Development and Implementation of an Autonomous Mobile 3D Printing Robot

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In the context of smart construction and sustainable development, additive manufacturing (AM) technology in the construction industry has been rapidly advancing. However, traditional AM equipment relies on fixed gantry system or rail systems, making it difficult to meet the demands of large-scale construction scenarios. To address these limitations, this paper proposes a mobile, simultaneous printing additive manufacturing system. The system consists of a small, mobile platform and a robotic arm, capable of printing single structures of any size using a single robot. It features a large printing range, high flexibility, and low deployment cost. The system can quickly respond to construction needs through autonomous mobility and infrared motion capture for error correction. This paper explores scientific issues related to small-scale devices in large-scale construction scenarios, including collaborative motion between the mobile platform and robotic arm, printing coupling control and distribution algorithms, motion control systems, as well as the hardware architecture and software implementation of the system. Through positioning and printing experiments, the mobile printing system's positioning accuracy and trajectory stability are evaluated, offering promising insights for the application and potential promotion of mobile 3D printing technology in the construction industry.

Keywords: *Robotic Fabrication, Mobile Robotic Systems, On-Site 3D Printing, Collaborative Control of Mobile Platform and Robotic Arm*

INTRODUCTION

In the context of smart construction and sustainable development, additive manufacturing (AM) technology in construction has developed rapidly, demonstrating high production efficiency and significant potential for reducing resource waste and achieving environmental sustainability (Bock and Linner, 2015). Currently, in addition to its widespread use in factory prefabrication, additive construction technology has led to a series of prefabricated component systems designed for on-site in-situ printing. (Sandeep and Kannan, 2021). For example, COBOD in Denmark and PERI in Germany have commercialized on-site additive manufacturing technology and successfully applied it in the construction of small residential projects (Dörfler et al., 2019).

Currently, most on-site additive construction employs static gantry or robotic arm solutions, which have multiple limitations. First, these devices rely on fixed spatial working structure systems such as trusses or rails, requiring adjustments based on building dimensions, which leads to a restricted printing range and difficulty in handling tasks outside of the operational limits. Additionally, these devices are large, making transportation and deployment difficult, especially in high-density urban areas or remote locations. (Asprone et al., 2018). Furthermore, large equipment struggles to achieve precise operations in confined spaces,

limiting its applicability. Finally, the installation and debugging process of these devices is complex and requires professional personnel, which is not only time-consuming and costly (see table 1) but also cumbersome when disassembling and reassembling, (Lim et al., 2012). significantly reducing deployment efficiency.

This paper proposes a solution based on a mobile 3D printing system (M3DP) for small-scale equipment to meet the on-site production demands in large-scale construction scenarios. The M3DP system consists of a small movable mobile platform connected to a robotic arm, offering an infinite planar printing range, high flexibility, and low deployment cost. The system is capable of adapting to complex production environments, conducting construction activities directly on-site through autonomous movement, and quickly responding and adjusting based on site needs. Additionally, the mobile 3D printing system has the potential for task parallelization: multiple autonomous mobile printing robots can collaborate to achieve clustered printing for large-scale construction projects (Dörfler et al., 2024), significantly improving overall construction efficiency.

For mobile 3D printing scenarios, challenges still remain in the coupling control of mobile platform-arm collaboration and maintaining 3D printing precision during movement. Therefore, this paper explores the study of mobile platform-arm collaborative motion, including the mechanism coupling control between the mobile platform and robotic arm, dynamic error correction algorithms and motion control strategies, as well as printing path planning techniques adapted to dynamic environments. (Dörfler et al., 2024) These studies aim to improve the stability and precision of the mobile printing system, providing reliable technical support for complex construction tasks.

RELATED WORKS

Recent research has advanced the use of mobile robots in large-scale 3D printing. Dörfler et al. (2024) analyzed the opportunities and challenges of applying mobile robots for building maintenance and repair, emphasizing integration in existing contexts. Zhang et al. (2018) demonstrated collaborative large-scale 3D printing with multiple robots, enabling flexibility and scalability. Tiryaki, Zhang and Pham (2019) proposed the "printing-while-moving" concept, allowing robots to print continuously during movement, improving efficiency for large-scale tasks. Sustarevas, Kanoulas and Julier, (2022) further explored autonomous mobile 3D printing along large-scale trajectories, focusing on task-consistent path planning to ensure printing quality. Dielemans et al. (2022) presented a case study on mobile additive manufacturing using clay formwork for in-situ concrete construction, showcasing the adaptability of mobile robots in specialized construction tasks. These studies collectively demonstrate the potential of mobile robotic 3D printing, while highlighting challenges such as path planning, system integration, and task coordination.

These studies highlight M3DP's potential to enhance scalability and task automation. However, challenges such as dynamic environment positioning accuracy, multi-agent coordination, and real-time control persist. Future research must integrate multi-sensor fusion and intelligent algorithms to further improve M3DP's performance and applicability in complex environments.

Table 1
Comparison of on-site and prefabricated construction 3D printing systems

Robot Configuration	Construction Method	Print Area Size (m^2)	Printing Height (m)	Repeat Accuracy (mm)	Equipment Weight (t)	Team Representative	Equipment* Cost (×10k USD)	Deployment Cost (×10k USD)	Total Cost (×10k USD)
Gantry	In-situ	$14.6 \times \infty$	8	3	8	Tongji Univ. COBOD (Denmark)	45	1.5	46.5
Cylindrical	In-situ	$\pi \times 5.5^2$	3.3	0.2	2	Construction-3D (France) Hebei Univ.	45	0.8	46.8
Fixed Robotic Arm	In-situ	$\pi \times 6.75^2$	7.1	0.1	6	Construction-3D (France) Hebei Univ.	25	0.8	25.8
Fixed Arm	On-site Prefabricated	2.7×1.2	1.5–3	0.02–0.08	6	ETH Zürich Autodesk Toolbox	45	0.5	45.5
Lifting Robotic Arm	In-situ / Factory Prefab	$\pi \times 3.2^2$	3	0.1	4	Fab-Union CyBe (Netherlands)	30	0.6	30.6
Rail-based Robotic Arm	In-situ	$3.2 \times \infty$	5	0.2	3	Tsinghua Univ. Vertico (Netherlands)	22	1.2	23.2
Parallel Robot	In-situ / Factory Prefab	$12.6 \times \infty$	4	0.3	3	WASP, HINDCON	30	0.6	30.6
Our Printer	On-site Prefabricated	$\infty \times \infty$	3	5	0.07	UCL–Julius Sustarevas (This case)	3	1	4

*All equipment and deployment costs are estimated values based on publicly available sources and project experience. Actual figures may vary depending on manufacturer specifications, procurement conditions, and regional factors.

Figure 1
Representative mobile and stationary 3D printing systems: (a) Gantry-based; (b) Cylindrical; (c) Fixed Arm; (d) Prefabricated Arm; (e) Lifting Robotic Arm; (f) Rail-based; (g) Parallel Robot; (h) Our mobile printer

PAPER OVERVIEW

This chapter introduces a compact autonomous mobile 3D printing robot for in-situ prefabrication, addressing key challenges such as adapting small-scale devices to large-scale construction
and coupling mobility with printing. It focuses on five key research areas: kinematic optimization of the mobile platform, system integration, dynamic error correction algorithms, coupling control allocation, and printing path planning. The robot's hardware and software architecture are outlined,
and its performance is validated through 3D printing experiments(Fig 2).

ROBOT HARDWARE

The hardware setup includes an 8-Mecanum-wheel mobile platform, a 6-axis UR robotic arm, and a pumping system. The robotic arm is mounted on the mobile platform via a coupling mechanism and equipped with a printing extruder. The arm has a reach of 1,300 mm, repeatability of ±0.03 mm, and a payload capacity of 10 kg. The Mecanum-wheel mobile platform is controlled by an STM32F407VET6 microcontroller, which connects to motor encoders, motor drivers, and a Bluetooth communication module. The pumping system includes an air compressor, pneumatic pump, material barrel, and delivery hoses. The positioning system consists of motion capture cameras and reflective markers on the mobile platform and 3D printing extruder(Fig 3).

Power optimization for the compact mobile platform.

To support an estimated 200 kg, an 8-wheel configuration with clamp-type Mecanum wheels was used, each rated for 25 kg. The mobile platform frame was modified to a rigid structure by removing springs, adding aluminum profiles, and incorporating cross-bracing for added stability. These changes stability. A 1:2 timing pulley system replaced couplings to further increase torque,

optimizing the mobile platform' performance and stability.

System integration and spatial optimization.

The layout design ensures the UR10 robotic arm operates without interference within its 1,300 mm joint workspace. The mobile platform's center of gravity is positioned near the frame's geometric center to maintain balance and optimize performance.

Electrical system. The system uses a high-to-low voltage converter to isolate the UR10 arm (48V) from the motors (24V), ensuring efficient power conversion and reducing heat generation, thus improving system stability and reliability.

Printing extrusion system set-up.

The printing system features a compact, high-speed 3D printing extruder mounted on the robotic arm, utilizing a screw-based extrusion mechanism. A DJI M2006 P36 brushless motor drives the system, with PID closed-loop control managed by an STM32F103C8T6 microcontroller. The pumping system transports material from the barrel to the 3D printing extruder using an air compressor, pneumatic pump, and delivery hoses. barrel to the 3D printing extruder through backend connections.

SOFTWARE SYSTEM

The mobile platform employs an STM32F407 development board-based control system integrated with a Bluetooth communication module, utilizing Python's PyBluez library for remote Bluetooth communication control to ensure real-time performance and user-friendly operation. The UR10 robotic arm connects to the control computer via an Ethernet interface, achieving precise motion control and printing task execution through customized command sets and communication protocols. This integrated hardware-software architecture significantly enhances system scalability and operational efficiency, effectively addressing the dynamic demands of complex construction scenarios.

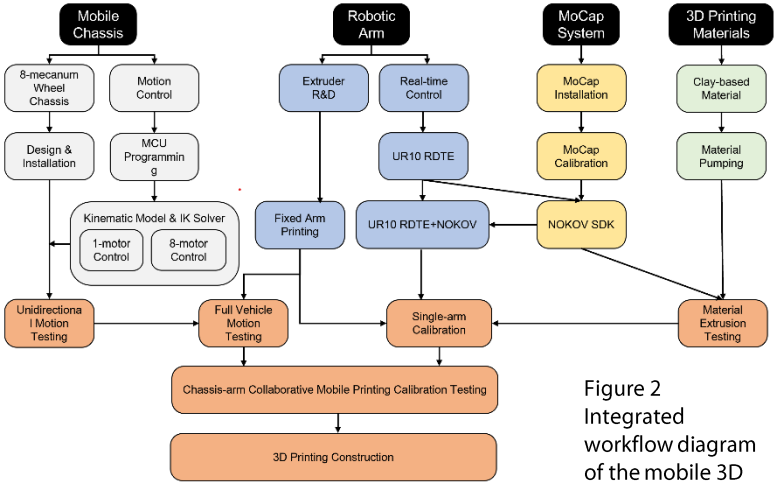

Figure 2
Integrated workflow diagram of the mobile 3D printing system

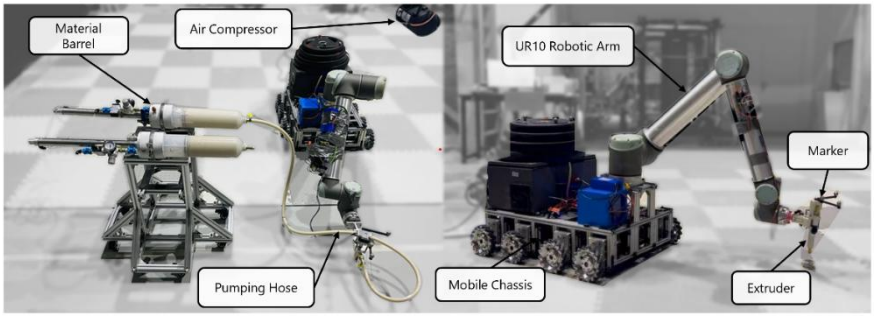

Figure 3
The hardware system

Overview of vehicle-manipulator coordinated system.

The vehicle-manipulator coordinated system is an integrated automated system that achieves stable operations in complex environments through precise motion control and dynamic posture adjustments. Its core components include:

Mobile platform system. An eight-wheel mobile platform design, combined with an STM32

microcontroller and Bluetooth module, enables efficient kinematic resolution for precise steering, lateral movement, and acceleration, delivering exceptional maneuverability and responsiveness.

Posture execution system. Rhino software is utilized for 3D modeling and path planning, coupled with high-precision control of the UR10 robotic arm to achieve accurate joint positioning and motion execution, enhancing operational efficiency and task accuracy.

Global error correction system. Infrared motion capture cameras and the NOKOV SDK monitor and adjust the global pose of the mobile platform and end-effector in real time, ensuring high-precision operations in dynamic environments.

End-effector system. Equipped with a dual-component extruder head, the system precisely controls material extrusion speed and volume, accommodating diverse 3D printing materials to ensure stability and versatility.

Coupling control principles.

For the basic workflow and algorithms, the core of vehicle-manipulator coupling control involves real-time monitoring and adjustment of the robotic arm and mobile platform positions using advanced sensing. Optical motion capture devices collect 3D printing extruder pose data, which is processed by the host computer to calculate errors and generate a correction matrix. This matrix is then decomposed into specific adjustments for both the robotic arm and mobile platform, ensuring high accuracy and stability during printing. The host computer uses algorithms to process this data for precise control.

Pose error calculation. $\Delta P = P_T - P_R$, PT represents the target pose of the 3D printing extruder, and PR denotes the actual pose measured by the motion capture system.

Correction matrix generation. Using error data, the system computes the pose correction matrix MC, which typically involves converting pose errors into executable control commands interpretable by the control system.

Decomposition of the correction matrix. $M_c = T_c(R) + T_c(C)$. The correction matrix is decomposed into two parts — one for the robotic arm, $T_C(R)$, and the other for the printing trolley, $T_C(C)$.

Through these steps, the main control computer sends the calculated correction values to the corresponding actuators, enabling real-time adjustments of the robotic arm and the printing trolley's poses to match the predefined target positions.

For the pose transformation and correction in multi-coordinate systems, pose transformation and correction rely on real-time feedback and dynamic adjustment. This process involves the following key steps:

Pose transformation. Based on the difference between the theoretical pose of the 3D printing extruder and the actual pose measured by the motion capture system, the system first calculates the target pose correction value:

$$K = K_p \cdot \Delta P + K_{i \int \Delta P}\, dt + K_d \frac{d\Delta P}{dt} \qquad (1)$$

Here, K_p, Ki, and K_d are the proportional, integral, and derivative gains of the PID controller, respectively.

Inverse kinematics calculation. For the robotic arm, inverse kinematics calculation is required to determine the motion path of each joint:

$\theta = \mathrm{IK}(P_c)$, where IK represents the inverse kinematics function, and θ denotes the joint angles of the robotic arm.

Dynamic deviation correction and adjustment. Using the calculated correction values, the system dynamically adjusts the poses of the robotic arm and the printing trolley. This involves complex control logic to ensure that the devices maintain their optimal pose throughout the entire operation.

Multi-level coupled control. The vehicle-arm coupled system optimizes coordination through dynamic adjustment, error compensation, and hierarchical control. Predictive control compensates

for latency, while real-time feedback enables error correction and position-speed adjustments. Hierarchical control combines the platform's wide-range support with the end-effector's precision, improving system performance and operational accuracy.

Closed-loop motion control.

In the closed-loop motion control of the vehicle-arm coupled system, emphasis is on coordinating the Mecanum-wheeled mobile platform and robotic arm to achieve precise dynamic deviation correction. The mobile platform's motion control is based on kinematic calculations, extending the traditional four-wheel model to an eight-wheel model to enable more complex mobility strategies. The motion control algorithm proceeds as follows:

Establishment of the kinematic model. $M_{\text{drive}} = \text{f}(\theta_1, \theta_2, \ldots, \theta_8)$, here, θi represents the rotation angle of the i-th wheel, and Mdrive is the drive matrix, which determines the velocity and direction of the vehicle.

Command decoding and execution. ASCII codes are used as control signals, which are decoded by the microcontroller to drive the corresponding motors, adjusting the movement according to the predefined path and speed.

Path planning and execution. By combining the current position state with the target state, an optimal driving path is calculated using a path planning algorithm.

Motion deviation correction is achieved through a real-time feedback mechanism that continuously adjusts the position and rotational pose of the Mecanum-wheeled trolley to ensure accurate movement along the predefined trajectory. The specific correction process can be represented by the following formula:

Position and pose correction:

$\Delta\theta = \arctan2(y_{\text{target}} - y_{\text{current}}, x_{\text{target}} - x_{\text{current}})$

$\Delta x = x_{\text{target}} - x_{\text{current}}$,

$\Delta y = y_{\text{target}} - y_{\text{current}}$,

When $\Delta x^2 + \Delta y^2 < "threshold"$ or $|\Delta\theta| < 0.1$, the target is considered reached.

Dynamic adjustment algorithm. based on the position and pose deviations, the system dynamically adjusts the motion direction and speed in real time to minimize the time and energy required to reach the target position. $v_{\text{new}} = \text{AdjustSpeed}(\Delta x, \Delta y, \Delta\theta)$

Dynamic deviation correction algorithm and motion control under robotic arm coordination. The key to the dynamic deviation correction algorithm for the robotic arm lies in managing the interaction between the arm and the mobile platform, especially in achieving precise control when significant distance changes occur. Through inverse kinematics and dynamic path planning, the system can adjust the robotic arm's operations in real time to adapt to the movements of the mobile platform.

$\Theta = \text{InverseKinematics}(P_{\text{target}})$

Distance-Based Deviation Correction Strategy. When dis_tcp is significantly greater than r_arm, priority is given to adjusting the mobile platform's position. When dis_tcp is approximately equal to r_arm, the correction task is distributed between the mobile platform and the robotic arm. When dis_tcp is significantly less than r_arm, priority is given to rapid response by the robotic arm. Through this multi-level control strategy, the vehicle-arm coupled system can achieve high-precision and high-efficiency operation in dynamic environments, meeting the high-standard requirements of the experiment.

Printing path planning. In the vehicle-arm coupled system, printing path planning simplifies the mobile platform's movement while maintaining pose continuity for improved print quality and efficiency. Advanced algorithms like A* or genetic algorithms compute optimal trajectories, while dynamic adjustments to speed and acceleration ensure smooth movement. Real-time feedback allows immediate path adjustments, and simulation software previews paths to identify issues. These measures enhance precision, efficiency, and overall system performance in complex printing tasks.

EXPERIMENTAL VALIDATION

The experiments validated the system's robust performance: Experiment 1 confirmed that the 3D printing end effector maintains a stable hover through precise motion capture and real-time compensation; Experiment 2 demonstrated the mobile platform's ability to follow a straight, constant-speed trajectory under dynamic conditions while decoupled from the robotic arm; and Experiment 3 showed that fully integrated operations can achieve high-precision layer printing with inter-layer deviations of less than 1 cm.

Experiment 1: End-effector hovering stability

To ensure precise printing in complex tasks and mobile environments, the motion capture system tracks the positions of both the mobile platform and the print head in real time. The robotic arm dynamically adjusts its posture based on this data to compensate for platform movement, ensuring that the print head remains at a fixed hovering
point relative to the printing surface (see Fig. 4). This stabilization mechanism enhances printing accuracy and enables adaptation to complex operations in dynamic environments.

The experiment validated three critical aspects:

- **Positioning test**: Evaluated the accuracy and response speed of the motion capture system, ensuring it could reflect positional changes rapidly and accurately in real-world scenarios.
- **Communication efficiency**: Tested the communication between the control host, mobile platform, and robotic arm. Efficient communication enables seamless collaboration, ensuring timely transmission of control commands and status updates for stable operation.
- **Motion compensation algorithm**: Verified the algorithm's ability to maintain the fixed

The results demonstrated reliable performance of the motion capture system, uninterrupted communication, and accurate execution of the motion compensation algorithm in all test scenarios.

Experiment 2: Decoupled printing of mobile platform and robotic arm

In this experiment, the mobile platform moves translationally from left to right, while the robotic arm moves along the front-back axis, extruding material at a constant speed. (see Fig.5) The experiment decouples the mobile platform motion from the robotic arm's actions, focusing on verifying whether the mobile platform maintains constant velocity and follows a straight trajectory after corrections from the motion capture system. This tests the mobile platform's stability under varying load conditions.

System calibration ensured accurate positional data, and the mobile platform was commanded to move smoothly along a predefined path under dynamic load variations from the robotic arm. Speed and trajectory deviations were monitored to analyze dynamic response and path stability. The robotic arm's motion drives continuous printing, with printing speeds adjusted under predefined material humidity conditions. Print quality was assessed across different speeds, determining the
maximum feasible speed while maintaining print integrity.

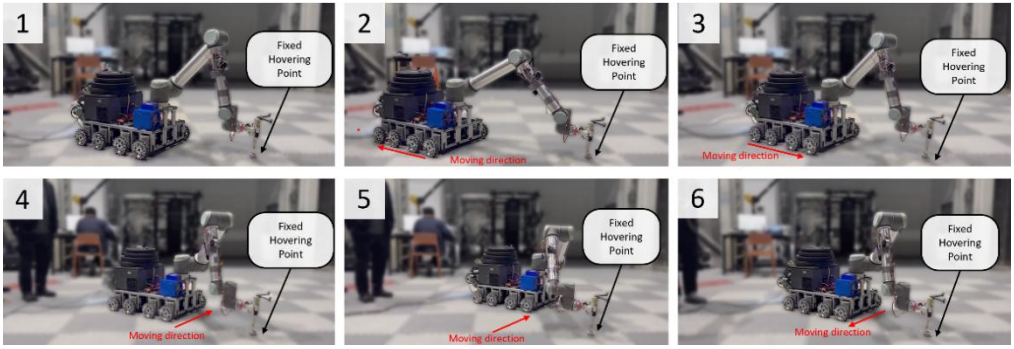

Figure 4
Snapshots of the end effector hovering stability test.

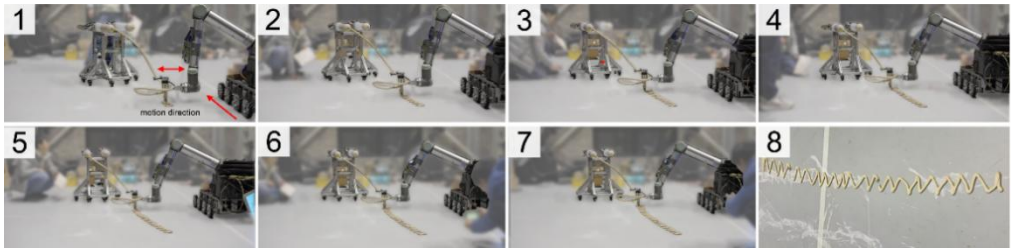

Figure 5
Snapshots of robotic arm-mobile platform decoupled printing test

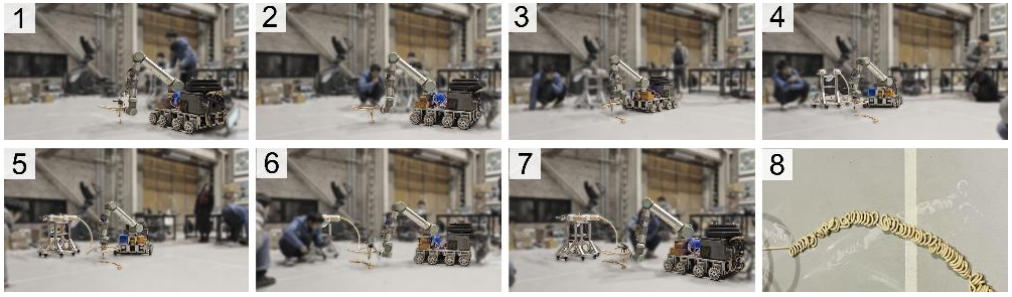

Figure 6
Snapshots of Integrated multi-layer printing test

Experiment 3: Integrated multi-layer printing test

Building upon the previous two experiments, all modules—including the mobile platform, robotic arm, and 3D printing extruder—were integrated into a fully collaborative system. The system executed printing along predefined curved paths (see Figure 6): the mobile platform coordinated with the robotic arm and extruder to complete the first layer(frames1-4). Subsequently,
printing of the second layer commenced from the endpoint of the first(frames 5-7).

After both layers were printed, the alignment between them was examined using precision inspection. The results demonstrated strong consistency, with inter-layer deviation remaining under 1 cm. These findings validate the system's control accuracy, synchronization capability, and operational stability.

CONCLUSION AND PERSPECTIVE

Future small-scale autonomous mobile 3D printing systems will evolve toward swarm collaboration, intelligent control, and high efficiency. The vehicle-arm collaborative control method proposed here enables multi-robot cooperation, significantly improving construction efficiency.

As shown in Figure 6, the system includes (1.) mobile 3D printing robots, (2.)prefabricated components, (3.) optical motion capture cameras, (4.) lifting devices, and (5.) on-site assembly,

Compared to traditional gantry systems, it reduces deployment costs and increases flexibility for complex environments. Future improvements will focus on multi-sensor fusion and intelligent positioning to enhance navigation and cooperation.

However, a critical limitation remains: the current dependence on global optical motion capture systems for precision control somewhat offsets the flexibility advantages of mobile robots. This reliance poses challenges for deployment in sites where such infrastructure is unavailable or impractical. Therefore, reducing or eliminating this dependency through advanced onboard sensing and localization techniques is a key direction for future research, essential for realizing fully autonomous, scalable, and flexible mobile 3D printing in large-scale construction.

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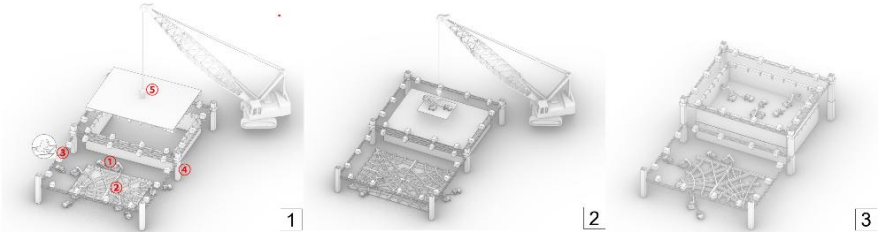

Figure 7
On-site prefabrication of architectural components using small mobile 3d printing robots

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