ECE 445/ME 470

SENIOR DESIGN PROJECT

FINAL REPORT

Supernumerary Robotic Limbs

Team #27

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May 31, 2024

Abstract

The concept of Supernumerary Robotic Limbs (SRL) aims to augment human physical capabilities by providing additional appendages that can be utilized for multitasking or rehabilitation purposes. These limbs have the potential to transform human-machine interaction and extend the possibilities for human augmentation and assistance. The primary objective of this design is to integrate SRL with the human body, enhancing functionality and usability while focusing on safety and ergonomics. The proposed SRL system is designed to be like a chair with a backrest, with two robotic limbs that adjust to the user's needs and provide support in challenging environments, such as working under a boat's hull.

The system incorporates a motion system with electric push rods and wheels for mobility, a power system with a 12V battery, and a control system that includes a remote controller and a closed loop control unit. The design addresses workplace injuries and aims to improve worker comfort, safety, and efficiency. The project also emphasizes ethical considerations and safety standards to ensure the well-being of the users.

Keywords: human-augmentation, ergonomic design, remote control system, safety standards

Contents

1 Introduction

1.1 Problem and background

Supernumerary limbs can be helpful in daily activities or specific workplace tasks, which are additional appendages attached to the human body to enhance physical capabilities, such as providing extra arms for multitasking or aiding in rehabilitation after injury. The advantages of Supernumerary limbs are numerous. They can not only act as physical arms to complete some daily tasks, but can also help with some works which requires high precision. Overall, the integration of supernumerary limbs holds the potential to revolutionize human-machine interaction and expand the possibilities for human augmentation and assistance[1].

The primary goal of designing supernumerary limbs is to integrate them with the human body while enhancing functionality and usability. Some components, including the mechanism of limbs, electronics for actuation and control interface, are vital to the success to the product. In dangerous environment or some postures that are uncomfortable and arduous, a type of supernumerary robotic limbs is designed to attach to a human body that can support the human by acting as additional legs.

According to the US Bureau of Labor Statistics, in 2014 there were over 190,000 workplace injuries in manufacturing sectors and 50,000 injuries in agriculture[2]. Overall, the cost of workplace injury amounted to over $190 billion and resulted in over 1.1 million lost days of work[3]. Out of all workplace injuries in 2014, approximately one in three was a musculoskeletal disorder[4].

In our study, we have identified significant challenges faced by workers responsible for soldering beneath the hull of a boat. When boats sail at sea, the hull is susceptible to damage due to seawater corrosion. Therefore, regular maintenance and cleaning are essential for preserving the vessel's condition. Without proper care, the hull may become corroded, significantly shortening its service life. For small and lightweight boats, machinery is available to lift the vessel and facilitate hull cleaning or soldering, as illustrated in Figure 1. This equipment can raise or lower the boat to a convenient working height, allowing workers to stand comfortably and perform their tasks without needing to adjust their height.

Figure 1: Importance of cleaning boat bottom and lifting machine

However, for larger and heavier vessels like destroyers, adjusting the boat's lifting height is impractical. In such cases, adjusting the worker's height becomes more suitable. Workers often need to look up and raise their arms to perform soldering in confined spaces, which is labor-intensive and prevents them from working for extended periods. While lying down might alleviate some issues, this posture also presents its own disadvantages. Lying on their backs strains their posture and limits maneuverability, compromising their ability to work effectively. Workers often struggle to control soldering tools as one hand is needed to stabilize themselves.

To address these challenges, we propose developing a specialized support system that enables workers to position themselves securely beneath the hull while freeing their hands for soldering tasks. This system could incorporate ergonomic padding, adjustable harnesses, and stabilization mechanisms to enhance worker comfort, safety, and efficiency in this demanding environment.

1.2 Solution

A novel type of supernumerary robotic limbs has been developed to offer support, enhance the safety of workers in hazardous environments, and improve their comfort, enabling them to work for extended periods. This innovative system, designed to resemble a chair with a backrest, provides users with reliable support. Two robotic limbs are incorporated to coordinate their position based on user requirements, controlled via a remote control device fixed to the system. This control allows the user to adjust the limbs' length as needed. At the base of the limbs, wheels are installed to facilitate smooth movement, allowing the entire system to move with the user. Once a task is completed in one location, the user can simply sit on the device and glide effortlessly to a new spot using the friction between their shoes and the surface. This design ensures seamless workflow without requiring the user to stand up and detach from the system. Since the system operates independently from the human body, the robotic limbs function as additional legs, freeing up the worker's hands while enhancing overall body stability. Consequently, workers can maintain a continuous workflow and focus on their tasks without interruptions, significantly improving safety and efficiency in demanding environments.

1.3 Visual aid

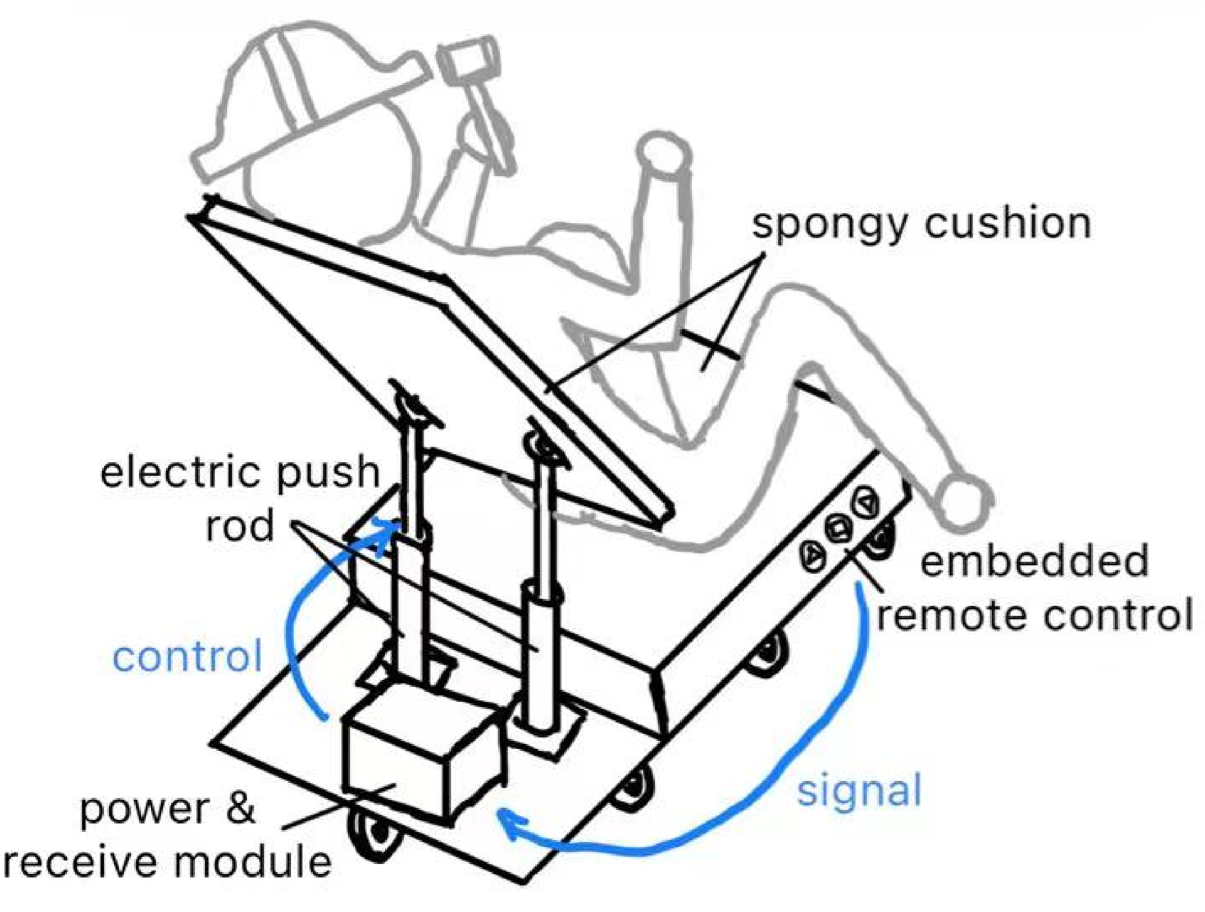

Figure 2: Visual aid of the project

Figure 2 provides a visual representation of the project. As illustrated, the worker can rely on the back plate supported by two electric push rods. The spongy cushion beneath provides comfortable seating for the user, enhancing the ergonomic design. This setup allows the worker to sit securely while freeing both hands to work without restrictions. The embedded remote control provides intuitive adjustments for comfort and convenience, while the power and receive module ensures the efficient operation of the system.

2 Design

2.1 Block diagram

Figure 3 shows the block diagram of our design, which illustrates the architecture and flow of the wearable robotic support system. The system is powered by a 12V lithium battery that provides energy to two linear actuator motors and the sensor module. These actuator motors are regulated via a closed-loop control mechanism that receives feedback from various sensors, including Hall, length, angle, and pressure sensors. This control mechanism adjusts the position of the mechanical linkage of the wearable frame, which supports the user ergonomically.

The system also incorporates mixed reality (MR) glasses to offer a user-friendly interface, allowing the user to access relevant data and system controls through an integrated web page. The web page receives processed data from a server, which collects information transmitted via a ZigBee transmitter. The server processes the sensor data for real-time monitoring and control. The wearable frame is worn by the user to provide support and comfort, and the entire system is designed to ensure efficient, accurate positioning while offering useful data visualization and control capabilities through wireless communication.

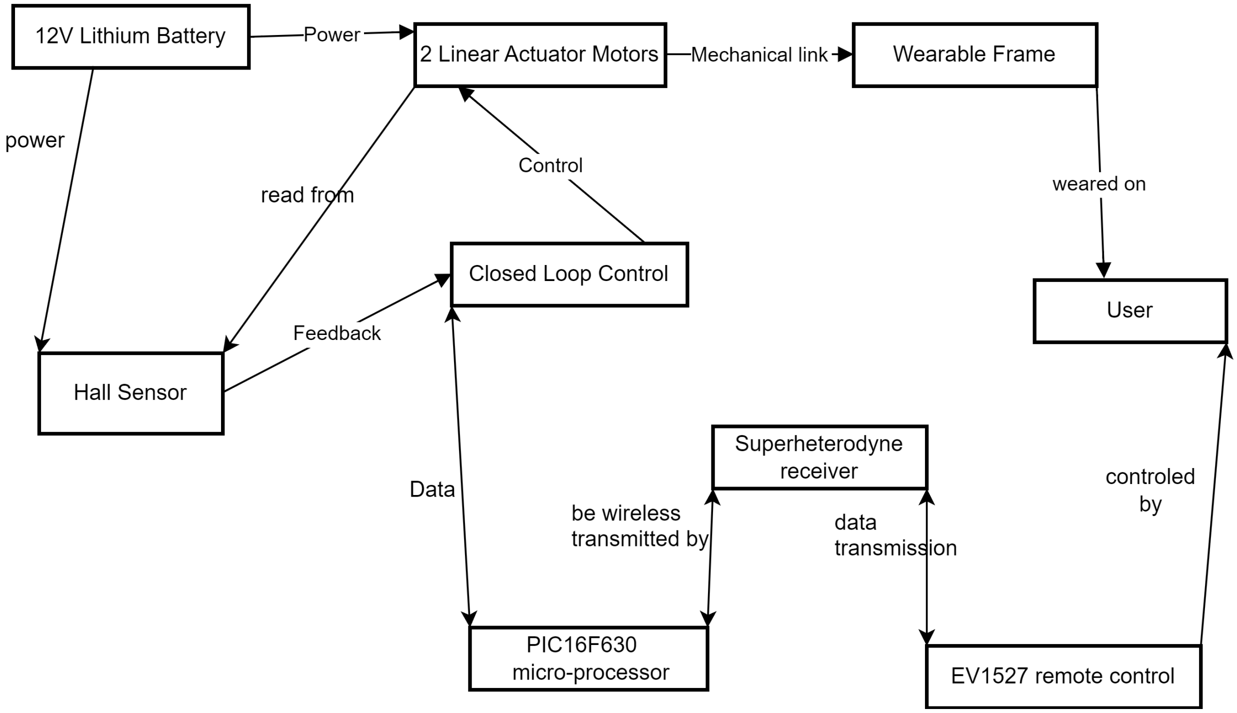

Figure 3: Block diagram of the project

2.2 Design overview

The computer-aided design (CAD) model of the project, illustrated in Figure 4, showcases the intricate structure and functionality of the primary components. The back plate (1) is designed to offer reliable ergonomic support for the user, securely mounted on the base plate (2). Both plates are constructed from lightweight yet sturdy aluminum alloy, striking a balance between strength and ease of mobility. The back plate's inclination is finely controlled by an electric push rod, or linear actuator (3), which enables precise adjustments to the angle, ensuring optimal ergonomic support. A second electric push rod, positioned behind the back plate but obscured in the figure, provides complementary support, thereby balancing the system's operation. The control box (4) contains the motor control board and the power supply unit that drive the electric push rods, making it the command center of the system. This ensures that all adjustments to the back plate are swift and reliable. Mounted at the base of the structure, the seven universal wheels (5) enable the system to glide smoothly and effortlessly across various surfaces. At the position of (6), there is a remote controller to control the length of electric push rods which is not modelled in the figure. This mobility allows the structure to seamlessly follow the user's movements, ensuring continuous support while adapting to changing positions. This modular design enables the user to remain comfortable and focused during demanding tasks, significantly reducing the need for manual repositioning or support adjustments. The system's adaptability ensures ergonomic alignment and stability, reducing the risk of strain while enhancing productivity and safety. Overall, the design prioritizes the worker's well-being and efficiency, providing a practical, highly maneuverable solution for extended work in hazardous or confined environments.

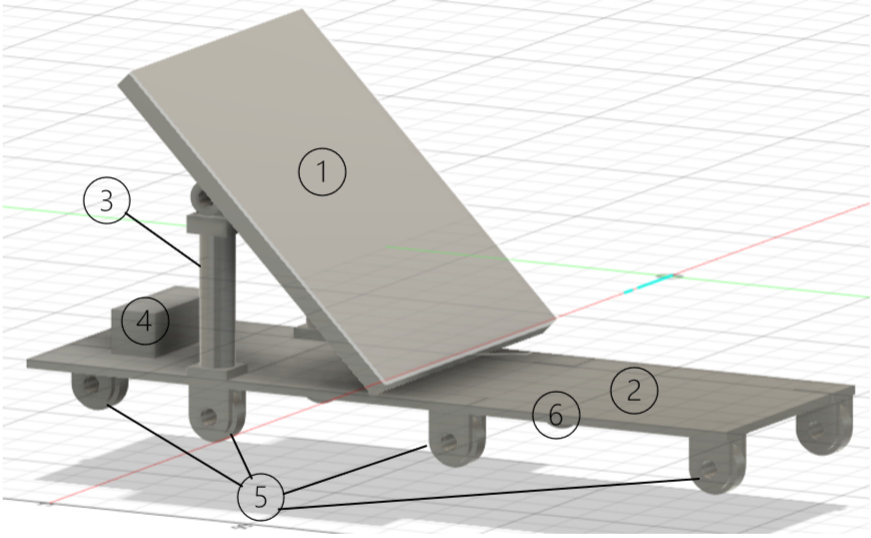

Figure 4: CAD model of the project

Figure 5: Final design

Figure 5 depicts the final version of our supernumerary robotic limb support system, designed to enhance ergonomic support and mobility for workers performing tasks in challenging environments. The system is built to resemble a chair with a backrest and a seating platform, both covered with a layer of leather over spongy cushions for added comfort. The backrest is mounted on two electric push rods that allow for precise angle adjustments, ensuring that the user can find a comfortable and supportive position. These push rods are connected to a base plate that houses the power and control modules, ensuring seamless operation. The seating platform extends from the base, allowing the user to sit directly on it with their feet extending beyond the edge. This design allows the user to use the friction between their shoes and the ground to move the system, facilitated by the seven strategically placed universal wheels. Four of these wheels include locking mechanisms to keep the system stationary when required. The combination of comfortable cushioning, adjustable support, and smooth mobility makes this design particularly effective for tasks requiring prolonged periods of work in confined or awkward spaces, such as soldering beneath boat hulls. The integration of ergonomic considerations and practical functionality ensures that this system significantly enhances worker comfort, safety, and productivity.

2.3 Subsystems

In complex engineering projects like this one, the relationship between the system and its subsystems is fundamental to achieving overall performance, flexibility, and reliability. The entire structure functions as an integrated system, where the primary components (the back plate, base plate, electric push rods, control box, and universal wheels) work together to support the user ergonomically. However, each component acts as a subsystem, with its own distinct role in achieving the broader system goals. For instance, the electric push rod subsystem ensures that the back plate's inclination is adjustable, aligning with the user's ergonomic needs. Similarly, the control box subsystem governs the motor control board and power supply, enabling seamless operation of the push rods. The universal wheel subsystem ensures free mobility, allowing the user to move smoothly across various surfaces. These subsystems interact harmoniously, providing the structure with the modularity, adaptability, and comfort necessary for a comprehensive support system. The carefully orchestrated relationship among these interconnected subsystems is crucial for achieving ergonomic efficiency, operational safety, and user productivity.

2.3.1 Motion system

The primary components that contribute to the motion subsystem are the seven universal wheels at the base of the design. This subsystem fulfills a critical practical requirement: it is rarely the case that only a single location beneath the hull requires soldering. The system aims to allow the worker to move seamlessly from one spot to another without standing up or exiting the design. Instead, the user can remain comfortably reclined on the back support, similar to sitting on a sofa. When movement is required, the user can unlock the locks on the wheels and use the friction between their shoes and the ground to glide smoothly in any direction.

Seven universal wheels are strategically placed for optimal structural strength, stability, and budget control. The arrangement of the wheels draws inspiration from the tricycle's triangular shape, which is known for its inherent stability. Six of these wheels are equipped with locks, ensuring that the system remains stationary when needed. The right six wheels in Figure 4, which have locks, can be easily reached by the user to engage or disengage them, whereas the leftmost wheel is out of reach and therefore does not have a lock, as it would be impractical to access. This arrangement provides a balance between stability and user convenience. Other factors will be discussed in Verification sector.

While we explored alternative wheel types, such as Mecanum wheels, which can be electronically locked and provide superior control, we chose universal wheels due to budget constraints. Mecanum wheels offer advanced features like precision motor-driven control and electrical locking mechanisms, yet they are costly. Despite these considerations, the universal wheels with locking mechanisms effectively meet the requirements for flexibility, control, and seamless movement while prioritizing ergonomic comfort and ease of use. The overall configuration allows workers to remain mobile without compromising productivity, providing reliable support and enhancing workflow efficiency.

2.3.2 Electric push rod

The purpose of using electric push rods, also known as linear actuators, is to precisely adjust the worker's sitting posture. In this design, the point where the user's back meets the back plate, the point where the user sits on the bottom plate, and the point where the electric push rods are attached to the bottom plate together form a right-angled triangle. By extending or retracting the electric push rods, which represent the shorter side of the right-angled triangle, the angle between the user's back (the hypotenuse) and the ground changes accordingly. This mechanism allows the worker's posture to be smoothly adjusted from a reclined position to an upright sitting position, and vice versa. The expected adjustable angle typically ranges from 20 degrees to 45 degrees. However, several factors can constrain this, including the original length of the electric push rods and the worker's physical dimensions, such as height, leg length, and other measurements.

By modifying the length of the actuators, this support system provides a flexible range of positions, offering a significantly more comfortable posture compared to a non-adjustable back plate. This adaptability allows the user to assume a broader range of positions, providing improved ergonomic support and a greater scope of movement. Several critical parameters of the electric push rods, including length adjustment range and control precision, will be thoroughly examined in the verification section to ensure the system operates efficiently and effectively across different working conditions.

2.3.3 Support structure

The support structure of our design is built around two key components: the back plate and the bottom plate. Ensuring these elements are comfortable is essential as they directly interact with the user. To achieve this, we have chosen to cover both plates with spongy cushions, layered with leather to emulate the feel of a sofa. Understanding that the bottom plate will bear the majority of the user's weight, we have incorporated two layers of sponge on the bottom plate, while the back plate features a single layer. This configuration aims to provide both stability and comfort, enabling prolonged use without discomfort.

Given that these plates form a substantial portion of the system's bulk, reducing their weight is a priority. However, this must be done without sacrificing structural integrity or reliability. To balance these requirements, we have selected aluminum alloy for the construction of the plates. This material choice allows us to keep the weight down while ensuring the necessary strength and durability.

Additionally, the protruding bolts that secure the universal wheels could potentially cause discomfort, affecting the overall user experience. Our solution to this problem was to use two layers of sponge on the bottom plate, which we found, through testing, effectively eliminates any discomfort from the bolts. This ensures that the system remains ergonomic and comfortable to use. Through these thoughtful design considerations, we have developed a support structure that is both comfortable and robust, meeting the high standards needed for effective ergonomic support and reliable operation.

2.3.4 Power system

The energy system is straightforward. In essence, it comprises batteries and wiring that connect the batteries to the remaining modules to supply power. We have opted for 12V batteries. Initially, our research revealed that the majority of linear motors available in the market operate at voltages of 12V, 24V, and 36V. However, those operating at 24V and 36V typically deliver thrust exceeding 500N, surpassing our requirements and budget constraints. Moreover, selecting a lower voltage enhances the safety of our device and helps alleviate heating issues. The batteries will be positioned centrally between the two electric push rods on the backplate. This placement shields them from the surrounding rigid structures, effectively preventing any potential crushing of the batteries.

Taking into account our goal of enabling the worker to operate the device for a minimum of three hours while wearing it, and considering our research findings indicating a motor power consumption range of 36-60W, we need to perform some calculations. Moreover, linear motors typically utilize an internal screw-type structure that, when stationary, can automatically lock through mechanical means, resulting in minimal power consumption. Consequently, we will base our calculations on a scenario where one-third of the working time involves the electric push rod in operation.

Given these factors, we can determine the necessary battery size. Let's consider the worst-case scenario: continuous operation of the motor at its maximum power consumption of 60W for one-third of the time, equating to one hour.

Energy consumption for one hour of operation is given by $Power \times Time$. To cover a three-hour work period, the total energy required would be:

$$W = P \times t = 60\,\mathrm{Wh} \times 1\,\mathrm{hour} = 60\,\mathrm{Wh}$$

where W represents the total energy, P denotes the energy consumption per hour, and t symbolizes the total working hours. Thus, the battery capacity should be at least $60\,watt\text{-}hours\ (Wh)$ to ensure the device operates for three hours under the specified conditions.

2.3.5 Control system

The control system is paramount for the operation of the electric push rods. The control mechanism is designed around a user-friendly remote controller featuring three intuitive buttons: up, down, and stop. These controls are strategically placed within the chair's spongy cushion, allowing the user to effortlessly adjust the vertical position of the electric push rods, thereby controlling the body's support and elevation. The system is engineered to activate and cease the push rods' movement in response to the user's commands, providing precise and reliable operation.

Initially, the electric push rods were delivered with wired controllers, necessitating separate control for each rod. Recognizing the limitations and potential hazards of a wired system, especially in dynamic work environments, we opted to innovate towards a wireless solution. This transition not only clears the workspace but also affords the user greater flexibility and mobility.

To facilitate wireless control, we selected the EV1527 encode IC module from American EV Semiconductor, renowned for its efficiency and reliability in wireless communication. The principle of the remote-control chip will be explained in detail in the next section. This module is ideal for our application due to its balance of performance and power consumption. We integrated this module into a custom-designed remote controller, which communicates with the electric push rods' motor drivers. The control system is underpinned by a PIC16F630 microprocessor-based platform that forms a closed-loop system. This system ensures that both push rods operate in synchrony, maintaining an equal length and providing balanced support.

Drawing from open-source resources, we refined the existing designs to suit our specific requirements. We streamlined the functionalities, removing unnecessary components, and re-engineered the PCB layouts for both the remote controller and the receiving end. This customization process involved meticulous selection of components, including a micro-controller for processing commands and sensor inputs, solid-state relays for reliable control of the motors, and a voltage regulator to ensure a stable power supply. The entire control system is powered by a rechargeable lithium-ion battery, chosen for its compact size, high energy capacity, and safety features, making it ideal for technological applications.

2.4 Remote Control system

2.4.1 Transmission End

The EV1527 wireless encoding chip, developed by CMOS technology, is a critical component in our remote control system, offering a comprehensive solution for secure encoding. This chip is capable of pre-burning up to 1,048,576 unique code combinations, a feature that is essential for enhancing the security and individuality of each remote control unit.

The encoding process of the EV1527 is initiated through user inputs via button presses. The chip features four button input pins as shown in Figure 6, each of which can trigger a unique code sequence. These sequences are pre-determined and securely stored within the chip, ensuring that each code is both unique and non-replicable. The encoding mechanism is user-friendly, with an intuitive interface that allows for seamless code generation and transmission.

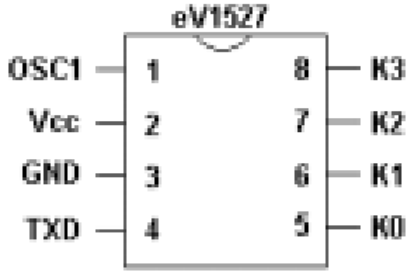

Figure 6: Pin diagram of EV1527

Power efficiency is a key consideration in our design, and the EV1527 supports this with a low power consumption profile. It operates within a wide voltage range of 3.0V to 13V. This ensures prolonged battery life for our remote control devices. The internal oscillation circuit of the EV1527, requiring only an external resistor, simplifies the design and reduces component count, leading to a cost-effective and streamlined remote control solution.

The EV1527 is designed to integrate seamlessly with a compatible decoding chip, such as the PIC16F630. The PIC16F630's learning capabilities enable it to recognize and store codes emitted by the EV1527, establishing a secure and responsive communication link between the remote control and the controlled device. The software-based decoding approach of the EV1527 enhances its security features, making it resistant to code scanning and replication.

The performance of the EV1527 in our design underscores its suitability for applications requiring secure and efficient wireless communication. The chip's unique encoding capabilities, low power consumption, and compatibility with decoding chips have enabled us to develop a remote control system that is both secure and reliable.

The application circuitry for our remote controller, centered around the EV1527, is designed for simplicity and functionality. The primary components include the power supply, button inputs, and the serial data output pin. This straightforward design ensures that our remote control system is user-friendly and cost-effective.

As shown in Figure 7, pin 5 to pin 8 of EV1527 are the key input pins, they contain a grounding resistance and are connected to the power supply through a button. When a key is pressed between SW1 and SW3, the corresponding pin of EV1527 has a high level, which triggers the EV1527 chip. Pin 4 outputs the corresponding data string, which is transmitted through the amplifier and oscillation circuit; At the same time, when the button is pressed, the diode conducts and the light-emitting diode also conducts and emits light, indicating that a signal is being sent out; When there is no button pressed, there is no power supply, the LED does not light up, and the chip is in a state of no power loss. The frequency of the signal is determined by the resistance R on pin 1 and the power supply voltage on pin 2.

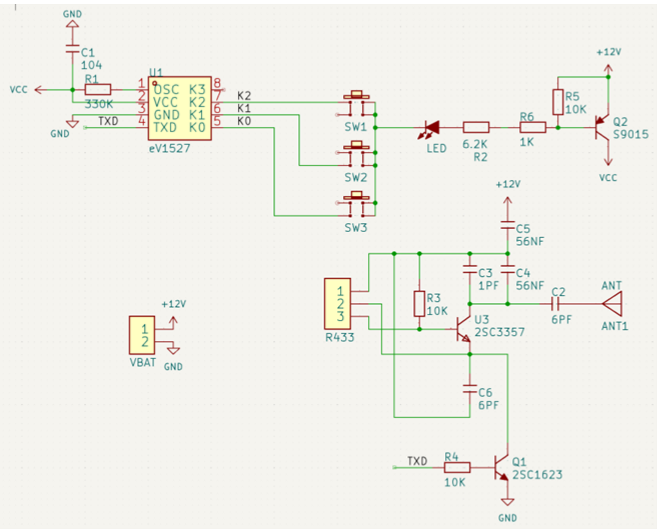

Figure 7: Schematic drawing of the remote controller

The following Figure 8 is the PCB design of our remote controller.

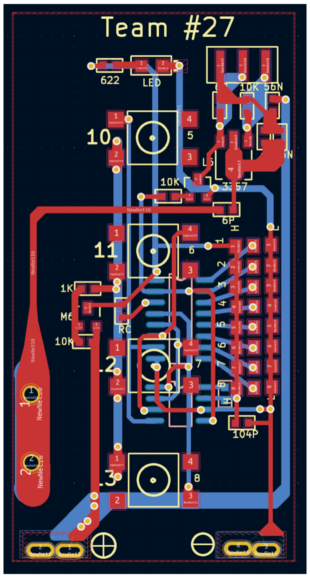

Figure 8: PCB drawing of the remote controller

2.4.2 Control Motherboard

The following figure 9 is the 2D shcematic of the electronic circuit of the control motherboard. It contains three parts: power supply circuit, relay circuit and the microprocessor.

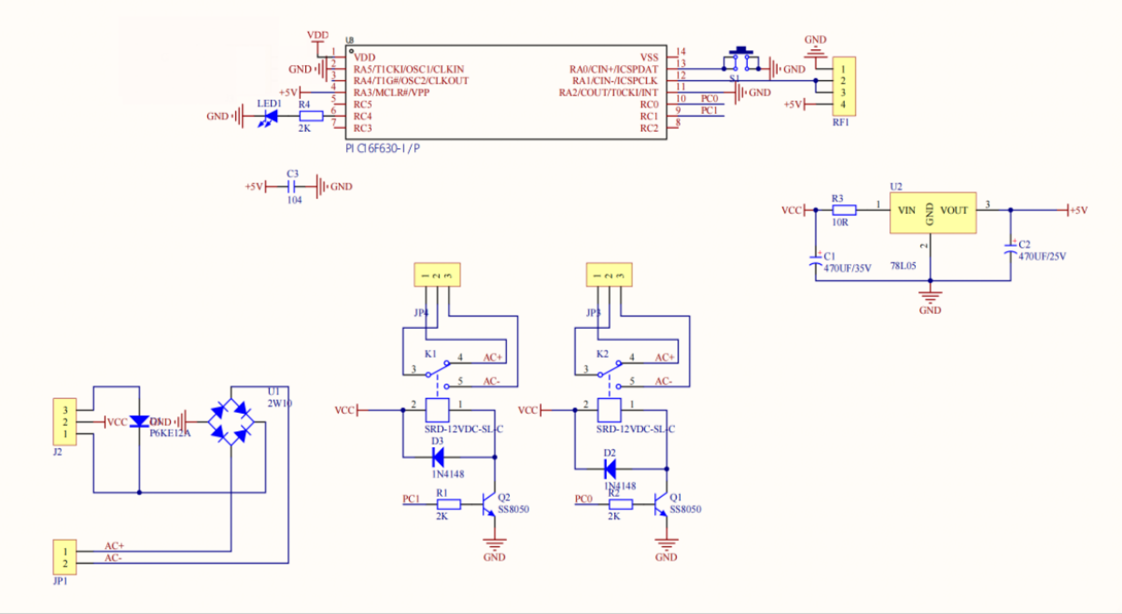

Figure 9: Schematic drawing of the control motherboard

Figure 10 and Figure 11 make up the power supply circuit, which converts alternating current to direct current and regulates the voltage to 5V.

JP1: Input AC+ and AC-. U1: Rectifier bridge, rectifier alternating current into pulsating direct current. C1, C2: Filter capacitor, smooth pulsating DC. D1: Regulator diode, used to protect the circuit. U2 (78L05) : Voltage regulator chip, voltage regulator to 5V. R3: Current limiting resistor to protect voltage regulator chip. C3: Decoupled capacitor to further smooth the output voltage.

If we input AC power through JP1, first the rectifier bridge will output pulsating DC power in J2. Then through the R3 and 78L05 voltage regulator chip, the final result is a flat 5v DC for the entire control board.

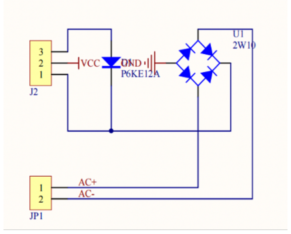

Figure 10: Rectifier bridge

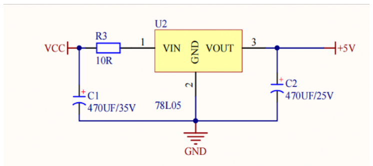

Figure 11: Voltage regulator circuit

Figure 12 is relay circuit, which mainly used to control the relay, and then control the load.

JP2, JP4: Interfaces for connecting loads. K1, K2: relays for switching loads. Q1, Q2 (SS8050) : NPN triode for driving relays. D2, D3 (1N4148) : Diodes that prevent the reverse electromotive force generated by the relay coil from damaging the triode. R1, R2: Base limiting current resistance, protecting the triode. PC0, PC1: control signal input, used to control the relay on and off.

Initial state: Both PC0 and PC1 are low, triode Q1 and Q2 are not on, the relay K1 and K2 coils are not powered on, and the load is not switched on.

Excitation state: When PC0 (PC1) is high voltage level, Q1 (Q2) is switched on, the current passes through the relay K1 (K2)coil, K1 (K2) draws, and the load is switched on.

Pin of JP4 and JP5 will be connected with two wires of the motor respectively. The positive charge will make the electric push rod elongate, and the negative charge will make the electric push rod shorten.

Protection measures: When the relay coil is powered off, the reverse electromotive force is eliminated by a parallel 1N4148 diode, protecting the triode from high reverse voltage.

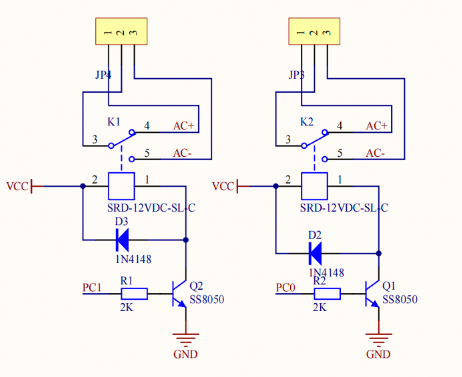

Figure 12: Two relay

Figure13 is the microprocessor PIC16F630, and the superheterodyne receiving module is on the right, as shown in Figure 14.The intermediate frequency(IF) signal is obtained through a mixer of 6.7458Mhz and 433Mhz, and the digital signal is obtained through a series of operations for decoding.

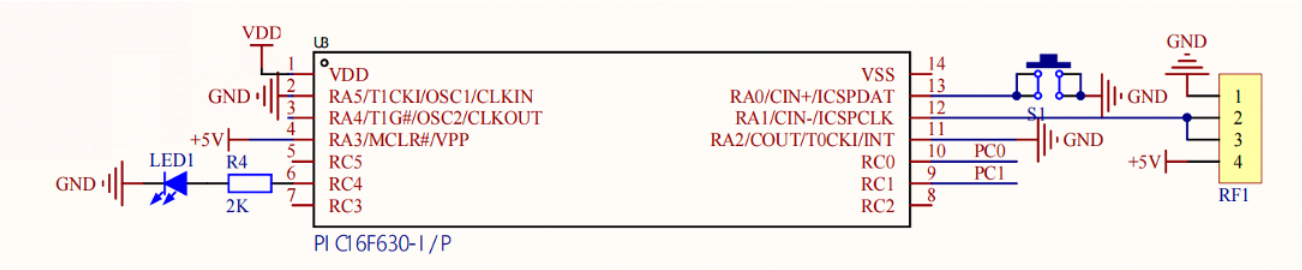

Figure 13: PIC16F630

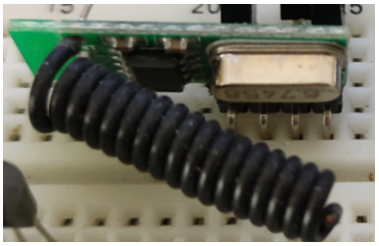

Figure 14: Superheterodyne receiver

The main control codes please refer to Appendix.

3 Verification

Design verification plays a pivotal role in the engineering process, ensuring that a product not only meets its specified requirements but also performs reliably in practical applications. This phase involves thorough testing and evaluation of every component and subsystem to confirm their proper functionality. The significance of design verification lies in its proactive approach to identifying and rectifying potential issues before the product reaches full-scale production or deployment. This preemptive action helps to avoid costly failures and guarantees both safety and efficiency. By systematically verifying the design, engineers can validate their assumptions, refine their models, and ensure compliance with industry standards and regulations. This rigorous process enhances the overall reliability and quality of the final product while building stakeholder confidence in its effectiveness and sustainability. In our project, the design verification process has been instrumental in resolving ergonomic, stability, and functionality challenges, culminating in a robust and user-friendly solution.

3.1 Structure design

Our initial design is depicted in Figure 6, with the primary differences centering on the bottom plate. In this original concept, the user would sit directly on the ground, and the entire system would be secured to the user's back using shoulder-strap belts. Linear actuators would adjust the system's length, altering the user's angle and height as needed. We envisioned that these belts would fix the system to the user's back so that the user could move from one location to another without standing up. They could remain seated and glide across the ground, with the system following. However, this design encountered significant issues during assembly and testing.

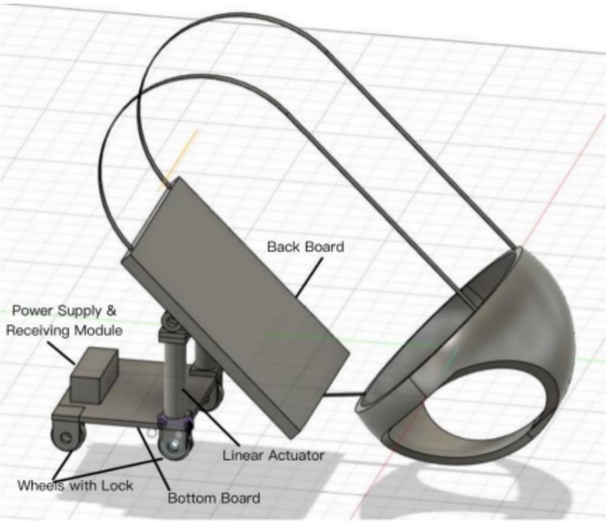

Figure 15: Former design of the project

3.1.1 Wearable solution

Firstly, securing the system to the user presented significant challenges. To firmly secure the system in place, the belts needed to be tightly fastened, which led to substantial discomfort for the user. Inadequately tightening the belts resulted in relative motion between the user's back and the back plate while reclining. This relative motion allowed the user to move with the design as intended, but it was not without issues. Adjusting the electric push rods' length introduced friction between the back plate and the user's clothing, causing the fabric to lift and resulting in a sensation of being lifted by the clothing.

This unintended effect necessitated continuous adjustment of the user's posture to prevent the feeling of choking caused by the upward pull on their clothing. This discomfort not only undermined the system's ergonomic intent but also created a potential safety risk due to the unstable posture the user would have to maintain. Additionally, the reliance on friction for secure support indicated a fundamental flaw in the design, as it could compromise user safety over prolonged periods, particularly if the belts loosened due to wear or shifting. The cumulative effect of these factors made it clear that a more sophisticated and user-friendly securing mechanism was needed to offer both stability and comfort without compromising ergonomic support.

3.1.2 Moving solution

Secondly, the proposed movement mechanism proved insufficient. Although the system included four universal wheels designed to facilitate movement, the user's seat remained in direct contact with the ground. This situation led to various frictional interactions: rolling friction between the wheels and the ground, static friction between the user's shoes and the surface, and sliding friction between the user's pants and the ground. Consequently, the friction between the pants and the surface resulted in wear and potential damage to the user's clothing.

This inadequate design highlighted critical limitations in ensuring comfortable and effective movement. The intention was for the user to glide smoothly across different locations without needing to stand up. However, the reliance on sliding friction created significant resistance that impaired mobility and risked causing discomfort or injury to the user. Additionally, the direct ground contact of the seat introduced potential ergonomic concerns, as the uneven distribution of weight could exacerbate wear on the user's pants and contribute to a less stable seated posture. Such issues underscored the necessity for reevaluating the movement subsystem to incorporate a solution that minimizes frictional resistance and enhances user comfort, safety, and durability.

3.1.3 Wheel lock

Additionally, the design lacked ergonomic consideration. To achieve stability, users had to lock the universal wheels and rely on their friction with the ground. However, all four wheels were positioned behind the user, with the left two wheels being particularly challenging to access when tightly secured by the belts. This arrangement made locking those wheels essentially impractical. The right-side wheels were also inconvenient to reach due to the limited rotation permitted by the belts securing the user.

If the user wished to lock the wheels, they had to extend their arms backward while their gaze remained forward, as only the head could rotate due to the fixed position on the back plate. For most people, it is virtually impossible to see the locks positioned behind them while their body remains fixed to the back plate. As a result, the locking mechanism could not be accessed or adjusted easily, undermining its utility and posing potential ergonomic and safety challenges for users seeking to stabilize their posture. The system, therefore, required a more user-friendly solution that enabled intuitive and reliable wheel locking without forcing awkward or constrained movements.

3.1.4 Instability

Finally, the system displayed considerable instability during practical application. When a person reclined against the back plate, the external force applied resulted in the entire system rotating around the axis of the right-side wheels. This instability revealed that even moderate external forces could generate significant moments, causing undesirable rotation of the whole system. Furthermore, the entire design proved susceptible to tilting because the center of gravity fell outside the area bounded by the four universal wheels. As a result, the structure was unable to reliably support the weight of a human, posing a significant safety risk and necessitating a re-evaluation of the system's balance and stability.

3.1.5 Summary of flaws

These design flaws highlighted the need for a more stable, ergonomic, and user-friendly solution, prompting a re-evaluation and redesign of the system. And lengthening the bottom plate perfectly solved above problems.

3.1.6 Improved accessibility to wheel locks

Lengthening the bottom plate allowed for a more ergonomic placement of the universal wheels, which brought about significant improvements in accessibility and user comfort. With the extended plate, we were able to reposition the wheels closer to the sides and front of the user, rather than keeping them confined to the back. This new configuration meant that the wheels were within easy reach, making the locking mechanism far more accessible.

Previously, users had to extend their arms awkwardly backward to engage or disengage the wheel locks while their bodies remained fixed to the back plate. This motion was not only uncomfortable but also impractical, as it forced users to rely on limited rotation of their heads and shoulders, which could lead to strain and potential injury. With the wheels repositioned, users can now reach the locks with a simple sideward or forward motion, maintaining a more natural and comfortable posture.

This adjustment significantly enhanced the user-friendliness of the system. By facilitating an intuitive reach for the wheel locks, we eliminated the need for awkward body movements and reduced the physical strain on the user. This is particularly important for maintaining comfort and preventing musculoskeletal issues during prolonged use. Additionally, the improved accessibility of the wheel locks means that users can secure and release the wheels quickly and effortlessly, making the system more practical and efficient to use.

Moreover, the new placement of the wheels also contributes to a safer user experience. In the original design, the difficulty in accessing the wheel locks could have led to situations where the wheels were not properly secured, increasing the risk of unwanted movement and potential accidents. By making the locks easier to reach, we ensure that users are more likely to engage them correctly, thereby enhancing the overall safety of the system.

3.1.7 Enhanced stability

The original design's instability stemmed from an unfavorable distribution of the system's center of gravity, which often extended beyond the area supported by the four wheels. This misalignment made the system prone to tipping or rotating, especially when subjected to external forces, thereby compromising user safety and reliability. By lengthening the bottom plate, we were able to effectively increase the system's base area, which significantly lowered the center of gravity.

This modification provided a broader and more stable support surface that could better accommodate the user's weight. With a more extensive base, the forces exerted by the user were distributed more evenly across the system, reducing the likelihood of unwanted tipping or rotation. The extended bottom plate ensured that the center of gravity remained well within the area bounded by the wheels, enhancing the overall stability of the structure.

As a result, the system became much less susceptible to instability, even under varying conditions and user movements. This improvement was crucial for ensuring both the safety and reliability of the design. Users could recline against the back plate or move around without the risk of the system becoming unbalanced or tipping over. The enhanced stability also contributed to a more predictable and secure user experience, allowing the system to perform reliably in real-world applications.

Moreover, the increased base area meant that the system could handle external forces more effectively, maintaining its stability even when the user shifted their weight or applied pressure to different parts of the structure. This robustness was essential for the practical use of the system in various environments, ensuring that it could support the user securely throughout their tasks.

3.1.8 Better weight distribution

The extended bottom plate facilitated a more even distribution of the user's weight across the entire system. By providing additional support beneath the user's body, the load was spread out more evenly, reducing the stress on any single point and minimizing the risk of structural failure. This adjustment also helped to mitigate the moment forces that previously caused the system to tilt, further enhancing the overall stability.

By extending the bottom plate, we were able to create a more balanced platform that supports the user's weight more effectively. This design change ensures that the load is not concentrated on a few critical points, which could lead to excessive wear or potential structural failure over time. Instead, the weight is distributed across a larger area, reducing the stress on individual components and improving the durability of the entire system.

Additionally, the extended bottom plate addresses the issue of moment forces that caused the system to tilt in its earlier iterations. With a broader base of support, the design now resists tipping and rotational forces more effectively. This improvement is crucial for maintaining the stability of the system, especially when the user shifts their weight or applies pressure in different directions.

3.1.9 Enhanced ergonomics

With the bottom plate extended, users could sit more comfortably with their legs fully supported, akin to sitting on a sofa. This setup significantly reduced the strain on the user's body by providing a more ergonomic and natural seating position. The extended plate allowed the user to distribute their weight more evenly, which alleviated pressure points and minimized discomfort during prolonged use.

This enhanced seating position also facilitated a more intuitive interaction with the system. Users could now use their feet to assist with minor adjustments and movements, making the system easier and more practical to operate. This capability to use foot movements for small adjustments further increased the ease of use and allowed for more precise positioning without needing to rely solely on upper body strength or awkward movements.

3.2 Electric push rod

Figure 6 illustrates the initial version of our design, where the electric push rods were oriented perpendicularly to the bottom plate. In the second version, however, we positioned the electric push rods perpendicular to the back plate instead. This adjustment was made upon realizing that linear actuators cannot effectively withstand radial forces. Thus, we modified the orientation to reduce radial forces and simultaneously maximize axial force. Measurements of the original length and maximum extension length of the electric push rods were taken from this second version. The original length was 260 mm, and the maximum extension was 410 mm, allowing the angle to range from 20 to 45 degrees.

However, upon assembling all components, we found that this configuration was prone to tilting. The back plate’s weight caused a moment that was exacerbated by having the push rods perpendicular to the back plate rather than the bottom plate. This increased the tilting moment and compromised stability, ultimately prompting a return to the initial configuration of the push rods.

To address the issue of radial forces, we opted for linear actuators with a high reduction ratio to generate greater lifting force, even though this resulted in a slower adjustment speed of 10 mm/s. This slower speed was considered a worthwhile trade-off to ensure stable vertical movement and adequate support.

4 Cost and Schedule

4.1 Cost Analysis

Our team have four members and the total project duration is ten weeks. Based on our estimation, this project can be completed eight hours per week. We set an hourly salary of $20:

$$4 \times \$20\,/\text{hour} \times 2.5 \times 8 \times 10 = \$16,000$$

Table 1: Costs

Name	Manufacturer	Price	Qty	Total
Steel frame	Shanghai Tingwan Metal	$5.4	1	$5.4
Filler material (cotton)	Yaoyang Packing Store	$3.2	1	$3.2
Electric pushing rod	Songli Technology Co., Ltd	$62.85	2	$125.7
Bearing	Shenzhen Dashan Bearing	$1.1	2	$2.2
Locking wheel	Zhejiang Linglang	$5.15	4	$20.6
12V battery	Sanrijing Technology Co., Ltd	$4.1	2	$8.2
PCB	PCBWay	$14.3	2	$28.6
Total				$193.9

The parts we need in this project are listed above. Thus, if we produce ten of this product, it would cost a total of $17939.

4.2 Schedule

This is the schedule from the week we wrote design document to the final demo week. Seen in next page, Table 2.

Table 2: Schedule

Week	**Haotian Jiang**	**Xuekun Zhang**	**Yichi Zhang**	**Yushi Chen**
Week 7 3/25/2024	Determine the details of the design and purchase linear actuator and wheels	Research and discuss the possibilities of our current design and update our design	Research, purchase Bluetooth modules	Review basic knowledge of Arduino, assemble the framework with teammates
Week 8 4/1/2024	Design the connectors and find factories to process	Design our PCB board and preliminary test	Design PCB board	Learn the principle of remote control
Week 9 4/8/2024	Try to assemble the design and may redesign some parts	Complete the connection of the PCB board and the entire system and the preliminary test	Attempt to start modulating and demodulating Bluetooth signals	Gain open-source documents and optimize the PCB design
Week 10 4/15/2024	Finish assemble	Perfect and complete testing of our control method	Connect the components to the whole system	Connect to motor control and finalize testing
Week 11 4/22/2024	Initial use testing, correction and redesign of its inadequacies.			
Week 12 4/29/2024	The final optimization and testing.			
Week 13 5/6/2024	Mock demo and final demo!! Finished!			

5 Conclusion

5.1 Accomplishments

Our project has successfully met its high-level design objectives, with key achievements as follows:

- The control system's integration of an Arduino-based platform allows for precise synchronization of the electric push rods, ensuring balanced support for the user.
- The custom remote controller, utilizing the nRF8532 Bluetooth module and featuring an intuitive three-button interface, has been prototyped with positive feedback on its ease of use and operability, facilitating reliable control of the SRL.
- Tolerance analysis of the electric push rods confirms safe operation and support within specified limits, enhancing the system's reliability.
- The power system, with a 12V lithium battery, has been validated to support over three hours of continuous use, aligning with typical operational needs.

5.2 Uncertainties

Our equipment has essentially achieved all the functions we envisioned. However, there is one drawback: due to limitations in the stroke of the electric push rod and its length, our initial angle is slightly larger than we originally imagined. This means that in practical use, there is a certain limitation on the height of the workspace that users can access. This may restrict the versatility of the equipment in certain situations.

Additionally, our wheels still utilize manual locking. Users need to step on or press the pedal on the wheels to lock them. However, due to the design of our wheels, locking them now requires more force from the user. This may cause some inconvenience in use. We will certainly address this issue to improve the usability and user experience of the product.

5.3 Ethical considerations

In the realm of developing supernumerary limbs, prioritizing ethical considerations is paramount, ensuring adherence to principles outlined in the IEEE and Code of Ethics [5] and ACM Code of Ethics and Professional Conduct [6]. The design and deployment of supernumerary limbs must uphold individual autonomy, privacy, and equity, while transparent communication fosters societal trust. Concurrently, strict adherence to safety standards and regulatory protocols is essential to mitigate potential risks associated with supernumerary limbs. Biomechanical compatibility, ergonomic design, and preemptive measures against unintended harm during operation are central to ensuring user safety.

In terms of safety, we need to consider multiple factors:

Firstly, when working in narrow spaces, using linear motors with adjustable angles can greatly improve work efficiency. However, this also brings some potential safety hazards.

If workers accidentally keep pressing the remote control, it may lead to head collisions, resulting in serious injuries. Therefore, in the design, consideration should be given to how to prevent such situations, such as setting up warning systems or automatic stop functions.

Secondly, the safety of the power source is also crucial. When working in high-temperature environments, the power source may continue to generate heat, causing discomfort or even danger to workers. In addition, poor power source design may cause electric leakage, increasing the risk of fire. Therefore, when selecting a power source, it must be ensured that it meets safety standards and takes into account the special requirements of the working environment. In our application scenario, because of the normal operation of the user, there is no high temperature environment that can overheat the battery. However, complex working environments may cause physical damage to the battery, such as severe deformation when the battery is impacted, punctured or compressed, which can cause danger. To this end, we plan to design a hard metal shell on the outside of the battery to protect the safety of the battery.

Furthermore, since working in narrow spaces such as sewers often encounters humid environments, the equipment must have good waterproof performance. Otherwise, the equipment may get damp, causing circuit shorts or even complete failure. To address this issue, waterproof materials or sealing techniques can be used in the design to ensure the reliability and stability of the equipment in humid environments.

Additionally, the responsiveness of the remote controller is also crucial. After operation, the remote controller should be able to respond promptly to ensure the accuracy and safety of the operation. Moreover, to cope with emergencies, consideration can be given to installing an emergency braking device in the equipment to stop the operation of the equipment promptly, ensuring the safety of workers.

Last but not least, when we enter an environment where motors are humming, drills are spinning, and cutting tools are cutting through material, every step counts and safety becomes your top priority. I always start with the essentials - personal protective equipment (PPE). When we worked on the project, no one operated the tools without wearing safety goggles to prevent accidental debris. Earmuffs or earplugs are necessary to protect our ears from the relentless hum of machinery and are crucial to preventing long-term hearing damage. Gloves are not in doubt; They protect our hands from scratches and severe cuts, and for anyone carrying heavy equipment, steel-toed boots are a must to protect their feet. Before we use the tool, we will seek the help of the tutor first, and try to do it in the presence of the tutor. It's vital that each of us knows the machine we're using inside out - not just how to boot it up, but its quirks, safety features, and what to do if things don't go according to plan. Of course, faced with different work tasks, we choose the right tools for the task, strictly follow the manufacturer's guidelines, and always ensure that safety protections are not only present, but properly protected - these are practices that we follow without compromise. Finally, before we actually start drilling or cutting, we make adequate emergency preparations. Everyone knows the quickest route to the nearest exit. We also know how to shut down equipment immediately in an emergency.

In summary, to ensure the safety of the working environment, we need to fully consider various potential risk factors in equipment design and power source selection, and take corresponding measures to reduce risks and ensure the safety of workers.

5.4 Future work

We have essentially completed the main design and construction work, and have connected all the connecting components and preliminarily upgraded their surface materials for comfort. Next, we will focus on adding some features that are more convenient for users to use. We plan to add a tool box near the base plate on the outside, so that users can easily put their needed tools, screws, etc., at hand. We will also make certain upgrades to the locking system of the wheels. Currently, locking the wheels is a bit too cumbersome. We hope to add a leverage kit to the locking wrench to increase torque, making it easier for users to lock the wheels.

References

[1] D. A. Kurek and H. H. Asada, "The mantisbot: Design and impedance control of supernumerary robotic limbs for near-ground work," in *2017 IEEE International Conference on Robotics and Automation (ICRA)*, IEEE, 2017, pp. 5942–5947.

[2] B. of Labor Statistics, *News release*, USDL-15-2086, US Department of Labor, Oct. 2015.

[3] J. P. Leigh, "Economic burden of occupational injury and illness in the united states," *The Milbank Quarterly*, vol. 89, no. 4, pp. 728–772, 2011.

[4] U. B. of Labor Statistics, *Nonfatal occupational injuries and illnesses requiring days away from work in 2014*, https://www.bls.gov/opub/ted/2015/nonfatal-occupational-injuries-and-illnesses-requiring-days-away-from-work-in-2014.htm, 2015.

[5] *7.8 ieee code of ethics*, IEEE Code of Ethics, Accessed: https://www.ieee.org/about/corporate/governance/p7-8.html, 2018.

[6] *Code of ethics*, Association for Computing Machinery, Accessed: https://www.acm.org/code-of-ethics, 2023.

Appendix A Main control codes

```
unsigned char learn_cnt, l_cnt2, key_tmp, fan_reg;
unsigned int t0_cnt;
extern unsigned char qk_cnt, dk_cnt;
extern unsigned char CSR0, CSR1, CSR2;
extern void recieve(void);

//
void delay_1ms(unsigned char cnt)
{
    unsigned char i;
    do
    {
        i = 249;
        do
            asm("nop");
        while (--i != 0);
    } while (--cnt != 0);
}

void Erase_120(void)
{
    unsigned char i;
    for (i = 0; i < 120; i++)
        EEPROM_WRITE(i, 0xff);
    EEPROM_WRITE(126, 0);
    delay_1ms(5);
}

// SN
bit Verify_120(void)
{
    unsigned char i, addr, tmp;
    addr = 0;
    i = 40;
    do
    {
        tmp = EEPROM_READ(addr++);
        if (qk_cnt != 0) //
        {
            if ((tmp & 0x01) == 0) { addr += 2; continue; } //
            if (((tmp & 0x80) == 0) || ((CSR0 & 0x80) == 0))
            {
```

```
                if (((tmp ^ CSR0) & 0xf0) != 0) { addr += 2; continue; }
            }
        }
        else //
        {
            if ((tmp & 0x01) == 1) { addr += 2; continue; } //
            if ((tmp ^ CSR0) & 0xf0) { addr += 2; continue; }
        }
        tmp = EEPROM_READ(addr++);
        if ((tmp ^ CSR1) != 0) { addr += 1; continue; }
        tmp = EEPROM_READ(addr++);
        if ((tmp ^ CSR2) != 0) { addr += 0; continue; }
        return 1;
    } while (--i != 0);
    return 0;
}

bit delay_1s_stop(void)
{
    TMR0 = 0;
    learn_cnt = 15;
    while (1)
    {
        recieve();
        if (CARRY == 1)
        {
            Verify_120();
            if ((CARRY == 1) && ((CSR0 & 0x0f) == 0x04))
            {
                work_led = w_off;
                led_up = 0;
                led_down = 0;
                return 1;
            }
        }
        if (T0IF)
        {
            T0IF = 0;
            if (--learn_cnt == 0)
                return 0;
        }
    }
}

void Write_a_sn(void)
```

```
{
    unsigned char tmp;
    tmp = EEPROM_READ(126);
    if (tmp > 120)
        tmp = 0;
    EEPROM_WRITE(tmp++, CSR0);
    EEPROM_WRITE(tmp++, CSR1);
    EEPROM_WRITE(tmp++, CSR2);
    EEPROM_WRITE(126, tmp);
    delay_1ms(5);
}

void init(void)
{
    TMR0 = 0;
    T0CS = 0;
    PS0 = 1; PS1 = 1; PS2 = 1; // 1/256
    PSA = 0; // TIMER 0
    RAPU = 1;
    T1CON = 5;
    PORTA = 0;
    CM0 = 1; CM1 = 1; CM2 = 1; // SET CMP AS DIGITAL I/O
    WPUA = 0x33; // RA2 & RA3 NEED NOT PULL UP
    TRISA = 0x3d; // RA1 OUT
    PORTC = 0;
    TRISC = 0x38;
}

bit read_s_port(unsigned char cnt)
{
    unsigned char i;
    TRISA2 = 1;
    while (1)
    {
    rrr:
        i = cnt;
        if (RA2)
        {
            do
            {
                if (RA2 == 0)
                    goto rrr;
            } while (--i != 0);
            RA2 = 1;
            TRISA2 = 0;
```

```
                return 1;
            }
            else
            {
                do
                {
                    if (RA2 == 1)
                        goto rrr;
                } while (--i != 0);
                RA2 = 1;
                TRISA2 = 0;
                return 0;
            }
        }
    }

    void do_up(void)
    {
        t0_cnt = 3662;
        if (led_down == 1)
        {
            led_down = 0;
            delay_1s_stop();
            if (CARRY == 0)
            {
                work_led = w_on;
                led_up = 1;
            }
        }
        else
        {
            work_led = w_on;
            led_up = 1;
        }
        MOTOR_POSITIVE = 1;
        MOTOR_NEGATIVE = 0;
    }

    void do_down(void)
    {
        t0_cnt = 3662;
        if (led_up == 1)
        {
            led_up = 0;
            delay_1s_stop();
```

```
        if (CARRY == 0)
        {
            work_led = w_on;
            led_down = 1;
        }
    }
    else
    {
        work_led = w_on;
        led_down = 1;
    }
    MOTOR_POSITIVE = 0;
    MOTOR_NEGATIVE = 1;
}

void do_stop(void)
{
    work_led = w_off;
    led_up = 0;
    led_down = 0;
    MOTOR_POSITIVE = 0;
    MOTOR_NEGATIVE = 0;
}

main()
{
    volatile unsigned char j;
    OSCCAL = _READ_OSCCAL_DATA();
    init();
    led_up = 0;
    led_down = 0;
    work_led = w_off;
    TRISA2 = 1;
    recieve();
    t0_cnt = 3662;
    while (1)
    {
        if (T0IF) // 0.065536 S
        {
            T0IF = 0;
            fan_reg <<= 1;
            if (fan)
                bitset(fan, 0);
            if (--t0_cnt == 0) // 4 minutes
            {
```

```
        work_led = w_off;
        t0_cnt = 3662;
        led_up = 0;
        led_down = 0;
        MOTOR_POSITIVE = 0;
        MOTOR_NEGATIVE = 0;
    }
}
key_tmp = PORTC & 0x38;
j = 6;
do
{
    if ((PORTC & 0x38) != key_tmp)
    {
        j = 6;
        continue;
    }
} while (--j != 0);
recieve();
if (CARRY == 1)
{
    Verify_120();
    if ((CARRY == 1) || (key_tmp & 0x38) != 0x38)
    {
        if ((key_stop == 0) || (CSR0 & 0xf) == 4)
        {
            do_stop();
        }
        if ((key_up == 0) || (CSR0 & 0xf) == 8)
        {
            if (fan_reg == 0)
                do_up();
            else
                do_down();
        }
        if ((key_down == 0) || (CSR0 & 0xf) == 1)
        {
            if (fan_reg == 0)
                do_down();
            else
                do_up();
        }
    }
}
if (RA2 == 1)
```

```
{
    work_led = w_off;
    led_up = 0;
    led_down = 0;
    TRISA2 = 0;
    RA2 = 1;
    TMR0 = 0;
    learn_cnt = 153;
    while (1)
    {
        recieve();
        if (CARRY == 1)
        {
            if ((CSR0 & 0xf) == 2)
            {
                Write_a_sn();
                learn_cnt = 5;
                do
                {
                    RA2 = 0;
                    delay_1ms(250);
                    RA2 = 1;
                    delay_1ms(250);
                } while (--learn_cnt != 0);
                TRISA2 = 1;
                break;
            }
        }
        if (!T0IF)
            continue;
        T0IF = 0;
        if (--learn_cnt == 0)
        {
            TRISA2 = 1; // 10 second reach
            break;
        }
        TRISA2 = 1;
        if (read_s_port(10) == 1)
        {
            if (++l_cnt2 == 32)
            {
                TRISA2 = 0;
                RA2 = 0;
                Erase_120();
                delay_1ms(250);
```

```
                        delay_1ms(250);
                        delay_1ms(250);
                        delay_1ms(250);
                        TRISA2 = 1;
                        break;
                    }
                }
                else
                {
                    if (l_cnt2 != 0)
                        l_cnt2--;
                }
            }
        }
    }
}
```