ME 470 / ECE 445: Senior Design Laboratory

Design Document

Supernumerary Robotic Limbs

Group Number: 27

Team Members

Haotian Jiang (hj24)

Xuekun Zhang (xuekunz2)

Yushi Chen (yushic3)

Yichi Zhang (yichiz8)

Instructor: Liangjing Yang

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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 investigation, we've discovered that workers tasked with soldering beneath the hull of a boat often face significant challenges. Working in such confined spaces requires them to lie on their backs, which not only strains their posture but also limits their ability to maneuver and work effectively. In this position, workers typically struggle to maintain stability and control over their soldering tools, as they require at least one hand to support themselves. To address these issues, we propose the development of a specialized support system that allows workers to comfortably and securely position themselves beneath the boat while freeing up their hands for soldering work. This system could include a combination of ergonomic padding, adjustable harnesses, and stabilizing mechanisms to enhance worker comfort, safety, and efficiency in this demanding environment.

1.2 Solution

A new type of supernumerary robotic limbs is proposed to provide support and enhance the safety of workers working in dangerous environment. This supernumerary robotic limbs for human body support is designed to be worn like a backpack. Two robotic limbs can coordinate their position according to the user's need. At the bottom of limbs, wheels are installed so that the system can move with the wearer. For example, when he finishes the task in one location and want to move to another spot, he doesn't need to take off the system. Instead, He can sit on the floor and utilize the traction between his shoes and the surface to glide seamlessly from one spot to another, ensuring continuous workflow without the hassle of removing the support system. Since the system is independent from human body and the robotic limbs work as additional legs, the worker's hands are totally free while the stability of his body is enhanced. In addition, we also hope to add accessories for MR Glasses, so that users do not need a remote control to manipulate the movement and shape of the robot arm in a narrow space, but simply operate through the screen presented on the MR.

1.3 Visual aid

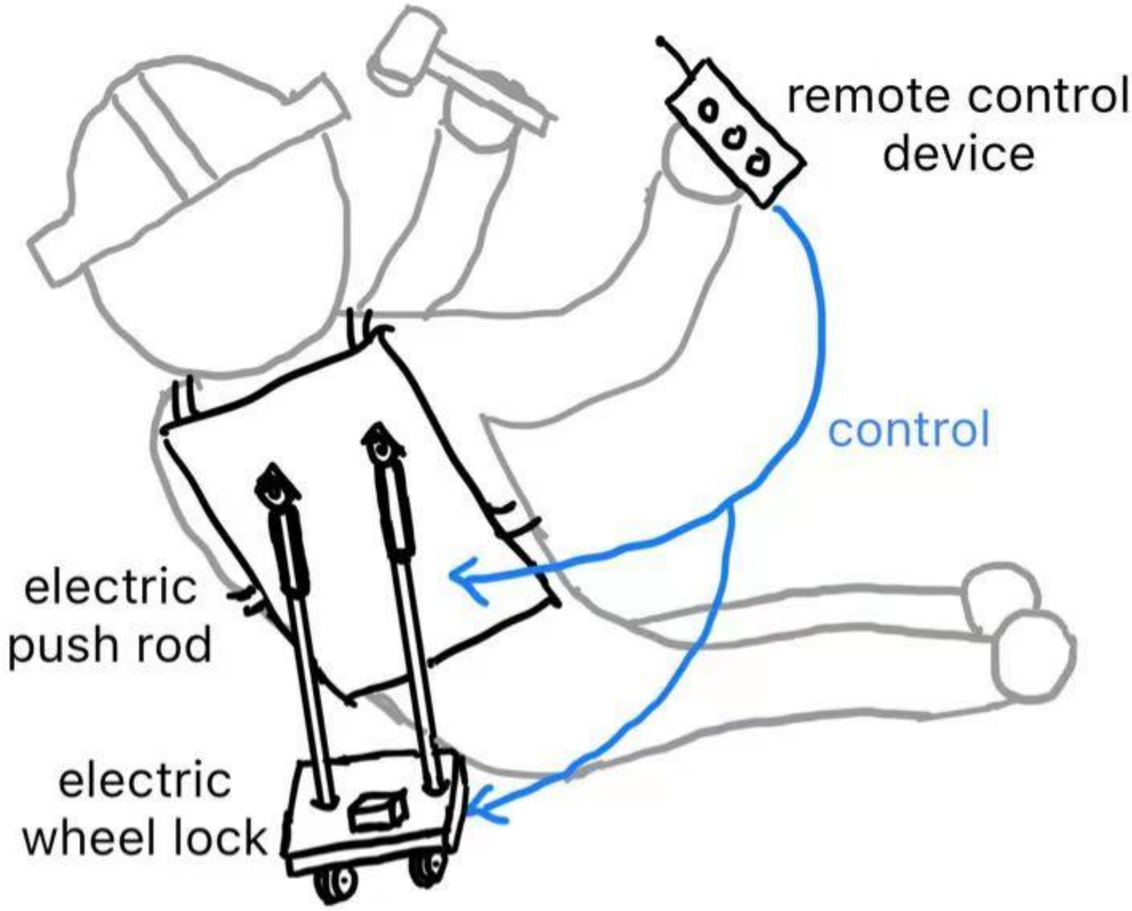


Figure 1: Visual Aid of the Project

1.4 High-level requirements list

- The maximum force that the system can provide must be high enough so that the limbs can support human body when the acute angle between the wearer's back and the ground is small.
- The linear actuator has to react fast and accurate enough to guarantee the fast response. Also, since there are two linear actuator, the synchronism between two cylinders are also vital to the stability of the design.
- Since the supernumerary robotic limbs are worn as backpack on the back of a human, it has to be adjustable and comfortable for different people of different size and back characteristics to use.

2. Design

2.1 Block diagram

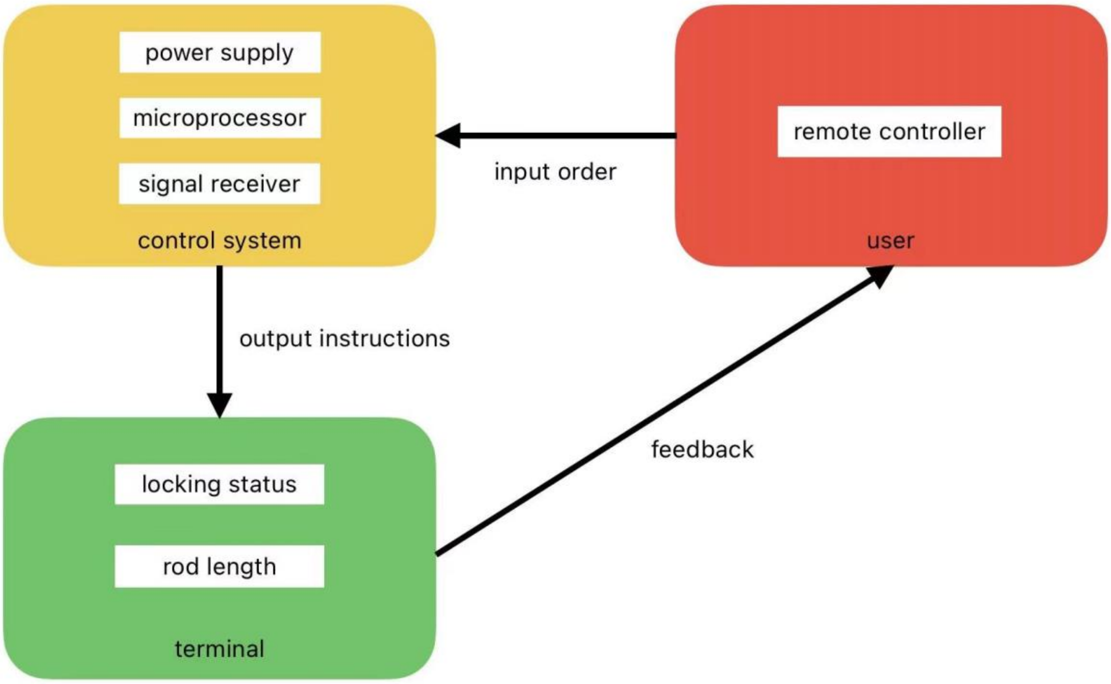


Figure 2: Block Diagram

2.2 Physical Design

On the left side of the horizontal plate, there is a cuboid housing the battery, while four universal wheels are positioned beneath the plate to enhance stability and provide a horizontal force component. The inclined plate serves as the backpack, housing a PCB (Printed Circuit Board) internally. The PCB's primary function is to regulate the two vertical rods, designed to function as linear actuators. During operation, the length of the linear actuators can be adjusted to accommodate varying requirements in diverse working environments. The backpack is secured to the user's body using shoulder-strap-like belts.

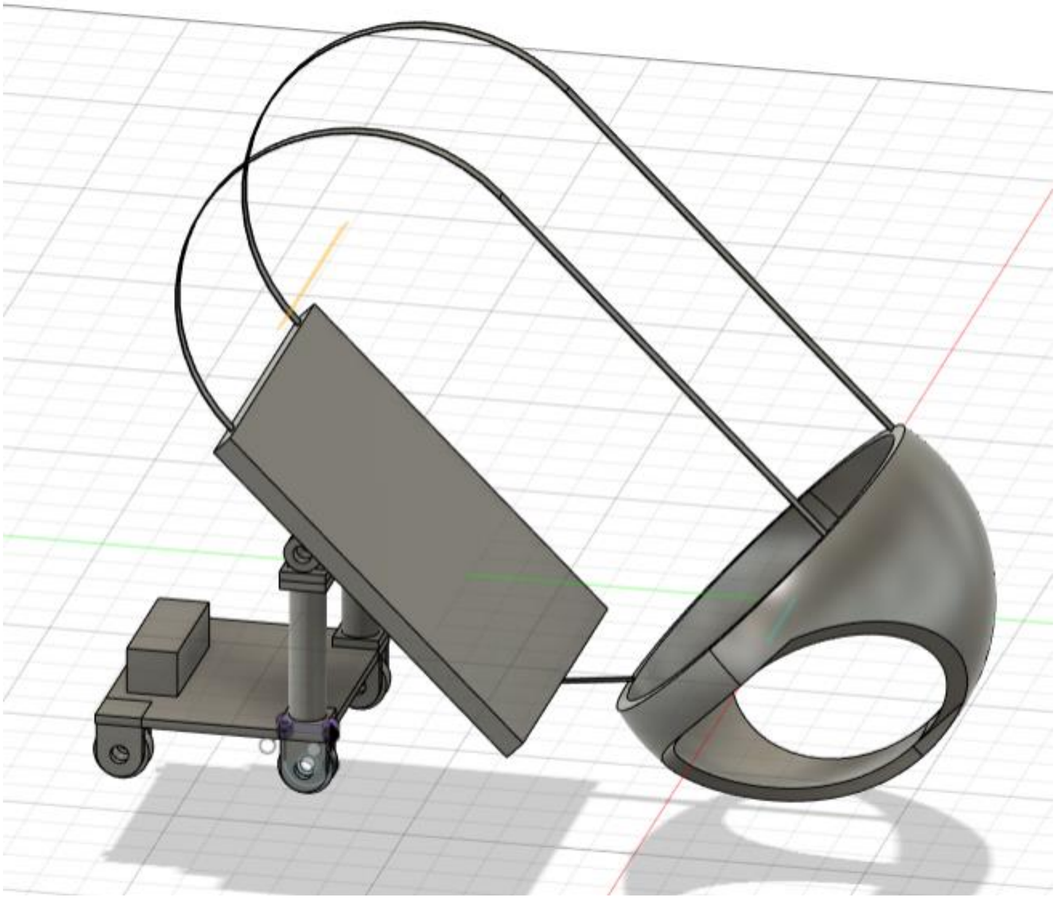


Figure 3: Physical Design

2.3 Subsystem requirements

2.3.1 Moving wheels

According to our design specifications, the mobile wheels located at the base of each limb should possess the capability to move in all 360-degree directions and also be lockable. When unlocked, these wheels serve to support the design and seamlessly accompany the user's movement from one location to another. However, when the user requires stability for tasks such as soldering in a crouched position, the wheels can be locked to prevent rotation, providing additional support to the user's body. Considering convenience of use, an electrically controlled lock would be more suitable than a manual lock. Another matter concerns the tilting of the system. We have decided to install the batteries at the end of the board to ensure proper counterbalance. Additionally, the exposed design also facilitates easier battery charging.

Upon researching, we found that universal wheels with locking mechanisms perfectly align with our requirements. Although Mecanum wheels also offer these features and precise motor-driven control, we opted for universal wheels due to budget constraints. Despite the precise motor control capability of Mecanum wheels, universal wheels fulfill our needs effectively while remaining cost-effective.

Requirements	Verification
1. Should be able to withstand the weight of a person lying on it 2. Can automatically lock in place and stop rolling upon receiving signals 3. Will not slip under most conditions	1. We will choose stainless steel or cast iron to ensure the structure of the wheels to enhance their strength. We will also increase the diameter and width of the wheels to improve their load-bearing capacity. If necessary, we will select wheels with ball bearings to enhance their stability performance. 2. By installing electromagnetic locking devices on the caster wheels, the locking mechanism can be electronically controlled to open or close. When the electromagnetic lock is in the closed state, the caster wheels can freely rotate; whereas when the electromagnetic lock is in the open state, it prevents the caster wheels from rotating, thereby locking the wheels. We will implement control of the caster wheels through a microcontroller. 3. We will choose materials such as rubber or polyurethane to achieve better slip resistance. Additionally, we will add appropriate patterns and textures to the surface of the wheels.

2.3.2 Linear actuators

The alignment of the linear actuators perpendicular to the ground is essential, a condition ensured by the presence of a plate and four wheels. The primary role of these linear actuators lies in the adjustment of the angle between the rear plate and the ground surface. This adjustment is facilitated by varying the length of the cylinders, exploiting the fixed hypotenuse length resulting from the 90-degree angle formed between the cylinders and the ground. Consequently, alterations in cylinder length induce changes in the shape of the supporting right triangle. Synchronization between the two cylinders is paramount to maintaining stability in the design; failure to achieve synchronism may compromise stability, potentially leading to imbalance and consequent user instability. To mitigate this risk, selection criteria for the cylinders prioritize those equipped with PLC (Programmable Logic Controller) control, facilitating closed-loop control mechanisms that ensure precision in cylinder length adjustments. Moreover, considering that the device is intended to support the human upper body, the operational range of the cylinders assumes critical importance to prevent cylinder failure and associated operational inadequacies.

Requirements	Verifications
1. Should be able to support radial and axial force component. 2. The speed and the force the linear actuator can provide should be reasonable. 3. The adjustable length of the actuator should meet the requirements of ergonomic 4. The two linear actuators should maintain the synchronism when working.	1. We will purchase linear actuators with reasonable stroke and force. These parameters will be measured from a standard adult. 2. To maintain the synchronism, sometimes we need to reset the linear actuators.

2.3.3 Wearable system

The primary principle of the wearable system is to accommodate a broad spectrum of users with varying body sizes and characteristics, necessitating adherence to ergonomic principles. To this end, we have incorporated a belt into our design, which serves dual functions. Firstly, akin to the straps on a backpack, the belt features adjustable length, enabling it to conform precisely to individuals of diverse body sizes. Secondly, the design of the belt aims to prevent slippage between the wearer and the back plate. By securely tightening the belt, the back plate becomes affixed to the wearer's back, facilitating immediate movement of the system with the wearer.

Requirements	Verifications
1. Should be able to easy to put on and take off 2. Should be comfortable and not strangle when worn for a long time 3. The material should be strong and not easily broken	1. We will carefully design the way of wearing and try on each version of the way of wearing after the design, to find the unreasonable part of the design, and simplify the wearing process. 2. We will try to design wider wear systems with larger pressure areas. 3. We will first investigate the wearing systems on the market, such as backpacks, seat belts, high-altitude safety locks, etc., and then screen the materials we need according to their materials and design our own wearing system.

2.3.4 Battery

To meet the functionalities of our wearable device, we require a battery. Considering constraints such as space and equipment, we deem purchasing a single battery to be the safer option. The selected motor has a rated power of 60W and operates at 12V. The battery needs to be integrated into the device for wearable use. Hence, among battery types, we find lithium-ion batteries to be the most suitable choice. Not only do they offer sufficient energy, but their weight also aligns well with the wearable aspect.

Moreover, we aim for the wearer of the device to be able to work for at least three hours while wearing our equipment. Therefore, we estimate that a battery capacity of around 15Ah would be required. A lithium-ion battery of this size, approximately 30cm × 30cm × 5cm, and weighing about 1kg, would be suitable for wear.

Lithium-ion batteries are known for their high energy density and lightweight nature, making them ideal for portable applications. It's crucial to adhere to safety protocols when using batteries, and we will ensure the selected battery includes safety features such as overcharge, over-discharge, and short-circuit protection.

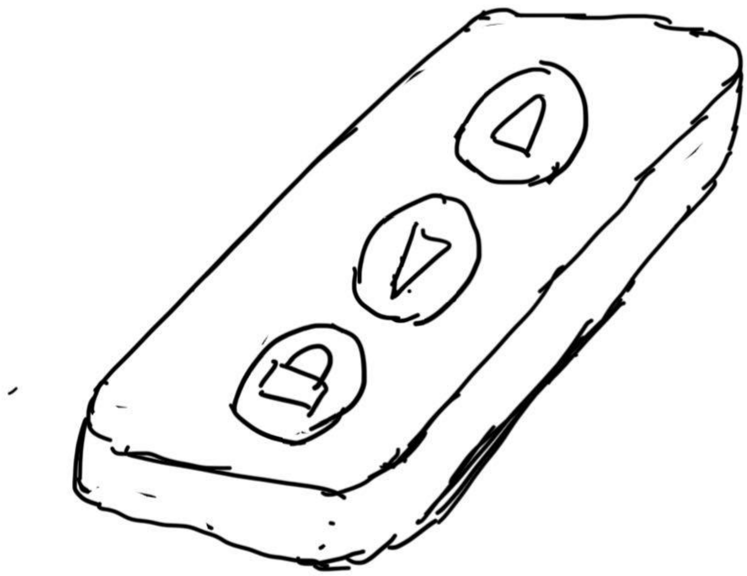
Requirements	Verifications
1. It should be safe and maintain its safe state under compression and high temperatures. 2. The volume and weight should not be too large, because it should be worn on the body.	1. According to the requirements, our batteries have the following characteristics: high voltage, large energy ratio, long storage life, good high and low temperature performance, and good safety.

3. The battery capacity should be larger, so that the entire system can be used for a longer time.	Currently we plan to use lithium batteries to meet our design needs.

2.3.5 Remote Control

Our remote controller is designed to provide straightforward functionality, focusing on three primary commands: ascend, descend, and lock/unlock the wheels. Recognizing the importance of user convenience, we have opted for a wireless design to enhance usability.

In pursuit of ergonomic excellence, the remote controller boasts dimensions of 35mm x 75mm, carefully crafted to fit comfortably in the user's hand. Constructed from robust yet lightweight plastic material, the casing ensures durability without compromising portability. Refer to the accompanying rough sketch for a visual representation of its design.



Fig： Remote Controller Sketch

As for communication technology, after thorough consideration, we have concluded that Bluetooth communication offers the optimal balance of low power consumption and seamless connectivity. Given our requirement to transmit only three simple signals, Bluetooth serves as an ideal solution for our needs. Therefore, we need to design a Bluetooth transmission module. This device is required to convert the signal from the button into a Bluetooth signal. We will choose Nordic Semiconductor's nRF52 series Bluetooth module as our transmission module to convert electrical signals to Bluetooth signals. It offers the advantage of low power consumption.

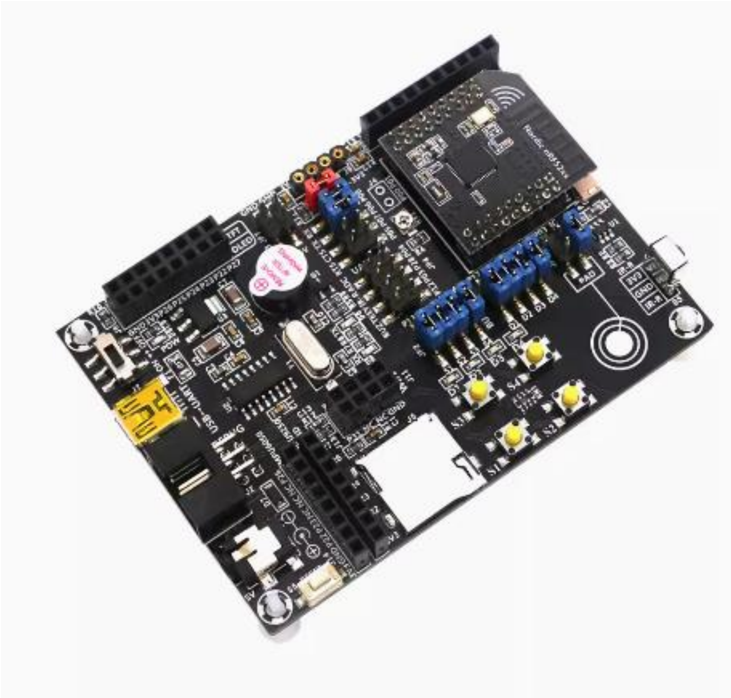
Regarding power supply, our choice of size 7 dry batteries serves to streamline operation. By eliminating the need for frequent recharging, we ensure uninterrupted functionality over an extended period, allowing the remote controller to fulfill its duties reliably.

Requirements	Verifications
1. Adequate working time 2. Sensitive reaction	1. Use the lowest power-consuming transmission device: Bluetooth, and power it with two size 7 batteries. 2. We will opt for a higher-performance processor and optimize its antenna design to achieve faster response times.

2.3.6 Control Integration

For the final control integration, we will develop a PCB (Printed Circuit Board). The functionalities required for our device are straightforward. We have three inputs in total: signals for controlling ascent, signals for controlling descent, and signals for controlling wheel locking. Likewise, we have only these three outputs. We will mount this module on the rear panel of our device.

Here we also need to set up a Bluetooth receiving module. We will also use the nRF52 series receiving module. Then, we will decode and process the signals in the chip on the PCB board to control the components.



Fig：nRF52832 Bluetooth Developement Board

2.4 Tolerance analysis

The first tolerance we must maintain is the slight inaccurate angle between the linear actuator and the ground. In the real practice, there has to be some irregularity on the floor and the worker’s body move will also cause some disturbance to the linear actuator. Thus it can not guarantee to be vertical to the ground. The small disturbance will cause a radial force inside the linear actuator which may cause stuck in the actuator. However, this is evitable and can be repaired quickly.

3. Cost and Schedule

3.1 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:

$$4 * \$20/hour * 2.5 * 8 * 10 = \$16,000$$

The parts we need in this project are listed below:

Part	Manufacturer	Quantity	Cost (including	Description

			process)	
steel frame	Shanghai Tingwan Metal	1	$5.4	The overall framework includes steel plates on the back and a wearable base.
filler material (cotton)	Yaoyang Packing Store	1	$3.2	Provide a buffer on the back to enhance the user experience.
electric pushing rod	Zhongshan Songli Electronic Technology Co., Ltd	2	￥125.7	Control the rise and fall of the human body.
bearing	Shenzhen Dashan Bearing	2	$2.2	When the length of the push rod changes, the bearings are needed to adjust the angle between the back and the ground.
self-locking wheel	Zhejiang Linglang	4	$20.6	Change the position of the device on the ground.
12V battery	Shenzhen Sanrijing Electronic Technology Co., Ltd	1	$4.1	It can serve as a power source to drive push rods and electronic locks.
PCB	PCBWay	1	$14.3	It is installed inside the remote control. The machine shop labor hours are approximately 48 hours.
Total	$175.5			

Thus, if we produce ten of this product, it would cost a total of $17755.

3.2 Schedule

Week	Haotian Jiang	Xuekun Zhang	Yichi Zhang	Yushi Chen
3/24/2024	Determine the details of the design and purchase linear actuator and	Research and discuss the possibilities of our current design and	Research, purchase Bluetooth modules	Research, purchase suitable motor

	wheels	**update our design**		
3/31/2024	**Design the connectors and find factories to process**	**Design our PCB board and preliminary test**	**Design PCB board**	**Design PCB board**
4/7/2024	**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.**	**Attempt to modulate the motor.**
4/14/2024	**Finish assemble**	**Perfect and complete testing**	**Connect the components to the whole system.**	**Connect my parts and finalize testing.**
4/21/2024	**Conduct environmental testing**			
4/28/2024	**Final debugging**			

4. Discussion of Ethics and Safety

In the realm of developing supernumerary limbs, prioritizing ethical considerations is paramount, ensuring adherence to principles outlined in the IEEE and ACM Code of Ethics. 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.

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.

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.

References

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