Cross-Layer Reinforcement Robot for 3D Printing Concrete: Hardware, Software, and Validation

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Abstract. A significant technical challenge faced by 3D printing concrete (3DPC) is integrating reinforcing materials, such as steel fibre and rebar, across multiple layers. Additionally, an automated reinforcement process is essential to ensure the installation precision of the reinforcement and maintain the construction efficiency of 3DPC. This study proposes a robotic system to achieve collaborative work between cross-layer reinforcement installation and concrete printing. The proposed system consists of two main modules: a concrete printing module and a cross-layer reinforcement installation module. This study developed a simple Cartesian robot as a preliminary cross-layer reinforcement installation module, which can work with a gantry-style 3D printer. A set of software based on Robot Operating System 2 was used to control the robot's actions. The robot has three linear joints and one revolute joint, the revolute joint enables the insertion of cross-layer reinforcement at different angles. With specially designed end-effectors, this robot can handle different reinforcing materials. Steel fibre and U-shaped steel rebar were adopted to rein-force the printed concrete, and then X-Ray Computed Tomography (XCT) scanning analysis was used to verify the reliability of this system.

Keywords: 3D printing concrete; Robot; Cross-layer reinforcement; Steel fibre; Inserted steel rebar.

1 Motivation and Background

3D printing concrete (3DPC) is a novel method to construct structures by depositing concrete layers through a computer-guided nozzle. It lends itself to the efficient fabrication of complex shapes without formwork and with less labor. However, this layer-by-layer approach produces a potential weak interface bond between concrete layers. The performance of this interface is highly dependent on factors that are difficult to control, such as concrete surface moisture and printing time interval [1–3]. This unpredictable weak bond causes 3DPC structures to disintegrate and suffer cross-layer cracking under complex loads [4]. Therefore, cross-layer reinforcing materials are needed to bear the tensile force inside 3DPC and improve the resilience of 3DPC structures. In addition, automatic methods of installing the cross-layer reinforcements

https://doi.org/10.24355/dbbs.084-202408200644-0

are also required to ensure the manufacture of 3DPC structures as an efficient autonomous process.

Researchers have proposed different forms of cross-layer reinforcement for 3DPC, such as steel fibre [5], nails [6–10], rivet [11], and rebar [12, 13]. However, rather than searching for automatic and reliable ways to install these cross-layer reinforcements, these studies focused on testing the effects of these novel methods. Robotized and industrialized production of cross-layer reinforced 3DPC structures is a complex problem that has not been solved till now. The complexity is attributed to the following factors: a) coordination between concrete printing devices and reinforcement devices; b) automated material supply for the reinforcement device; and c) robotic sensing for quality control.

This paper presents our first step towards realizing a cross-layer reinforced 3DPC production system: a specification of the hardware and software of a robotic system and the development of a prototype cross-layer reinforcement robot. The robot can accurately incorporate two types of cross-layer reinforcements, steel fibre and U-shaped rebar, into the printed concrete, providing preliminary validation of the feasibility for the proposed system. The software of this robot is based on the open-source framework, Robot Operating System 2, which allows easy up-scaling for future testing.

2 Concept of a collaborative robotic system

2.1 Hardware

A smooth production workflow requires the synchronization of two processes: installing cross-layer reinforcement and extruding concrete. In our proposed robotic system, these two processes are carried out by two separate robotic modules, the concrete printing module and the cross-layer reinforcement installation module. The rationale for this two-module setup is that these two processes are not motion-wise compatible. For a smoothly printed concrete filament, the concrete extruder should move continuously. Meanwhile, to install cross-layer reinforcement with precision, the base of the reinforcement device should remain stationary when installing each piece of reinforcement. By decoupling the robotic motion of the two processes, the two-module collaborative system allows reinforcement devices to carry out more precise and more complex operations. However, this brings up the issue of coordination between the two modules, which should be resolved by the system's control software.

The concrete printing module should consist of one or more concrete printing robots. Each concrete printing robot should be able to move its end-effector on a programmed printing path and extrude concrete at its end. Concrete printing robots are already commercially available.

The cross-layer reinforcement installation module should consist of one or more cross-layer reinforcement robots. The cross-layer reinforcement robot includes several functional components: a) mobile platform, e.g., mobile robotic arm; b) raw reinforc-

https://doi.org/10.24355/dbbs.084-202408200644-0

ing material supply unit; c) reinforcing material processing unit; and d) reinforcing material installing device.

Fig. 1 illustrates an example of a simple two-robot collaborative system. For on-site structural construction with large-scale concrete printing, however, each module must contain several robots working in parallel. Insufficient numbers of robots would result in significant time intervals between the installation of reinforcement and the extrusion of concrete, while the reinforcing material can only be properly installed when the concrete is fresh.

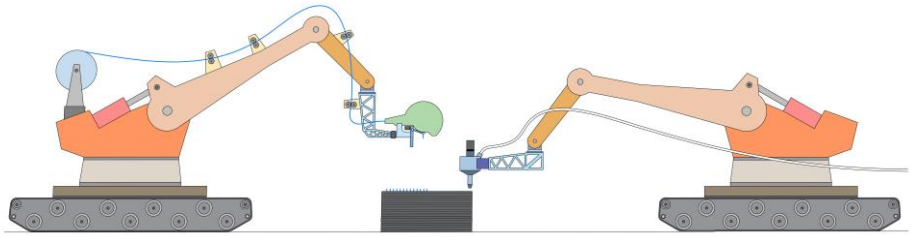

Fig. 1. Scheme of a simple two-robot collaborative system. The robot arm on the right, which have a concrete extruder at its end, acts as the concrete printing module. The robot arm on the left, which has a steel fibre inserting tool at its end, acts as the cross-layer reinforcement installation module. Steel reinforcement is transmitted to the end of the robot by a set of rollers and inserted into printed concrete.

2.2 Software

A two-tier software architecture is proposed to integrate the two robotic modules. The first tier is called the coordination tier, which distributes construction tasks through three layers of allocation, as shown in Fig. 2. In the first level of allocation, the structure design file reader reads the design file and simply passes the structure design to the task sequence planner. Task sequence planner breaks up the structure design into a sequence of stable partial structure configurations and then converts it into a sequence of tasks that the concrete printing module and the cross-layer reinforcement installation module should take. The task sequence planner passes the tasks to the concrete printing task allocator and cross-layer reinforcement task allocator as the second level of task allocation. In the third level of allocation, the concrete printing task allocator and cross-layer reinforcement task allocator pass each task to an individual robot fitted for the job. Feedback is passed upstream simultaneously. The task sequence planner consults the structure stability checker to see whether the structure remains stable during construction.

The second tier of software is named the robot tier, and its architecture is shown in Fig. 3. Programs in this tier run on individual robots. The operation controller receives tasks from the coordination tier. It then breaks up the task as a list of robot actions. It controls the robot's movement by issuing the target position of all joints to the joint trajectory planner. The joint trajectory planner then generates a collision-free and efficient joint trajectory and passes it to the actuator controller for execution. The opera-

https://doi.org/10.24355/dbbs.084-202408200644-0

tion monitor gathers real-time status data from actuators and sensors, compares these data with the command from the operation controller, and informs the operation controller on whether the issued target has been achieved. The operation monitors also provide information about obstacles for the joint trajectory planner.

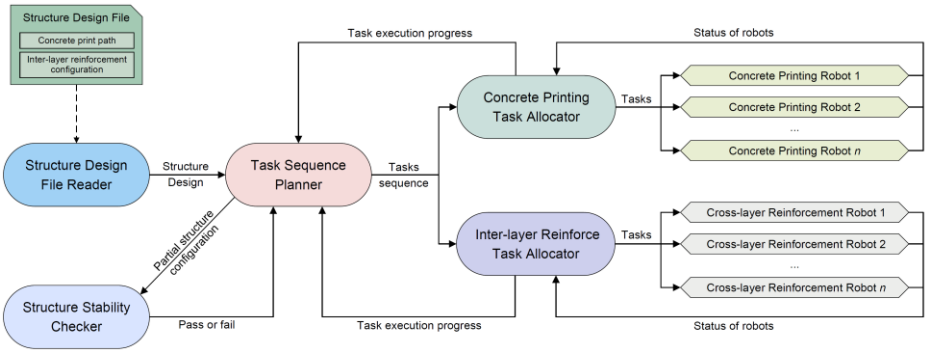

Fig. 2. Coordination tier of software.

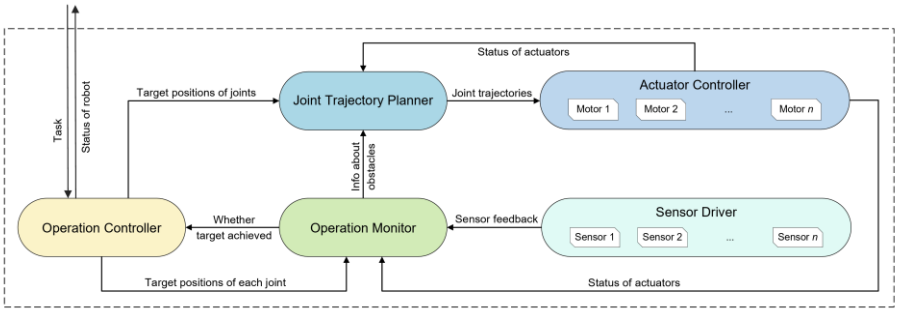

Fig. 3. Robot tier of software.

3 Validation with a Cartesian robot

We developed a Cartesian robot as a cross-layer reinforcement robot, as shown in Fig. 4a and Fig. 4c. The linear X joint, linear Y joint, and a revolute joint together form a 3-DoF mobile platform. The revolute joint allows reinforcing materials to be installed at a desired angle. A specially reinforcing material installing device is mounted on this platform. Two reinforcing material installing devices were designed: a rebar installer that can push U-shaped rebar into printed concrete and a steel fibre installer that can insert steel fibre into printed concrete. They can integrate reinforcing material into 3DPC in such a way that they across multiple concrete layers.

The Cartesian robot collaborate with a gantry-styled concrete 3D printer; its dimensions are: 2550 mm (length) × 2350 mm (width)× 2520 mm (height). The printable

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material was a commercial ready-to-mix dry mixing mortar GL-0712 developed by Hangzhou Guanli Intelligent Technology Co., Ltd.

In this testing setup, reinforcing materials are supplied to reinforcing material installing devices manually. The diameter of the adopted rebar was 6mm, its leg length was 107 mm, and its width was 72 mm; it could be adopted as stirrups in 3D printed structure elements such as beams. The diameter of the adopted steel fibres was 0.8 mm, and their length was 64 mm.

The reinforcing materials were installed into rectangular blocks of printed concrete; after their installation, several additional layers of concrete were printed to cover the exposed part of the reinforcing material. 100 mm × 100 mm × 100 mm sample cubes of concrete containing the reinforcing material were obtained by saw-cutting; they were sent for X-ray computed Tomography (XCT) scanning.

Fig. 4b and Fig. 4d are XCT images of concrete with cross-layer reinforcing material installed inside. The intended angle between the reinforcing material and layer interface was 45°, and the actual values of this angle measured from the images exhibit slight deviations from the desired value. This deviation could be attributed to numerous factors, such as the unevenness of the floor, errors in the alignment between the coordinates of the reinforcement robot and the 3D concrete printer, and the uncertain dynamics between the reinforcing material and the printed concrete.

The robot's end-effector is restricted to movement within a plane, which is clearly limited in terms of flexibility and is not suited for large-structure printing. The slim form factor of the reinforcement robot was chosen to enable easy coordination with a gantry-style concrete printer. If a mobile robot arm was used as the mobile platform for the reinforcement robot, the collision avoidance problem would become much more complex. Collision avoidance between full-scale mobile robots will be addressed in future studies.

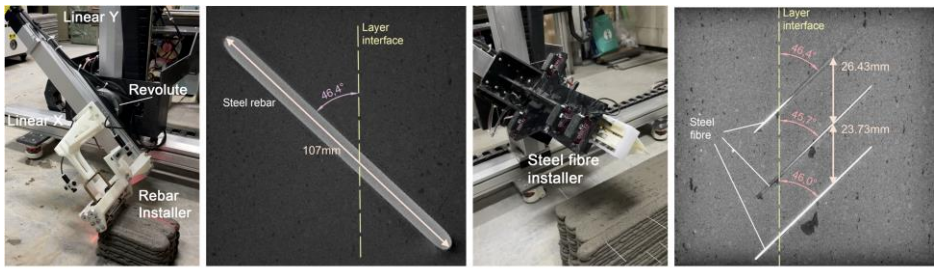

Fig. 4. Robot function testing and results: (a) robot inserting U-shaped rebar; (b) XCT image of rebar in printed concrete; (c) robot inserting steel fibre; (d) XCT image of steel fibre in printed concrete.

The paradigm of the robot tier (Fig. 3) was followed in developing the control software for the cross-layer reinforcement robot. The software was realized by utilizing the Robot Operating System 2 framework, in which modular programs are defined as individual Nodes. An inertial measurement unit (IMU) was adopted to provide sensor

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feedback on the inclination angle of reinforcing material installing devices. The software automatically controls the robot's trajectory and the reinforcing material installation process. However, the coordination tier of the software is not realized, but emulated by the human operator. In other words, the human operator decides when the concrete printer should be printing and when the cross-layer reinforcement robot should act.

4 Future steps

This paper presents the concept of a multi-robot system in which the concrete printing robots collaborate with the cross-layer reinforcement robots. The software of the system has two tiers: the coordination tier and the robot tier. A simple cross-layer reinforcement robot was developed, and its software adopted the proposed robot tier. However, the coordination between the cross-layer reinforcement robot and the concrete printer was still done by a human operator. Further development steps are needed to validate the concept of the coordination tier: a) design a file format to store cross-layer reinforced 3DPC structure design; b) develop a reliable structure stability checker; and c) develop a simulation environment for testing different task sequence planning and task allocation strategies.

Once the coordination tier of the software is ready, the production testing can be scaled up: mounting the reinforcing-material-installing device onto mobile robotic arms and testing whether it can collaborate with a mobile concrete printer in constructing a concrete structure. The research on efficient ways to achieve automatic raw reinforcing material supply and processing will also be our focus in the future; a key in this research direction is how to avoid voids between reinforcing material and 3DPC and improve the bond between them.

References

1. Sanjayan, J.G., Nematollahi, B., Xia, M., Marchment, T.: Effect of surface moisture on inter-layer strength of 3D printed concrete. Construction and Building Materials 172, 468–475 (2018) https://doi.org/10.1016/j.conbuildmat.2018.03.232
2. Keita, E., Bessaies-Bey, H., Zuo, W., Belin, P., Roussel, N.: Weak bond strength between successive layers in extrusion-based additive manufacturing: measurement and physical origin. Cement and Concrete Research 123, 105787 (2019) https://doi.org/10.1016/j. cemconres.2019.105787
3. Xu, Y., Yuan, Q., Li, Z., Shi, C., Wu, Q., Huang, Y.: Correlation of interlayer properties and rheological behaviors of 3DPC with various printing time intervals. Additive Manufacturing 47, 102327 (2021) https://doi.org/10.1016/j.addma.2021.102327
4. Liu, H., Xiao, J., Ding, T.: Flexural performance of 3D-printed composite beams with ECC and recycled fine aggregate concrete: Experimental and numerical analysis. Engineering Structures 283, 115865 (2023) https://doi.org/10.1016/j.engstruct.2023.115865
5. Bester, F., Heever, M., Kruger, J., Cho, S., Zijl, G.: Steel fiber links in 3D printed concrete. In: Bos, F.P., Lucas, S.S., Wolfs, R.J.M., Salet, T.A.M. (eds.) Second RILEM International

https://doi.org/10.24355/dbbs.084-202408200644-0

Conference on Concrete and Digital Fabrication, pp. 398–406. Springer, Cham (2020) https://doi.org/10.1007/978-3-030-49916-7_41
6. Hass, L., Bos, F.: Bending and pull-out tests on a novel screw type reinforcement for extrusion-based 3D printed concrete. In: Bos, F.P., Lucas, S.S., Wolfs, R.J.M., Salet, T.A.M. (eds.) Second RILEM International Conference on Concrete and Digital Fabrication, pp. 632– 645. Springer, Cham (2020) https://doi.org/10.1007/978-3-030-49916-7_64
7. Geneidy, O., Kumarji, S., Dubor, A., Sollazzo, A.: Simultaneous reinforcement of concrete while 3D printing. In: Bos, F.P., Lucas, S.S., Wolfs, R.J.M., Salet, T.A.M. (eds.) Second RILEM International Conference on Concrete and Digital Fabrication, pp. 895–905. Springer, Cham (2020) https://doi.org/10.1007/978-3-030-49916-7_87
8. Perrot, A., Jacquet, Y., Rangeard, D., Courteille, E., Sonebi, M.: Nailing of layers: A promising way to reinforce concrete 3D printing structures. Materials 13(7) (2020) https://doi.org/10.3390/ma13071518
9. Wang, L., Ma, G., Liu, T., Buswell, R., Li, Z.: Interlayer reinforcement of 3D printed concrete by the in-process deposition of u-nails. Cement and Concrete Research 148, 106535 (2021) https://doi.org/10.1016/j.cemconres.2021.106535
10. Cao, X., Yu, S., Zheng, D., Cui, H.: Nail planting to enhance the interface bonding strength in 3D printed concrete. Automation in Construction 141, 104392 (2022) https://doi.org/10.1016/j.autcon.2022.104392
11. Bester, F., Kruger, J., Zijl, G.: Rivet reinforcement for concrete printing. Additive Manufacturing 67, 103490 (2023) https://doi.org/10.1016/j.addma.2023.103490
12. Marchment, T., Sanjayan, J.: Lap joint reinforcement for 3D concrete printing. Journal of Structural Engineering 148(6), 04022063 (2022) https://doi.org/10.1061/(ASCE)ST. 1943-541X.0003361
13. Cao, X., Yu, S., Cui, H.: Experimental study of the in-situ rebar splicing technique to reinforce 3D-printed concrete in vertical directions. Construction and Building Materials 400, 132756 (2023) https://doi.org/10.1016/j.conbuildmat.2023.132756

https://doi.org/10.24355/dbbs.084-202408200644-0