ECE 445

SENIOR DESIGN LABORATORY

FINAL REPORT

A Climbing Robot For Building 3D Printed Concrete Wall

Team #28

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May 10, 2024

Abstract

In the burgeoning field of 3D construction printing, the development of climbing construction robots represents a critical innovation, offering substantial improvements in efficiency, waste reduction, and mechanization. This paper introduces a novel class of robots engineered to address the unique challenges of high-rise and complex architectural construction through advanced 3D printing techniques. These robots are designed to adeptly navigate and adapt to various surface geometries and textures, enhancing both structural integrity and architectural aesthetics through intelligent construction methods. Equipped with systems for precise spatial positioning and concrete reinforcement, the robots aim to revolutionize the construction process by performing in situ 3D concrete printing on vertical surfaces, thus demonstrating significant potential in multi-story building applications. Initial demonstrations have focused on the robot's ability to ascend and operate on a 3D printed concrete wall, confirming its operational stability and versatility in real-world construction environments. This abstract encapsulates the integration of mobile printing systems, robust control mechanisms, and advanced movement capabilities, paving the way for future developments in automated construction technology.

Contents

1 Introduction

1.1 Purpose

The current state of 3D printing in construction presents a promising outlook in reducing construction waste, enhancing efficiency, shortening project timelines, minimizing labor, and advancing mechanization. By integrating structural strength with architectural aesthetics through digital design and mechanical construction, 3D printed concrete has seen increasing application in buildings, urban landscapes, and bridge structures. Nations like the United States and Germany have introduced 3D printed structures to the market, and China has successfully constructed multi-story buildings using this technology. The primary objective now is to tackle the key technological challenges in realizing multi-story building and high-rise construction and intelligent manufacturing through 3D printing. Despite the advancements in 3D printing for construction, the technology faces limitations, particularly in high-rise construction. The existing equipment, including mixing, pumping, controlling, and printing systems, relies heavily on a climbing system to function in the vertical axis. While traditional high-rise construction has seen automation through climbing formwork systems, adapting these for 3D printed structures is challenging due to the textured cross-sections and non-linear spatial forms inherent to 3D printing. Similarly, the current generation of climbing robots, designed for tasks like construction, maintenance, and reconnaissance, faces difficulties in adhering to and climbing vertical surfaces with complex textures or materials.

Our objective is to pioneer the development of a new class of climbing construction robots, designed to navigate and adapt to various spatial geometries and textured surfaces. These robots will play a crucial role in the intelligent construction of large-scale, high-rise, and complex-shaped buildings through 3D printing technology. The innovation lies in the integration of mobile systems that ensure precise spatial positioning alongside advanced construction systems. These systems are not only capable of 3D printing but also equipped for the intelligent reinforcement of concrete structures, enhancing structural integrity and design flexibility. To demonstrate the efficacy of our approach, our initial goals include showcasing the robot's ability to ascend and operate on a 3D printed concrete wall—a critical step towards validating its functionality in real-world construction scenarios. Additionally, we aim to highlight the robot's capability in executing the 3D concrete printing process in situ on vertical surfaces. This demonstration will serve as a proof of concept for the robot's practical application in additive construction of multi-story and high-rise buildings, confirming its operational stability and versatility in changing construction environments.

1.2 Functionality

1.2.1 Clamping and Horizontal Movement

The robot is designed to clamp onto cement walls and move horizontally. This functionality allows the robot to adapt to walls of different thicknesses and textures, ensuring stable operation on vertical surfaces.

This capability is crucial for the robot to perform its tasks on real construction sites, where wall characteristics can vary greatly. The ability to clamp and move horizontally ensures that the robot can navigate and operate efficiently across different sections of a building's exterior or interior. This adaptability directly supports the robot's role in the intelligent construction of high-rise and complex-shaped buildings, where maneuverability and positional accuracy are essential for structural integrity and architectural precision.

1.2.2 Load Bearing Capacity

The robot needs to withstand a load of 15kg, including its self-weight. This load capacity is essential for carrying building materials such as concrete and reinforcement fibers during the construction process.

The load-bearing capacity is vital for the robot to serve as a functional part of the construction process, not just in printing but also in transporting materials needed on different parts of a building. By supporting this weight, the robot can operate autonomously on the construction site, reducing the need for human intervention and enhancing the efficiency and safety of the building process. This capability directly ties into the project's goal of enhancing structural integrity and design flexibility through intelligent reinforcement and material placement.

1.2.3 Concrete Extrusion Nozzles with Sufficient Degrees of Freedom

The concrete extrusion nozzles are equipped to allow mobile printing within a certain range. This includes multiple axes of freedom, enabling the nozzles to adjust their position and angle precisely according to the construction requirements.

The versatility of the concrete extrusion nozzles is key to implementing complex architectural designs and adapting to the variable geometries of modern buildings. This flexibility in the printing process allows for the creation of intricate designs and structures directly on-site, which is a critical component of additive construction technology. The ability to adjust the nozzle positioning dynamically enhances the robot's effectiveness in creating multi-story and high-rise buildings where each layer may have different specifications and challenges.

1.3 Subsystem Overview

The climbing construction robot's success hinges on the seamless integration of its four essential subsystems: the Control System, Construction System, Power Supply System, and Movement System. At the heart of this operation lies the Control System, equipped with ample storage and a microcontroller to process building model files into actionable G-code instructions. Utilizing ROS and CAN protocols, it orchestrates high-level operations and real-time control, interfacing with other subsystems to execute precise construction tasks.

The Construction System, driven by multiple stepper motors and a sophisticated X-Y-Z

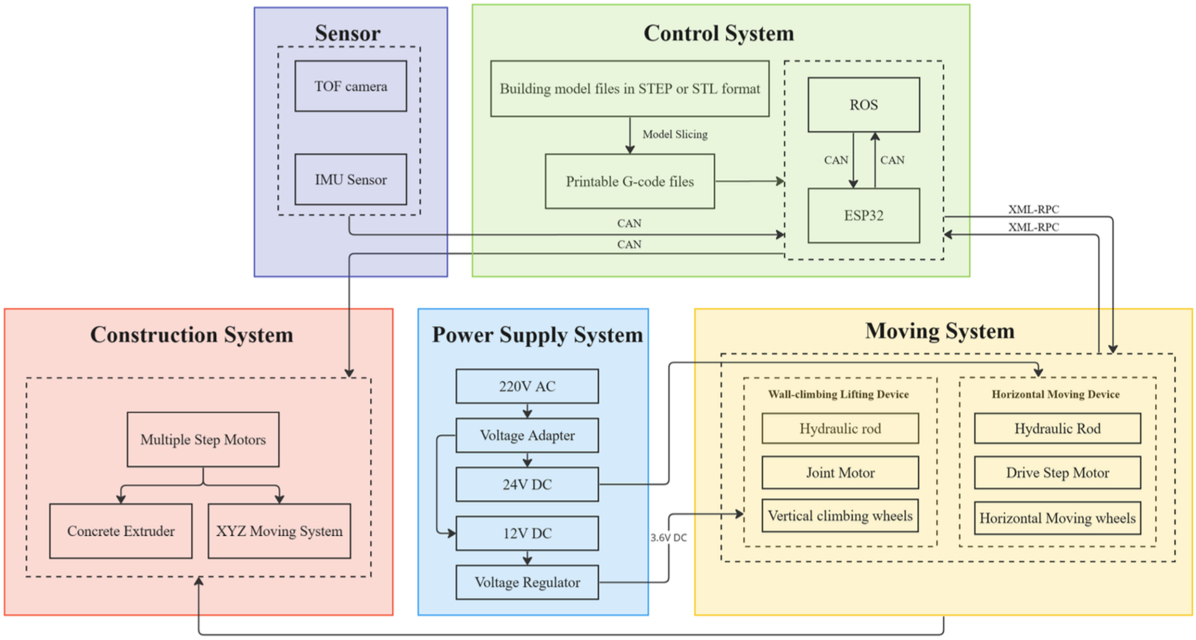

Figure 1: Block Diagram

Movement mechanism, translates these instructions into tangible construction actions. It extrudes concrete and maneuvers with precision, guided by the Control System's commands. Meanwhile, the Power Supply System ensures uninterrupted operation, regulating voltage from 220V AC down to 24V and 12V DC, with dedicated branches for specific voltage requirements. Lastly, the Movement System provides the robot with the agility to navigate vertical and horizontal surfaces using hydraulic rods and climbing wheels, responding to movement directives from the Control System. This integrated approach not only streamlines construction processes but also enhances adaptability, efficiency, and safety, marking a significant leap forward in automated construction technology.

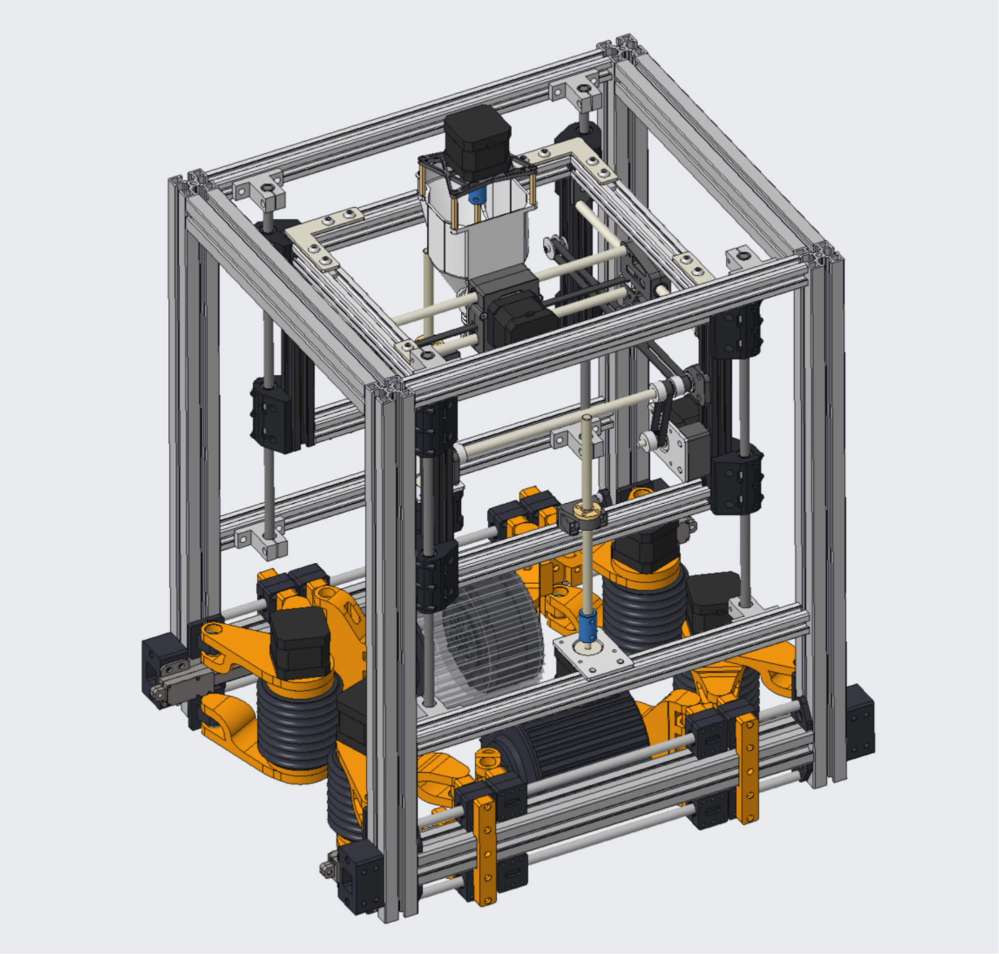

Figure 2: Project CAD

2 Design

2.1 Construction System

The printing system located in the center of the whole equipment, it is mainly used to complete the various printing tasks, it has an independent X-Y-Z movement subsystem and a concrete extruder.

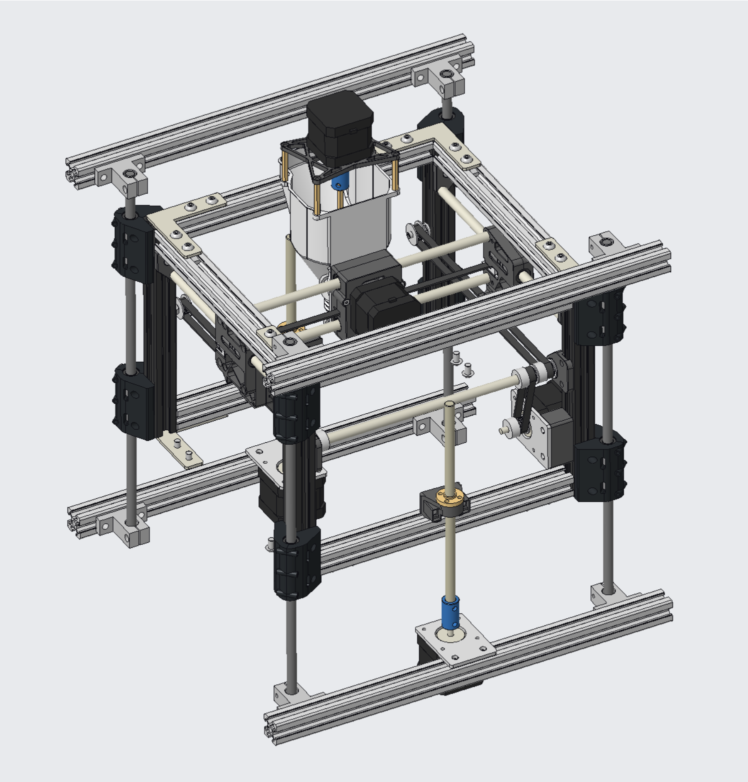

Figure 3: Construction System CAD

2.1.1 X-Y-Z Movement Subsystem

The X-Y-Z moving subsystem is a pivotal component of the climbing construction robot, employing stepper motors for precise and independent control. It effectively mitigates vibrations during horizontal movements, ensuring high-precision printing capabilities. With a generous stroke of 200mm in the X-Y-Z direction, this system minimizes reliance on the horizontal movement subsystem, optimizing efficiency by reducing the frequency of their usage. This sophisticated mechanism not only enhances the robot's maneuverability but also contributes significantly to achieving accurate and intricate construction outcomes.

In the design of our 3D printing system, the horizontal movement subsystem for the X-Y direction employs a precision motor-driven mechanism. This mechanism controls synchronous belts to finely adjust the position of the extruder in the XY plane, crucial

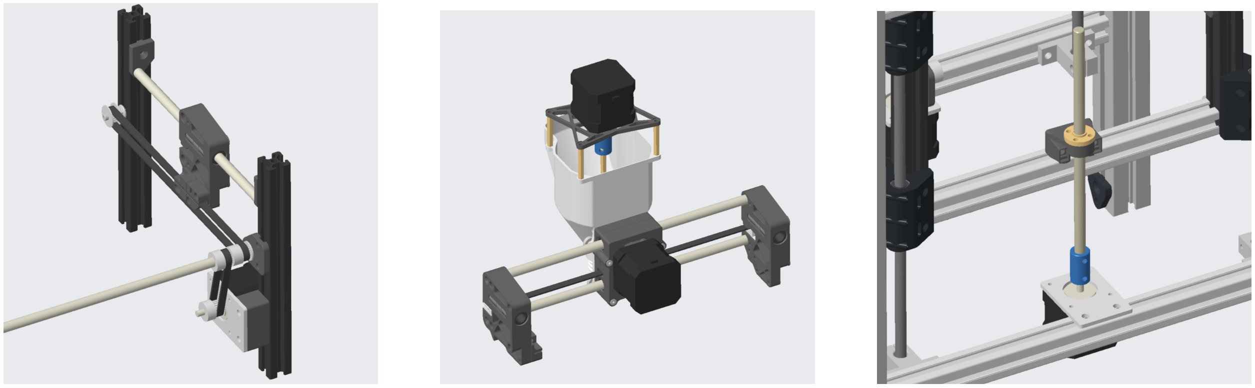

Figure 4: Details of X-Y-Z Movement Subsystem

for achieving high-resolution printing. The synchronous belts are equipped with an advanced tensioning system, ensuring consistent tension and preventing slippage, which enhances print accuracy and the lifespan of the belts. For vertical movement along the Z-axis, our system uses a dual-threaded rod setup, where each rod is operated by its dedicated motor. This dual-motor configuration allows for synchronized and smooth vertical movement of the extruder, critical for layer-by-layer construction in 3D printing. The independent control over each rod helps in maintaining the extruder's alignment and eliminates the risk of skewing, which is essential for producing precise and structurally sound builds. To further reinforce the stability and precision of vertical movements, four robust vertical guide rods are strategically placed at each corner of the framework. These guide rods are made from high-grade steel, designed to withstand the stresses of continuous operation while ensuring that the Z-axis movement is not only smooth but also perfectly linear. This setup minimizes vibrations and mechanical play, significantly improving the overall quality of the printed objects by ensuring that each layer is deposited with exceptional accuracy.

2.1.2 Concrete Extruder

The concrete extruder is a critical component of our construction robot, comprising several key elements to facilitate precise and efficient concrete deposition. At its core is a 3D printed aggregate bin, strategically designed to hold and manage the concrete mix. Controlled by a step motor, a vertical screw within the extruder serves as the primary mechanism for extruding the concrete through the bottom nozzle. Additionally, this screw features a stirring rod, ingeniously incorporated to maintain an optimal consistency within the aggregate bin. By stirring the concrete mix, the rod ensures uniformity and proper slump, crucial for achieving consistent quality in extrusion. Moreover, the diameter of the concrete nozzle is adjustable, providing control over the extrusion rate and allowing for precise adjustment according to construction requirements. Together, these components form a robust and versatile concrete extruder system, essential for the successful realization of our construction endeavors.

3D printed concrete differs from conventional construction materials. In addition to meet-

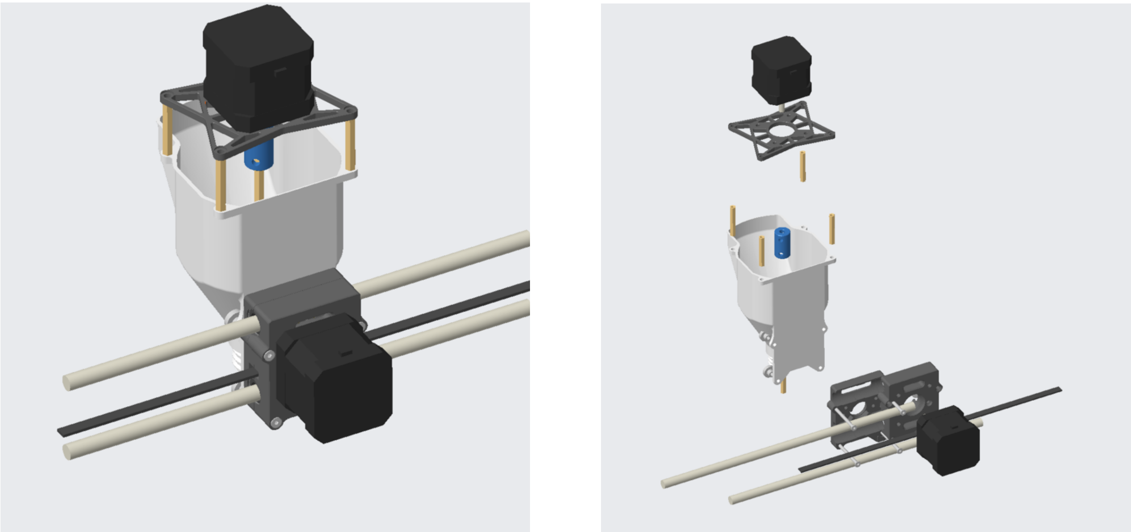

Figure 5: Details of Concrete Extruder

ing the basic mechanical properties of concrete, it must also possess appropriate fluidity, early strength, extrudability, and buildability. Currently, mainstream 3D printed concrete often uses a wet concrete mix with a flowability between 170 and 190 mm, which provides good extrudability and buildability. To ensure that 3D printed concrete walls can harden to sufficient strength in a short period, the concrete for this project also needs to have strong early strength. Research has shown that using quartz sand as a mineral admixture can increase the fluidity of the cementitious material but may weaken its early strength. However, alkali activators can effectively enhance the early strength of concrete. Therefore, this project uses PO 42.5 grade cement combined with quartz sand and improves early strength using alkali activators. The effects of quartz sand ratio and alkali activator content on the concrete's fluidity and setting time are shown in Table 1 and Table 2. Accordingly, for this project, a concrete with a 4% alkali content and a 30% quartz sand content was selected as the material for 3D-printed concrete.

Table 1: The Effect of Quartz Sand Content on The Performance of Concrete Materials

Quartz Sand (%)	**Fluidity (mm)**	**Initial Setting Time (min)**
10	151	8.1
20	162	14.2
30	189	23.3
40	205	24.8

Table 2: The Effect of Alkali Content on The Performance of Concrete Materials

Alkali Content (%)	Fluidity (mm)	Initial Setting Time (min)
3	222	42.1
4	214	19.9
5	178	18.9
6	152	11.2

2.2 Movement System

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 horizontally.

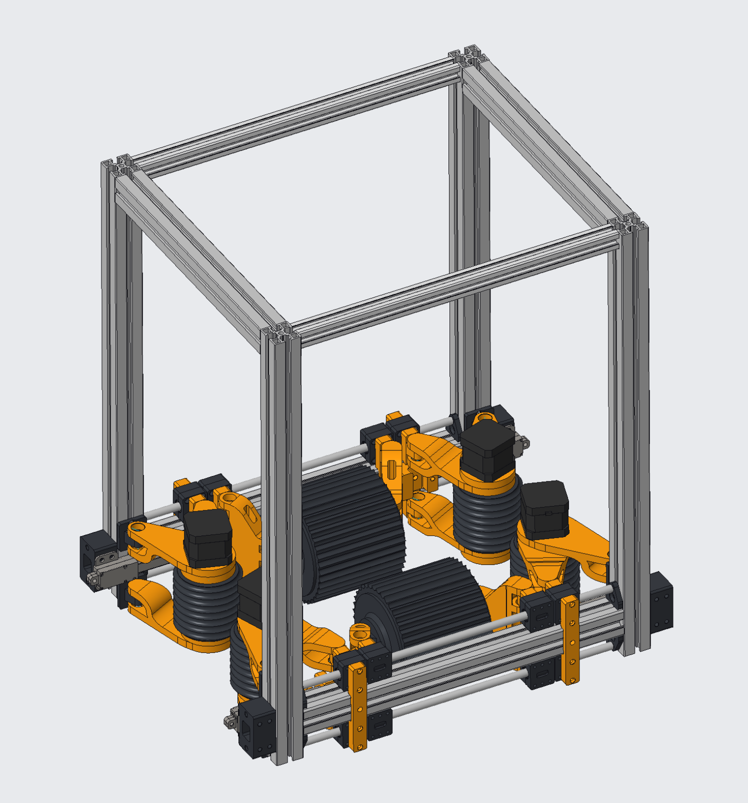

Figure 6: Movement System CAD

2.2.1 Horizontal Movement Subsystem

The horizontal movement subsystem consists of a specially shaped wheel body, a hydraulic rod and a step motor. The specially shaped wheel body has a surface shape complementary to the layer pattern on the surface of the 3d printed concrete wall, which can increase the friction between the wheel body and the wall surface and achieve stable horizontal movement.

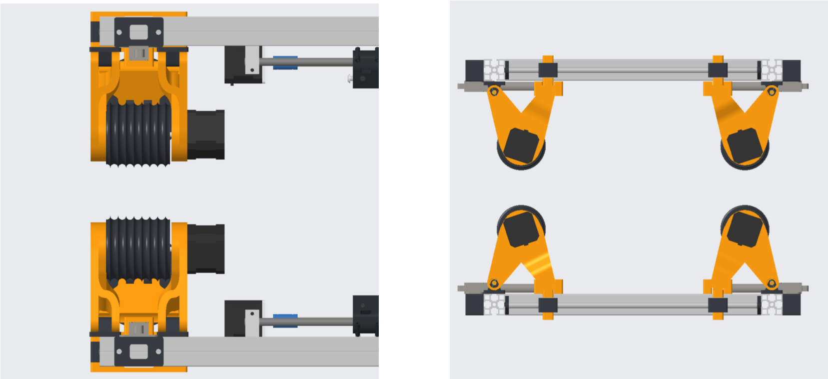

Figure 7: Details of Horizontal Movement Subsystem

Four wheels, each featuring a unique shape, are individually powered by motors to exert inward clamping forces, securing them firmly to the wall surface. Additionally, to accommodate walls of varying widths, we have integrated a slider mechanism that enables horizontal adjustment of the wheels' positions. This dynamic feature allows for precise customization of the distance between the clamping points, ensuring optimal grip and stability across a range of wall thicknesses. Such versatility not only enhances the system's adaptability but also ensures consistent printing quality regardless of the structural context.

2.2.2 Wall Climbing Lifting Subsystem

The vertical climbing device consists of the same special shape wheel body as the horizontal moving device, hydraulic rod and stepping motor. Among them, the special shape of the wheel body compared to the horizontal mobile device wheel body rotated 90 degrees placed, the surface shape and 3d printed concrete wall surface of the single layer layer pattern complementary, can increase the friction between the wheel body and the wall surface, to realize the vertical climbing. The step motor is an articulated motor (cybergear, xiaomi co.) with a torque of 4N.m, which gives the device sufficient power to carry the printing device for construction.

Considering the significant force required to climb walls, especially since the total system weight can reach up to 15 kilograms, our climbing wheels are designed to be relatively large. The drive motors for these wheels are also exceptionally powerful, featuring high torque to handle the substantial load. Initially, we encountered a significant design challenge: it was extremely difficult to fit the large motors and climbing wheels in the compact space allocated on each side of the device. This space also needed to accommodate a pair of sliders for adjusting to the thickness of the wall. To resolve this issue, we ingeniously designed the climbing wheels to partially enclose the motors. This innovative arrangement allowed us to maintain the length of the climbing wheels without reducing their

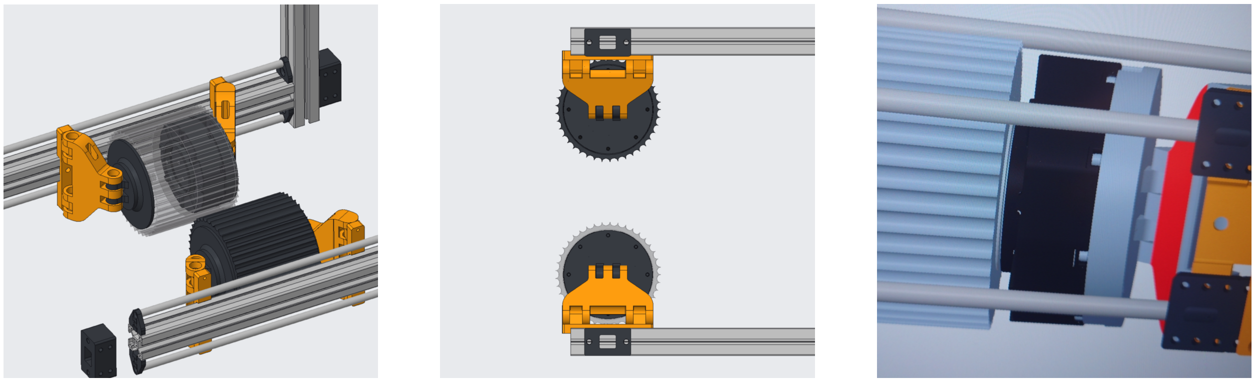

Figure 8: Details of Wall Climbing Lifting Subsystem

size, crucial for effective wall engagement. Additionally, we managed to integrate the entire shutdown mechanism within the same length, maximizing space efficiency. This design not only optimizes the use of space but also enhances the system's overall functionality and reliability, enabling it to operate smoothly on various wall surfaces.

2.2.3 Wheel Drive Control

The control of the wheel drive is achieved through differential drive, whereby the two wheels on the same side are operated by an identical algorithm and can be regarded as two independent wheels. The position and orientation updates are expressed by the following equations:

$$x_{t+1} = x_t + v_t \cos(\theta_t)\Delta t \tag{1}$$

$$y_{t+1} = y_t + v_t \sin(\theta_t)\Delta t \tag{2}$$

$$\theta_{t+1} = \theta_t + \omega_t \Delta t \tag{3}$$

where x_t and y_t are the current position, θ_t is the current orientation, v_t is the linear velocity, ω_t is the angular velocity, and Δt is the time interval.

The inverse solution of the wheel position is done by the transformation matrix which is:

$$R = R_x(\alpha)R_y(\beta)R_z(\theta) \tag{4}$$

$$T = \begin{bmatrix} a \\ b \\ c \end{bmatrix} \tag{5}$$

$$M = \begin{bmatrix} \cos(\beta)\cos(\theta) & -\cos(\beta)\sin(\theta) & \sin(\beta) \\ \sin(\alpha)\sin(\beta)\cos(\theta) + \sin(\theta)\cos(\alpha) & -\sin(\alpha)\sin(\beta)\sin(\theta) + \cos(\alpha)\cos(\theta) & -\sin(\alpha)\cos(\beta) \\ -\sin(\alpha)\sin(\theta) + \sin(\beta)\cos(\alpha)\cos(\theta) & \sin(\alpha)\cos(\theta) + \sin(\beta)\sin(\theta)\cos(\alpha) & \cos(\alpha)\cos(\beta) \end{bmatrix} \tag{6}$$

Where R is the rotation matrix, T is the translation vector, and M stands for the transformation matrix. The device acquires the attitude data of the device via the IMU sensor integrated into the extruder and the GNSS chip. The host computer then calculates the position of the wheel body based on the acquired attitude data using the transformation matrix, and subsequently adjusts the wheel rotation speed in accordance with the CAD model information.

2.2.4 FEA, DFA and DFM

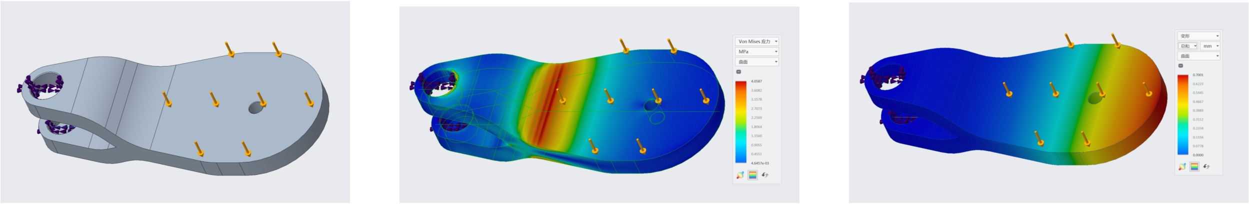

Figure 9: Analysis of the X-axis slider

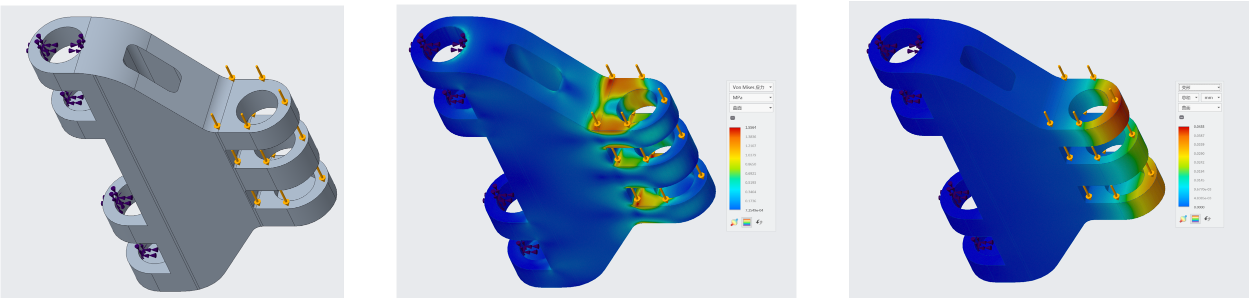

Figure 10: Analysis of the wheels for horizontal movement

In this section, we conduct a stress deformation analysis of two critical load-bearing mechanisms: the wheels for horizontal movement and the X-axis slider. A safety factor of two times is applied to account for deformation under stress. The material used for these components is BambuLab PETG-CF, chosen for its robust mechanical properties. Importantly, the direction of the applied load is perpendicular to the XY orientation of the 3D printed material. This orientation is crucial as it significantly influences the mechanical behavior and durability of the components under operational stresses.

2.3 Control System

The control system is central to managing and directing all the machine's operations. It's composed of a microcontroller, stepper motors, hydraulic rod, input, positioning sensors, output ports and display interface. The microprocessor esp32, is the heart of the control unit, it executes the firmware controlling the whole machine. The stepper driver is responsible for driving the stepper motor and control the movement of the machine and the extruder. A TF card is used to load the firmware and the G-code program we want to run.

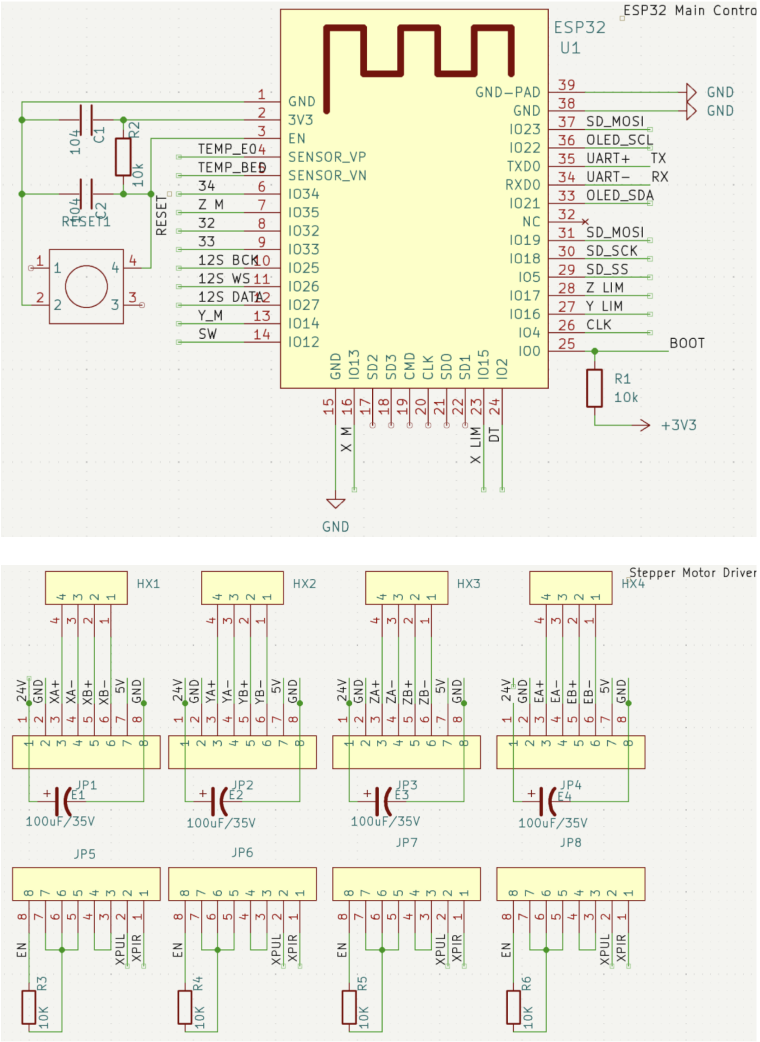

Figure 11: Schematics of ESP32 Main Controller and Stepper Motor Driver

Both a monitor and a 3D interface is used to visualize the control of the machine. The control system ensures climbing machine need to be able to clamp by applying enough pressure to both sides with a hydraulic rod and move horizontally to accommodate walls. Cooperated with the positioning sensor, the control unit controls the nozzles to move within the degree of freedom predefined in the firmware and constrained by the overall structure design. Due to the stepper motors not providing sufficient torque to support the entire machine, we have revised the design to use larger torque servomotors intended for robotics to power the vertical movements. However, due to differences in communication protocols, we need to use an open-source SDK to send and receive signals to control the motion of the servomotors.

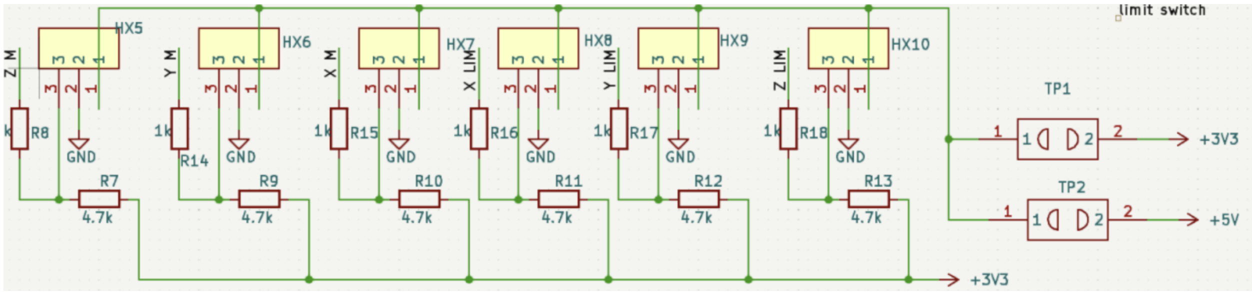

Figure 12: Limit Switch Schematic

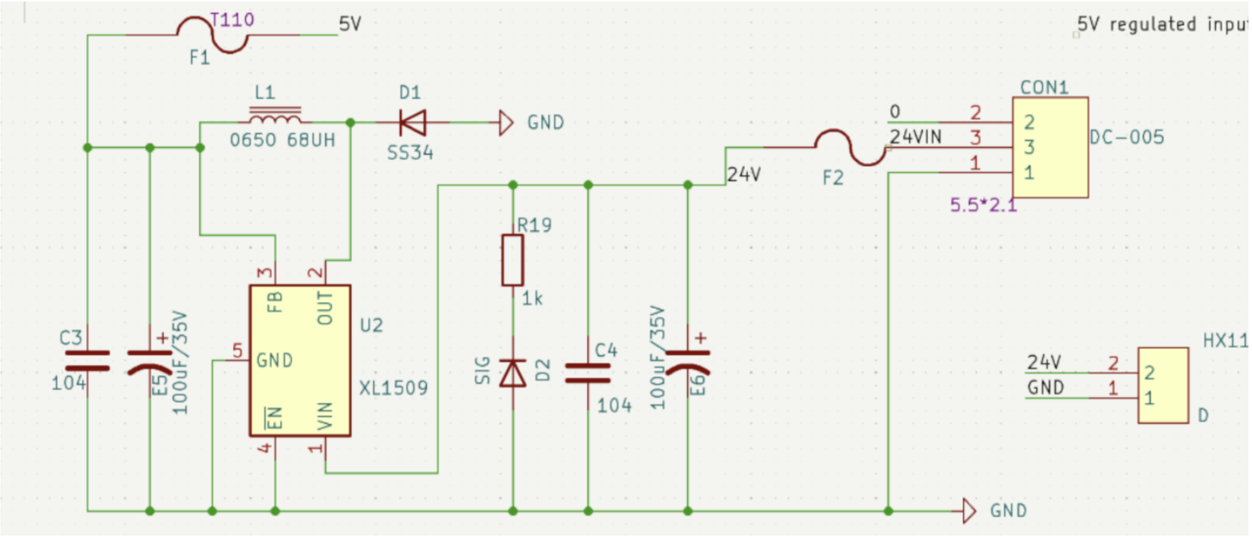

Figure 13: 5V regulated input

3 Verification

3.1 Construction System

Table 3: Verification of Construction System

Requirements	**Verification**	**State**
Independent X-Y-Z axis movement with a 200mm stroke in each direction.	The test reduced reliance on movement systems with extended axis strokes.	Achieved
High-precision printing with compensation for vibration during movement.	Confirm precision printing with vibration compensation in operational test.	Achieved

3.2 Movement System

Table 4: Verification of Movement System

Requirements	**Verification**	**State**
Wheels must match the 3D wall pattern for maximum friction.	Perform friction test on sample wall section. Conduct controlled speed trials on a vertical surface.	Achieved
System supports up to 15kg for robot and payload stability.	Load test with 15kg weight on a mock-up system.	Achieved
The stepping motor must provide a minimum torque of 4N.m for vertical lifting.	Test wheel grip in vertical orientation for adherence. Verify stepping motor torque output meets or exceeds 4N.m.	Achieved
The equipment must climb upwards smoothly and with no pauses.	Confirm stable vertical lifting with full construction payload.	Achieved

3.3 Control System

Requirements	Verification	State
Within a certain range, prioritize the movement of the printer's X and Z axes accurately. Upon reaching a set limit, allow the entire robot to move horizontally on the X-axis and clamp on the wall stably.	Set up a test environment with preset limits for the X and Z axes, control the movement of the robot and observe if the printer part moves independently before reaching the limit. After reaching the limit, attempt to control the entire robot's movement in the respective axis and verify the correctness of the response.	Achieved
If the robot moves to the boundary of the concrete wall, the robot stops moving, and only the printer's X-axis part can continue to move.	Move the robot to the boundary in a simulated concrete wall environment with a clear boundary. Attempt to move beyond the boundary, observing the robot stopping and only the printer's X-axis continuing the movement.	Achieved
Provide a stable 5V input from a source of 24V	Measure the voltage at the regulated output using a multimeter, ensuring it stabilizes at 5V within an allowable deviation.	Achieved

4 Costs

Our fixed development costs are estimated at 200RMB / hour for four people for 16 hours per week. We believe that within this semester (16 weeks) we will have completed approximately 90% of the final design, including the mobile system, the build system, and the control system. Our parts and manufacturing prototype costs are estimated as 2618.95RMB each:

Table 5: Parts List and Costs

Part	Amount	Cost (single item)
PCBs	1	106 RMB
European Standard Aluminum Profile 2020	5	15 RMB
European Standard Aluminum Profile 3030	2	30 RMB
Optical shaft M8	6	14 RMB
Step Motor 42	9	11.8 RMB
Box bearing slides	2	3.5 RMB
Shaft support	8	1.5 RMB
Rigid Couplings	2	0.9 RMB
Horizontal Motor Mounts	2	2.2 RMB
Flange bearings	2	0.75 RMB
Synchronizer Wheel	2	0.95 RMB
Idler pulleys	3	0.95 RMB
Spring	2	1.2 RMB
Synchronous Belt	1	18 RMB
Closed End Timing Belt	4	0.05 RMB
Limit Switches	2	1.3 RMB
Aluminum profile connecting plate	20	1 RMB
Hexagon socket head	8	3.12 RMB
Hexagonal cup head	3	4.94 RMB
Hexagon socket countersunk head	2	3.43 RMB

Continued on next page

Table 5 continued from previous page

Part	Amount	Cost (single item)
Hexagon socket cup head Self-tapping	2	3.28 RMB
Square Nuts	1	3.32 RMB
Hand nuts	1	4.84 RMB
T-Nut	2	2.18 RMB
Double Hexagonal Pillar	2	4.94 RMB
Washers	1	3.5 RMB
Concrete	1	12 RMB
Quartz sand	1	15 RMB
3D print materials	2000	0.5 RMB
Cybergears	2	499 RMB

Our cost to build a product is 2,618.95RMB, which is far less than what the market currently sells existing concrete 3d printers for, and our product has advantages that the market's existing products do not have, which will make our product very competitive.

5 Schedule

We planned our schedule to ensure timely completion of each phase. Here is an outline of the planned schedule:

1. Weeks 1-2: Project initiation, team roles assignment, and procurement of initial materials.
2. Weeks 3-4: Development of the initial design and block diagrams for each subsystem. Begin basic coding for control systems.
3. Weeks 5-6: Start construction of the X-Y-Z movement mechanism and the climbing subsystem prototypes.
4. Weeks 7-8: Integration of the concrete extruder with the moving mechanisms.
5. Weeks 9-10: Initial testing of individual subsystems and debugging.
6. Weeks 11-12: Integration of all subsystems into a single unit. Begin comprehensive system testing.
7. Weeks 13-14: Performance optimization and adjustments based on testing feedback.
8. Weeks 15-16: Final testing, preparation of final report and presentation.

6 Conclusion

We successfully designed and built a robot for constructing 3D-printed concrete walls. The comprehensive design and integration of the robot's subsystems were pivotal in achieving our objectives.

6.1 Key Design and System Integration Successes

1. X-Y-Z Moving System: The implementation of our X-Y-Z moving mechanism ensured that the robot could navigate and adjust its position with high precision across three axes. This enables printing tasks for potentially diverse architectural designs in modern construction.
2. Concrete Extrusion System: Our concrete extruder is equipped with a vertically controlled screw and adjustable nozzles. This allows consistent, high-quality concrete layer deposition. This system's ability to modify extrusion rates and patterns in real time was important in adapting to varying design requirements.
3. Climbing Mechanism: The climbing subsystem, which integrates uniquely shaped wheels and a hydraulic system, demonstrated preferable mobility on vertical surfaces. This feature is essential for maintaining stability and operational efficiency when the robot ascends or descends along the constructed walls. This also enables the printing of buildings with greater heights.
4. Control System: Our control system utilizes a microcontroller-based architecture, coupled with ROS and CAN protocols the control system. The system is capable of translating digital blueprints into precise G-code commands. Integrating with our control board, the system enables the execution of G-code commands by precise controlling of the motors.

6.2 Uncertainties

1. Surface Adhesion Variability: The robot's performance on different surface textures and materials showed variability, which may affect stability in real-world scenarios. Further research is needed to enhance the adaptability of the climbing subsystem.
2. Scalability: While the robot performs as expected in controlled environments, scaling the robot for larger or more complex construction projects may introduce new challenges that require additional development and testing.

6.3 Future Work

Future work will focus on enhancing the robot's adaptability to various building materials and environmental conditions. Alternatives such as incorporating AI and machine learning algorithms for real-time surface analysis and decision-making could greatly improve operational accuracy and efficiency. Additionally, exploring lighter and more durable materials for the robot's structure could enhance mobility and reduce power consumption.

7 Ethics and Safety

Our safety protocols are meticulously developed to comply with IEEE's directive to hold paramount the safety, health, and welfare of the public. This includes careful design considerations of the power supply system which manages a 220V AC input and outputs both 24V and 12V DC after conversion and regulation, in alignment with the ethical design and sustainable development practices outlined in the IEEE Code of Ethics [1].

In adherence to the ACM Code's principle of avoiding harm, we implement a continuous monitoring protocol for the project's operation, proactively identifying and addressing any anomalies in the construction process to mitigate any unintended negative consequences [2]. The handling of the generated G-code files from the STEP or STL formatted building model files, processed through the Control System, is subjected to stringent validation to avoid operational errors that could lead to system failure.

Respecting privacy and data integrity is a cornerstone of our ethical commitment. Our project's Control System safeguards are in line with the ACM Code's guidelines to protect the privacy of others and the confidentiality of data against unauthorized access and disclosure [3]. Furthermore, the communication protocols, including the CAN bus and ESP32, adhere to the IEEE Code's call for disclosure of factors that might endanger the public or the environment.

The development of our climbing robot for 3D printing concrete walls serves as a practical application of our commitment to societal benefit, aligning with the IEEE Code of Ethics. This robot significantly mitigates workplace hazards in construction, embodying the IEEE's directive to prioritize the safety, health, and welfare of the public [1]. As the robot automates a process traditionally associated with high risk, it not only reduces danger but also exemplifies the sustainable development practices encouraged by IEEE. Furthermore, by potentially improving infrastructure in underserved areas, this innovation echoes IEEE's intention to utilize technology for community welfare and human development.

In the spirit of transparency and ethical responsibility, a whistleblower policy is integrated into our project management plan. This encourages team members to report any concerns regarding safety or ethical conduct, providing a clear alignment with the ACM's emphasis on professional accountability and the IEEE's standard of rejecting bribery and unlawful conduct [4].

References

[1] *Ieee code of ethics*, Available: https://www.ieee.org, IEEE Board of Directors, Jun. 2020.

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