A Climbing Robot

For Building 3d Printed Concrete Wall

ECE 445 Design Document

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3/27/24

1 Introduction

1.1 Obejective

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.

Our goal is to develop a new class of climbing construction robots that can adapt to any spatial geometry and textured surfaces, enabling the intelligent construction of large-scale, high-rise, and complex-shaped buildings using 3D printing technology. This includes developing mobile systems for precise spatial positioning and construction systems capable of 3D printing and intelligent reinforcement of concrete structures.

1.2 Background

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 wall climbing robot must be able to provide a stable and movable construction platform for additive construction on multi-story or high-rise buildings formed from 3d printed concrete. The more primary demonstrable goals are to show the device climbing on a 3d printed concrete wall and a display of the printed concrete process.

1.3 High-Level

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

2 Design

Nodes within this system are structured into four essential sections as shown in Fig. 1 for successful operation: A Control System, Construction System, Power Supply System, and Moving System. The Control System, equipped with up to 16GB of storage and a microcontroller, processes building model files into printable G-code files, interfacing through ROS and CAN protocols. The Power Supply System ensures continuous operation with a voltage regulator that steps down from 220V AC to 24V DC and further to 12V DC, with a specific branch providing 3.6V DC. The Moving System integrates hydraulic rods and step motors with vertical and horizontal mobility through climbing wheels. Lastly, the Construction System employs multiple stepper motors for a concrete extruder and an X-Y-Z moving mechanism, indicating a sophisticated approach to automated construction and modeling.

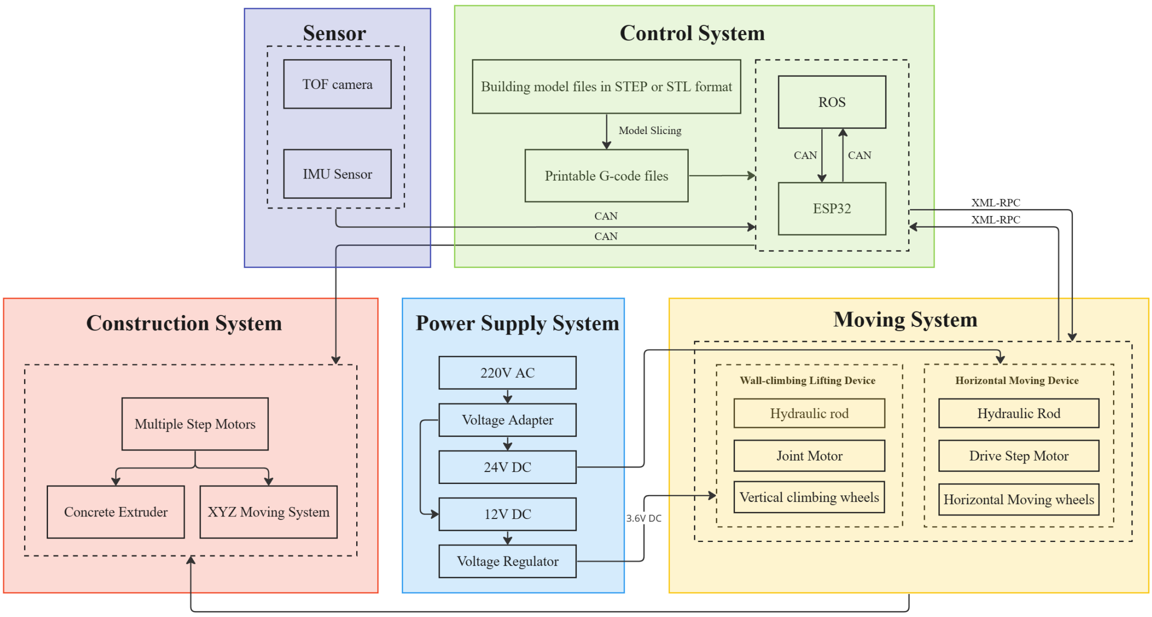

Fig. 1. Block Diagram

As shown in figure 2, the physical design will consist of three different systems, we will replace the construction system shown in figure 2 with the construction mechanism shown in figure 3, which will make the design and machining of the construction system faster and more feasible. The whole device will be made of aluminum alloy and petg material except for the hardware, which will give the whole device high rigidity and strength.

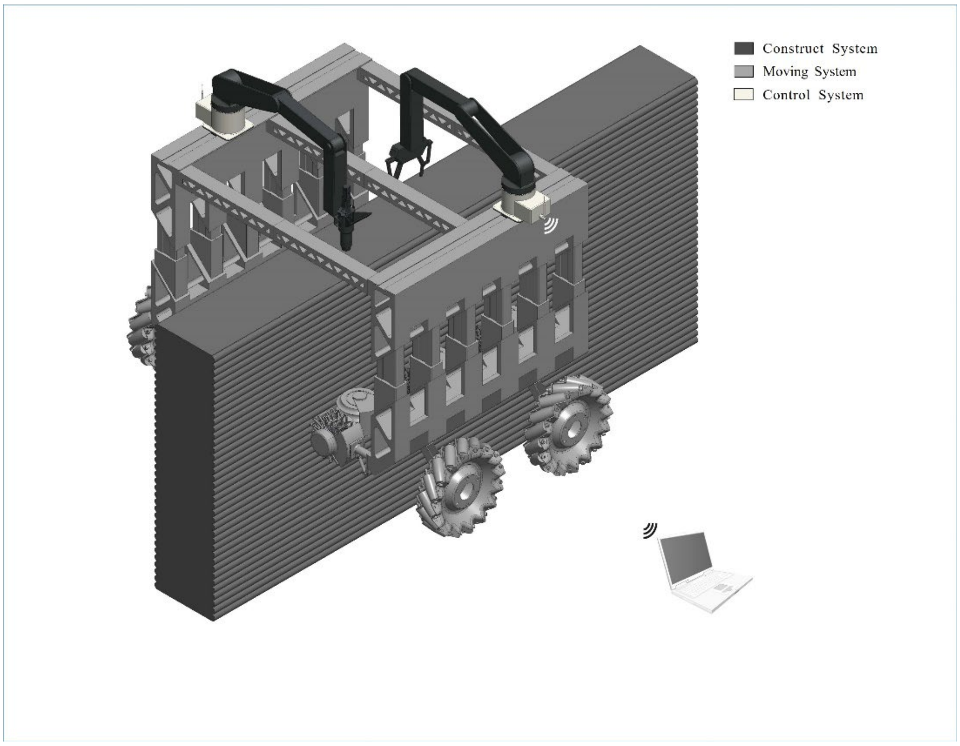

Fig. 2. Physical design CAD in patent

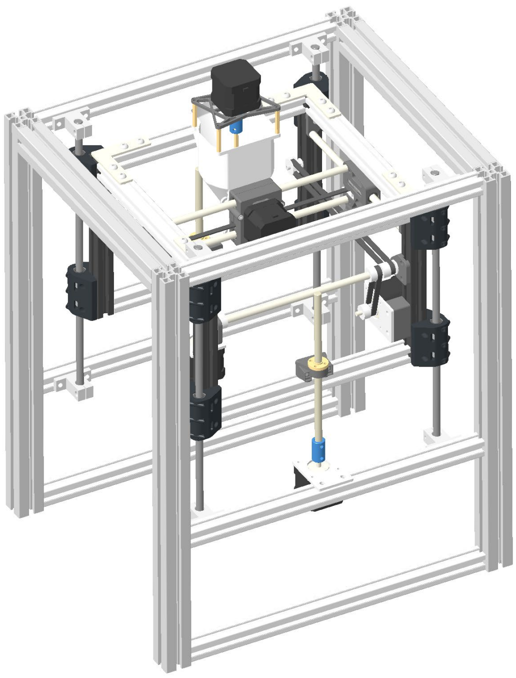

Fig. 3. Physical design of Construction System

2.1 Movement System 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 horizontally.

2.1.1 Horizontal Moving System

The horizontal movement device consists of a specially shaped wheel body, a hydraulic rod and a step motor. Wherein 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.

Requirements	Verification
1. Wheels must match the 3D wall pattern for maximum friction. 2. System supports up to 30kg for robot and payload stability.	1. Perform friction test on sample wall section. 2. Load test with 30kg weight on a mock-up system. 3. Conduct controlled speed trials on a vertical surface.

2.1.2 Wall Climbing Lifting System

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 (cyber-gear, xiaomi co.) with a torque of 4N.m, which gives the device sufficient power to carry the printing device for construction.

Requirements	Verification
1. The stepping motor must provide a minimum torque of 4N.m for vertical lifting. 2. The equipment must climb upwards smoothly and with no pauses	1. Test wheel grip in vertical orientation for adherence. 2. Verify stepping motor torque output meets or exceeds 4N.m. 3. Confirm stable vertical lifting with full construction payload.

2.2 Construction System Requirements

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 axis can be moved, they use stepper motors for independent control, can be in the horizontal movement of the device movement of the vibration generated by the compensation, to achieve high-precision printing, and the printing system itself in the X-Y-Z direction with a stroke of 200mm, which can reduce the frequency of the use of the vertical climbing system and the horizontal movement of the system.

Requirements	Verification
1. Independent X-Y-Z axis movement with a 200mm stroke in each direction. 2. High-precision printing with compensation for vibration during movement.	1. Validate XYZ axes provide 200mm travel via displacement testing. 2. Confirm precision printing with vibration compensation in operational test. 3. The test reduced reliance on movement systems with extended axis strokes.

2.4 Control System

The control system is designed to execute program instruction, process data and control other modules. It uses drive modules to control actuators (such as motors, stirrers, telescopic rods) to perform the physical actions of the robot, including horizontal movement, climbing, as well as the movement of 3D printers and the printing of concrete.

Requirements	Verification
1. Within a certain range, prioritize the movement of the printer's X and Z axes. Upon reaching a set limit, allow the entire robot to move horizontally on the X-axis or climb on the Z-axis on the wall. 2. 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. 3. Provide a stable 5V input from a source of 24V	1. 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. 2. 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. 3. Measure the voltage at the regulated output using a multimeter, ensuring it stabilizes at 5V within an allowable deviation.

2.5 Power Supply

The power supply always provides the circuit with 12v and joint motor with 12v. It is powered by a 12v DC power supply charger and a 24v DC power supply charger with a long cable to ensure long device working time and long distances power supply.

2.5.1 12v & 24v DC power supply charger

This node will provide 12v & 24v voltage to the circuit and joint motor constantly. Because of the time-consuming process of printing buildings, the use of lithium batteries not only significantly increases the load on the machine, but also adds significant production costs. The use of power supplies and longer cables not only reduces the load on the machine itself, but also ensures stable running at all times.

Requirements	Verification
1. Deliver constant 12V and 24V DC to the circuit and joint motor. 2. System design to minimize load and ensure stable operation over long periods.	1. Test for stable 12V and 24V output over extended operational duration. 2. Measure machine load reduction compared to battery use. 3. Assess operational stability with extended cable setup.

2.5.2 Voltage Regulator

This low dropout regulator provides the required 3.6V to the stepper motor from a 12v supply. This chip XL1509 regulator must be able to handle the peak input from the DC charger (12.3V) and the minimum input from the DC charger (10.8V).

Requirements	Verification
1. Output steady 3.6V for stepper motors from a variable 10.8V-12.3V supply. 2. Use XL1509 regulator chip to manage voltage to the system's specification	1. Test regulator output with peak and minimum input from DC charger. 2. Confirm consistent 3.6V delivery under variable input conditions. 3. Verify thermal performance during extended operation.

2.6 Schematics

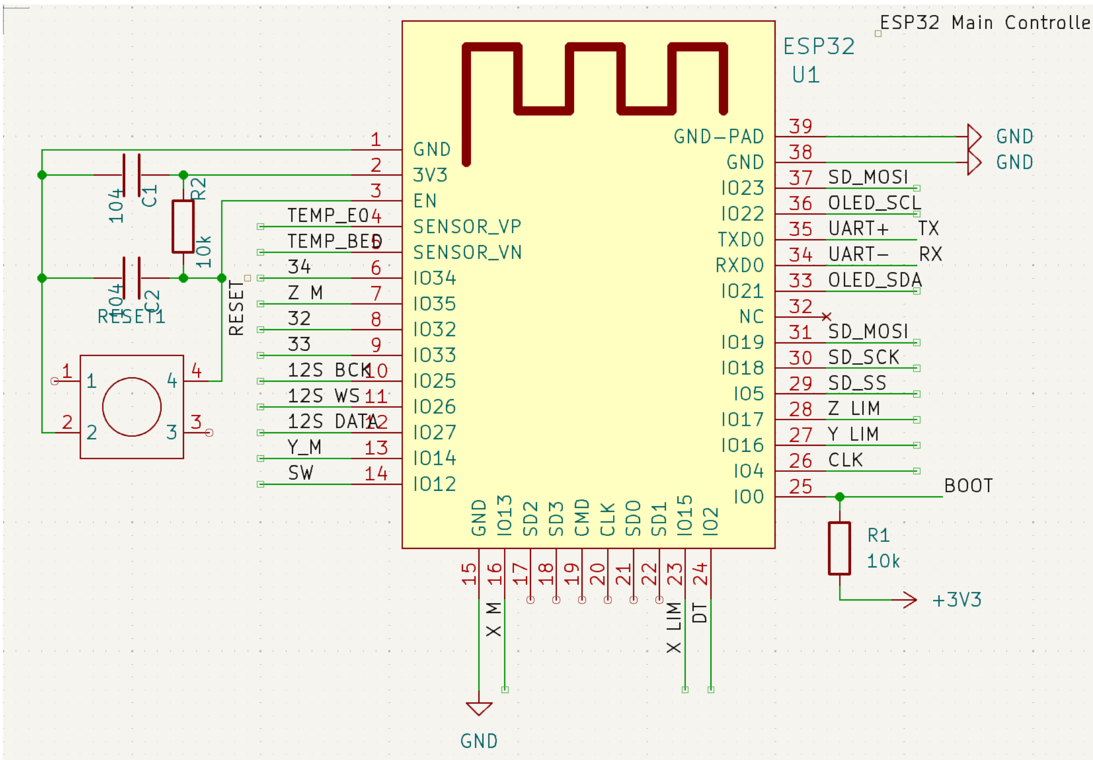

Fig. 4. ESP32 Main Controller

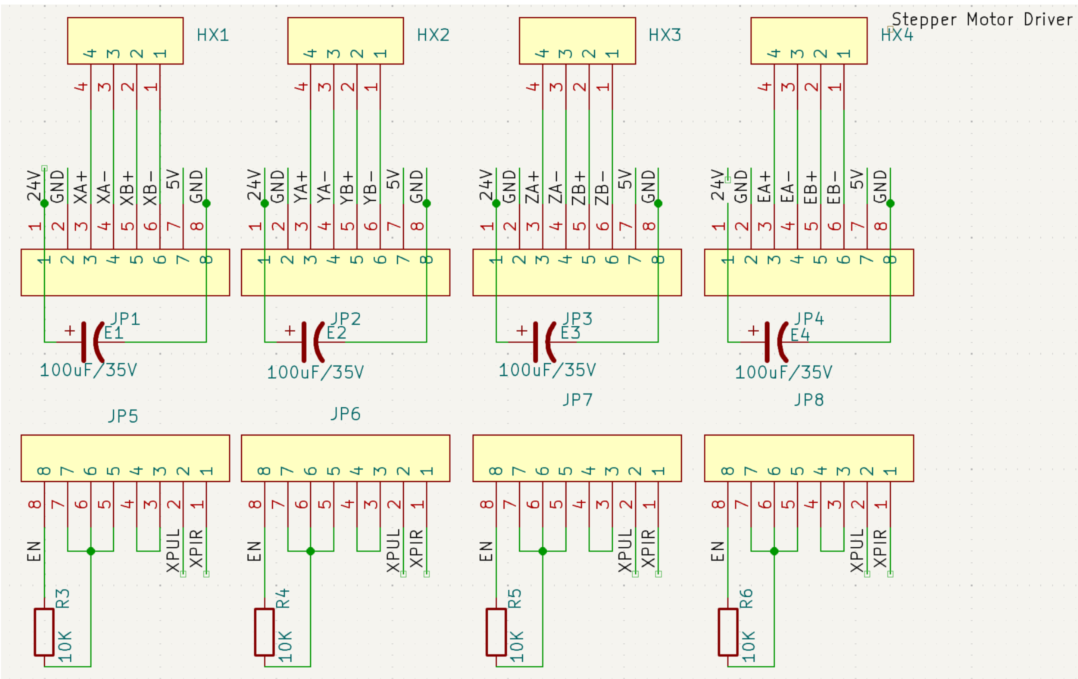

Fig. 5. Step Motor Driver

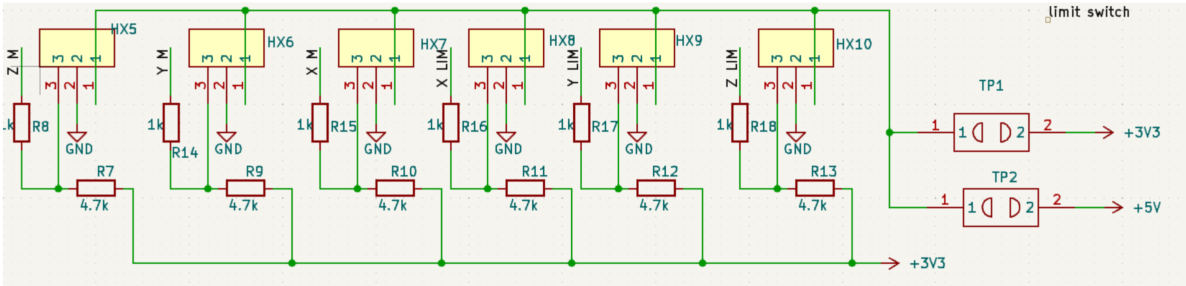

Fig. 6. Limit Switch

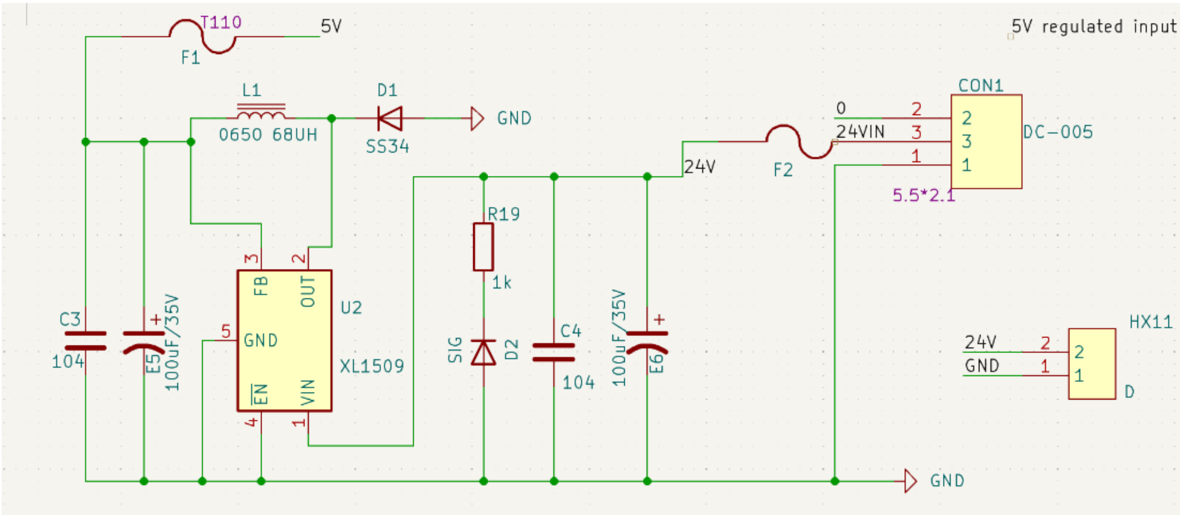

Fig. 7. 5V regulated input

2.7 Board Layout

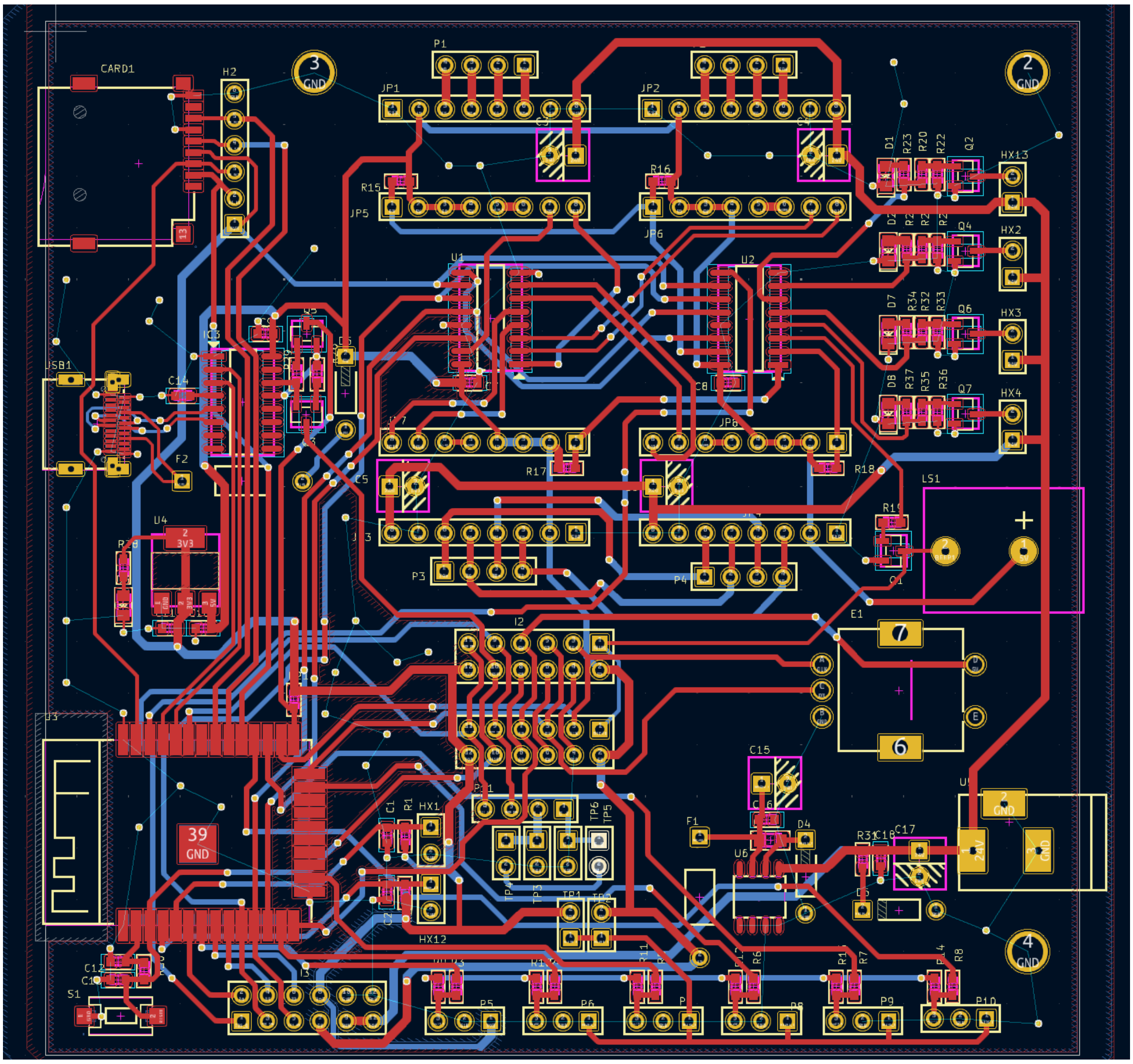

Fig. 7. PCB Layout

2.8 Tolerance Analysis

In the exploration of critical success factors for our XYZ-axis movable 3D concrete printer project, we identify "truncation error" as the most challenging requirement to manage. In the context of 3D printing, especially with the emerging domain of 3D concrete printing, ensuring the precision of the print head's movement along the pre-defined trajectory is crucial for producing high-quality construction components. However, given the physical characteristics of concrete and the complexity of the printing process, accurately controlling the print head's movement becomes exceedingly challenging, with the management of truncation error becoming a key to precise control. Mathematically, the first-order approximation of truncation error can be described with the formula:

$$\hat{e}_T = \widetilde{N}p = \widetilde{N}\widetilde{N}^T\widetilde{N}^{-1}\widetilde{N}^T e - \widetilde{N}\widetilde{N}^T\widetilde{N}^{-1}\widetilde{N}^T\widetilde{N}p$$

In this formula, $\widetilde{N}$ represents the untruncated filtered B-spline matrix, signifying the system's response to control inputs; p symbolizes the control points, representing the predetermined trajectory of the print head movement; e denotes the tracking error without truncation, indicating the difference between the system's output and the desired output.

To minimize truncation error, we have employed several key strategies:

1. Optimizing the filter length LH to accommodate the system's dynamics and reduce errors introduced by truncation. The filter length determines how much historical information is considered when computing control signals. By appropriately choosing LH, we can balance computational complexity and control accuracy.

2. Given the singular values of the $\widetilde{N}$ matrix, we optimize the system's control strategy by selecting an appropriate distribution of control points p The magnitude of singular values affects the system's sensitivity to control signals, and a rational distribution of control points can effectively reduce the system's response error.

3. Implementing a compensation strategy to further reduce the impact of truncation error on print quality, quantifiable through the formula:

$$eT^2 \leq \gamma_T \left(\frac{1}{\sigma_{minN}}\right) e^2 + p^2$$

Here, γ_T is a coefficient related to truncation error, and σ_{minN} is the minimum singular value of the $\widetilde{N}$ matrix, influencing the amplification of error.

3 Costs

Our fixed development costs are estimated at ￥200 / 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.

$$4 \times \frac{￥100}{hr} \times \frac{16hr}{wk} \times \frac{16wks}{0.9} = ￥113778$$

Our parts and manufacturing prototype costs are estimated as ￥2618.95 each:

Part	Amount	Cost (single item)
PCBs	1	￥106
European Standard Aluminum Profile 2020	5	￥15
European Standard Aluminum Profile 3030	2	￥30
Optical shaft M8	6	￥14
Step Motor 42	9	￥11.8
Box bearing slides	2	￥3.5
Shaft support	8	￥1.5
Rigid Couplings	2	￥0.9
Horizontal Motor Mounts	2	￥2.2
Flange bearings	2	￥0.75
Synchronizer Wheel	2	￥0.95
Idler pulleys	3	￥0.95
Spring	2	￥1.2
Synchronous Belt	1	￥18
Closed End Timing Belt	4	￥0.05
Limit Switches	2	￥1.3
Aluminum profile connecting plate	20	￥1
Hexagon socket head	8	￥3.12
Hexagonal cup head	3	￥4.94
Hexagon socket countersunk head	2	￥3.43
Hexagon socket cup head Self-tapping	2	￥3.28
Square Nuts	1	￥3.32
Hand nuts	1	￥4.84
T-Nut	2	￥2.18
Double Hexagonal Pillar	2	￥4.94
Washers	1	￥3.5
Concrete	1	￥12
Quartz sand	1	￥15
3D print materials	2000	￥0.5
Cybergears	2	￥499
Total		￥2618.95

Our cost to build a product is $2,618.95, 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.

4 Schedule

Week Starting	Jianye Chen (Mechanical)	Zhenghao Zhang (Mechanical)	Benhao Lu (Software)	Shenhua Ye (Software)
3/1/24	Conceptualize climbing device mechanics	Initial sketches of lifting device	Set up software development environment	Gather software requirements
3/8/24	Design power drive and load-bearing mechanisms	Draft detailed lifting device plans	Begin control software architecture	High-level logic for control systems
3/15/24	Prototype surface adaptation mechanisms	Model anchor lock modules	Develop preliminary control algorithms	Simulate control logic against models
3/22/24	Test power drive efficiency	Test anchor lock strength and stability	Implement control software with test data	Interface mockups for feedback systems
3/29/24	Integrate material feed mechanism with climbing device	Design joint mechanisms for surface adaptation	Design software for material flow regulation	Develop feedback system for print accuracy
4/5/24	Conduct small-scale load-bearing tests	Optimize joint mechanisms for efficiency	Test software with material flow mockup	Integrate feedback system into control software
4/12/24	Field test climbing mechanisms	Refine and adjust lifting device	Debug and refine control software	System integration testing
4/19/24	Stability enhancements for climbing device	Field testing and adjustments for lifting device	Optimize material flow control logic	Enhance feedback system accuracy
4/26/24	Finalize climbing device design for production	Prepare lifting device for final integration	Finalize control software for demonstration	Prepare feedback system for live demo
5/3/24	Integrate all mechanical components	Quality checks on mechanical systems	System-wide integration tests	Perform software stress tests
5/10/24	Load and stability verification	Final mechanical adjustments	Software optimization for reliability	Finalize software documentation
5/17/24	Prepare mechanical system for demonstration	Ensure mechanical system meets specs	Debugging and last-minute software fixes	Rehearse presentation and demo setup

5 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 [1] [4].

References

[1]. IEEE, "IEEE Code of Ethics," IEEE Board of Directors, June 2020.

[2]. ACM, "ACM Code of Ethics and Professional Conduct," ACM Council, 2018.

[3]. ACM, "1.2 Avoid Harm," in ACM Code of Ethics and Professional Conduct, ACM Council, 2018.

[4]. ACM, "1.7 Treat All Persons Fairly," in ACM Code of Ethics and Professional Conduct, ACM Council, 2018.

[5]. Molong Duan, Deokkyun Yoon, Chinedum E. Okwudire, A limited-preview filtered B-spline approach to tracking control – With application to vibration-induced error compensation of a 3D printer, Mechatronics, Volume 56, 2018, Pages 287-296