parts on the Python component's output side. It is essential to preserve the same ratio between the input and output files to ensure accurate centroid mapping in subsequent stages.

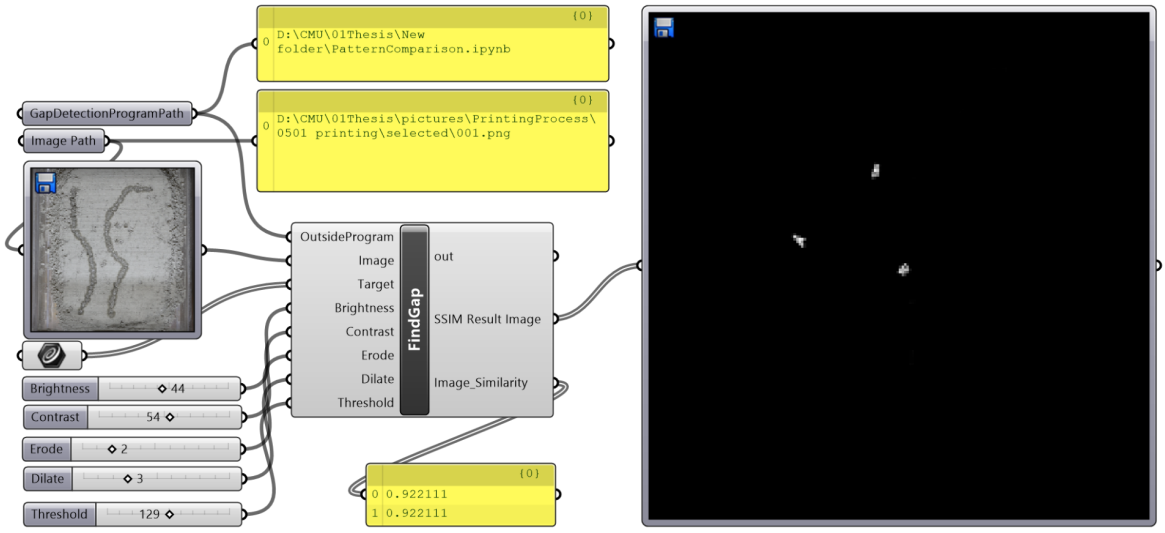


Table: Dimension of two print products; Left: Without Image Monitoring; Right: With Image Monitoring

Accurate Mapping of Centroids Using Ground Truth

Subsequently, the image captured by the Realsense camera serves as the ground truth, facilitating the program's ability to map centroids back to the coordinate system accurately. The process can be broken down into the following distinct steps: (1) identifying corresponding feature points present in both the high-resolution Canon R6 image and the low-resolution Realsense camera image; (2) calculating the transformation matrix applicable to the high-resolution image; (3) applying the transformation matrix to the output image, which is marked with the centroids of the missing parts; (4) determining the coordinates of the missing part centroids based on the low-resolution image frame's coordinates within the Rhino software; (5) obtaining the points of the missing parts within Rhino; and (6) acquiring the two closest points from the predefined path points for each missing part centroid.

Demonstrating Layer Thickness Variations with Plastic Fibers

In order to demonstrate layer thickness variations, plastic fibers were strategically incorporated after each printed layer. Our previous research revealed that plastic fibers impede binder spreading between layers, reducing adhesion and potentially causing green body collapse during excavation. To address this issue, plastic fibers were randomly arranged to ensure no overlap between layers. This approach not only mitigated the risk of green body collapse but also effectively highlighted layer thickness differences, providing valuable evidence that our proposed pipeline and custom-developed system are suitable for various mixing ratios and layer thicknesses of concrete composites.



Plastic fiber indicates the difference of layer thickness

The resulting observations confirmed that the plastic fibers effectively highlighted the differences in layer thickness for various layers, providing valuable evidence that our proposed pipeline and custom-developed system are indeed suitable for different mixing ratios and layer thicknesses of concrete composites. This innovative approach, coupled with the integration of image-based monitoring techniques, ensures enhanced quality control and accurate pattern reproduction throughout the 3D concrete printing process.

Mechanical Problem



Left: Mechanical Stucked*; Mid:* 1st Round Image Monitoring; *Right:* 2nd Round Image Monitoring

An observation of critical importance is that the longevity of the performance of our self-developed devices can be compromised during extended printing operations, particularly those exceeding a duration of five hours. Specifically, the printing head and the attached nozzle, both of which are linked to a stepper motor, are susceptible to overheating and subsequent power loss.

This mechanical issue surfaced during our second test print, resulting in an insufficient binder being dispensed for a specific layer. Fortunately, our integrated image monitoring system identified the incomplete sections and instructed the robotic arm to reposition and dispense additional binder.

However, the detection process is more time-consuming than the average operational task, which leads to a delay in the printing process. During this interval, the upper surface of the mixtures was exposed to air and began to dry out. This resulted in some sections of the previously printed layer turning a whitish color, indicative of drying. This change in color led to a misinterpretation by the image monitoring system, which mistakenly identified these areas as also lacking in binder. Consequently, it issued a command for additional binder dispensation over those regions. After two iterations of binder dispensation, the printed pattern became more uniform and closely aligned with the desired output. While the detection process and binder re-dispensation prolonged the printing process, it significantly enhanced the final print's accuracy and consistency.

In essence, this experience underscores the importance of real-time monitoring in 3D printing. While it may extend the process duration, it provides an opportunity to rectify errors during the printing process, thereby ensuring the production of high-quality and accurate prints.

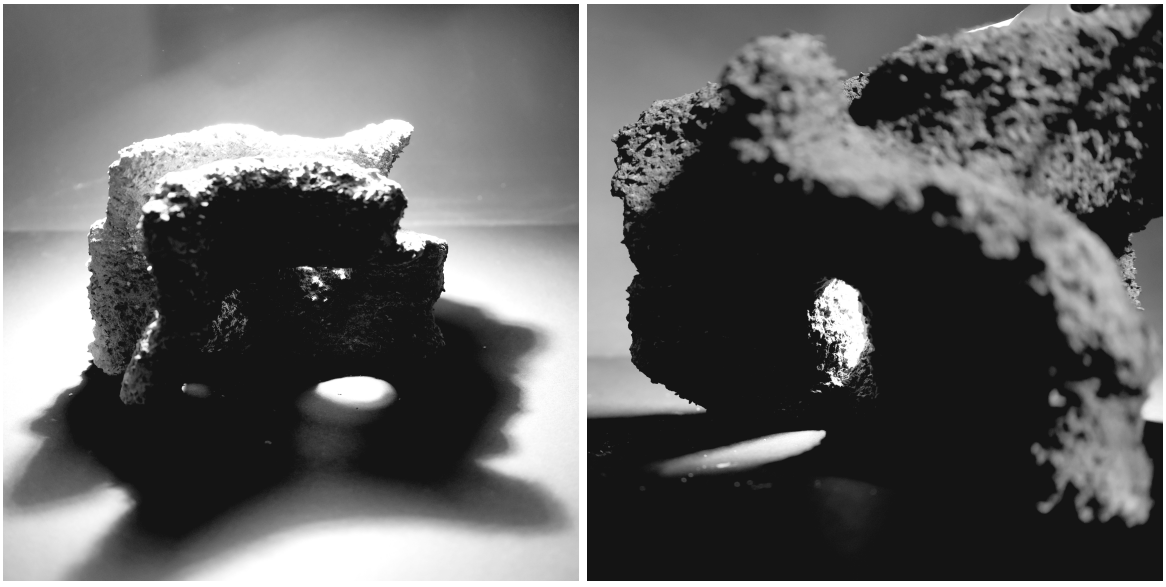
Final Print

In light of the findings from the most recent 3D printing test, several modifications have been implemented to optimize the final print. The previous test highlighted certain deficiencies, prompting the refinement of the projected shape into a more square configuration. This transformation was made in response to the preceding results.

A significant challenge posed by the previous design was the difficulty in cleaning the bottom part post-printing due to the excavation process. To circumvent this issue, a restructured shape, inverted from its original form, was designed and sliced for printing. This modification anticipates an ease in post-printing cleanup. Concurrently, to mitigate the bleeding effects incurred by excessive support deposit paths, the quantity of these paths was reduced. This step aimed at enhancing the overall print quality by minimizing distortions and imperfections.

Additionally, we noted from the previous printing test that a smoother and flatter top surface significantly aids the gap detection process. To achieve this, we opted to increase the amount of material deposited in each layer. This strategy ensures a cleaner and smoother top surface, thereby facilitating more efficient gap detection.

Lastly, by increasing the quantity of material used for each layer, a cleaner surrounding area for the selected Region of Interest was ensured. This will lead to a more polished final print, enhancing the overall quality and aesthetic appeal of the product.



Final Printing

Implications for Future Research and Applications

The complexity of 3D concrete printing processes was examined throughout this work, with a focus on material characterisation, choosing the appropriate concrete composite mixing ratio,

and the creation of an image-based monitoring system. Our research showed how important it is to obtain the appropriate pattern precision and green body strength for excavation by carefully balancing material ratios, layer thickness, and binder spacing. Additionally, the image-based monitoring system efficiently found gaps and anomalies in the printed patterns, improving the production process' overall quality and effectiveness.

Our test prints' outcomes demonstrated the advantages of image-based monitoring, including less binder consumption, lighter products, and better form correctness. The system's flexibility in adapting to different concrete composite mixing ratios and associated layer thicknesses proved useful for a variety of printing applications. Additionally, our research into printing partial minimum surface objects demonstrated the capability of our specially built method for printing complicated shapes in various dimensions.

The integration of Grasshopper with our external gap detection program streamlined the optimization process for gap detection, mapping, and binder dispensing. The use of high-resolution images and the incorporation of plastic fibers to demonstrate layer thickness variations provided valuable insights into the printing process.

In reflection, this study offered a comprehensive understanding of the factors affecting 3D concrete printing and the development of an innovative monitoring system to ensure accurate pattern reproduction and consistent quality control. By combining material optimization, image-based monitoring techniques, and a robust pipeline, we have laid a solid foundation for future research and advancements in 3D concrete printing processes. Our findings have the potential to transform the construction industry, facilitating the development of reliable and mechanically stable printed structures for various applications

Moreover, the image-based monitoring system employed in our study contributes significantly to the overall quality and efficiency of the manufacturing process. The system's adaptability to different concrete composite mixing ratios and corresponding layer thicknesses demonstrates its versatility for diverse applications, enabling it to cater to a variety of construction projects.

4. Conclusion and Discussion

4.1. Conclusion

Through our research, a practical pipeline for incorporating image-based monitoring into 3D concrete printing techniques used in construction has been created. By fusing a high-resolution camera with a depth camera, we have developed a useful method for monitoring the printing process in real-time, offering improved quality control for each printed layer. Through a variety of trials, the advantages of image-based monitoring have been proven to include reduced binder consumption, lighter products, and greater form accuracy, all of which result in more dependable and long-lasting 3D printed structures.

This study also looked at several quality assurance procedures for 3D printing fields. By experimenting with different mixture ratios and layer thicknesses, we have discovered a lot

about how to improve the uniformity of binder jetted regions. This knowledge will be extremely helpful for the development of hybrid materials as well as the 3D printing of concrete for usage in structures.

4.2. Contribution

The study has made significant progress in our knowledge of image-based monitoring in additive manufacturing and cleared the way for advancements in the 3D printing of concrete for application in the building sector. By addressing the identified limitations and further expanding the existing process, the possibility for large-scale, high-quality 3D printed buildings will become more feasible, which will transform the building industry.

4.3. Limitation

It's crucial to understand that the printing and gap detecting procedures are not entirely automated by current technology. This limitation allows room for future developments that might optimize the whole printing process and raise its accuracy and productivity. Additionally, the research has demonstrated that hardware leakage may negatively impact the accuracy of binder extrusion, underlining the need for more precise hardware to enhance the overall performance of 3D concrete printing. There is always opportunity for improvement, even if the current technology has effectively incorporated image-based monitoring into 3D concrete printing. Future work should focus on fully automating the printing and gap detection processes, as well as addressing issues with hardware leakage and binder extrusion accuracy. By fine-tuning the hardware components and boosting the system's accuracy, the construction industry may benefit from more trustworthy and robust 3D printed structures that incorporate the benefits of image-based monitoring.

4.4. Future Work

Although the selective binder jetting approach, which is a powder-based printing technique, will not be constrained by the length of the hose and pressure in the pump, robust powder tanks are required to contain powder in each layer and the size of the tanks limits the component. In the meantime, a potential solution would be allowing another machine to dispose of the mixing materials in a boundless site considering the angle of repose to make the mobile printer traverse around as long as the robotic arm can reach the tasks at hand. Whatsmore, the refill of the binder and carrying volume, on the other hand, will create a trade-off situation in which a greater volume of the binder will reduce the moving distance but a small amount of the binder will waste time on refilling.

There are several intriguing opportunities for additional growth in addition to tackling the present limits. For instance, the multi-robot form of the conceptual framework can significantly boost production, although it is inherently more difficult. It calls for a motion planning algorithm, for example, that can plot the best routes for mobile bases while taking into account numerous printing pathways, multi-robot obstacle detection, and material supplementation.

Bibliography

[1]. Leusch, Verena, et al. “On the invention of gold metallurgy: The gold objects from the Varna I cemetery (Bulgaria)—Technological consequence and inventive creativity.” Cambridge Archaeological Journal 25.1 (2015): 353-376.

[2]. ISO/ASTM 52900(en) Additive manufacturing — General principles — Terminology

[3]. Attaran, Mohsen. “The rise of 3-D printing: The advantages of additive manufacturing over traditional manufacturing.” Business horizons 60.5 (2017): 677-688.

[4]. Michaels, Steven, Emanuel M. Sachs, and Michael J. Cima. “Metal parts generation by three dimensional printing.” 1992 International Solid Freeform Fabrication Symposium. 1992.

[5]. Hossain, Md Aslam, et al. “A Review of 3D Printing in Construction and its Impact on the Labor Market.” Sustainability 12.20 (2020): 8492.

[6]. Brun, Francis, et al. “Experimental study on 3D printing of concrete with overhangs.” RILEM International Conference on Concrete and Digital Fabrication. Springer, Cham, 2020.

[7]. Sachs EM, Haggerty JS, Cima MJ, Williams PA. Three-Dimensional Printing Techniques, US5340656 A; 1993

[8]. Wohlers T. Wohlers report 2014: 3D printing and additive manufacturing state of the industry; 2014. ISBN 978-0-9913332-0-2.

[9]. Valente, Marco, Abbas Sibai, and Matteo Sambucci. “Extrusion-based additive manufacturing of concrete products: revolutionizing and remodeling the construction industry.” Journal of composites science 3.3 (2019): 88.

[10]. Cesaretti, Giovanni, et al. “Building components for an outpost on the Lunar soil by means of a novel 3D printing technology.” Acta Astronautica 93 (2014): 430-450.

[11]. Gibson, Ian, et al. Additive manufacturing technologies. Vol. 17. Cham, Switzerland: Springer, 2021.

[12]. Talke, Daniel, Klaudius Henke, and Daniel Weger. “Selective Cement Activation (SCA)–new possibilities for additive manufacturing in construction.” Proceedings of IASS Annual Symposia. Vol. 2019. No. 6. International Association for Shell and Spatial Structures (IASS), 2019.

[13]. Buswell, Richard A., et al. “3D printing using concrete extrusion: A roadmap for research.” Cement and Concrete Research 112 (2018): 37-49.

[14]. Lowke, Dirk, et al. “Particle bed 3D printing by selective cement activation–Applications, material and process technology.” Cement and Concrete Research 134 (2020): 106077.

[15]. Xia, Ming, Behzad Nematollahi, and Jay Sanjayan. “Influence of binder saturation level on compressive strength and dimensional accuracy of powder-based 3D printed geopolymer.” Materials science forum. Vol. 939. Trans Tech Publications Ltd, 2018.

[16]. Keating S, Spielberg NA, Klein J, Oxman N (2014) Version digital construction platform: a compound arm approach. Robot Fabr Archit Art Des 4:99–110

[17]. Bell, Julian Leland. Development of an experimental platform for architectural-scale robotics: the Digital Construction Platform. Diss. Massachusetts Institute of Technology, 2017.

[18]. Keating, Steven J., et al. “Toward site-specific and self-sufficient robotic fabrication on architectural scales.” Science robotics 2.5 (2017): eaam8986.

[19]. http://www.life.dad.puc-rio.br/projetos-english/NEXTBot-english.html

[20]. http://www.life.dad.puc-rio.br/projetos-english/3eDBot-english.html

[21]. Marques, Lucas Galvan, Robert Austin Williams, and Wenchao Zhou. “A mobile 3D printer for cooperative 3D printing.” 2017 International Solid Freeform Fabrication Symposium. University of Texas at Austin, 2017.

[22]. Steck, Jason, et al. “A mobile robot gripper for cooperative 3d printing.” 2017 International Solid Freeform Fabrication Symposium. University of Texas at Austin, 2017.

[23]. Tiryaki, Mehmet Efe, Xu Zhang, and Quang-Cuong Pham. “Printing-while-moving: a new paradigm for large-scale robotic 3D Printing.” 2019 IEEE/RSJ International Conference on Intelligent Robots and Systems (IROS). IEEE, 2019.

[24]. Sauter, Andreas. TechBot: A Multimaterial Mobile 3D Printing Platform. Diss. Tennessee Technological University, 2019.

[25]. Xu, Xuchu, Ziteng Wang, and Chen Feng. "Projector-Guided Non-Holonomic Mobile 3D Printing." 2021 IEEE International Conference on Robotics and Automation (ICRA). IEEE, 2021.