Towards Adaptive Additive Manufacturing

Image-based Monitoring for Binder Jet 3D Printing of Coarse Composite Concrete Powders

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1 Result of robotic binder jetting using coarse composite concrete powder supported by an image-based monitoring system.

ABSTRACT

In the context of concrete 3D printing, this study explores the possibility of image-based monitoring for quality evaluation and improvement in powder-based binder jetting procedures for the use of coarse powders. The project's main goal is to create an integrated feedback loop that incorporates an image-based monitoring system into the printing process. This allows for real-time analysis for quality control and simultaneous incorporation of coarse, composite powders. The overarching goal is to expand the possibility of binder jetting towards more diverse powder sources that would enable a circular economy and material reuse. This study investigates how coarser concrete powder and composite mixing ratios affect the printing process, thus laying the groundwork for the future use of hybrid materials instead of just using homogeneous standard powders. In this framework, image-based monitoring aids in more adaptive printing processes in additive manufacturing, which will ultimately help us create 3D-printed structures that are produced with higher accuracy and sustainablility. These developments will also significantly impact 3D concrete printing in building applications, encouraging innovation and better performance in the additive manufacturing sector.

INTRODUCTION AND IMPACT

Amidst the global upsurge in construction, and the pressing need for carbon neutrality, construction sites currently account for around 37 percent of annual carbon dioxide emissions, according to United Nations Environment Programme (UNEP) 2022. Our research delves into a thorough investigation of the role of image-based monitoring in 3D concrete binder jetting a technique that is gaining increasing traction as a viable solution for the construction industry of the future. The potential of this methodology to minimize material waste and reduce carbon emissions during the construction process forms the cornerstone of our investigation.

Presently, binder jetting technologies operate within certain constraints, predominantly due to the granularity specifics of the highly processed powders utilized. Characteristics such as controlled particle size and roundness are critical, as they aid in the flow and spread of the aggregate during the powder printing process. However, these particular powder characteristics also act as a limitation, excluding coarser and more varied powders. Our objective is to subvert these limitations and augment the range of construction materials. By allowing for the inclusion of varied powders, we aim to facilitate the use of recycled or underutilized materials to reduce the demand for non-renewable natural resources. This approach aligns with the need for ecologically friendly construction processes, and satisfies the demand for construction materials without compromising environmental sustainability. This exploration underscores the potential of 3D concrete printing and image-based monitoring to revolutionize the construction industry and contribute significantly to a sustainable and post-material economy.

Our research aims to expand the impact of binder jetting within a future, circular, material, construction economy of advanced manufacturing by allowing for a wider range and character of powder granularity. The shift to image-based monitoring was influenced by unpredictable changes in binder-powder interactions when altering aggregate ratios or powder materials. By expanding the selective binder deposition feedback loop enabled by computer vision, this study contributes to the ability of the mechanical printing process to adapt to changes in binder deposition amounts and locations, locally and in real time.

This robotic binder jetting experiment, aided by image-based monitoring, is primarily focused on the use of coarse composite powders for concrete — a mixture of water, cement, sand, and aggregate. The precision and quality control provided by image-based monitoring makes it a powerful tool for managing the binder expansion in these traditional concrete materials. Crucially, this research not only underlines the efficacy of image-based monitoring in concrete printing, but also opens the door for a wider array of printable materials. This includes non-standard powders, such as recycled waste materials and functionally graded materials (FGMs). Hence, while our immediate application is concrete, the insights gathered have broader implications, potentially reducing the need for exhaustive material characterization when introducing novel powder materials into binder jetting processes. This study focuses on exploring how 3D concrete printing could contribute to the construction of energy-efficient buildings, thereby reducing the overall energy demand and the associated environental impact. Concurrently, future advancements in printable materials and expedited material characterization processes will be explored to facilitate the sourcing of diverse regional materials proximal to the construction site. Utilizing regional resources will reduce the energy costs involved with transportation. Additionally, situating the selection of construction materials in the context of locally available resources would encourage the use of regionally and sustainably obtained materials. The synergistic reductions in embodied energy through localized material sourcing and operating energy needs, due to energy-efficient design will further accentuate the environmental advantages of 3D-printed buildings.

Our exploration was conducted in the context of larger research focused on non-toxic binder jetting of varied powders, utilizing water as the main activating agent within the printing process. This study primarily aims to overcome prevailing challenges associated with the precision and quality of the printing process when using varied aggregates. We have designed and implemented a novel pipeline that utilizes computer vision to enhance the geometric fidelity and binding quality of components produced through a deposition feedback loop. Expanding upon the processes developed in this study would enable greater variability in aggregate usage, and facilitate more flexible and adaptive advanced manufacturing processes involving various concrete composites. At the same time, this research proves that with the help of image-based monitoring, 3D printing can be much more precise and only use the exact amount of material required, which could reduce waste during the additive manufacturing process.

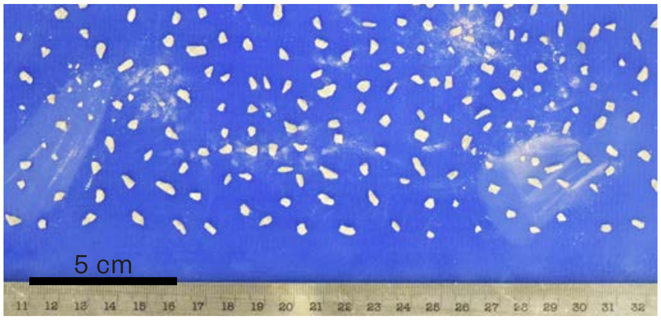
Through this research, we have highlighted the importance of material characteristics, layer thickness, and binder spacing in generating accurate geometric patterns and achieving robust green body strength. This work represents a significant advancement in the field of additive manufacturing, showcasing the potential for innovative use of image-based monitoring in 3D concrete printing.

LITERATURE REVIEW

Binder jetting technology, first patented by Emanuel Sachs in 1993, at MIT, used a combination of gypsum-based powder and water-based binder for printing tasks (Sachs 1993). The landscape of this technology has evolved significantly since then, with significant contributions by ExOne (Wohlers 2014) and innovations such as the D-shaped approach (Valente 2019) and the Binder Jetting technology by Voxeljet Company (Cesaretti 2014), which have facilitated large-scale printing with intricate designs and superior print quality. Clay 3D printing and concrete casting has also drawn attention by creating complex shapes with high accuracy (Mozaffari 2023).

Three comprehensive studies have delved into the intricacies of binder jetting termed 'Particle Powder Bed Fusion 3D Printing' (PBF-3DP). Powder bed fusion 3D printing, through selective cement activation, is a novel technology with transformative prospects for the construction industry. In a comprehensive review, Lowke (2018) examined the potential applications of PBF-3DP in concrete construction, highlighting its precision, environmental benefits, and ability to utilize recycled materials. However, the study also shed light on prevailing challenges, including high equipment costs, skill requirements, and material constraints. Meanwhile, their work provides a contemporary outlook on PBF-3DP, showcasing its successful application in fabricating complex concrete structures, such as bridge columns and building facades. This highlights its potential to redefine sustainable and cost-effective construction practices (Lowke 2020). Researchers' investigation examines the impact of various process parameters, such as layer thickness, printing speed, and curing conditions, on the packing density of the particle bed, which significantly determines the printed structure's strength, durability, and water permeability (Talke 2023). Our study aims to expand the applications of PBF-3DP by utilizing water-based, selective, cement activation with irregular aggregate particle sizes.

The incorporation of sensory technologies like optical, acoustic, or thermal sensors has been instrumental in enabling image-based real-time surveillance during the binder jetting process. Notably, the use of digital image correlation (DIC) for in situ monitoring of additive manufacturing (AM) has been widely reviewed (Cunha 2021). Digital image correlation, a non-contact optical technique, effectively measures the full-field deformation of a surface,



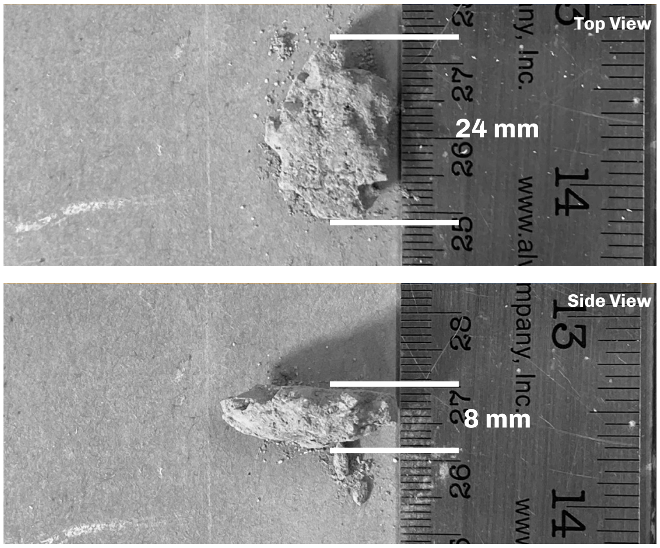
2 Aggregate size analysis. Measured in centimeters.

Table 1

Aggregate Morphology and Different Composite Density

		Aggregate Samples		
		1	2	3
Length and Width (cm)	Average	1.23	1.15	1.20
	Median	1.20	1.12	1.14
Roundness	Average	0.67	0.69	0.67
	Median	0.75	0.76	0.74
		Material Mixing Ratio (Cement: Sand: Aggregate)		
		1:1:1	1:1:2	1:1:3
Bulk Density (g/cm∧3)		1.7212	1.8052	1.8973
Compact Density (g/cm∧3)		1.7393	1.8340	1.9477
Compact Ratio (percent)		1.0516	1.5954	2.6564

3 Table1: It is worthy to note that the ratio of cement to sand to aggregate is measured by weight.



4 As we noticed an increase in water-based binder quantity and the overlapping of binder expansion, a significant enlargement in horizontal expansion was observed. However, interestingly, this increase in horizontal expansion was not proportionally reflected in the penetration depth. This suggests a more nuanced relationship between binder expansion and its impact on both the horizontal spread and vertical penetration within the material matrix.

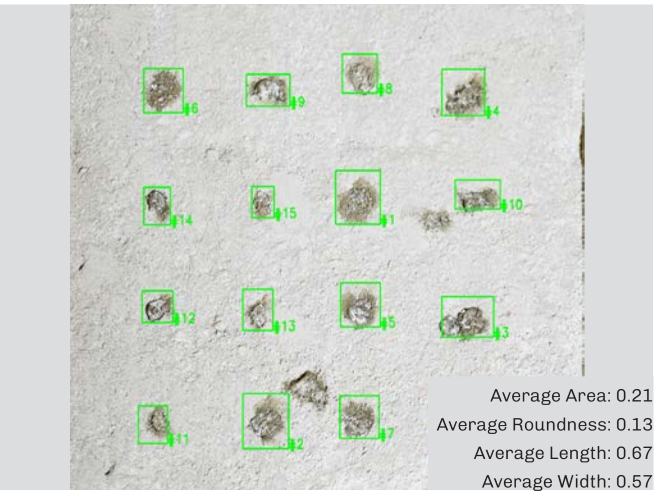
making it optimal for tracking the deformation and failure of AM parts during printing. Another innovative method employs digital image analysis (DIA) for quality control in AM powder beds (Boschetto 2023, Liu 2023). By tracking powder particle movements, this approach can detect defects like voids and clumps, consequently improving AM part quality.

The advancements in multi-material printing processes have significantly expanded the possibilities for fabricating complex and heterogeneous structures. A systematic review of multi-material AM reveals varying design strategies, part properties, and potential applications, including the creation of cellular metamaterials (Nazir 2023). Further studies, such as one evaluating the mechanical and photocatalytic properties of TiO2-reinforced, cement-based materials in binder jet 3D printing, have shown promising results (Liu 2023). Likewise, the development of a novel hybrid method to additively manufacture denser graphite structures using binder jetting demonstrates significant potential in producing high-performance structures (Popov, 2021).

RESEARCH METHODS

Material Characterization

Characterizing cement-based powders is integral to optimizing binder jetting processes in 3D printed structures. Parameters, such as particle size, distribution, morphology, and specific surface area play a vital role in powder bed spreading and binder deposition, directly impacting the stability and consistency of printed components. Fine-tuning the ratios of various materials is essential, given the wide-ranging dimensional diversity of concrete composites. Aggregate size impinges on layer thickness and binder dispersion across different mixing ratios, which, in turn, modulates densities and void fractions within the



5 Single droplet printing test (Cement: Sand: Aggregate = 1:1:2).

Table 2

Single Droplet Printing Test Results Analysis

	Material Mixing Ratio (Cement: Sand: Aggregate)		
	1:1:1	1:1:2	1:1:3
Horizontal Expansion Length (cm)	0.663	0.720	0.790
Horizontal Expansion Width (cm)	0.570	0.600	0.670
Horizontal Expansion Aree (cm^2)	0.205	0.225	0.300
Standard Deviation	0.062	0.087	0.103

6 Table2: To investigate the horizontal expansion of each droplet on the surface of different mixing ratio concrete composite, we designed the path to extrude only one droplet for each point. The horizontal expansion evaluation indicated that an increased aggregate ratio tends to introduce greater unpredictability in horizontal binder expansion. Moreover, we observed an enlarged disparity within identical mixing ratios. Notably, a higher aggregate ratio typically results in a larger horizontal expansion pattern.

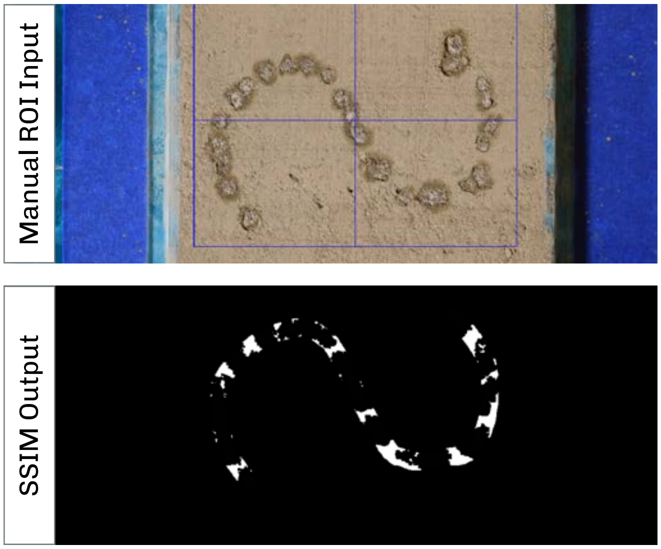
7 Shortline printing test (Cement: Sand: Aggregate = 1:1:2).

Table 3

Shortline Printing Test Results Analysis

		Penetration Depth at Mixing Ratio		
		1:1:1	1:1:2	1:1:3
Saturation Rate	14%	0.3 cm	0.3 cm	0.5 cm
	18%	0.4 cm	0.6 cm	0.8 cm
	22%	0.7 cm	1.0 cm	>1.0 cm

8 Table 3: To investigate the vertical penetration of certain saturation rates with different mixing ratio of concrete composite, we designed the path to extrude droplets for each line. The penetration depth in the 3D printed composite is contingent on the saturation rate and the composite's mixing ratio. Our observations indicate that a higher proportion of aggregates in the mix results in a deeper penetration depth at a constant saturation rate (as defined by the weight ratio of binder to cement). An increased saturation rate results in deeper penetration at the same mixing ratio.



9 Leveraging the Structural Similarity Index Measure (SSIM), we identified discrepancies between the actual printed pattern and the original digital model. This analysis helped pinpoint the contours of missing parts, thereby enabling precise corrective binder placement in the subsequent stages of the printing process.

composite.

Our study focused on aggregate dimensions that mainly varied between 1.12 cm and 1.20 cm (Figure 2), averaging 1.193 cm (Figure3). This presented certain challenges in achieving uniform spreading due to the low particle roundness. The mixing ratio also plays a crucial role in determining the density and porosity of the composite, which has a significant impact on the internal air pressure during cement solidification. A higher aggregate ratio leads to a decrease in internal air pressure during the solidification process, allowing the binder to permeate through voids more effectively (Figure 3). This results in increased porosity within a layer, which is a critical parameter for optimizing layer thickness in 3D concrete printing to enhance structural quality and material efficiency.

Concrete Composite Mixing Ratio Selection and Image Monitoring Test

In this study, we seek to identify the optimal saturation rate and layer thickness, which are pivotal factors for efficiency and quality in 3D printing processes. Here, we define the saturation rate as the weight ratio of water-based binder to cement. Determining the ideal saturation rate and layer thickness is critical to ensure excellent layer adhesion and a satisfactory overall result. For water-based binder jetting deposition, we engineered mix designs for cement-based materials by varying proportions of cement, sand, and aggregate in accordance with binder spacing to achieve geometrical fidelity and adequate green body strength. Binder adjustments were performed to facilitate rapid permeation on the surface of the powder mixture.

We addressed concerns such as oversaturated printing leading to shape deviations, and undersaturated printing resulting in inadequate strength by conducting single droplet and short line printing tests with different concrete composite mixing ratios by weight (1:1:1, 1:1:2, and 1:1:3). We utilized a 100 mm x 100 mm x 10 mm printing bed, an IRB-120 robot, and an image-based monitoring system with a high-resolution camera to carry out these tests.

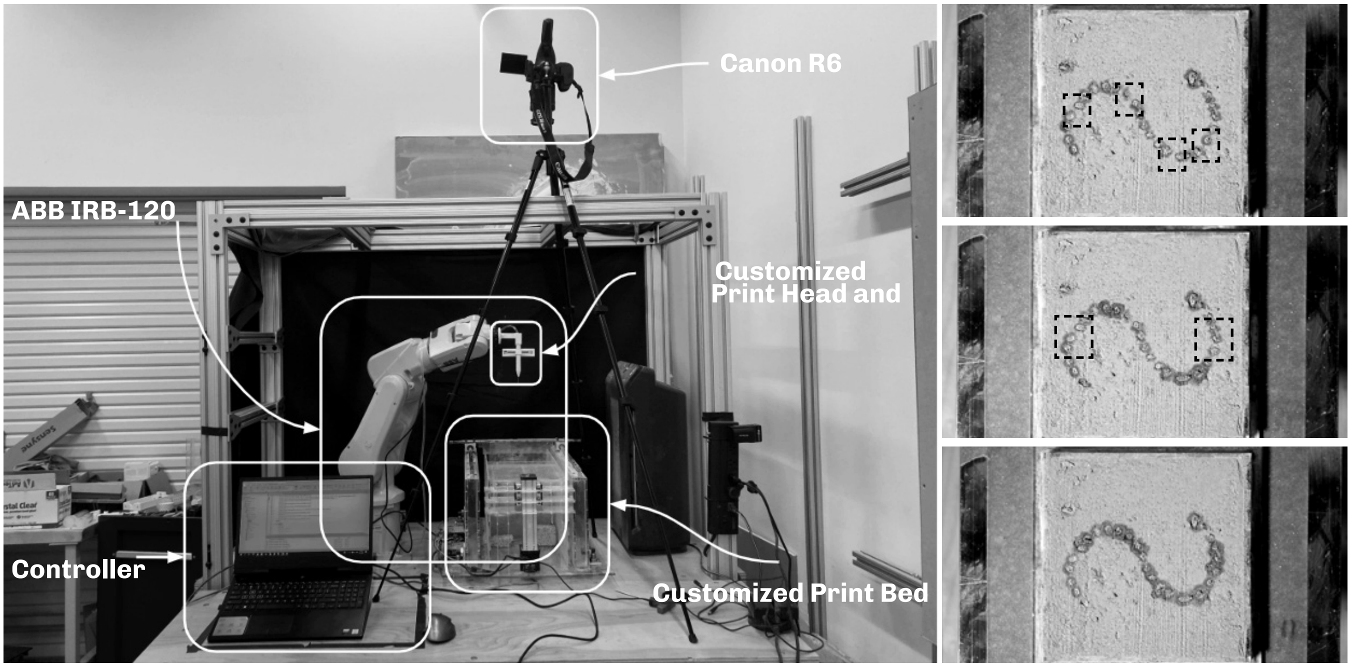
The image capturing system, with a color temperature of 6700 Kelvin (K), enhanced the analysis of the images. The tests showed that a higher proportion of aggregates resulted in more unpredictable horizontal binder expansion due to decreased density and increased porosity within the layer (Figure 5).

The single droplet test prints revealed 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 (Figure 6). This effect may result from the decreased density and increased compatibility of the concrete composite with a higher aggregate ratio, which can lead to increased voidness within a single layer.

Short-line tests (Figure 7) revealed that the penetration depth of varying concrete composite mixing ratios also impacted the vertical binder travel. Larger binder spacing curtailed pattern bleeding and penetration depth. Concrete composites with a lower aggregate ratio and larger binder spacing resulted in reduced bleeding and shallower penetration, while a higher aggregate ratio with smaller binder spacing led to a significant increase in the bleeding area (Figure 8). Based on these findings, we identified appropriate layer thicknesses for different mixing ratios: 3 mm for a 1:1:1 ratio, 5 mm for a 1:1:2 ratio, and 8 mm for a 1:1:3 ratio.

Image-Based Monitoring System Development

The printing pathway for each layer, derived from the original digital model's slicing process, is crucial in determining both the performance and aesthetic appeal of printed products. However, we noticed that mechanical issues cause errors extenuated by irregularity of powder particles, such as inaccurate binder placement or part omission. These errors impact the quality of the final product. These inconsistencies or gaps emerging during the printing process can result from multiple factors, including printing material properties or equipment



10 Upper: Printing Setup with IRB-120; Right-up: binder placement of 3.5 mm spacing pattern printing; Right-mid: binder placement of first-round add binder; Right-bottom: binder placement of second-round add binder; The accompanying images elucidate the interplay of the printing setup and multiple image sensors, a cooperative mechanism integral to the gap detection and filling process. This cooperative system contributes significantly to the control of quality and accuracy in the 3D printing process.

misalignment. Consequently, the quality of the printed path, an essential aspect of product excellence, can be adversely affected.

Our image processing pipeline (Figure 9), developed with Python's OpenCV library, is designed to address this issue and to detect gaps in binder droplet wetting patterns. The pipeline compares predefined printing paths generated from the slicing digital model with captured images of each printed layer's results. The system includes four primary stages: preprocessing, contour identification, similarity comparison, and gap visualization. This system is adaptable to various printed patterns, and autonomously detects and presents gaps, thus enhancing manufacturing quality and efficiency.

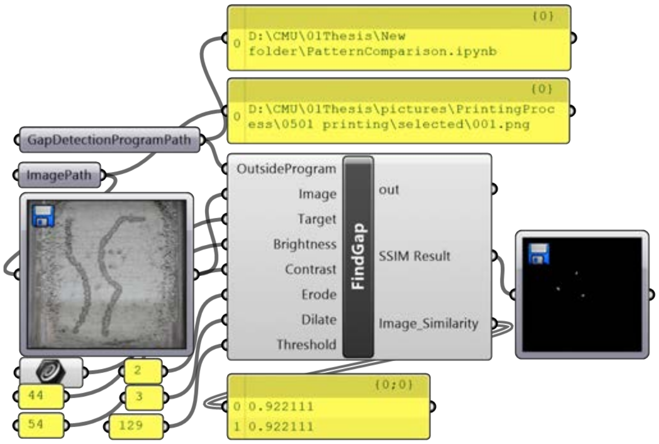
Contours in the image are detected using OpenCV's 'findContours' function. To focus the analysis on significant contours, we apply a filtering criterion based on the size of the contour areas. Specifically, only contours that have an area larger than the mean, plus one standard deviation of all contour areas, are selected for further analysis. This approach helps to eliminate minor contours that might arise from noise or minor features in the image, allowing us to concentrate on the main, significant contours. By focusing on these contours, the algorithm effectively identifies gaps and inconsistencies in the most critical areas of the pattern. The Structural Similarity Index Measure (SSIM) (Wang 2004) is employed to compare the similarity between the digital model contours and the printed output. Structural similarity index measure, is a reliable measure as it considers brightness, contrast, and structural information within the images.

The gap visualization stage involves highlighting and pinpointing detected gap centroids on a background image. OpenCV's ‘drawContours’ function and circle functions are used to represent gaps, assisting users in swiftly identifying issues within the printed pattern. By visualizing detected gaps, users can comprehend the problems within the printed pattern more effectively, and decide on the most suitable corrective measures.

Pipeline Set-up and Printing Process

This study highlights the effectiveness of a holistic pipeline designed for identifying discrepancies, and formulating corrective pathways in 3D printed constructions, thereby augmenting shape precision. The integral components of this pipeline include a depth camera, computers, a printing bed, robotic arms, and imaging technology, all of which work in conjunction to address the challenges of gap detection and localization accuracy.

Commencing with a predefined path derived from the desired pattern and printing parameters such as layer thickness and binder spacing, an IRB-120 robot initiates the printing (Figure 10). Post-printing of each layer, high-resolution images are captured by cameras. These



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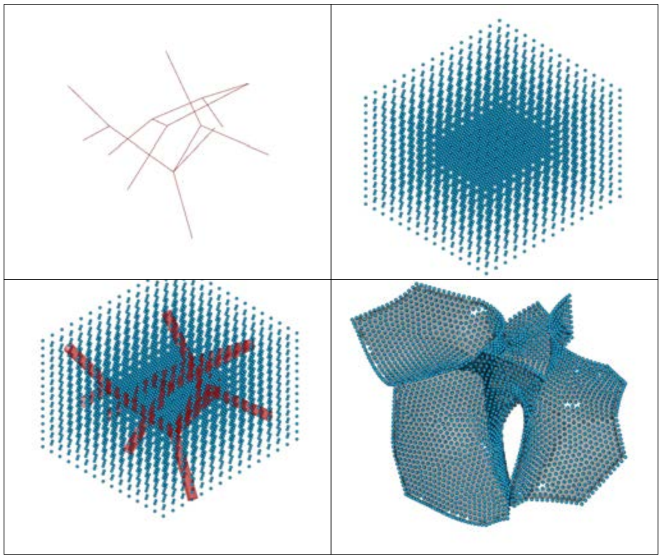
11 The process and the result of integrated gap detection within Grasshopper..

12 Uniform mixing ratio composite and a layer thickness of 5mm. Left: 2mm binder spacing (continuous pattern); Right: 3.5mm spacing (image monitoring to fill gaps).

13 Different mixing ratios on layer thickness vary from 3mm, 5mm, and 8mm. Left: 2mm binder spacing (continuous pattern); Right: 3.5mm spacing (image monitoring to fill gaps).



14 Generating a minimal surface object design through the SphereCollide and PointSolicCollide components in Kangaroo plugin for Grasshopper.

images undergo processing and comparison with the predefined path, considering multiple concrete composite mixing ratios. When the pattern accuracy dips below a predetermined threshold, missing regions are mapped and localized, ensuring meticulous quality control and precise pattern reproduction.

Moreover, we introduced a Python component for embedding our gap detection program, optimizing gap detection, mapping, and binder dispensing through an integrated approach within the Grasshopper environment. This facilitated access to images captured by Canon R6 and Realsense cameras through the FilePath component. The gap detection program outputs the contours and centroids of absent parts, maintaining an equivalent ratio between input and output files for precise mapping (Figure 11).

To ensure the accuracy of mapping centroids back to the coordinate system, we used the Realsense camera image as the ground truth. This involved a process of identifying corresponding feature points in both high and low-resolution images, calculating and applying a transformation matrix, and locating coordinates of missing parts in the Rhino software. This cohesive approach fosters the creation of reliable 3D printed constructions, enhancing the efficiency of the additive manufacturing process.

RESULTS AND REFLECTION

Comparative Test Prints

We conducted two preliminary tests to validate the proposed pipeline and system. The first employed image-based monitoring with a uniform mixing ratio composite and a layer thickness of 5mm.

We compared a 2mm binder spacing (continuous pattern) with a 3.5mm spacing (image monitoring to fill gaps) (Figure 12), demonstrating superior quality and accuracy with image-based monitoring. The second test examined the effects of different mixing ratios on layer thickness variations (Figure 13). We compared oversaturated printing with the correct saturation rate, highlighting the benefits of image-based monitoring.

The first test indicated that image-based monitoring led to decreased binder usage, a lighter final product, and enhanced shape accuracy. The wall thickness decrease from 22 mm to 15 mm, and sample weight decrease from 534 g to 391 g. Wall thickness was reduced by 31.82%, weight by 26.78%, and binder usage from 54 ml to 50.5 ml (Figure 12). The second test exhibited similar benefits across different concrete composite mixing ratios and corresponding layer thicknesses. The wall thickness was 20 mm and sample weight was 792. After applying image monitoring system, the wall thickness was 25.00% thinner, weight was reduced by 31.82%, and binder usage fell from 48 ml to 39.5 ml, confirming the system's effectiveness (Figure 13).

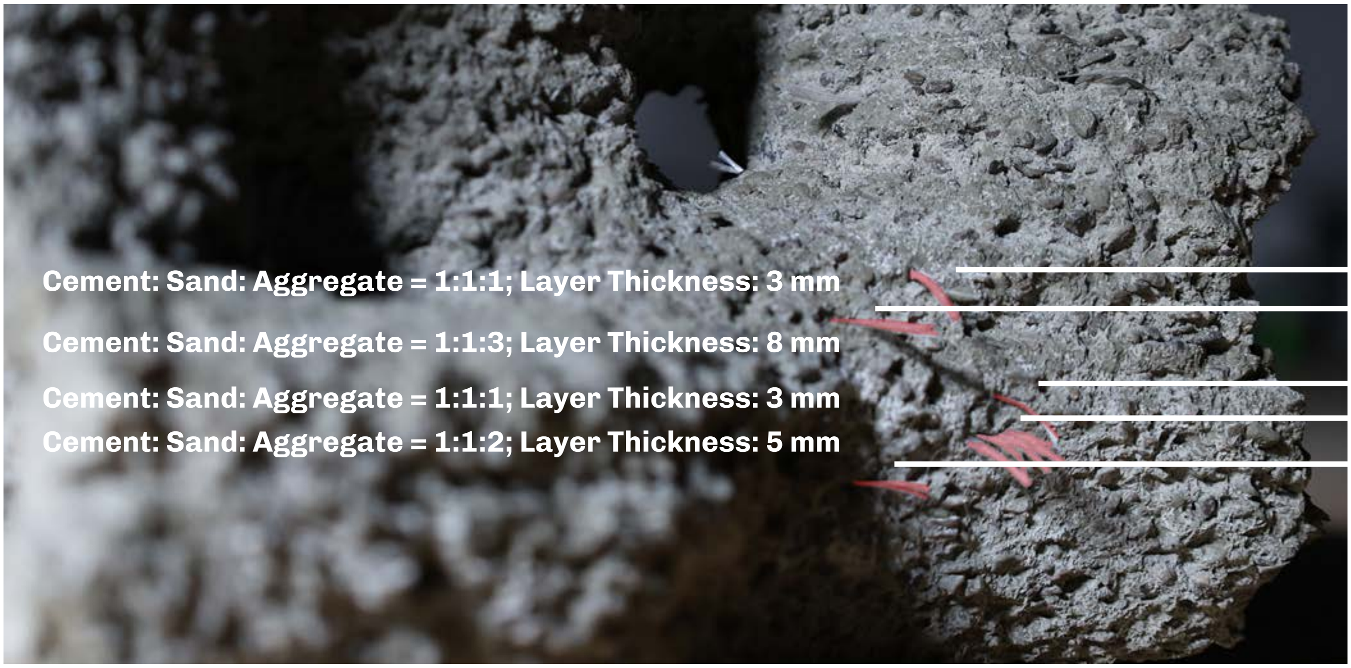
Proof of Concept Test Prints

Proof of concept involved printing intricate, partial, minimal surface objects using our pipeline and integrated with the lab setup mentioned above, demonstrating the adaptability for complex shape printing across various dimensions. A unique geometry was designed, integrating minimal surface principles, defined boundaries, and collision components. This was achieved using SphereCollide and SolidPointCollide components from the Kangaroo plugin, further refined by custom shape-finding rules (Figure 14).

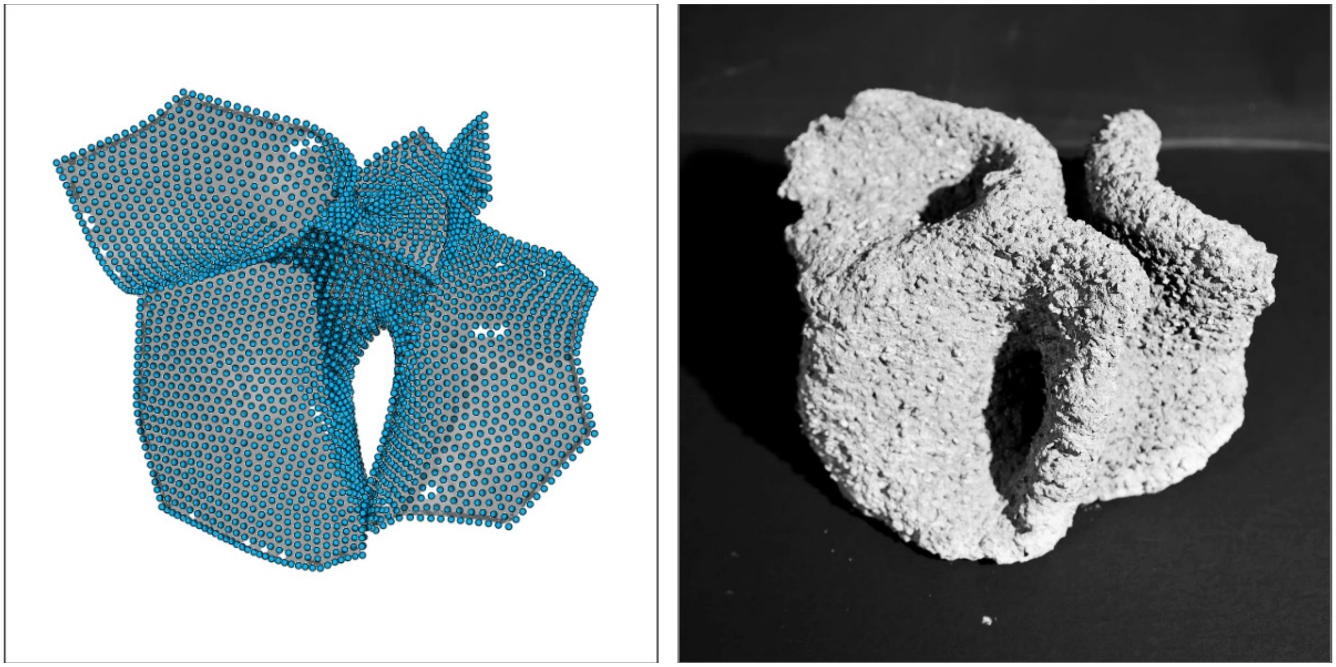
To visualize print-layer thickness variations, plastic fibers were incorporated after each printed layer. We previously found that plastic fibers obstruct binder spreading between layers, reducing adhesion and potentially causing collapses. To mitigate this, fibers were arranged randomly, ensuring no overlap between layers (Figure 15).

The use of plastic fibers effectively highlighted layer thickness differences, providing evidence that our pipeline and system are suitable for various mixing ratios and layer thicknesses of concrete composites. This innovative approach, combined with image-based monitoring techniques, ensures enhanced quality control and accurate pattern reproduction throughout the 3D concrete printing process.

The latest 3D printing test identified several areas for further optimization. Excessive support deposit paths in the previous design led to bleeding effects, distorting the print quality. To mitigate this, we reduced the number of support paths, aiming to minimize imperfections.



15 The incorporation of plastic fibers within the printed layers enables clear visualization of variations in layer thickness. The upper images show the layer thickness variation from 3 mm to 8 mm in the printing process. Those highlighted with red areas represent the plastic fiber between layers.



16 Final Print Product; as demonstrated by the juxtaposition of the digital model and its physical counterpart, substantiates our system's adaptability to different mixing ratios and layer thicknesses, delivering commendable shape accuracy. This showcases our system's proficiency in managing diverse printing tasks, upholding precision and quality across various conditions.

We also observed that a smoother, flatter top surface aids the gap detection process. To achieve this, we increased the quantity of material deposited in each layer, ensuring a cleaner top surface and more efficient gap detection. Additionally, by using more material per layer, we ensured a cleaner surrounding area for the selected region of interest. This change will enhance the final print's overall quality and aesthetic appeal. The implemented modifications aim to optimize the 3D printing process, improving both the functional and visual aspects of the final product (Figure 16).

CONCLUSION

Our study explored the field of 3D concrete printing, with a particular focus on material optimization, mixing ratios, and the implementation of an image-based monitoring system. We emphasized the crucial roles of material properties, layer thickness, and binder spacing in producing precise patterns and obtaining satisfactory green body strength. The introduced monitoring system proved effective in identifying printing gaps, thus improving both quality and operational efficiency. Moreover, the system demonstrated adaptability across a range of concrete composites and layer thicknesses. The advantages associated with the monitoring system, such as reduced binder consumption, lighter products, and enhanced shape accuracy, were validated through a series of experimental trials. The benefits associated with the monitoring system, encompassing reduced binder consumption, lighter end-products, and improved shape accuracy, were confirmed through a sequence of experimental trials. Through these trials, we verified that the use of image-based monitoring, in tandem with binder jetting techniques, resulted in enhanced accuracy and a reduction in the unnecessary use of materials during the printing process. Also, our research highlighted the transformative potential of image-based monitoring in 3D concrete printing, moving us closer to the realization of sustainable construction practices. The ongoing refinement of this method is likely to revolutionize the construction industry with the advent of large-scale, high-quality, and sustainable 3D-printed buildings.

In the pursuit of advancing the applications of this integrated system, there is ample potential for further exploration and refinement. Two particular areas that warrant attention are the complete automation of the printing process and the development of a gap detection mechanism. These aspects have not yet been thoroughly explored, and represent avenues for future research and improvement.

Additionally, our study highlights the importance of gaining a deeper understanding of different materials, including non-standard and waste materials. This understanding is particularly relevant for future investigations involving functionally graded materials (FGMs). Exploring the possibilities and characteristics of FGMs would contribute to expanding the capabilities and applications of 3D concrete printing.

In conclusion, our research has illuminated the potential of image-based monitoring in additive manufacturing, thus establishing a path for progress in 3D concrete printing within the construction industry. By further refining this method, we stand at the threshold of revolutionizing the construction industry with large-scale, high-quality, 3D-printed buildings that are sustainable in nature. The implications of these developments may be far-reaching, and have the potential to shape the future of construction practices.

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