A Mobile Robotic Concrete Additive Manufacturing System Toward Underwater Applications

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Abstract –

This paper presents a scaled mobile robotic additive manufacturing system (AM) developed to investigate system-level feasibility toward underwater applications, with a focus on concrete-based material deposition. The proposed platform integrates a tracked mobile base, a lightweight robotic manipulator, a syringe-based extrusion unit, and a centralized–distributed wired control architecture. Rather than aiming to demonstrate a fully submerged underwater robot, this work emphasizes system-level integration, coordinated behavior validation, and underwater-oriented design considerations.

Cement-based deposition experiments were conducted to verify the integrated execution of locomotion, positioning, and material extrusion within a unified mobile platform. To improve printing accuracy, a MATLAB-based inverse kinematics method was introduced for manipulator pose planning, enabling four-layer deposition with improved path accuracy. In addition, component-level waterproofing validation was carried out for both the sealed control electronics and the waterproofed servo motors through 24-hour immersion tests, confirming stable operation of all electrically sensitive components under submerged conditions.

By focusing on subsystem integration and coordinated task execution, this study provides a theoretical experimental platform for exploring mobile concrete additive manufacturing toward underwater deployment and establishes a foundation for future research on scalable underwater construction robotics.

Keywords –

Mobile concrete additive manufacturing; Underwater robotics; Construction robotics; Robotic material extrusion; Wired control architecture; System integration

1. Introduction

1.1 Background and Motivation

Additive manufacturing (AM) has been widely investigated in the construction domain to automate fabrication processes, reduce labor demand, and enable complex geometries that are difficult to achieve using conventional methods [1]. Comprehensive reviews by Buswell et al. and Lim et al. have identified extrusion-based concrete printing as one of the most mature and promising approaches for construction-oriented AM, particularly in controlled and semi-controlled environments [2].

Most existing construction AM systems rely on stationary platforms, such as gantry systems or fixed-base robotic arms, which inherently limit the workspace and adaptability of the fabrication process; therefore, mobile additive manufacturing has been increasingly recognized as a promising alternative [3]. To address these limitations, recent studies have begun to explore mobile and non-traditional AM paradigms [4]. Notably, Zhang et al. demonstrated aerial additive manufacturing using multiple autonomous robots, revealing that material deposition can be achieved even in highly dynamic and unconstrained environments[5][6]. This work highlights the potential of extending AM beyond conventional fixed and ground-based settings.

In parallel, underwater construction, inspection, and maintenance have long been recognized as critical yet challenging tasks due to limited accessibility, high operational risk, and constrained human involvement[7][8]. Bellingham and Rajan emphasized that robotic systems play a key role in enabling operations in hostile and remote environments, including underwater settings, where conventional construction approaches are impractical [9]. However, existing underwater robotic systems primarily focus on inspection, intervention, or material removal, while material addition and additive manufacturing remain largely unexplored at the system level, as shown in Table 1.

Table 1. Comparison of existing construction AM systems, underwater robotic systems, and the proposed platform

System type	Mobility	Material deposition capability	Key gap / relation to this work
Conventional construction AM systems	Limited	Yes	Limited mobility for underwater-oriented deployment
Underwater robotic systems	Yes	Rarely	Lack of additive manufacturing integration
Proposed system	Yes	Yes	Bridges mobile AM and underwater-oriented robotic deployment

1.2 Challenges for Underwater Deployment

Extending mobile additive manufacturing toward underwater deployment introduces a series of technical challenges at the system level, particularly in terms of electrical systems, mechanical design, communication architecture, and material handling.

From the perspective of electrical and actuation systems, waterproofing of motors and electronic components is essential for underwater-oriented operation, particularly under high hydrostatic pressure conditions [10]. As the degrees of freedom of robot systems increase, the required waterproofing effort and associated cost also increase accordingly. Previous studies on underwater robotic systems have shown that sealing and protecting actuators becomes increasingly complex as the number of joints and electrical interfaces grows [9].

In underwater robotic systems, wireless communication methods such as Wi-Fi and Bluetooth are generally unreliable due to severe signal attenuation in water. It has been widely reported that underwater environments impose fundamental limitations on electromagnetic communication, making wired communication particularly important for underwater-oriented mechanical systems [11]. Accordingly, wired communication plays a critical role in task allocation, command transmission, and system debugging.

In addition to actuation and communication challenges, material feeding and deposition also present significant difficulties for underwater-oriented additive manufacturing. Traditional concrete 3D printing systems typically rely on complex pumping, mixing, and extrusion mechanisms located close to the deposition nozzle. Such system configurations have been identified as difficult to adapt to underwater environments due to increased system complexity and waterproofing requirements [2].

Material selection further constrains system design. The material must be compatible with compact extrusion mechanisms, capable of being transported through flexible hoses, and sufficiently stable after deposition in underwater or semi-underwater conditions. Balancing extrudability, deposition stability, and system integration constraints remains a key challenge for scaled experimental platforms targeting underwater deployment.

Inspired by these challenges, this study investigates mobile concrete additive manufacturing toward underwater deployment from a system-integration perspective. The work does not aim to present a fully submerged underwater concrete printing robot, nor does it claim novelty in material formulation or extrusion principle. Instead, it focuses on the integration and preliminary validation of the key functional modules required for underwater-oriented mobile additive manufacturing. The main contributions of this work are threefold: (1) the development of a scaled mobile concrete additive manufacturing platform integrating a tracked mobile base, a lightweight robotic manipulator, and a syringe-based extrusion unit; (2) the implementation of a centralized–distributed wired control architecture for coordinated locomotion, manipulation, and material deposition under communication constraints relevant to underwater applications; and (3) the experimental validation of integrated system behavior through coordinated printing experiments, inverse-kinematics-based pose planning, and component-level waterproofing of electrically sensitive modules. Together, these contributions establish an integration-driven experimental platform for future underwater construction robotics.

2. Related Work

2.1 Robotic Additive Manufacturing in Construction

Robotic additive manufacturing has been widely investigated in the construction domain, particularly for concrete-based fabrication. Existing studies have demonstrated the feasibility of extrusion-based concrete printing using stationary robotic arms, gantry systems, and fixed-base robotic platforms under controlled or semi-controlled environments. These systems primarily focus on material formulation, extrusion mechanisms, and geometric accuracy.

While such approaches have achieved promising results in laboratory and on-site settings, most construction-oriented robotic AM systems remain stationary and rely on stable ground conditions, which inherently limits their adaptability to complex, constrained, or dynamically changing environments [12].

2.2 Limitations of Existing Systems

Despite advances in both robotic additive manufacturing and underwater robotics, several limitations can be identified in existing systems. Construction-oriented AM platforms are predominantly stationary and operate in above-water environments, while underwater robotic systems rarely incorporate material deposition capabilities beyond inspection or intervention tasks [13].

Furthermore, few studies investigate mobile additive manufacturing under submerged conditions at the system level, particularly with respect to coordinated locomotion, manipulation, material extrusion, and control architecture. These limitations motivate the development of experimental platforms that explore the feasibility of mobile underwater additive manufacturing through integrated robotic system design.

3. System Architecture

3.1 Overall System Overview

A scaled robotic system is adopted in this study for experimental validation. The overall system consists of a tracked mobile platform, a lightweight multi-degree-of-freedom robotic manipulator, and a syringe-based material extrusion system, as shown in Figure 1 and Figure 2. All subsystems are designed with compact dimensions and reduced weight, making them suitable for integration into a scaled experimental platform. Although the system incorporates several underwater-oriented design considerations, the current prototype is primarily validated in a non-submerged environment.

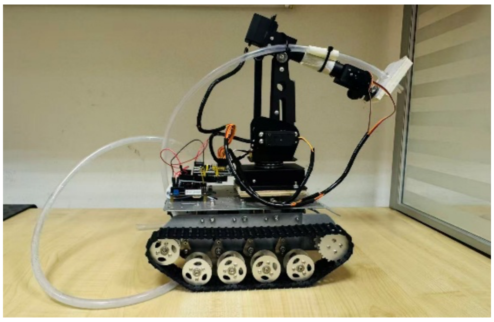

Figure 1. Overview of tracked mobile platform

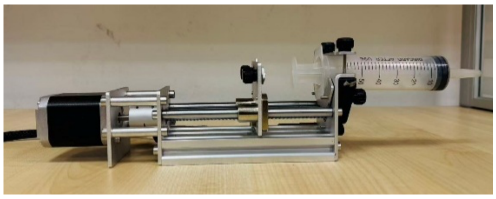

Figure 2. Overview of the Syringe-Based Material Extrusion System

3.2 Underwater Tracked Mobile Platform

The tracked mobile platform provides the robotic system with autonomous planar mobility in underwater environments. Compared with conventional four-wheel differential drive or Mecanum-wheel platforms, the tracked configuration requires only two DC drive motors to achieve fundamental locomotion functions, including forward motion, backward motion, and steering. This design significantly simplifies motion control commands while maintaining sufficient maneuverability.

During underwater operation, robotic motion is strongly affected by hydrodynamic resistance, which may lead to position or trajectory deviations. The tracked mechanism increases the contact area between the platform and the ground, thereby improving motion stability and mitigating the influence of water-induced disturbances.

From an engineering perspective, the use of a two-motor tracked drive also reduces the complexity and cost of waterproofing. Fewer drive motors are required to be sealed and protected, which simplifies the waterproof treatment of the power and control components. The detailed waterproofing strategy for the motorized components will be discussed in subsequent sections.

In addition to the drive motors, the tracked system incorporates multiple passive idler wheels. Five idler wheels are arranged on each side of the platform and combined with spring-based suspension elements. This configuration helps absorb shocks when the robot moves over uneven surfaces and effectively reduces vibration transmission to the robotic manipulator. Such vibration mitigation is particularly important for additive

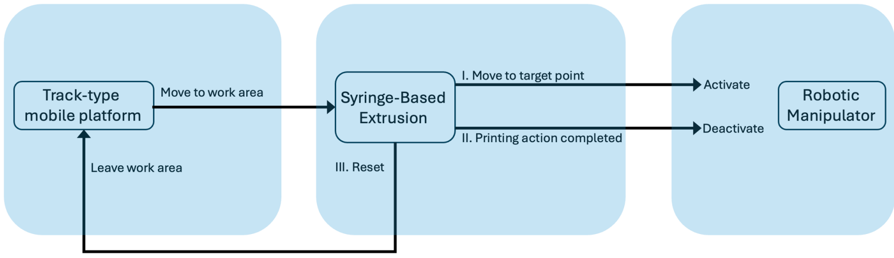

Figure 3. Control and task coordination workflow of the mobile additive manufacturing system.

manufacturing and material repair tasks, which demand relatively high positional and operational accuracy.

3.3 Robotic Manipulator and Motion Strategy

In this study, a lightweight, six-degree-of-freedom desktop robotic manipulator is employed as the end-effector unit of the proposed robotic system. The manipulator consists of a serial chain of rotational joints actuated by servo motors, featuring a compact structure, low weight, and ease of deployment, which makes it suitable for integration with a small-scale mobile platform.

Compared with industrial-grade robotic arms, this type of manipulator exhibits limitations in terms of payload capacity and positioning accuracy. However, it offers significant advantages in system integration, control complexity, and experimental feasibility, which are particularly beneficial for scaled experimental platforms.

In the proposed system, the manipulator is not intended to function as an independent high-precision device. Instead, it serves as an execution submodule within a mobile underwater additive manufacturing system, operating in coordination with the tracked mobile platform and the syringe-based material extrusion system. Accordingly, the focus of this study is not on the kinematic performance of the manipulator itself, but on its integration within a mobile construction robotic system, the associated control strategy, and task-level behavior design.

3.4 Syringe-Based Material Extrusion System

To enable material deposition in the additive manufacturing process, a syringe-based material extrusion system is designed and implemented in this study. The system integrates a stepper motor with a linear guide mechanism, allowing syringes of different sizes to be installed. In the present work, a 50 ml syringe is employed.

The syringe nozzle is connected to the extrusion outlet via an airtight flexible hose. The hose has a length of approximately 2 m, and its distal end is mechanically mounted to the end-effector of the robotic manipulator, as illustrated in Figure 1. This configuration enables coordinated operation between the extrusion system and the manipulator while maintaining overall system compactness and flexibility.

For practical operation, the electrical control and driving components of the extrusion system are intentionally placed outside the underwater environment. This arrangement facilitates material loading, maintenance, and extrusion rate control. Upon receiving control commands, the stepper motor drives the linear carriage along the guide rail at an approximately constant speed, pushing the syringe plunger forward and delivering material to the deposition nozzle in a continuous manner.

Compared with conventional concrete 3D printing systems that rely on screw extrusion or pumping-based material delivery, the proposed syringe-based approach is intentionally adopted as a compact and integration-friendly deposition module for scaled validation. In the present prototype, the 50 ml syringe is not intended as a target configuration for practical construction, but as a feasible choice for demonstrating coordinated operation between the extrusion system, the robotic manipulator, and the mobile platform. Although the current deposition volume is limited, the underlying actuation principle does not fundamentally preclude future scaling through larger reservoirs, higher-force linear drive modules, or multiple synchronized actuation units[14]. Therefore, the extrusion system should be understood as an integration-oriented experimental module rather than as a finalized construction-scale delivery solution.

3.5 Centralized Distributed Control Architecture

The system adopts a centralized–distributed control architecture, as illustrated in Figure 3. An Arduino UNO board is employed as the central supervisory controller and communicates with multiple subsystem controllers through wired connections. Specifically, the Arduino UNO is connected to an STM32-based controller of the tracked mobile platform, a dedicated control board of the robotic manipulator, and the stepper motor driver module of the syringe-based material extrusion system.

Within this architecture, the Arduino UNO is responsible for task-level scheduling and behavior triggering, while the subsystem controllers handle low-level execution.

4. Material Selection and Experimental Methodology

4.1 Selected Cement-Based Material and Mixing Ratio

In this study, material selection was intended to support system-level validation rather than material innovation or optimization. The experiments adopted a cement–water mixture as the extrusion material. Based on preliminary extrusion trials, water-to-cement ratio of 0.40 was adopted for the system-level experiments.

At this mixing ratio, the syringe-based extrusion system was able to operate safely within the rated working capacity of the stepper motor, while maintaining continuous material flow through the delivery hose. In addition, the extruded material exhibited sufficient plasticity and shape stability after deposition, allowing the deposited filament to maintain basic geometric continuity during extrusion and early-stage deposition.

4.2 Deposition Procedure and Observations

To validate the feasibility of the proposed mobile robotic additive manufacturing system, a complete task execution procedure was designed and implemented. The overall operation consists of a sequence of coordinated actions, including platform locomotion, positioning, material deposition, and departure.

Specifically, after system initialization, the tracked mobile platform moves to a predefined working location. Once the platform reaches the target position, the mobile base stops and the robotic manipulator is triggered to execute a pre-programmed offline motion. During this stage, the manipulator follows a predefined deposition trajectory while the syringe-based extrusion system delivers material in synchronization with the manipulator motion. Upon completion of the deposition task, the manipulator returns to a safe configuration, and the mobile platform resumes motion to exit the printing area.

Based on the above operation procedure, the robotic system successfully performed material deposition experiments using the selected cement-based mixture. Figure 4 presents a snapshot captured during the printing process, illustrating the coordinated operation of the mobile platform, robotic manipulator, and extrusion system. The deposition process demonstrates continuous material extrusion and layer-by-layer placement, providing visual evidence of the system's capability to execute mobile additive manufacturing tasks.

The cement specimen and the associated deposition results are further presented and discussed in subsequent sections.

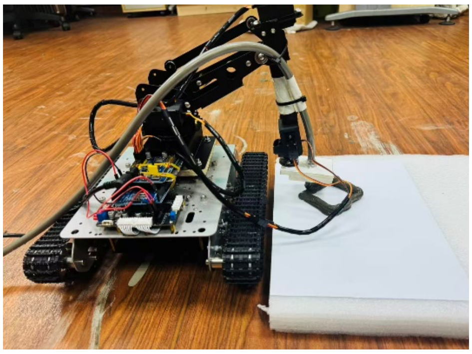

Figure 4. Snapshot during the printing process

5. Experimental Results

5.1 Coordinated Operation of the Mobile Platform and Robotic Manipulator

During the experiments, the electrical control system and the power transmission components of the proposed robotic platform operated reliably, enabling the successful extrusion and deposition of cement-based material. The system was able to complete the predefined task sequence and produce a printed cement specimen, demonstrating the overall feasibility of the integrated mobile additive manufacturing system.

5.2 Layered Deposition Results

For the cement-based printing task, a four-layer deposition strategy was adopted, and representative printed specimens obtained with delivery hoses of different diameters are shown in Figure 5. Overall, the system successfully executed the predefined deposition paths, and no obvious path deviation was observed during printing, particularly in the first three layers. Although slight deformation was observed in the printed specimens, it mainly appeared as lateral leaning of the printed walls rather than downward collapse or sudden material failure. This behavior is attributed primarily to the limited early-stage load-bearing capacity of the cement slurry, which did not include coarse aggregates or additional strengthening constituents. Nevertheless, compared with the earlier two-layer printing results, the present four-layer specimens demonstrate improved deposition accuracy and path consistency, thereby providing meaningful validation of the robotic printing process and the feasibility of integrated system operation.

Further improvement in multi-layer shape retention will be pursued in future work through optimized material formulation and rheological control.

Figure 5. Printed cement specimen

5.3 System-Level Observations

Throughout the experimental procedure, the three main subsystems—the tracked mobile platform, the robotic manipulator, and the syringe-based material extrusion system—operated in a coordinated manner under the supervision of the central controller. Once the mobile platform stopped at the designated working location, the actions of all subsystems were triggered and coordinated through the central supervisory board.

Communication between the central controller and the subsystem control boards was implemented via wired serial interfaces using TX and RX connections. During the entire task execution process, command transmission and feedback reception remained continuous and reliable, and no communication interruption or command loss was observed.

The experimental results indicate that the proposed centralized–distributed control strategy provides a robust foundation for system-level cooperation in underwater mobile additive manufacturing tasks.

5.4 Waterproofing Validation of Control Electronics and Servo Motors

Although the entire robot has not yet been fully submerged as an integrated system, the waterproofing performance of all electrically sensitive components in the current prototype has been experimentally validated at the component level.

For the control electronics, a sealed enclosure was constructed to house the control board and cable interfaces, as shown in Figure 6. The enclosure was fully sealed using plastic steel epoxy putty and polymer-based butyl rubber waterproof sealing materials, in order to protect the electronic components under complete submersion. For the three servo motors mounted on the manipulator, waterproof treatment was further applied by filling the gear transmission section with sealing silicone grease and applying insulating waterproof protection to the internal circuit boards.

A 24-hour immersion test was then conducted for both the sealed control board enclosure and the waterproofed servo motors. During the test, the components remained fully submerged in water for the entire duration. No visible air bubbles were observed from the servo motors during immersion, indicating that the sealing treatment remained intact. In addition, when powered on underwater, all three servo motors operated normally, as shown in Figure 7. After the 24-hour test, the control board also continued to function properly, with stable signal input and output maintained throughout the experiment.

These results demonstrate that, although the full robotic system has not yet been tested under complete underwater deployment, all electrical components involved in the current prototype have been successfully validated for underwater operation. Compared with only evaluating the system in partial or splash-resistant conditions, this long-duration component-level immersion test provides more direct evidence of waterproofing effectiveness. In future work, custom protective shells fabricated using ASA-based 3D-printed parts will be developed for the robot, with the goal of enabling full-body submerged operation.

Figure 6. Sealed control electronics enclosure for underwater operation

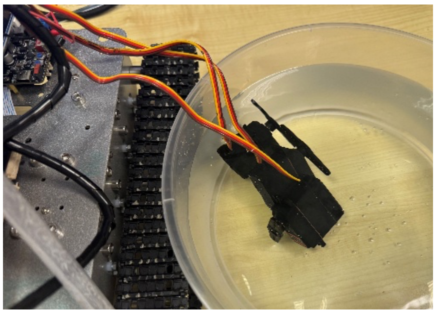

Figure 7. The operation of the servo motors in water

6. Discussion

6.1 Advantages of the Proposed Mobile AM System and Behavior Coordination

The proposed mobile additive manufacturing system offers several advantages over conventional stationary or single-function robotic platforms. By integrating locomotion, manipulation, and material extrusion into a single system, the robot is capable of performing additive manufacturing tasks beyond fixed working locations. This mobility is particularly advantageous for underwater environments, where access and positioning are often constrained.

The centralized–distributed control architecture further enhances system robustness by enabling reliable coordination among multiple subsystems through wired communication. Experimental results demonstrate stable task execution without communication interruption, indicating that the proposed control strategy is well suited for underwater robotic applications where wireless communication is unreliable.

In addition, the system adopts an offline programming strategy for the robotic manipulator, allowing predefined motion sequences to be executed once triggered by the central controller. This approach reduces the computational burden on the central control unit and improves overall system stability. By decoupling high-level task scheduling from low-level motion execution, coordinated behaviors among the mobile platform, manipulator, and extrusion system can be achieved in a predictable and repeatable manner.

The combination of a lightweight robotic manipulator and a syringe-based extrusion mechanism provides a compact and flexible solution for scaled experimental validation. Rather than focusing on material optimization or structural performance, the proposed system emphasizes behavior coordination and system-level feasibility. As a result, the platform serves as an effective testbed for investigating mobile additive manufacturing in underwater environments and offers a practical foundation for future system scaling and refinement.

6.2 Manipulator Pose Algorithm

To improve the accuracy during the printing process, inverse kinematics was introduced in the subsequent model development. As shown in Figure 8, a right-handed robot base coordinate frame was established, with its origin located at the rotation center of Joint 1, and the positive x-axis aligned with the forward motion direction of the mobile platform. Based on this coordinate frame, a MATLAB-based inverse kinematics algorithm was developed to evaluate the reachability of the four-layer printing task points and to calculate the joint angles required for the manipulator to reach these positions. The sampled reachable workspace of the manipulator and the spatial locations of the four-layer square printing points were plotted together, and the results show that all predefined task points lie within the reachable workspace of the manipulator. As shown in Figure 9, the inverse kinematics results were summarized in tabular form, including the Cartesian coordinates of each task point, the reachability evaluation, and two possible inverse kinematics solution branches (A and B). In this study, branch A was selected as the final joint configuration for task execution.

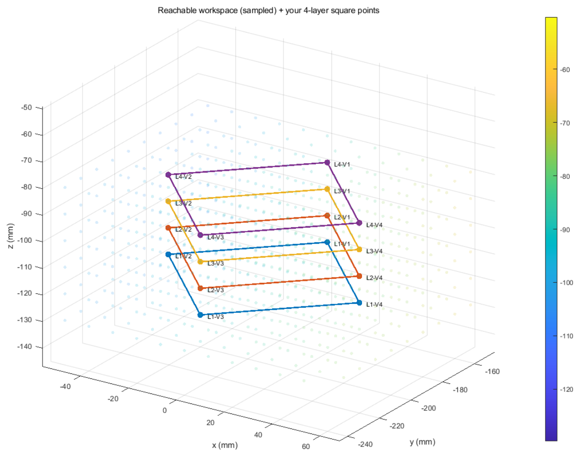

Figure 8. Reachable workspace and spatial layout

	Layer	Vertex	X	Y	Z	Reachable	Message	Q1_deg	Q2A_deg	Q3A_deg	Q4A_deg	Q2B_deg	Q3B_deg	Q4B_deg
1	1	1	0	-150	-120	☑	Reachable	-90	-94.8227	96.8257	-62.0030	8.2449	-96.8257	28.5809
2	1	2	-40	-190	-120	☑	Reachable	-101.8887	-73.1700	73.1292	-59.9592	4.0700	-73.1292	9.0592
3	1	3	0	-230	-120	☑	Reachable	-90	-52.7585	44.3100	-51.5515	-6.1911	-44.3100	-9.4989
4	1	4	40	-190	-120	☑	Reachable	-78.1113	-73.1700	73.1292	-59.9592	4.0700	-73.1292	9.0592
5	2	1	0	-150	-110	☑	Reachable	-90	-94.4605	100.9107	-66.4502	13.1582	-100.9107	27.7525
6	2	2	-40	-190	-110	☑	Reachable	-101.8887	-72.9825	77.3035	-64.3211	8.7534	-77.3035	8.5501
7	2	3	0	-230	-110	☑	Reachable	-90	-53.4564	49.8237	-56.3673	-1.0579	-49.8237	-9.1183
8	2	4	40	-190	-110	☑	Reachable	-78.1113	-72.9825	77.3035	-64.3211	8.7534	-77.3035	8.5501
9	3	1	0	-150	-100	☑	Reachable	-90	-93.7070	104.6663	-70.9594	18.1326	-104.6663	26.5337
10	3	2	-40	-190	-100	☑	Reachable	-101.8887	-72.4259	81.0324	-68.6065	13.3422	-81.0324	7.6902
11	3	3	0	-230	-100	☑	Reachable	-90	-53.6054	54.4628	-60.8575	3.7104	-54.4628	-9.2475
12	3	4	40	-190	-100	☑	Reachable	-78.1113	-72.4259	81.0324	-68.6065	13.3422	-81.0324	7.6902
13	4	1	0	-150	-90	☑	Reachable	-90	-92.5467	108.0942	-75.5476	23.1812	-108.0942	24.9131
14	4	2	-40	-190	-90	☑	Reachable	-101.8887	-71.5154	84.3481	-72.8327	17.8526	-84.3481	6.4955
15	4	3	0	-230	-90	☑	Reachable	-90	-53.3021	58.4099	-65.1077	8.2064	-58.4099	-9.7966
16	4	4	40	-190	-90	☑	Reachable	-78.1113	-71.5154	84.3481	-72.8327	17.8526	-84.3481	6.4955

Figure 9. Inverse kinematics results table

6.3 Limitations of the Current Prototype

Despite the successful system-level validation, two limitations of the current prototype should be noted. First, the material extrusion system adopts a 50 ml syringe, which constrains the deposition volume and limits the current experiments to small-scale specimens. However, this specification was intentionally selected for scaled feasibility validation and compact system integration, rather than as a target configuration for practical construction. The underlying actuation principle is not inherently restricted to this volume, and future scale-up could be achieved through larger reservoirs, higher-force linear drive modules, or multiple synchronized actuation units. Therefore, the present syringe capacity should be understood as a prototype-level design choice rather than a fundamental limitation of the proposed system concept.

Second, the current system relies on predefined, offline-programmed motion and does not yet incorporate onboard sensing or depth-camera-based perception. This limits the robot's ability to adapt to environmental variations in unstructured underwater settings. Nevertheless, for the present study, the printing tasks were conducted in a predefined workspace with predetermined deposition paths, and this configuration was sufficient to validate the basic underwater-oriented

3D concrete printing mode at the system level. In this sense, the absence of onboard sensing does not invalidate the current feasibility demonstration, but rather defines the present boundary of system capability. The integration of onboard sensing, such as an eye-in-hand depth camera or other perception modules, will be an important next step toward improving robot autonomy, adaptive positioning, and operation in more complex underwater environments.

7. Conclusions and Future Work

This paper presented a scaled mobile robotic concrete additive manufacturing system developed toward underwater applications. The main contribution of this study lies in the system-level integration of mobility, manipulation, material extrusion, wired control, and component-level waterproofing validation within a unified experimental platform. The proposed system combines a tracked mobile base, a lightweight robotic manipulator, a syringe-based extrusion unit, and a centralized–distributed wired control architecture to enable coordinated locomotion, positioning, and material deposition under underwater-oriented design considerations.

Future work will focus on four directions. First, full-body waterproof protection will be developed through custom ASA-based 3D-printed protective shells, followed by integrated submerged system testing. Second, the extrusion system will be scaled through larger reservoirs and higher-force actuation modules to improve deposition capacity for more realistic construction tasks. Third, a more suitable printable material will be investigated to improve shape retention and structural stability during multi-layer deposition, together with optimization of the nozzle and end-effector extrusion structure. Fourth, onboard sensing modules, such as depth cameras, will be integrated to enhance robot autonomy, adaptive positioning, and operation in more complex underwater environments. These efforts will further advance the system toward practical underwater mobile concrete additive manufacturing.

Acknowledgments

The support from Singapore MOE Tier 1 Fund (A8003222-00-00) is acknowledged.

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