A CLIMBING ROBOT FOR BUILDING 3D PRINTED CONCRETE WALL

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Content

1 Introduction

1.1 Problem:

The construction industry faces significant challenges with waste generation, labor intensity, and inefficiencies in construction processes. 3D printing in architecture offers promising solutions to these issues by reducing construction waste, improving efficiency, shortening project timelines, decreasing labor requirements, and enhancing mechanization. This technology supports energy conservation and emission reduction, contributing to environmental improvement. Globally, there are increasing applications of 3D printed concrete structures in architecture, urban landscapes, and bridge constructions, with markets in the United States, Germany, and various regions in China already embracing civilian constructions made through 3D printing. However, a critical technical challenge that persists is the advancement of 3D printing for high-rise buildings and intelligent construction. While existing technologies like climbing systems for traditional high-rise construction have automated and mechanized construction to some extent, they are not fully adaptable to the complex geometries and surface textures intrinsic to 3D printed concrete, limiting their application in more complex architectural forms.

1.2 Solution

This proposal introduces a novel solution that builds upon existing technologies to address the limitations in constructing complex and high-rise structures through additive intelligent construction. The proposed equipment, which is a key component of our solution, includes an integrated system capable of adapting to complex architectural geometries and surface textures. It encompasses a mobility system, a construction system, and a control system, all designed to function cohesively for the whole climbing and printing construction process. The proposed method and equipment aim to overcome the constraints of current 3D printing technologies, which are limited to small-scale, multi-layer construction. By integrating self-climbing and horizontal movement capabilities, our solution seeks to break through the spatial limitations of additive manufacturing, enabling the construction of large-scale, multi-layered high-rise buildings with complex geometrical forms. The core of this innovation lies in a comprehensive climbing and printing construction system that adapts to various architectural shapes and facades, providing a robust hardware foundation and control technology for intelligent construction in high-rise and diverse environmental conditions. Our approach not only extends the applicability of 3D printing in construction but also promises to revolutionize the way we build, merging structural integrity with architectural aesthetics seamlessly.

1.3 Visual aid

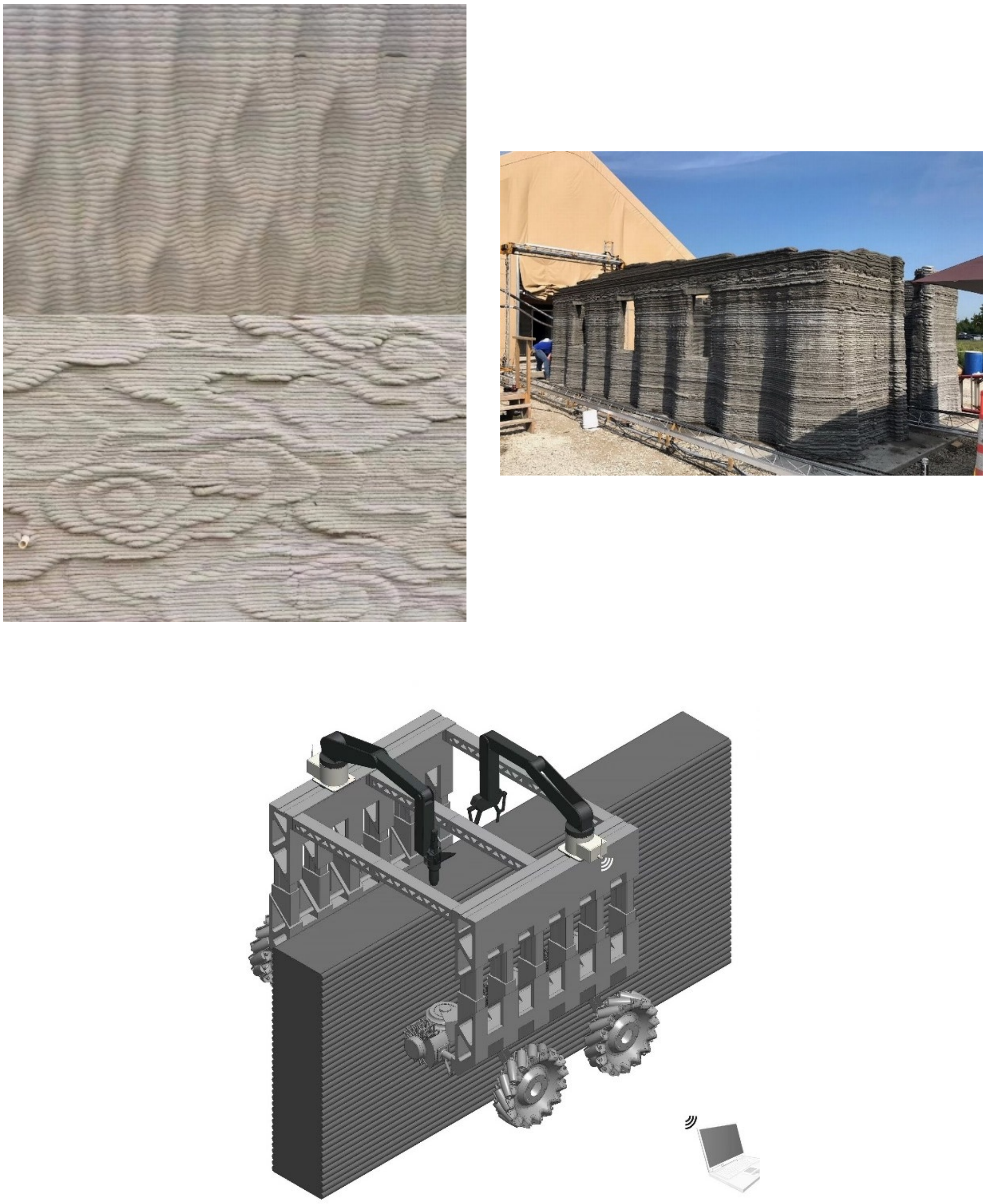

Figure 1: Application Scenario and System Overview

1.4 High-level requirements

1. The Self-climbing construction robots need to be able to climb and move horizontally to accommodate walls of different thicknesses.
2. The robot needs to be able to withstand a load of 15kg while fixed to the wall for carrying building materials.
3. The concrete extrusion nozzles have enough degree of freedom to realize mobile printing within a certain range.

2 Design

As shown below, the Control System serves as the command center with a STM32 microcontroller interpreting sensor data from a TOF Camera and Flow Sensor to manage the machine's actions, while interfacing with user inputs through the UI System. It coordinates with the Movement Subsystem, which grants the machine mobility through various motors, and the Printing System, which handles precise material manipulation with its mechanical arm and control nozzle. All of these components are energized by the Power System, which efficiently converts 220V AC into a stable 24V DC supply, ensuring seamless operation across the machine's functionalities.

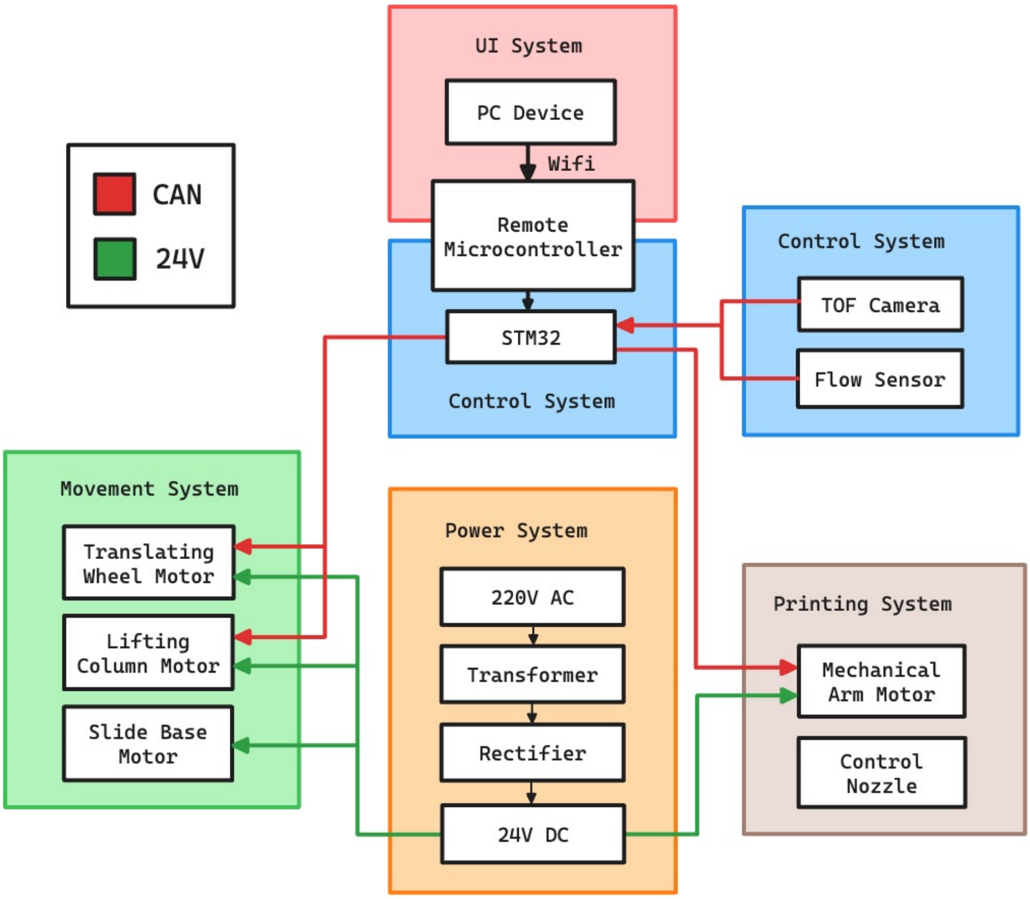

Figure 2: Top Level

2.1 Movement System Requirements

2.1.1 Horizontal Movement Subsystem Requirements

The movement system is designed to enable multidirectional spatial movement and is essential for adapting to complex architectural facades. It includes a wall-climbing lifting device that adapts to complex architectural facades and a construction support device that is adaptable to atypical architectural floor plans and can move accordingly.

Block Description: The movement system's primary function is to facilitate the equipment's navigation across various planes and surfaces, pivotal for the construction on complex and high-rise structures. The system must ensure seamless adaptation to different facade geometries, enabling construction on intricate building surfaces.

Interface Requirements: The movement system must integrate smoothly with the construction system, providing stable support and precise positioning to facilitate accurate construction activities. It must also communicate effectively with the control system to coordinate movements in sync with construction requirements.

Subsystem Functional Requirements:

- Must enable spatial multi-directional movement to navigate diverse architectural geometries.
- The wall-climbing lifting mechanism should securely affix to the internal and external surfaces of the printed walls.
- Needs to provide stable and controlled movement to maintain the integrity of the construction process.

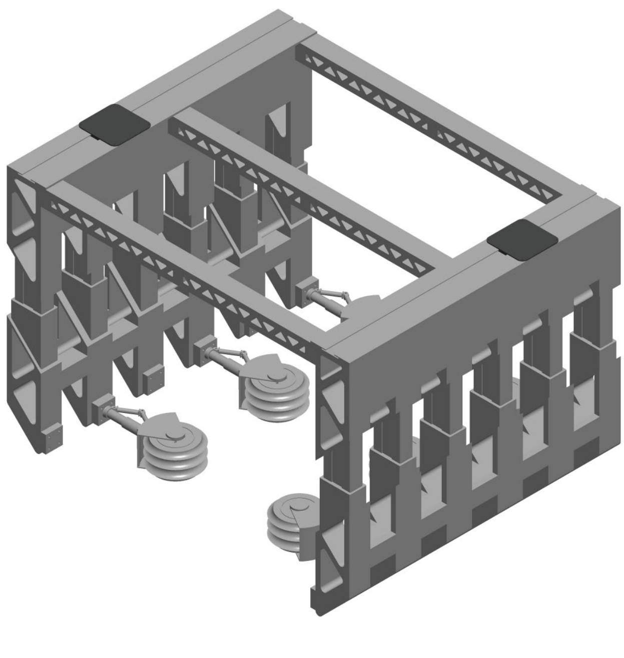

Figure 3: Horizontal Move Subsystem

2.1.1 Wall-Climbing Lifting Subsystem Requirements

This device is a crucial component of the movement system, allowing the equipment to ascend and adhere firmly to the printed walls' surfaces for construction.

Block Description: The wall-climbing lifting device is vital for enabling the equipment to navigate and affix to different wall geometries, facilitating construction across various architectural facets. It uses a 24V DC joint motor and a 24V DC hydraulic system for self-climbing, incorporating power driving, surface climbing, and hydraulic lifting capabilities.

Interface Requirements: The device must interact with the construction system to offer to receive and implement movement commands accurately.

Subsystem Functional Requirements:

- Equipped with a 24V DC joint motor and a 24V DC hydraulic system for effective climbing and stabilization.
- Should adjust its hydraulic pressure to maintain contact and friction against the building facade for steady climbing.
- Requires integration with a sensor suite to maintain alignment and adherence to the construction surface, preventing any slippage or misalignment.

These detailed subsystem requirements ensure each component significantly contributes to the 3D construction printing system's overall design and functionality, aligning with the high-level project objectives and specifications.

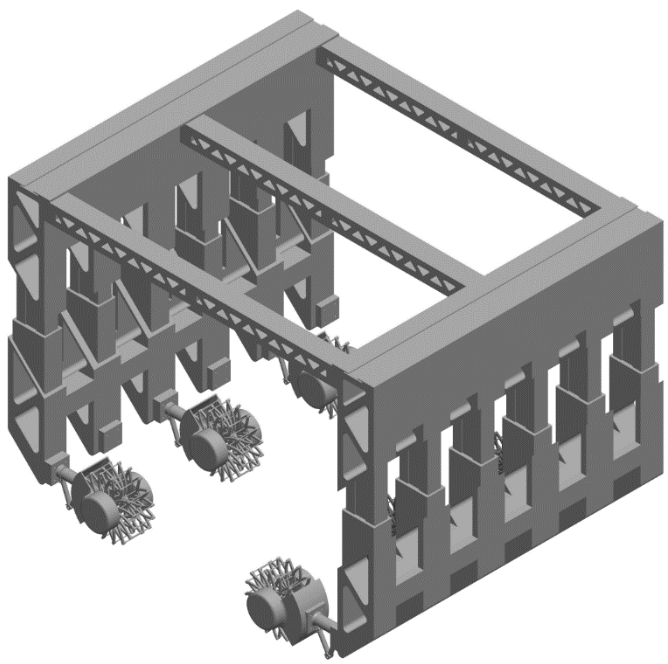

Figure 3: Wall-Climbing Lifting Device Subsystem

2.2 Construction System Requirements

2.2.1 Construction Support Subsystem Requirements

The construction support system is a pivotal component of the 3D printing architecture, enabling the precise creation of structures as per digital models. This system includes a translation wheel controlled by a 42-step motor, a rigid lifting column controlled by a screw and step motor, a rigid crossbeam, and a mechanical arm slide base driven by a belt and step motor.

Block Description: The construction support system's translation wheel features a flexible outer contour that can closely fit the atypical architectural planes, made from 98 hardness TPU. The lifting column can elevate within a specific range to ensure accurate positioning during the climbing construction phase. The mechanical arm extends the operational range, providing greater mobility for construction activities.

Interface Requirements: This system must interface seamlessly with the movement system to ensure precise positioning and stable construction. It should also communicate effectively with the control system for coordinated operation and with the material supply and reinforcement devices for integrated construction processes.

Subsystem Functional Requirements:

- The translation wheel must adapt to diverse architectural surfaces, ensuring tight adherence and stability.
- The lifting column must have adjustable height settings to maintain accurate construction alignment.
- The mechanical arm must provide extensive reach and precision, supporting various construction tasks.
- Stability in voltage at 24V ± 0.5V is essential for reliable operation.
- An emergency stop mechanism is required to prevent damage to the step motors in case of obstruction.

2.2. Material Supply Subsystem Requirements

This device prepares and delivers construction materials as per the digital construction model's requirements, ensuring the correct material flow and delivery to designated locations.

Block Description: The material supply device adjusts the flow of pre-mixed building materials based on the construction requirements, pumping them to the intended position. It is critical for maintaining the consistency and quality of the construction materials throughout the building process.

Interface Requirements: It must interface with the printing and reinforcement devices to synchronize the construction process, ensuring that material supply aligns with the printing and reinforcing phases.

Subsystem Functional Requirements:

- Must accurately control material flow to match the digital model's specifications.
- Requires integration with the control system for real-time adjustments and coordination.

2.3 Printing Device Subsystem Requirements

The printing device, equipped with a high degree of freedom mechanical arm and ToF camera, executes spatial positioning and real-time adjustments to enhance additive construction precision.

Block Description: This device allows for precise spatial positioning of the printing head, utilizing a ToF camera for real-time accuracy feedback, which is vital for the additive construction's precision and quality.

Interface Requirements: It needs to coordinate with the material supply device for consistent material flow and with the control system for accurate positioning and adjustment based on real-time feedback.

Subsystem Functional Requirements:

- High freedom mechanical arm must precisely position the printing nozzle as per the construction design.
- ToF camera integration is required for real-time accuracy feedback and adjustment.
- The device must be capable of printing compensation and flow compensation to maintain construction quality.

By detailing these subsystem requirements, the proposal ensures that each component of the construction system is well-defined, contributing effectively to the overall design and enabling the successful implementation of the 3D construction printing technology.

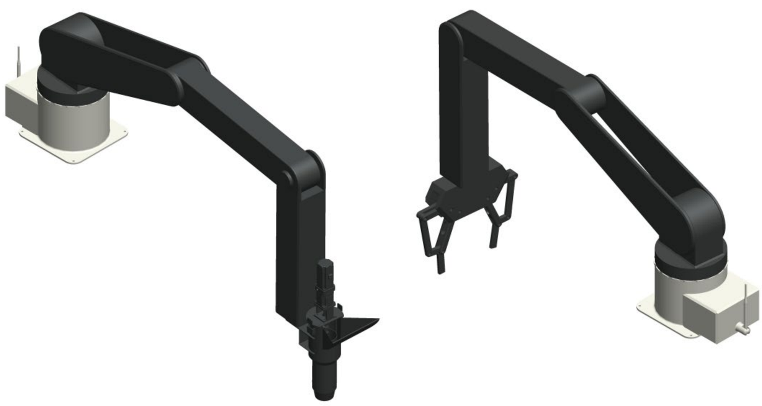

Figure 4: Printing System

2.4 Control System

The control system is central to the operation of the 3D construction printing system, facilitating positioning control, power control, and mechanical control. It coordinates the positioning of the construction devices, the distribution of printing materials, and oversees the spatial construction process.

Block Description: The control system is tasked with integrating positioning, power, and mechanical controls to ensure precise and efficient construction. It uses GPS for positioning, aligning overall and local coordinates through spatial lattice data to correct positioning accurately. The system's ability to distinguish between vertical climbing monitoring, planar construction control after stabilization, and printing elevation control post-climbing is vital for executing complex spatial structure construction intelligently.

Interface Requirements: The control system must interface effectively with the movement system, construction system, and material supply system to synchronize the construction process. The accuracy of GPS positioning, critical for the system's functionality, must be within 20mm.

Subsystem Functional Requirements:

- Must achieve GPS positioning accuracy within 20mm to ensure precise control over the construction process.
- Requires clear operational differentiation for vertical climbing, stable planar construction, and elevation control in printing after stabilization.
- Must maintain a stable voltage of 5V ± 0.1V to prevent component damage and ensure reliable system operation.

This detailed requirement list ensures the control system's effectiveness and reliability, addressing its critical role in the overarching design of the 3D construction printing system. By defining these specifications, the proposal underscores the control system's integral contribution to achieving high-level construction precision and efficiency.

2.5 Tolerance

In the design of our climbing machine, the precise control of the hydraulic rod's movement within a 0-8mm range poses a significant challenge due to potential risks of interference with the wall during the ascent, which could disrupt engine function. To ensure the rod operates within these tight tolerances, a thorough tolerance analysis is essential. This analysis would include examining the manufacturing tolerances of the rod and the accuracy of the control system, factoring in variables such as hydraulic fluid dynamics and feedback control algorithms. A simulation using a PID control model could validate the system's capability to maintain the precise movements required, adjusting the hydraulic pressure in real-time to stay within the defined tolerances and prevent wall contact.

The project's second critical risk factor involves material selection and structural integrity to support a 15kg load. The use of aluminum alloy for its strength-to-weight ratio, supplemented by plastic components with reinforcement ribs, is designed to meet this requirement. The feasibility of these materials under load can be assessed through finite element analysis (FEA) to predict how the chosen materials will react under stress and strain. By ensuring that the stress concentrations are below the materials' yield strengths and the deflections do not exceed the 5mm printing precision limit, we can demonstrate the robustness of our design. Additionally, incorporating GPS positioning with an accuracy of ±2mm will further augment the precision of the system, aligning with industry standards for automated climbing and printing machines.

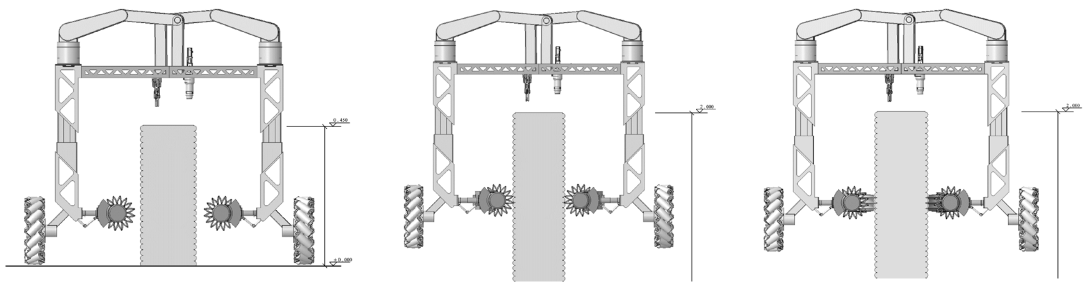

Figure 5: Consruction Work Flow Simulation

3 Ethics and Safety

In our project, we are developing a multifaceted system encompassing a user interface, control mechanisms, movement capabilities, and printing functionalities, similar to the subsystems outlined in the provided block diagram. The ethical considerations primarily revolve around the use of the control system, which includes sensitive components like the TOF Camera and the Flow Sensor. These devices could potentially infringe on privacy if misused; hence, in alignment with the ACM Code of Ethics, we are committed to protecting individual privacy throughout the development and deployment of our project (ACM Code of Ethics, Section 1.7). The safety of the system is paramount, particularly in the movement subsystem where motors are operational. Our design will adhere to the safety standards set forth by regulatory bodies such as OSHA and will follow the risk mitigation guidelines in accordance with industry standards such as ANSI/RIA R15.06.

During development, we will ensure that all testing of the movement and printing subsystems is conducted in controlled environments, minimizing risks to both developers and bystanders, a responsibility highlighted by the IEEE's code to "hold paramount the safety, health, and welfare of the public" (IEEE Code of Ethics, Principle 1). We will actively review state and federal regulations that govern the use of autonomous systems and robotics to guarantee compliance. Considering the potential risks of the power system—operating at 220V AC and converting to 24V DC—it is imperative to adhere to electrical safety standards, avoiding any ethical breaches pertaining to neglect of public safety. Regular safety audits and updates to our development process will be integral to ensuring that our project not only meets but exceeds the required safety protocols.

References

[1] "ACM Code of Ethics and Professional Conduct," Association of Computing Machinery, June 22nd, 2018. Available at https://www.acm.org/code-of-ethics

[2] Sun, X., Wang, H., & Lin, X. (2022). Additive Manufacturing of Concrete Structures. Architecture & Building Press.