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Large-scale 3D printing by a team of mobile robots

Xu Zhang, Mingyang Li, Jian Hui Lim, Yiwei Weng, Yi Wei Daniel Tay, Hung Pham, Quang-Cuong Pham*

Singapore Centre for 3D Printing, School of Mechanical & Aerospace Engineering, Nanyang Technological University, 50 Nanyang Avenue, 639798, Singapore

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ABSTRACT

Scalability is a problem common to most existing 3D printing processes, where the size of the design is strictly constrained by the chamber volume of the 3D printer. This issue is more pronounced in the building and construction industry, where it is impractical to have printers that are larger than actual buildings. One workaround consists in printing smaller pieces, which can then be assembled on-site. This workaround generates however additional design and process complexities, as well as creates potential weaknesses at the assembly interfaces. In this paper, we propose a 3D printing system that employs multiple mobile robots printing concurrently a large, single-piece, structure. We present our system in detail, and report simulation and experimental results. To our knowledge, this is the first physical demonstration of large-scale, concurrent, 3D printing of a concrete structure by multiple mobile robots.

1. Introduction

Compared to traditional construction techniques, 3D-printing (also known as Additive Manufacturing) carries the promise of faster, safer, more customizable, and less labour-intensive operations in multiple segments of the Building and Construction (B&C) industry [1]. Recent years have seen rapid developments in 3D-printing for B&C, from the formulation of printable materials [2–4], to the design of new printing systems [5–9], to commercialization [10,11].

A major hurdle to the widespread adoption of 3D-printing in B&C is the limitation on the sizes of the printed structures. As reviewed in detail in Section 2, most existing 3D-printing systems for B&C are based on a gantry, which can only print structures whose sizes are at most as large as that of the gantry itself. Some arm-based systems have been demonstrated, but the sizes of the printed structures in this case are limited by the reach of the robotic arm. One workaround consists in printing smaller pieces, which can then be assembled together. This workaround generates however additional design and process complexities, as well as creates potential weaknesses at the assembly interfaces.

To overcome this scalability issue, we propose in this paper a 3D-printing system based on a team of multiple mobile robots. Such a system can potentially print single-piece structures of arbitrary sizes, depending on the number of deployed robots. We demonstrate, for the first time to our knowledge, the actual printing of a single-piece concrete structure by two mobile robots operating concurrently (see Fig. 1 and video at https://youtu.be/p_jcG25tUoo). The size of structure is 1.86 m × 0.46 m × 0.13 m (length, width, height), which is larger than the reach of each robot arm taken separately (1.74 m), highlighting the need for multi-robot deployment. According to the classification method proposed in [12], where concrete 3D-printing techniques are classified based on object scale (x_o), extrusion scale (x_e), environment (e), assembly strategies (a) and support (s), our system of collaborative printing is categorized as $x_o^1 x_e^1 e^0 a^0 s^0$ with robotic complexity of r_6, which is higher than all state-of-the-art techniques as recorded in [12]. Note that concurrent printing is important to guarantee good bonding properties at the junctions: sequential printing would lead to fresh concrete adjoining hardened concrete at the junctions, weakening thereby the bonding strength [3,13].

Concurrent 3D printing by multiple mobile robots is difficult for several reasons. First, the robot motions must be carefully planned and coordinated to optimize material delivery while avoiding mutual collisions. Second, robot localization must be highly precise to ensure that the pieces printed by different robots are perfectly aligned. Finally, the mixing and pumping systems of the robots must be coordinated to deliver materials in a synchronized manner.

The remainder of the article is organized as follows. In Section 2, we review existing 3D-printing systems for B&C. In Section 3, we present in detail our system based on a team of mobile robots. In Section 4, we report the results of the multi-robot printing experiment. In Section 5, we discuss the advantages and limitations of the proposed system. Finally, in Section 5.1, we conclude and sketch some directions for future

* Corresponding author.
E-mail address: cuong@ntu.edu.sg (Q.-C. Pham).

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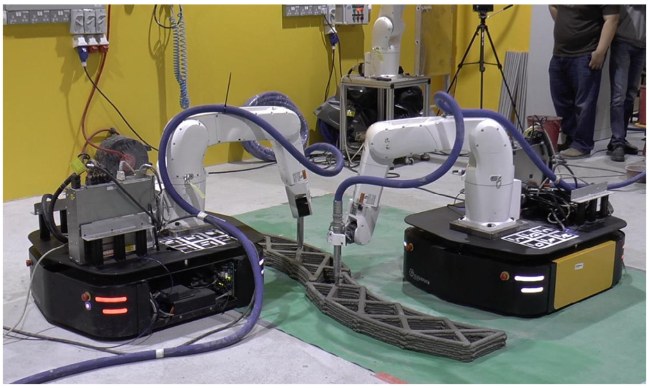

Fig. 1. Concurrent printing of a large, single-piece, concrete structure by two mobile robot printers. See the full video of the experiment at https://youtu.be/p_jcG25tUoo.

work.

2. Related works

2.1. Material development of 3D cementitious material printing

In recent years, various 3D concrete printing materials have been developed, categorized primarily into 3D printable plain concrete [2,3,14], 3D printable geopolymer [15], 3D printable fibre reinforcement concrete [16,17], 3D printable rapid hardening materials [18,19] and 3D printable earth-based materials [20]. These materials share a common emphasis on their rheological performances, which directly impacts the buildability and printability of 3D concrete printers, quantified by measurements such as printed height and pumping pressure respectively.

In the literature, several material models have been developed to understand material behaviour. Perrot et al. first established a model correlating yield stress and geometric factor to buildability [21], and his study was extended by Weng et al. towards more realistic application [22]. Weng's built-up model predicts the buildability of hollow cylinder using material static yield stress and geometric factor of the printing design. Wolfs et al. have shown that the elastic properties evolution is also critical in order to avoid structure collapse by buckling [23]. In another rheology study, Chhabra et al. proposed a model relating pumping pressure to rheological performance [24]. His model indicates that pumping pressure is governed by material plastic viscosity. Concrete is thixotropic [25] due to its continuous hydration, and this mean that its viscosity becomes less viscous when undergoing shear stress due to pumping. From these earlier works done, it is clear that the rheological property and elastic properties evolution of concrete are essential factors affecting concrete printing in terms of buildability and pumpability.

2.2. 3D concrete printing systems

Concrete printing systems can be divided based on their system mechanism, which is primarily gantry systems and robotic arm systems.

2.2.1. Gantry-based systems

The gantry system is widely adopted and uses a gantry to position the print nozzle in XYZ Cartesian coordinates. The build envelope of the gantry system is determined by enclosed volume of the gantry. A number of notable gantry systems include Contour Crafting [5,26–28], Concrete Printing [2,29,30] and D-shape [6].

These three techniques differ in their printing technique, with Contour Crafting and Concrete printing using an extrusion-based method similar to the Fused Deposition Method in additive manufacturing, and D-shape uses a binder jetting technique to selectively deposit binders on a powder bed made up of magnesium-based materials and sand. Another difference between Contour Crafting and Concrete printing is Concrete Printing's use of printing supports, which allows Concrete Printing to print full 3D topology as compared to Contour Crafting's vertical extrusion of a planar shape.

2.2.2. Arm-based systems

Robotic arm systems are relatively new compared to the gantry system counterparts. They provide additional roll, pitch and yaw controls to the end effector (print nozzle), allowing the print nozzle to perform more articulate print designs, such as printing with the tangential continuity method [7]. The tangential continuity method allows a smoother transition between print layers by maintaining a continuous rate of curvature change, giving a more aesthetically pleasing look. Another robotic arm system by Keating et al. [8] in Digital Construction Platform (DCP), they mounted the robotic arm on a track driven mobile platform for on-site fabrication of printed structures. DCP's system is also self-sufficient by recharging its electrical drive system with solar panels. One other mounted robotic arm system is Cybe RC 3Dp [31] which has a 6-axis robotic arm mounted on caterpillar tracks and is used in 3D printing the R&Drone Laboratory in Dubai [11].

2.2.3. Minibuilders

Minibuilders [9] presents an alternative approach for 3D concrete printing. They use three small mobile robots in the system. The first robot is equipped with a sensor that follows an initial marked path and builds the concrete foundation. The second robot is placed on the foundation and gripped the foundation with rollers before printing additional layers of concrete, and building up the structure. The last robot uses suction cups and pressurized air to print vertically up the printed structure and reinforced the printed structure which had only horizontal layers.

2.2.4. Summary

The biggest limitation in literature of printing system is their lack of scalability. Gantry-based system and stationary robotic arm system requires a massive external framework to support the single print nozzle in building the structure. While mobile robotic arm system helps extend the printing range, a single print nozzle still hoards the entire print space, limiting the efficiency of the printer. Although a multiple agent system is introduced by Minibuilders, their robots requires a harden structure for climbing and therefore has limited application as it involve waiting for the printed concrete to grant sufficient strength before deployment.

This gap in scalability motivates our project of a multi-robot printing system. Our system utilizes multiple mobile robot printers in a multi-agent setting to print their individual portion of a large print structure. They are capable of localization, collision avoidance and efficient coordinated printing through optimal robot placement. Our system demonstrate scalability by allowing users to introduces as many robots as needed in a shared environment for task completion in a fast and efficient manner.

2.3. Robotics background

Some robotics knowledge of the algorithms used in our proposed system for robot localization and planning is introduced in this section.

2.3.1. Simultaneous localization and mapping (SLAM)

Self-localization is critical for mobile robots to allow it to navigate its environment. The common strategy for localization in an unstructured environment involves using Simultaneous localization and mapping (SLAM) to construct and or update the map of the environment while keeping track of the robot in the environment [32–34]. A recent literature survey on state-of-the-art methodologies for