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BIM-enabled collaborative-robots 3D concrete printing to construct MiC with reinforcement

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ABSTRACT

3D concrete printing (3DCP) has attracted much attention in recent years due to its advantage of advancing the conventional construction sector. However, the wide adoption of 3DCP in infrastructure and housing construction, i.e., Modular Integrated Construction, is hindered by the challenge of introducing reinforcement rebars in printed structures. This paper aims to tackle the abovementioned limitation by the application of a BIM-enabled collaborative-robots 3DCP system. In the proposed system, Building Information Modelling (BIM) and robot-arm 3D concrete printers are integrated to be a seamless information communication platform. The data of printed concrete structures and reinforcement rebars are extracted, separated, processed, and analysed on a BIM platform (i.e., Revit) by using a self-developed script. Then, these obtained data are sent to two robots to conduct different printing tasks, i.e., concurrent concrete structure printing and reinforcement rebar placement, respectively. The proposed system is successfully validated by a case study conducted in a virtual environment. This work demonstrates a seamless framework for concurrent print concrete structure and place reinforcement rebars to advance the automation of 3DCP by integrating BIM with robot-arm 3D printers.

KEYWORDS 3D concrete printing; collaborative robots; modular integrated construction; building information modelling; reinforcement rebars; automation

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1. Introduction

The construction industry in Hong Kong has dramatically expanded over the past decade. The construction expenditure is anticipated to reach HK$340 billion by 2028 as estimated by the Construction Industry Council of Hong Kong (KPMG, 2018). Such massive market growth has led to concerns over productivity, efficiency, and sustainability. These issues are worsened by a chronic labour shortage and the aging workforce. Conventional construction practices are labour-intensive and time-consuming, with high waste generation (Buswell et al., 2018; Lu et al., 2019). Modular integrated Construction (MiC) has been proposed for construction projects by the Hong Kong government due to its advantages, such as reduced waste generation, on-site construction time, and manpower required, and improved quality, safety, and sustainability (Abdelmageed and Zayed, 2020; Arunothayan et al., 2020; Pan et al., 2021; Zheng et al., 2020).

However, the huge amount of formwork usage in MiC inhibits its wide application. The commonly used formwork represents 35%-60% of the overall costs of concrete construction (De Schutter et al., 2018; Zhu et al., 2021a), and 80% of the total worldwide waste is mainly contributed by the limited reuse value of timber formwork (Sanjayan et al., 2019).

3D concrete printing (3DCP), a formwork-free construction method, provides opportunities to overcome the limitation of MiC arising from formwork usage (De Schutter et al., 2018; Mechtcherine et al., 2019; Wangler et al., 2016). For example, a prefabricated bathroom constructed by 3DCP can achieve a reduction of 25.4% in overall cost, 85.9% in CO_2 emissions, and 87.1% in energy consumption compared to the precast unit (Weng et al., 2020). The above enhancements were found to be ascribed to the formwork-free construction of 3DCP.

Nevertheless, a major hurdle to the wide adoption of 3DCP in infrastructure and housing construction, i.e., MiC, is how to place reinforcement rebars in the printed structure during the concrete printing process. As will be reviewed in Section 2, the existing methods to introduce reinforcement rebars lack automation or engineering availability. Specifically, the methods of placing reinforcement rebars in the literature lack automation ability due to the manual placement process (Assaad et al., 2020; Zhu et al., 2021a). The wire arc additive welding process to introduce reinforcement is costly and challenging for engineering application due to the high temperature in the welding process (Mechtcherine et al., 2018).

This work is motivated by the limitations stated above. A BIM-enabled collaborative-robots 3DCP system is proposed to address the abovementioned challenges to achieve a concurrent concrete structure printing and reinforcement rebar placement process. This newly innovated system integrates Building Information Modelling (BIM) and robot-arm 3D concrete printers to achieve a seamless information communication platform.

The data of printed concrete structures and reinforcement bars are first extracted, separated, processed, and analysed on a BIM platform (i.e., Revit) using a self-developed script. Then, these obtained data are sent to two robots to conduct different printing tasks, i.e., concurrent concrete structure printing and reinforcement rebar placement. Finally, a case study is conducted to prove the feasibility of the proposed system in a virtual environment.

This work focuses on discussing the proposed system, through which the reinforcement can be automatically introduced into the printed structure based on the BIM data. In the future, another system, like a robot arm, can be employed to pour the self-compacting concrete into a predesigned hollow position, and thus bond the reinforcement with the printed formwork to make the whole structure a part of the integrity of structural applications.

2. Related works

In this section, the existing methods to introduce reinforcement in the printed structure are reviewed and elaborated. The review is organised in terms of pre-installed reinforcement, post-installed reinforcement, and in-progress reinforcement. Furthermore, their corresponding limitations are discussed. Finally, a summary of this section is provided, and the research gap is identified and emphasised.

2.1. Pre-installed reinforcement

The reinforcement installed before the material printing process is the pre-installed reinforcement method. Huashang Tengda (Huashang Tengda, 2016) proposed a method of pre-installed reinforcement, in which the reinforcement in both vertical and horizontal directions is pre-placed on site. The printable materials are then deposited around the reinforcement by a double-nozzle system. The drawback of this method is that the reinforcement needs to be manually installed.

2.2. In-process reinforcement

In-process reinforcement indicates that the reinforcement is introduced into the printed structure or materials during the printing process. For example, straight 3D-printed walls are reinforced by straight reinforcing bars, which are placed into fresh concrete parallel to the printing plane and then covered by a subsequent layer of concrete (Baz et al., 2020). More complex geometries are reinforced by placing pre-bent rebars, which are positioned in the predesigned location between the layers (Grasser et al., 2020). Micro-cable and steel mesh also can be introduced into the printed filaments as reinforcement (Bos et al., 2017; Ma et al., 2019; Marchment and Sanjayan, 2020). These methods are novel to reinforce 3D printed concrete, while they are limited by either automation (Grasser et al., 2020) or feasibility for structural applications (Bos et al., 2017; Ma et al., 2019; Marchment and Sanjayan, 2020).

To avoid the abovementioned challenges, Mechtcherine et al. (2018) suggested using Wire Arc Additive Manufacturing (WAAM). In the WAAM method, the reinforcing elements are built up in a dropwise manner enabling a maximum of geometric flexibility and improving bond performance between printed concrete and built reinforcement. However, the method is limited by the following: (1) the steel printing process is time-consuming and slower than the concrete printing process; (2) the concrete structure may be damaged by the high temperature generated in the steel printing process; and (3) the WAAM welding process is costly.

2.3. Post-installed reinforcement

In the post-installed reinforcement process, the printed concrete structures are used as the formwork followed by installing reinforcement and filling with casting material (Asprone et al., 2018; Assaad et al., 2020; Zhu et al., 2021b). The existing post-installed reinforcement methods are hard to achieve automatic integration reinforcement with 3DCP process.

2.4. Summary and research gap

The abovementioned methods in the literature have limitations: lacking the ability of automation and engineering availability. Specifically, the methods of pre-installed and post-installed reinforcement in the literature lack the possibility of automation. The in-process method, like WAAM welding processing, is costly and challenging for engineering applications due to the high temperature in the welding process.

The research gap in automation and engineering availability motivates this work on a BIM-enabled collaborative-robots 3DCP system to print concrete structures and place reinforcement rebars synchronously. The proposed system is challenging in several aspects. First, the data of the BIM model must be carefully processed and analysed to design concrete structure printing paths and identify the reinforcement bar placement position. Secondly, the concrete printing path needs to be optimised based on the position of reinforcement rebars to avoid collision between printed materials and reinforcement bars. Finally, the concrete structure printing and reinforcement rebar placement processes must be carefully planned and coordinated to optimise the concurrent working processes while avoiding mutual collisions.

To address the above challenges, BIM data are extracted, separated, processed, and analysed in the proposed system by a self-developed script in Dynamo. The concrete data are used to generate the printing path while the rebar data are used to optimise the printing path and obtain the placement positions. These data are sent to two robot printers to conduct different printing tasks. One robot prints the concrete structure, after which another robot places reinforcement rebars. These two robots are capable of localization, collision avoidance, and efficient coordination of the process through optimising BIM data.

3. Methodology and framework

3.1. Conceptual framework

The framework of the proposed system is illustrated in Figure 1. The system consists of two modules, i.e., BIM information processing module and robot manipulation module. The BIM information processing module can process and analyse the data of concrete structures and reinforcement rebars, respectively. Two functional units are adopted in the robot manipulation module to achieve a collaborative-robots process for concurrent concrete printing and reinforcement rebar placement.

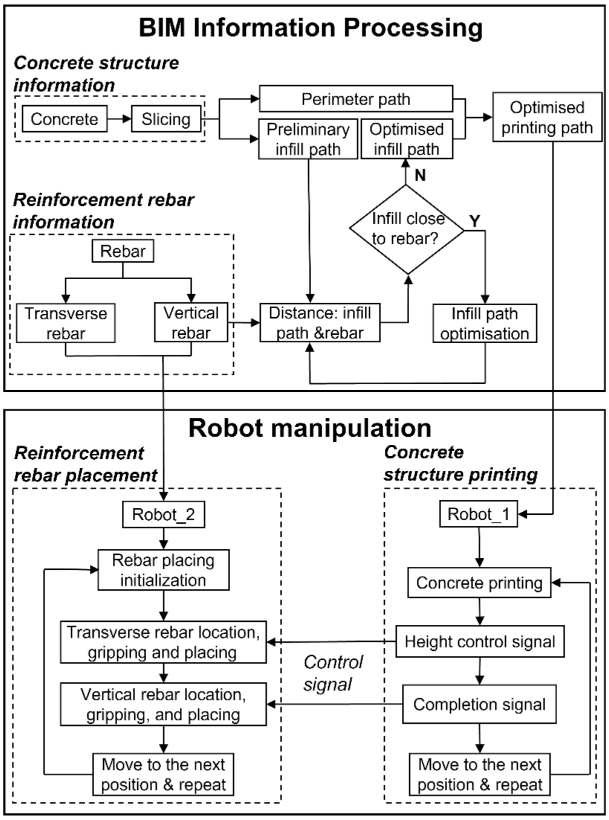


Figure 1. The framework of the proposed system.

More specifically, in the BIM information processing module, a concrete structure is firstly created in Revit. The data of the concrete structure are then processed by a self-developed Dynamo script to separate the data into two categories, i.e., data of concrete material and reinforcement rebars, respectively. Afterwards, a preliminary printing path of concrete material printing is generated (Section 3.2). Then, the vertical and transverse reinforcement rebar data are processed, respectively. The vertical reinforcement rebar data are adopted to optimise the concrete material printing path for collision avoidance between concrete material and vertical reinforcement rebars (Section 3.3). The transverse reinforcement rebar data are processed to obtain the location information of placing. Finally, the optimised printing path of concrete material and the data of reinforcement rebars are sent to two robots to conduct different construction tasks in the robot manipulation module (Section 3.4).

3.2. Data extraction and path generation for concrete structure printing

Weng et al. (2021) proposed a method to generate a continuous printing path based on a BIM model. A BIM model consists of different information, such as material information (e.g., brick, glass, and concrete) and functional information (e.g., doors, windows, floors, ceilings, and walls). These data can then be used as indicators to filter out components required for the 3DCP (Weng et al., 2021). For example, concrete and wall are two keywords to select printing elements for printing path generation in this work. As a result, only the wall segment made of the concrete material can be filtered out through the customised functional node by the developed script to design the continuous printing path.

The continuous printing path of concrete structure can be classified into two categories, i.e., perimeter printing path and infill printing path. The perimeter printing path is used to print the contour of the concrete structure. The infill printing path designed by this method is a continuous sinusoidal weaving path enabling support of the concrete contour (Diggs-McGee et al., 2019). The paths are generated by model meshing and slicing, point reordering and connecting, and machine-code conversion (Weng et al., 2021).

The main limitation of the abovementioned method is that it is challenging to tackle a structure with reinforcement rebars. To address this limitation, this study further extends the functionality of the self-developed script in Dynamo to process the designed structure with both concrete material and reinforcement rebars.

3.3. Reinforcement rebar information processing and infill path optimisation

The rebar information processing has two main objectives. One is to define and obtain a gripping location on the rebar for the robot to grip the reinforcement rebars based on the coordinate information extracted from the BIM data. This part is elaborated in Section 4.2. Another is to optimise the preliminary infill path for collision avoidance. The introduction of vertical reinforcement rebars in the concrete structure may cause collisions between the infill concrete printing path and vertical reinforcement rebars. In the conventional concrete structure design, the concrete

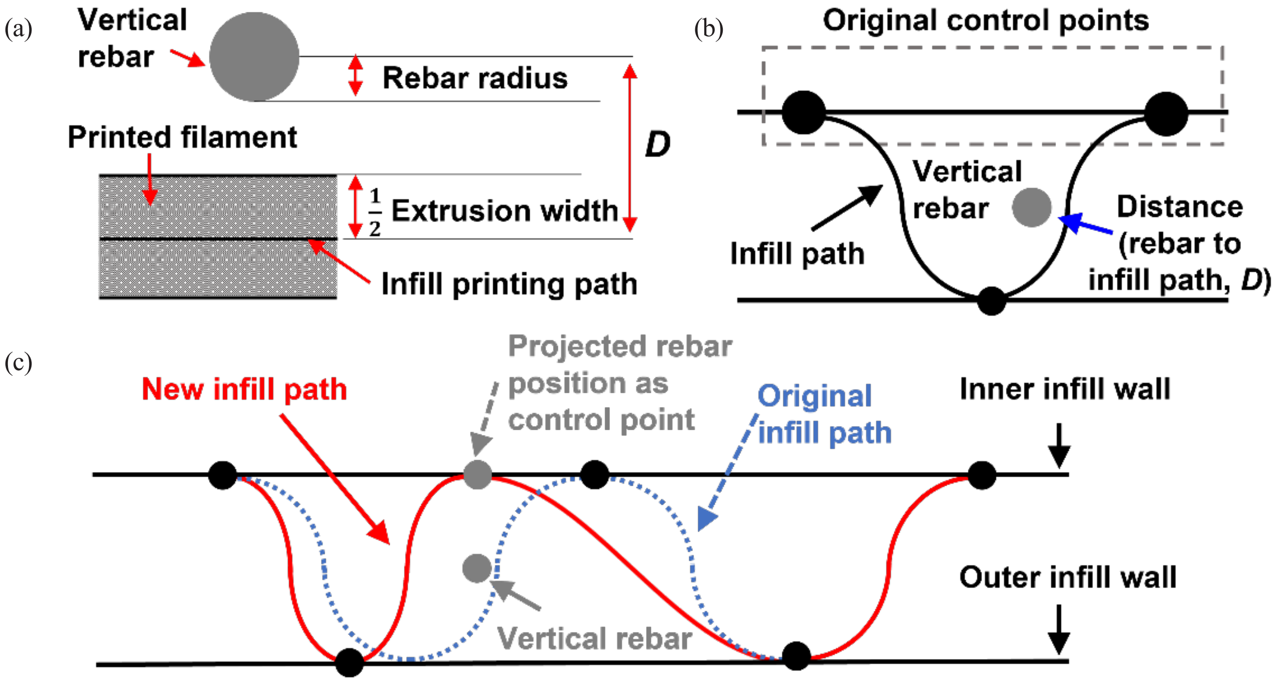


Figure 2. Schematic of infill path optimisation: (a) geometrical relation between rebars and infill printed filament; (b) rebar close to infill path; and (c) the optimisation of a close rebar.

cover is adopted to ensure the space between rebars and the contour of the concrete surface. Therefore, sufficient space can be provided to avoid collisions between rebars and perimeter printing paths. However, the infill printing path (Weng et al., 2021) may cause a collision due to the overlap between rebars' position and the infill path.

An optimisation algorithm of infill printing path is proposed to address the collision challenge. The geometrical relationship between vertical rebars and printed infill filament is schematically shown in Figure 2(a). To avoid a collision, the distance between the vertical rebars and infill printing path needs to satisfy the requirement as indicated by Equation (1):

$$D \geq R + \frac{1}{2} W_{\text{extrusion}}, \qquad (1)$$

where D is the distance (mm) between the centre point of rebar and infill printing path. R and $W_{\text{extrusion}}$ are rebar radius (mm) and the extrusion width of printed filament (mm), respectively.

The preliminary infill printing path is firstly generated in section 3.2. The distance for each vertical rebar to the infill path (D) is then calculated by the script developed in Dynamo. If Equation (1) fails to be satisfied, it indicates that the rebars are close to the infill path (close rebars, Figure 2(b)) and may cause a collision. The optimisation algorithm is designed as shown in Figure 2(c) to tackle the collision issue. The rebar is projected into the inner infill wall. The projected point then serves as a new control point to generate a new collision-free infill path.

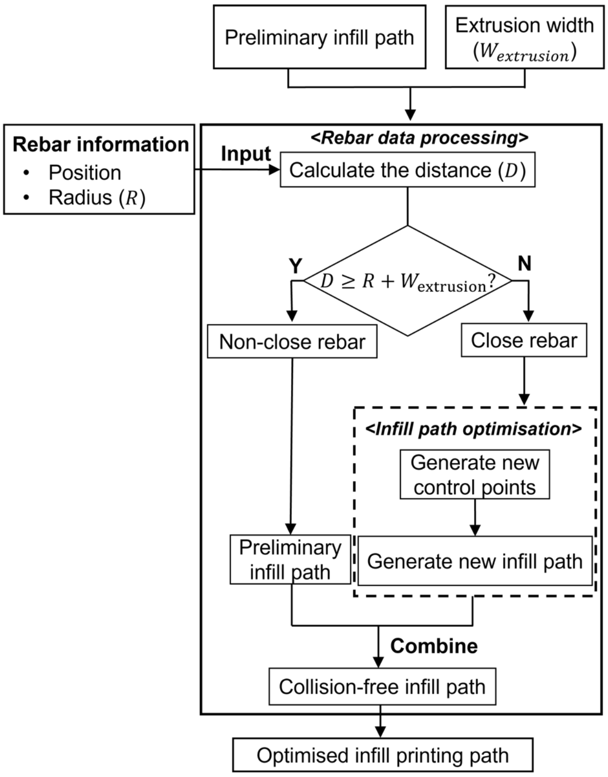
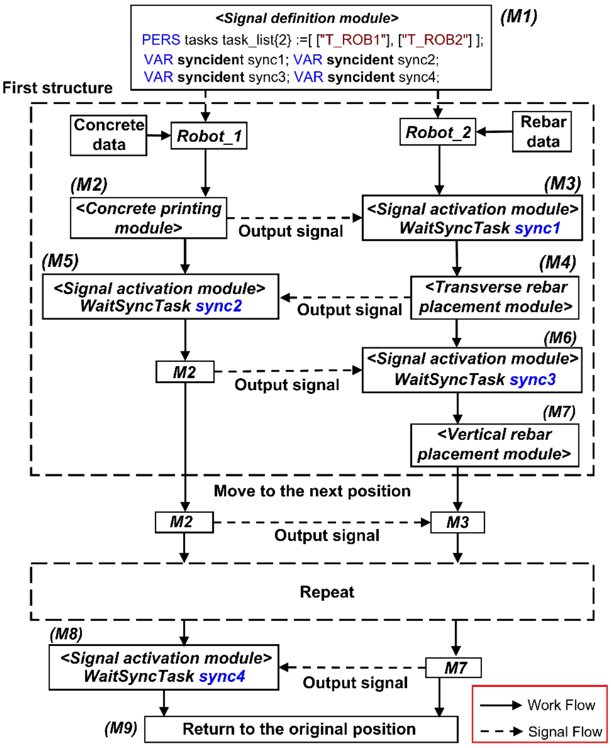


Figure 3. The framework of the optimisation algorithm.

3.4. Collaborative-robots motion planning

The motion planning of the collaborative-robots system is described in this section. The BIM data are processed first as discussed in Section 3.3. Then, the data of concrete structure and rebars are sent to two robots, i.e., Robot_1 and Robot_2, as shown in Figure 1. Robot_1 works on concrete structure printing while Robot_2 places rebars in the printed structure synchronously. In the whole process, the robot motion needs to be carefully designed to avoid a collision between rebars and printed materials and the mutual collision between two robots. The algorithm for controlling the robots is designed in RAPID. An overview of the algorithm is depicted in Figure 4.



```
PERS tasks task_list{2} :=[ ["T_ROB1"], ["T_ROB2"] ];
VAR syncident sync1; VAR syncident sync2;
VAR syncident sync3; VAR syncident sync4;
```

Figure 4. The algorithm for mutual collision avoidance.

To avoid a collision between rebars and printed materials, a pre-defined moving path of Robot_2 is designed and will be discussed in Section 4.2. The avoidance of mutual collision between two robots is achieved by the collaboration of two functional nodes, i.e., *syncident* and *WaitsyncTask*, as shown in Figure 4. Firstly, the control signal of *syncident* is sent to two robots (M1 in Figure 4), and the input of *syncident* triggers Robot_1 to print concrete structure (M2), while *WaitsyncTask* is sent to Robot_2 to stop its operation (M3). The height of the transverse rebar is extracted and sent to Robot_2. When the printed concrete reaches the height, a height control signal is sent to Robot_2, triggering Robot_1 to stop printing and Robot_2 to place a transverse rebar in the printed structure (M4). When M4 is completely executed by Robot_2, the next *WaitsyncTask* signal is sent to Robot_1 to continue printing the remaining layers (M5). After completion of printing, Robot_1 moves to the next position, and the third *WaitsyncTask* signal (M6) is sent to Robot_2. Then, Robot_2 starts to place vertical rebars (M7). When Robot_2 completes the M7, it moves to the next position, and a new signal of *WaitsyncTask* is sent to Robot_2 and stops its operation. When the rebars of the last structure are placed, a signal of *WaitsyncTask* from Robot_2 is sent to Robot_1 (M8), and the two robots will return to their original position (M9).

4. Results

4.1. System setup

This section presents a case study in a virtual environment to demonstrate the proposed BIM-enabled collaborative-robots 3DCP system. The overview of the system is shown in Figure 5. The system consists of two robot arms (ABB IRB2600), two moveable tracks, and a guide rail. The robot arm can move along the moveable track, and the guide rail is used to deliver rebars. A printing nozzle and a gripper are mounted on the robot as the end-effector of Robot_1 and Robot_2, respectively.

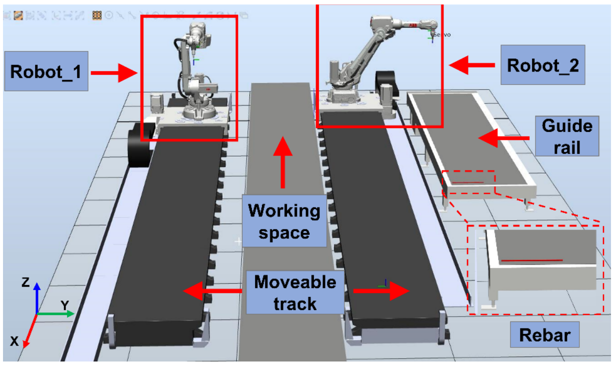


Figure 5. Overview of the system.

The BIM model of the reinforced concrete structure is shown in Figure 6(a). A circular concrete wall is designed with 14 vertical rebars (Figure 6(b)) and two circular transverse rebars placed at heights of 150 mm and 300 mm (Figure 6(c)), respectively. The coordinates of all the points in the transverse rebar are extracted to design the process of transverse rebar placement, as shown in Figure 7. The points with the maximum X value are filtered out as the target placement position (P_t) for the transverse rebar.

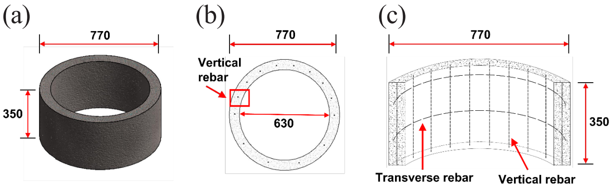
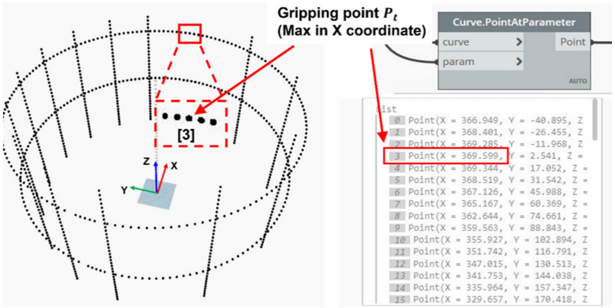


Figure 6. BIM model of a printed structure: (a) 3D view; (b) top view; and (c) cross-section view.



```
List
 0 Point(X = 366.949, Y = -40.895, Z
 1 Point(X = 368.401, Y = -26.455, Z
 2 Point(X = 369.285, Y = -11.968, Z
 3 Point(X = 369.599, Y = 2.541, Z =
 4 Point(X = 369.344, Y = 17.052, Z =
 5 Point(X = 368.519, Y = 31.542, Z =
 6 Point(X = 367.126, Y = 45.988, Z =
 7 Point(X = 365.167, Y = 60.369, Z =
 8 Point(X = 362.644, Y = 74.661, Z =
 9 Point(X = 359.563, Y = 88.843, Z =
 10 Point(X = 355.927, Y = 102.894, Z
 11 Point(X = 351.742, Y = 116.791, Z
 12 Point(X = 347.015, Y = 130.513, Z
 13 Point(X = 341.753, Y = 144.038, Z
 14 Point(X = 335.964, Y = 157.347, Z
 15 Point(X = 329.657, Y = 170.418, Z
```

Figure 7. Gripping point of transverse rebar in Dynamo.

The printing path of the concrete structure is generated and optimised based on the method described in Sections 3.2 and 3.3. In this study, both R and $W_{\text{extrusion}}$ are defined as 10 mm. The process of infill path optimisation is illustrated in Figure 8. The final continuous collision-free printing path is presented in Figure 9.

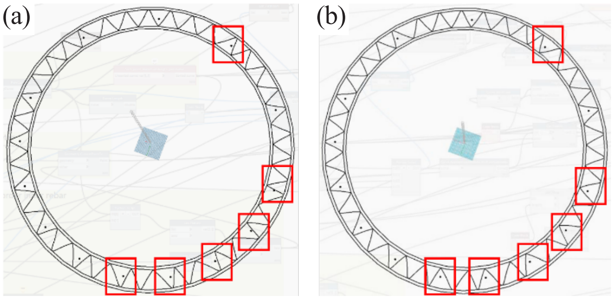


Figure 8. Infill printing path optimisation: (a) before optimisation; and (b) after optimisation.

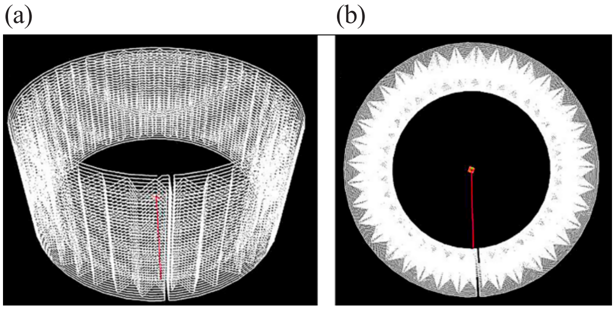


Figure 9. The final printing path: (a) front view; and (b) top view.

4.2. Simulation

The simulation process is shown in Figure 10, and the demonstration video can be found at https://youtu.be/P7x8CL0CxIw. Firstly, both robots are placed in their original positions (Figure 10(a)). Then, Robot_1 starts to print concrete structure layer atop layer by following the optimised printing path when the control signal is received (Figure 10(b) and (c)). Next, the height information of transverse rebars (150 mm and 300 mm in this work) is extracted and sent to Robot_2. When the printed concrete structure reaches these heights (150 mm or 300 mm), Robot_1 stops printing and moves to the initial position to avoid mutual collision. Meanwhile, a control signal is sent to Robot_2. After receiving the control signal from Robot_1, Robot_2 starts to grip the transverse rebar and places it in the predesigned position (Figure 10(d)). Afterward, Robot_1 continues to print the remaining layers. When the structure is fully printed, Robot_1 moves to the next position and sends another signal to Robot_2, which is triggered to grip and place the vertical rebars (Figure 10(e)). Finally, Robot_2 moves to the next position and waits for the control signal when the vertical rebar placement task is completed. The two robots repeat the abovementioned processes to construct all the designed structures and finally move back to the original position (Figure 10(f)).

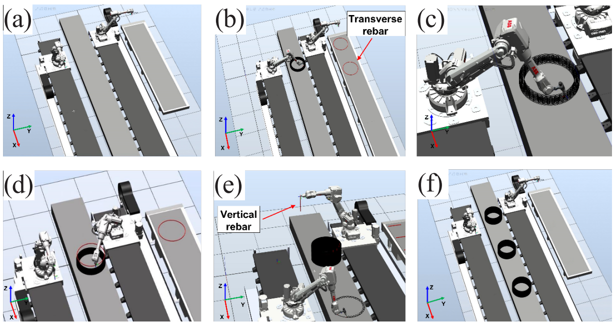


Figure 10. Simulation process: (a) Locate at the original position; (b) and (c) concrete structure printing by Robot_1; (d) transverse rebar placement by Robot_2; (e) vertical rebar placement; and (f) repeat and complete simulation. See the full video of the simulation at https://youtu.be/P7x8CL0CxIw.

The robot manipulation for transverse rebar placement is illustrated in Figure 11. Robot_2 firstly identifies the gripping point of the rebar, which has the minimum X value in the coordinate system of the simulation frame (Figure 11(a)). Secondly, the robot moves downwards and grips the rebar (Figure 11(b)). Thirdly, the robot rotates 180 degrees along axis 1 (Figure 11(c)) to ensure that the gripping point is changed to be the maximum X value after rotation. Afterwards, the gripper executes translation movement in the X-Y plane and aligns the gripping point to the pre-placement point (Figure 11(d)), which has the same X and

Y coordinates as P_t. Finally, the gripper moves downwards to P_t and places the transverse rebar (Figure 11(e)), followed by Robot_2 returning to the original position (Figure 11(f)).

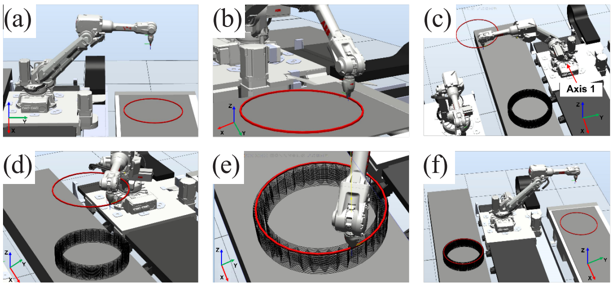


Figure 11. The transverse rebar placement process: (a) locate above the rebar; (b) grip the transverse rebar; (c) rotate 180 degrees along axis 1; (d) translate to the pre-placement point; (e) place the transverse rebar; and (f) return to the original position.

The robot motion for vertical rebar placement also needs to be carefully designed to avoid a collision between a vertical rebar and printed concrete filaments, as shown in Figure 12. Firstly, Robot_2 positions the gripper above the rebar (Figure 12(a)). Secondly, the robot moves downwards and grips the rebar (Figure 12(b)). Thirdly, the gripper rotates 90 degrees to manipulate the rebar into the vertical direction (Figure 12(c)). Then, the gripper locates at the position where the X and Y coordinates are the same as the rebar while the Z coordinate is 20 mm higher than that of the rebar in this study (Figure 12(d)). Afterwards, the gripper moves downwards to place the rebar in the designed position (Figure 12(e)). Finally, the gripper moves upwards and back to the initial position (Figure 12(f)).

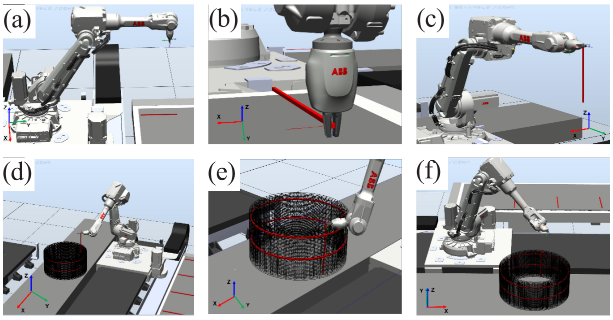


Figure 12. The vertical rebar placement process: (a) locate above the rebar; (b) grip the rebar; (c) rotate to vertical; (d) locate above the structure; (e) place the rebar; and (f) return to the original position.

The simulation demonstrates that the proposed approach can automatically and concurrently place both transverse and vertical reinforcement rebars in printed concrete structures. The whole simulation takes 1,162 seconds for Robot_1 to print a single concrete wall, and 56 seconds and 403 seconds are needed for Robot_2 to place two transverse rebars and 14 vertical rebars, respectively. It takes 4,045 seconds to build three reinforced circular concrete walls.

5. Discussion

A BIM-enabled collaborative-robots 3DCP system is proposed in this study to address the limitations of introducing reinforcement rebars in 3D printed concrete structures. In the proposed system, data of concrete material and rebars are separately processed and optimised in the BIM environment and then sent to the robot system. Then, two robots are employed to conduct concurrent concrete printing and rebar placement. The concept is successfully demonstrated by a case study in a virtual environment. In the future, another robot arm could be employed to pour the self-compacting concrete materials into predesigned hollow positions, and thus bond the reinforcement with printed formwork to form an integrated structural component.

The proposed system to introduce rebar reinforcement in 3DCP outperforms the existing methods in the literature. Specifically, compared to the manual placing of reinforcement rebars (Assaad et al., 2020; Zhu et al., 2021a), the proposed method can automate printed concrete structures and place rebars without collision by carefully designing robot motion based on optimised BIM data. In addition, the proposed system is more engineering available by using conventional rebars as the reinforcement compared with the WAAM process (Mechtcherine et al., 2018), in which a high-energy welding process significantly increases the cost of reinforcement rebars.

However, there are also challenges for the system to work robustly for applications in construction practices. The robots in this study are single-function, i.e., concrete printing and rebar placement, and thus resting time exists between two different construction tasks due to the constraint of robot functions. To enhance the collaboration of robots and printing automation, multi-function robots can be adopted in future works by integrating advanced technologies and algorithms. For example, computer vision and force control can be adopted to improve the manipulation of robots and the detection of rebars. Another major technical difficulty would be accurately detecting, gripping, and placing rebars under practical printing scenarios. When the rebars are randomly placed around the robot, which is common in a construction area, the robot vision would also have a vital role in addressing this challenge, while it has not been integrated with the proposed system yet. In addition, when placing the rebars in the printed structure, it is critical to design a real-time feedback control system to avoid the collision between the rebars and printed materials and make the system workable for various operation conditions. Moreover, an appropriate method to ensure that the rebar can stably stay in its designed position needs to be developed. Finally, the toolpath algorithm considered (Weng et al., 2021) is specific for the case study of lattice toolpath design based on weaving pattern and focused on vertical reinforcement placement.

In summary, it would be necessary to address these abovementioned limitations in future works to ensure that the system can be adopted in construction practices.

6. Conclusion

3DCP is an innovative technology to build formwork-free structures to advance the conventional construction sector. The wide application of 3DCP for infrastructure and housing construction is limited by introducing reinforcement rebars into a printed structure. A BIM-enabled collaborative-robots 3DCP system is proposed in this study to improve the automation and engineering availability of the process.

The proposed system integrates BIM with 3DCP to achieve a seamless information communication and work planning platform. Firstly, BIM data are separated, processed, and analysed by the self-developed script in Dynamo. A collision-free printing path is then optimised and generated according to the received BIM data. Afterwards, the processed BIM data are sent to two robots to conduct concurrent concrete structure printing and rebar placement. Finally, a case study is successfully conducted in the virtual environment.

The simulation results suggest that the proposed methodology and framework can be adopted to achieve a synchronised concrete structure printing and rebar placement process. Compared with the existing methods of introducing rebars into a printed structure in the literature, the proposed system is superior in its automation and engineering availability. The technical concern regarding the proposed system is its robustness when it works on a complex practical construction area, such as detecting and gripping randomly placed rebars. These potential challenges may be significantly mitigated by standard robotic techniques, such as robot vision, real-time feedback force control, and enhancing the pull-out strength of the rebar, which will be the future research works.

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Notes on contributors

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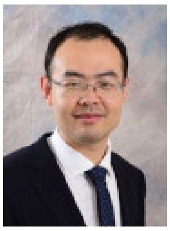

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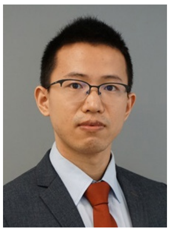

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References

[1] Abdelmageed S and Zayed T (2020). A study of literature in modular integrated construction - Critical review and future directions. *Journal of Cleaner Production*, 277, pp. 124044.

[2] Arunothayan AR, Nematollahi B, Ranade R, Bong SH and Sanjayan J (2020). Development of 3D-printable ultra-high performance fiber-reinforced concrete for digital construction. *Construction and Building Materials*, 257, pp. 119546.

[3] Asprone D, Auricchio F, Menna C and Mercuri V (2018). 3D printing of reinforced concrete elements: technology and design approach. *Construction and Building Materials*, 165, pp. 218-231.

[4] Assaad JJ, Yassin AA, Alsakka F and Hamzeh F (2020). A modular approach for steel reinforcing of 3D printed concrete-preliminary study. *Sustainability*, 12(10), pp. 4062.

[5] Baz B, Aouad G, Leblond P, Al-Mansouri O, D’hondt M and Remond S (2020). Mechanical assessment of concrete - Steel bonding in 3D printed elements. *Construction and Building Materials*, 256, pp. 119457.

[6] Bos FP, Ahmed ZY, Jutinov ER and Salet T (2017). Experimental exploration of metal cable as reinforcement in 3D printed concrete. *Materials*, 10(11), pp. 1314.

[7] Buswell RA, De Silva WL, Jones SZ and Dirrenberger J (2018). 3D printing using concrete extrusion: a roadmap for research. *Cement and Concrete Research*, 112, pp. 37-49.

[8] Huashang Tengda (2016). *Chinese construction company 3D prints an entire two-story house on-site in 45 days*. Available at: <https://3dprint.com/138664/huashang-tengda-3d-print-house>. [Accessed on 9 July 2022].

[9] De Schutter G, Lesage K, Mechtcherine V, Nerella VN, Habert G and Agusti-Juan I (2018). Vision of 3D printing with concrete - technical, economic and environmental potentials. *Cement and Concrete Research*, 112, pp. 25-36.

[10] Diggs-McGee BN, Kreiger EL, Kreiger MA and Case MP (2019). Print time vs. elapsed time: A temporal analysis of a continuous printing operation for additive constructed concrete. *Additive Manufacturing*, 28, pp. 205-214.

[11] Grasser G, Pammer L, Koell H, Werner E and Bos FP (2020). *Complex architecture in printed concrete: The case of the Innsbruck University 350th anniversary pavilion COHESION*. In: Second RILEM International Conference on Concrete and Digital Fabrication: Digital Concrete 2020. Eindhoven: Springer, pp. 1116-1127.

[12] KPMG (2018). *Construction 2.0 - Time to change*. Available at: <https://kpmg.com/cn/en/home/insights/2018/10/construction-2-0-time-to-change.html>. [Accesed on 18 March 2023].

[13] Lu B, Weng Y, Li M, Qian Y, Leong KF, Tan MJ and Qian S (2019). A systematical review of 3D printable cementitious materials. *Construction and Building Materials*, 207, pp. 477-490.

[14] Ma G, Li Z, Wang L and Bai G (2019). Micro-cable reinforced geopolymer composite for extrusion-based 3D printing. *Materials Letters*, 235, pp. 144-147.

[15] Marchment T and Sanjayan J (2020). Mesh reinforcing method for 3D concrete printing. *Automation in Construction*, 109, pp. 102992.

[16] Mechtcherine V, Grafe J, Nerella VN, Spaniol E, Hertel M and Füssel U (2018). 3D-printed steel reinforcement for digital concrete construction manufacture, mechanical properties and bond behaviour. *Construction and Building Materials*, 179, pp. 125-137.

[17] Mechtcherine V, Nerella VN, Will F, Näther M, Otto J and Krause M (2019). Large-scale digital concrete construction - CONPrint3D concept for on-site, monolithic 3D-printing. *Automation in Construction*, 107, pp. 102933.

[18] Pan W, Wang Z and Zhang Y (2021). Module equivalent frame method for structural design of concrete high-rise modular buildings. *Journal of Building Engineering*, 44, pp. 103214.

[19] Sanjayan J, Nazari A and Nematollahi B (2019). *3D concrete printing technology: construction and building applications*. Oxford: Butterworth-Heinemann.

[20] Wangler T, Lloret E, Reiter L, Hack N, Gramazio F, Kohler M, Bernhard M, Dillenburger B, Buchli J, Roussel N and Flatt R (2016). Digital concrete : opportunities and challenges. *RILEM Technical Letters*, 1, pp. 67-75.

[21] Weng Y, Li M, Ruan S, Wong TN, Tan MJ, OwYeong KL and Qian S (2020). Comparative economic, environmental and productivity assessment of a concrete bathroom unit fabricated through 3D printing and a precast approach. *Journal of Cleaner Production*, 261, pp. 121245.

[22] Weng Y, Mohamed NAN, Lee JS, Gan JH, Li M, Tan MJ, Li H and Qian S (2021). Extracting BIM information for lattice toolpath planning in digital concrete printing with developed Dynamo script: a case study. *Journal of Computing in Civil Engineering*, 35(3), pp. 05021001.

[23] Zheng Z, Zhang Z and Pan W (2020). Virtual prototyping- and transfer learning-enabled module detection for modular integrated construction. *Automation in Construction*, 120, pp. 103387.

[24] Zhu B, Nematollahi B, Pan J, Zhang Y, Zhou Z and Zhang Y (2021a). 3D concrete printing of permanent formwork for concrete column construction. *Cement and Concrete Composites*, 121, pp. 104039.

[25] Zhu B, Pan J, Zhou Z and Cai J (2021b). Mechanical properties of engineered cementitious composites beams fabricated by extrusion-based 3D printing. *Engineering Structures*, 238, pp. 112201.