Waste-Free Production of Ultra-thin Concrete Panels via Robotic 3D Printing and CNC Dynamic Bed Device

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Abstract. The production of freeform building panels in concrete is often limited by the fabrication capacity of custom formworks. Creating such formworks is time and labor-intensive as well as wasteful as the formworks are commonly discarded after use. This research develops a novel approach for the production of freeform panels through coupling robotic 3D Concrete Printing (3DCP) and a CNC Dynamic Bed Device (DBD). This enables the production of waste-free, freeform, and highly detailed concrete panels without requiring individualized formwork. The DBD features a composite printing surface made of silicone and a TPU grid, achieving two paradoxical aspects: maximum geometric flexibility while maintaining structural integrity and preventing buckling under the material's weight in the span between actuating pins. The geometric fidelity of the DBD is verified through a series of laser scans of the bed in convex, concave, complex saddle, and single-curved geometries. The production of complex freeform panels with textures through 3DCP and DBD involved nonplanar print path strategies. This is key in achieving consistent filament deposition and avoiding under/over-extrusion. The results included 5 unique 3DCP freeform panels. Each panel measured 50 × 50 cm.

Keywords: 3D Concrete printing · CNC dynamic bed · Bespoke freeform concrete panels · Facade panels · Doubly curved panels

1 Advancements in Freeform Concrete Panels Fabrication

Traditionally, creating concrete elements has necessitated the use of formworks. Unlike standardized concrete elements, the production of formworks for bespoke concrete elements such as freeform panels is both time and labor-intensive, leading to increased production costs and wasteful practices, which are exacerbated with each new design variation. 3D Concrete Printing (3DCP) promises to revolutionize the construction industry by enabling the creation of formless concrete structures, offering a great opportunity to streamline the manufacturing process of bespoke concrete elements. The predominant way of 3DCP is vertical 3DCP (V-3DCP), a method where the printed object is oriented

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vertically in reference to the 3D printing bed. Multiple researchers have investigated the opportunities of producing freeform geometries using V-3DCP [1].

However, V-3DCP faces several challenges due to the requirements for ensuring the concrete's pumpability and buildability. This can result in the following limitations when V-3DCP freeform panels: a) Adding openings to the panels is challenging without support material, b) There is a limitation on the dimensions of the panels as they need to be thicker as their height increases to maintain stability throughout the time of printing and c) Extreme curvatures may not be producible with V-3DCP without a substantial amount of support material for the print to succeed. These challenges have prompted the investigation into horizontal 3DCP (H-3DCP) for printing freeform panels. In contrast to V-3DCP, parts in H-3DCP are oriented horizontally on the printing bed, which not only makes it possible to overcome some of V-3DCP's limitations but also can lead to better surface quality.

H-3DCP's capability to produce bespoke freeform panels is constrained by the printing bed's geometry. To overcome this, some researchers have explored using static formworks such as CNC-milled formwork from foam to take the geometry of the desired panel, followed by 3DCP on the prepared formwork [2]. Another approach involves 3D printing a part mimicking the surface geometry of the panel using V-3DCP and then 3D printing the panel with the desired thickness using H-3DCP [3]. Both of these approaches, despite being successful in producing thin freeform concrete panels via H-3DCP, can substantially increase the manufacturing time of the panels by adding an extra manufacturing step. Moreover, these methods generate waste in the form of discarded formwork. To address this, various efforts have been directed towards developing reconfigurable and reusable 3DCP surfaces that can be utilized for H-3DCP [4–6].

2 Coupling Robotic 3D Concrete Printing with CNC Dynamic Bed Device

Expanding upon the current literature, this paper introduces an approach that combines robotic 3DCP using 1K extruder with a CNC Dynamic Bed Device (DBD), facilitating the production of waste-free, freeform, and highly detailed concrete panels without the need for bespoke, single-use formworks. The DBD features a novel composite 3DP bed material made of silicone and a TPU grid. This paper presents the methods utilized to construct this fabrication system and highlights the limitations and opportunities of leveraging this novel approach for the 3DCP of freeform concrete panels.

2.1 Design and Composition of the Dynamic Bed Device

The DBD consists of three primary components:

a) A 7×7 grid of independent linear actuators, each powered by a NEMA 17 stepper motor.
b) A 15 mm composite printing membrane. To replicate the provided digital twin, the membrane material must be elastic enough to stretch to the maximum distance between two neighboring actuators without undergoing plastic deformation. Although silicone offers the required elasticity, it leads to a linear stretch between

actuator endpoints, causing a faceted surface appearance with noticeable kinks at each actuator's end. To address this, a 3D printed honeycomb cellular lattice, Thermoplastic Polyurethane (TPU), shore 90A, was embedded, with silicon, shore 00–30, cast around it, providing a seamless and adaptive surface that overcomes the challenges presented by using soft elastic materials alone.

c) Fiberglass rods, 1.58 mm in diameter with a Flexural Modulus and a Tensile Modulus of 5.5 psi $\times 10^6$, are strategically placed to traverse actuator endpoints. These rods, running through the TPU grid, introduce slight protrusions that smooth out the surface by interpolating a curve across seven actuators in a row, effectively translating linear actuator movements to the 3D printing surface (Fig. 1).

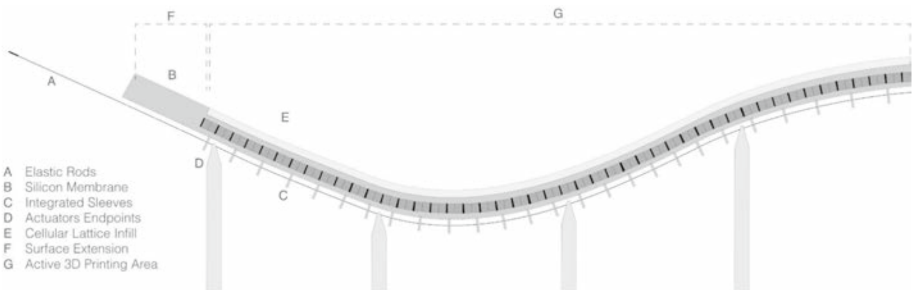

Fig. 1. A cross-section showcasing the building parts of the CNC Dynamic Bed Device

2.2 Fabrication System Architecture

The fabrication system architecture (Fig. 2) entails the following elements: A concrete mixing unit, MAI 2PUMP-PICTOR progressive cavity pumping system, and a KUKA KR-120 robotic arm. This robotic arm is equipped with a 1K cold extrusion 3DCP end effector, which is connected to the pumping system through a 5-m hose. The last part of this system that enables the fabrication of freeform panels is the DBD.

Coordination between the various elements of this system is achieved through two separate control systems. The first consists of a Beckhoff PLC, programmable logic controller, connected to a KUKA KR C4 controller. This part is responsible for ensuring a seamless synchronization between the robot's motion speed and the material deposition rate. The second control unit is responsible for controlling the CNC DBD; this entails control of the 49 independent linear actuators, each equipped with a motor encoder. These encoders are connected to their respective motor drivers, with the control tasks for all 49 drivers distributed among three Arduino Mega microcontroller boards.

2.3 Software Architecture

Starting from designing the freeform panel to its fabrication involves a series of interconnected software applications working together to ultimately control both control systems required for actuating the DBD and 3DCP with the robotic arm. The software architecture (Fig. 3) can be described as follows:

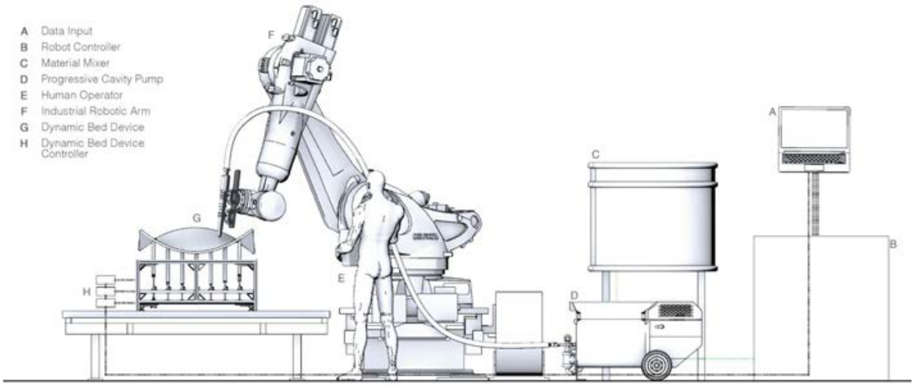

Fig. 2. Robotic 3DCP and CNC DBD system architecture

a) Grasshopper plugin to Rhinoceros modeling software was utilized to develop the computational design model, slicing the resulting geometry into printpath and generating the orientation frames for the printpath.
b) The orientation frames serve as inputs for KUKA prc, which performs inverse kinematics calculations for the robotic arm.
c) A custom Python algorithm is used to calculate the translation needed for each actuator based on the designed freeform surface. This is achieved by projecting a grid of points representing each of these actuators' home positions along the Z vector onto the freeform surface. The projected distance is then converted to the precise rotational steps needed for each linear actuator.
d) Rhinoceros 3D acts as the visualization platform for the collision detection simulation between the robotic arm and the DBD, allowing for off-line adjustments in the robotic arm configuration in the area of the collision.
e) Ultimately, 2 distinct files are generated. a) The resulting robot and external axis configurations are compiled into an SRC program. b) The sequence of actuation steps for the DBD is transcribed into C++ programs, which are then uploaded to the Arduino boards, directing the DBD to assume the specified geometric form.

3 Evaluation of the Developed Tools and Systems Through Experiments

3.1 Surface Scanning to Understand Geometric Limitations of the CNC-DBD

To assess the precision of the printing surface and ensure the 3D-printed panels accurately replicate the digital twin, a comprehensive analysis was conducted on 30 varied instances (Fig. 4). These instances covered a range of surface complexities, from convex, concave, complex saddle, and single-curved geometries. An LMI Technologies Gocator 2350 2D laser scanner, mounted on a Kuka KR120 robotic arm, was utilized for scanning, capturing between 25,601 and 53,498 data points for each surface.

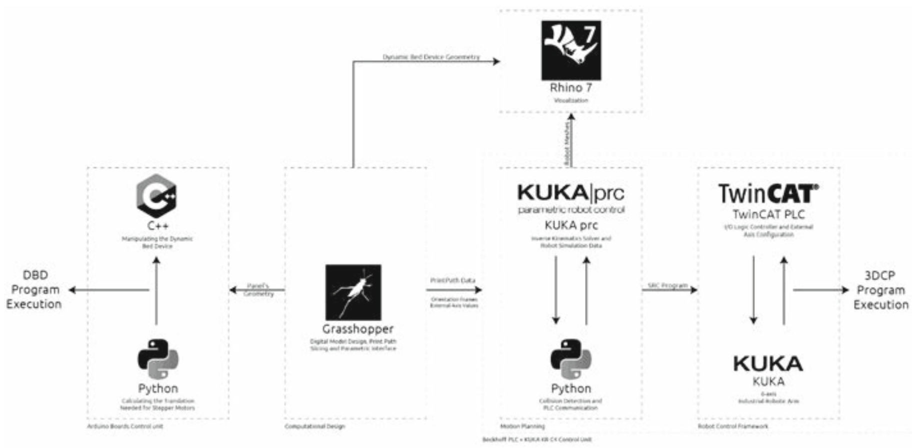

Fig. 3. Software Workflow for the Digital Design-to-Fabrication Process

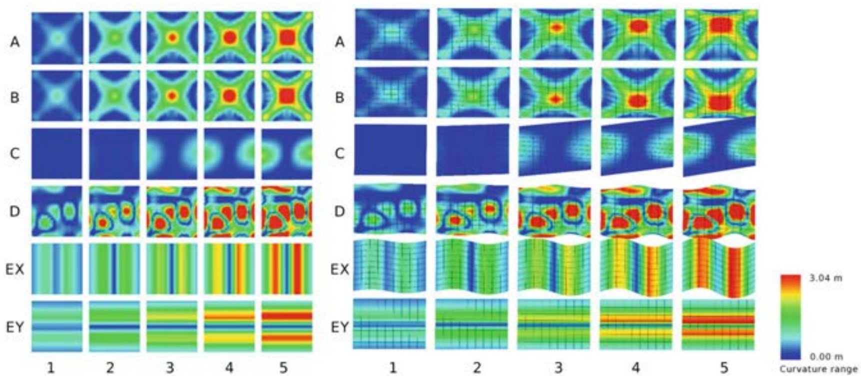

Fig. 4. A curvature range diagram of the surfaces used as test cases for evaluating the accuracy of the DBD (left) a top view of the surfaces, and (right) an isometric view of the surfaces.

The analysis (Fig. 5) revealed a predominantly right-skewed distribution in the composite histogram, indicating that most deviation points were clustered towards the lower end of the scale, with the highest frequency of points near zero deviation. Notably, 73.81% of data points showed a deviation of less than 3 mm, demonstrating a high level of accuracy in replicating the digital models.

3.2 3DCP of Various Freeform Panels to Understand the Potential and Limitations of the Process and Tools

Material Preparation and Mix. The fabrication method for the H-3DCP utilizes a 1K 3DCP process that involves several key steps: a) material preparation, b) mixing, c) pumping, and d) deposition of the material [7]. The concrete mix utilized for the 3DCP of the freeform panels in this paper did not include any concrete accelerating additives,

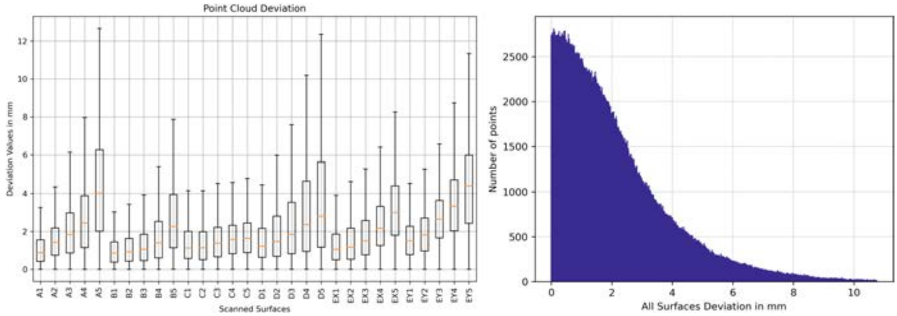

Fig. 5. The analysis of the laser scanned data of all the experimental surfaces (left) a box plot graph showing the errors of each surface, and (right) a histogram graph plotting all the scanned points on all the surfaces versus the deviation from the digital twin.

to prevent the clogging of the 1K 3DCP extrusion system. The concrete mix consists of fine sand, ordinary Portland cement, fly ash, water, and superplasticizer. The weights of each component for a single batch are outlined in (Table 1). To achieve a consistent mix, the dry parts were first combined and mixed for 2 min. Subsequently, water and superplasticizer were incrementally introduced into the dry mix. The entire mixture is then mixed for an additional 10 min to ensure thorough homogeneity.

Table 1. Single Concrete batch composition.

	Ordinary Portland Cement	Fly Ash	Silica-Sand	Water	Superplasticizer
Weight in grams	2898	3475.5	2215.5	1890	10.5

Panels Fabrication. To demonstrate the capabilities of the proposed approach, 5 unique 3DCP freeform panels, measuring 500 $\times$ 500 mm with a thickness varying between 10 and 20 mm, were fabricated (Fig. 6). The slicing for the printpath was achieved using an in-house developed algorithm that leverages the inherent properties of the NURBS surfaces. The algorithm uses the (u, v) parameter space of the NURBS surface as the points of division. From these division points, it generates either a zigzag or spiral toolpath that maintains a constant distance between segments.

To ensure a successful print, the end effector orientation vector was set to align with the normal vector of the closest point on the panel surface relative to the orientation frame's origin. The final texture on the panels was applied through post-processing of the printpath of the uppermost layer.

To facilitate easy detachment of the panels after the 3DCP process is concluded, the printing surface was treated with a form release agent prior to the beginning of each new 3DCP task. The robot motion speed was set at 0.1 m/s, resulting in the production of each panel taking 5 to 7 min. The panels were allowed a 24-h setting time before being removed from the DBD. This long setting time is a result of the lack of concrete setting accelerating additives, integrating these additives could have significantly reduced the curing period. Consequently, the extended setting time was necessary to ensure the panels achieved sufficient strength and stability before detachment.

Fig. 6. Resulting freeform panels from the developed process.

4 Conclusion

The research presented in this paper demonstrates the significant opportunities afforded by the proposed method for fabricating freeform panels. Further investigations in this domain can be directed along the following trajectories:

1. **Enhancing CNC DBD Precision:** Improve the precision of the CNC DBD system in replicating the digital twin to ensure higher fabrication accuracy.
2. **Reducing the setting time:** This can be achieved by utilizing 3DCP systems that incorporate concrete setting accelerator admixtures, such as 2K 3DCP systems. Additionally, developing a new 3D printing surface that can detach from the linear actuators while maintaining the geometry of the printed parts will allow the freshly 3D printed panels the necessary setting time without disrupting the fabrication process.

3. **Real-time tracking and material setting monitoring:** Implement real-time tracking of the DBD support structure to enable the creation of dimensionally accurate 3D structures. Additionally, develop methods for accurately recording the setting state of the printing material to ensure consistency and reliability in the fabrication process.
4. **Exploring Scalability for Larger Architectural Elements:** Investigate the scalability of this system for larger structures, such as shell structures and slabs.

References

1. Kamhawi, A., Aghaei Meibodi, M.: Extrusion based 3D concrete printing, complex geometries in 3D concrete printing, 3D Printing parameters. Manuscript under review for publication in The Journal of Automation in Construction, Manuscript No. AUTCON-D-24–00873 (2024)
2. McGee, W., Ng, T.Y., Yu, K., Li, V.C.: Extrusion nozzle shaping for improved 3DP of engineered cementitious composites (ECC/SHCC). In: Bos, F., Lucas, S., Wolfs, R., Salet, T. (eds.) Second RILEM International Conference on Concrete and Digital Fabrication. DC 2020. RILEM Bookseries, vol. 28. Springer, Cham (2020). https://doi.org/10.1007/978-3-030-49916-7_89
3. Ahmed, Z., Biffi, A., Hass, L., Bos, F., Salet, T.: 3D concrete printing - free form geometries with improved ductility and strength. In: Bos, F., Lucas, S., Wolfs, R., Salet, T. (eds.) Second RILEM International Conference on Concrete and Digital Fabrication. DC 2020. RILEM Bookseries, vol. 28. Springer, Cham (2020). https://doi.org/10.1007/978-3-030-49916-7_74
4. Costanzi, C.B., Ahmed, Z.Y., Schipper, H.R., Bos, F.P., Knaack, U., Wolfs, R.J.M.: 3D printing concrete on temporary surfaces: the design and fabrication of a concrete shell structure. Autom. Constr. **94**, 395–404 (2018)
5. Lim, J.H., Weng, Y., Pham, Q.-C.: 3D printing of curved concrete surfaces using adaptable membrane formwork. Constr. Build. Mater. **232**, 117075 (2020)
6. Battaglia, C.A., Miller, M.F., Zivkovic, S.: Sub-additive 3D printing of optimized double curved concrete lattice structures. In: Willmann, J., Block, P., Hutter, M., Byrne, K., Schork, T. (eds.) Robotic Fabrication in Architecture, Art and Design 2018. ROBARCH 2018. Springer, Cham (2019). https://doi.org/10.1007/978-3-319-92294-2_19
7. Albar, A., Chougan, M., Al-Kheetan, M.J., Swash, M.R., Ghaffar, S.H.: Effective extrusion-based 3D printing system design for cementitious-based materials. Results Eng. **6**, 100135 (2020)