ME 470 / ECE 445: Senior Design Laboratory

Project Proposal

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 require 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, when workers operate in cramped environments, such as underground pipelines or in hull of ships, they often need to kneel on the ground to carry out their tasks. In doing so, they rely on one hand to support themselves on the ground to maintain stability. However, this results in the worker having only one hand available for the task at hand. In this case, workers will only have one hand to use for construction, which is not only more tiring, but also very inconvenient. We want to have an object that would help workers support and move around in confined spaces while freeing up their hands to work more easily.

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 human. For example, when he finishes the task in one location and want to move to another spot, he does not need to take off the system. What he needs to do is to walk as usual. Also, some sensors are also included in the design to detect the movement intent of the human to provide extra help for him to stand up and sit down. 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

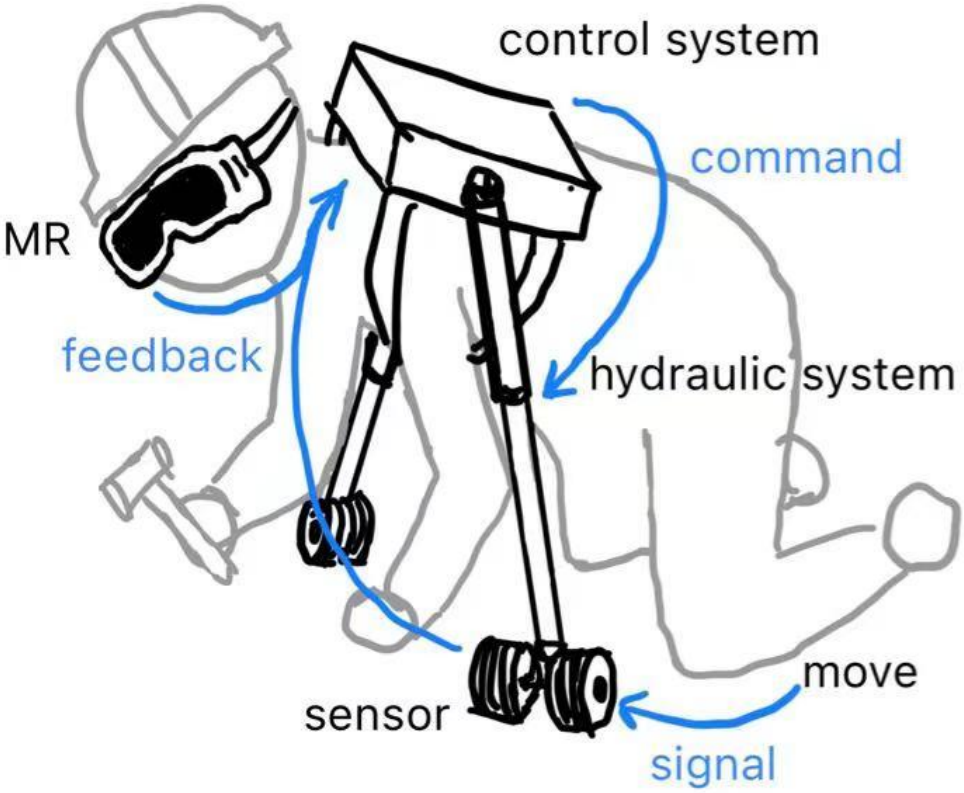

Figure 1: Visual Aid of the Project

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 angle is small.
- The identification of motion tendency has to be accurate, stable and response fast enough in order to make the system easy and reliable to use.
- 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

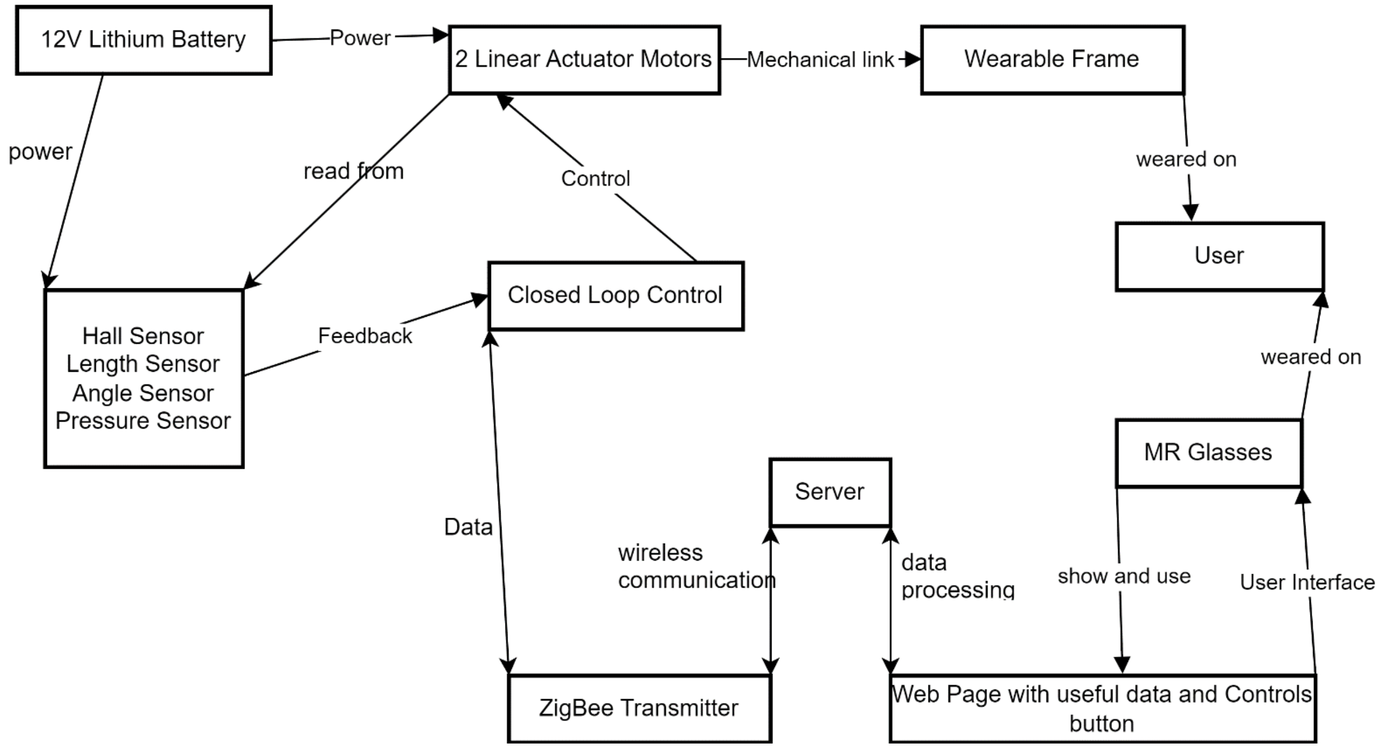

Figure 2: Block Diagram

2.2 Subsystem overview

Our design comprises three primary components: the backpack housing the entire control system and chips, two symmetrically designed limbs, and MR glasses. Each limb is equipped with a wheel at its base, facilitating rotation to ensure contact with the ground as the user moves. This innovative feature significantly alleviates the weight burden on the user's shoulders compared to non-wheeled supernumerary robotic limbs. In the absence of wheels, users must manually support the entire product while in motion, resulting in increased physical strain due to the product's weight distribution. When utilizing our design, the wheels located at the base of each limb remain locked, while sensors embedded within the limbs continuously monitor force changes. Based on these sensor inputs, the control system determines whether additional force should be applied to the limbs to assist the user in sitting down or standing up. This added force enhances the usability of the design, simplifying the user experience and facilitating effortless transitions between seated and standing positions.

Additionally, a pre-programmed learning algorithm is integrated into the control system to adapt to the unique usage habits of different individuals. This algorithm continually learns from user interactions, enabling the design to accommodate a wider range of users and expand its applicability across diverse populations. By capturing and analyzing user-specific data, the system optimizes its performance over time, ensuring a personalized and intuitive experience for all users. MR Glasses can put the robotic arm operation interface in front of the user, so that the user can control the movement of the robotic arm without unnecessary manipulators and actions. Moreover, compared to the instability of the sensor, the control window of MR Glasses controls the control system with a higher priority.

2.3 Subsystem requirements

2.3.1 Motion system

We divide the motion system into two parts: the electric push rod responsible for pushing the worker's back, and the wheels responsible for overall movement.
First, we will discuss electric push rods.

The linear actuators play a pivotal role in supporting the limbs. The length of the linear actuators adjusts dynamically based on the user's motion tendencies. For instance, when the user intends to stand up, sensors detect changes in force along the rod and transmit signals to the control system. Subsequently, the control system interprets these signals, discerns the user's motion tendencies, and generates a decision. Consequently, the control system outputs a command, prompting the linear actuators to provide the necessary force to assist the user in standing up.

According to our calculations, each rod must deliver a minimum force of 200 N to facilitate the user's standing motion comfortably, without exerting excessive pressure on the user's waist and knees. Additionally, it is imperative for the linear actuator to respond swiftly to these signals to ensure seamless support for the user's movements.

Based on the above, and in conjunction with market research, we have decided to opt for an electric push rod with a working voltage of 12V. Our rationale for selecting this voltage should be elaborated within the respective section of the functional system.
Next, we will talk about mobile 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 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.

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.

2.3.2 Sensor system

Several sensors are essential in our design to achieve our objectives effectively. Sensors to measure key parameters critical to the success of our design include:

1. Length sensor: Sensors are needed to measure the length of the linear actuators, allowing for dynamic adjustments based on the user's motion.

2. Angle sensor: Sensors will determine the angle between the rod and the ground, aiding in the detection of the user's motion tendencies and facilitating adjustments in response to changes in position.

3. Pressure sensor: We can detect the approximate posture of the worker when using the equipment by using pressure sensors distributed at various positions on the backplate. We will measure the pressure exerted on different parts of the backplate when the worker is working normally and set a threshold. If the pressure is too high or too low, the propulsion system will automatically stop working and return to its initial state.

In addition to these parameters, other relevant parameters may be incorporated into the system based on our evolving needs and practical considerations in the future. These sensors collectively contribute to the functionality and adaptability of our design, enhancing user comfort and safety.

2.3.3 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 = Power × Time. To cover a three-hour work period, the total energy required would be:

Total energy = Energy consumption per hour × Total working hours = 60Wh × 1 hours = 60Wh

Thus, the battery capacity should be at least 60 watt-hours (Wh) to ensure the device operates for three hours under the specified conditions.
What needs to be added is that, considering weight and portability, we have opted for lithium batteries.

We've chosen the most standard copper-core cables for the wiring to balance practicality and convenience. These cables will be easily accessible to us, whether we procure them externally or seek assistance from the school.

2.3.4 Control system

Our control system comprises two main modules: a remote controller and a control chip.
The remote controller will feature three buttons, allowing control over the electric push rod's ascent, descent, and halt. For convenience, we plan for the remote controller to be wired and securely fastened to the worker's chest using the safety harness. The wires connecting to the computation unit fixed on the backplate will be neatly integrated into the safety harness, minimizing any disruption to the surroundings. We will endeavor to design the PCB board inside the remote controller and employ 3D printing technology to create an enclosure.

The control chip consists of two computation units: an Arduino development board and a motor control board. The motor control board facilitates the connection between Arduino and the motors, where we will program instructions. Our strategy involves leveraging distance and angle sensors to monitor the device's orientation. For instance, if sensor feedback indicates a tilt to the left, we'll command the left motor to lift and stabilize the posture. Should the left motor reach its maximum extension, instructions will be relayed to retract the right motor. This automatic posture correction feature will activate 2 seconds after receiving instructions from the remote controller. Additionally, an emergency braking mechanism will be implemented based on data from the previously mentioned pressure sensors.

2.4 Tolerance analysis

2.4.1. Electric Push Rods

For the electric push rods in the supernumerary robotic limbs, tolerance analysis is crucial to ensure they operate within safe limits while providing the necessary support. Length tolerances are essential, as incorrect lengths could either prevent full extension and retraction or cause the rods to exert excessive force, leading to potential injury or damage to the device. Diameter tolerances must also be controlled to prevent the rods from jamming or wobbling, which would affect precision and stability. Additionally, force output tolerances need to be strictly managed to ensure the rods can support the intended loads without malfunctioning, ensuring both safety and functionality.

2.4.2. Wheels

The wheels of the device must be designed with precise diameter tolerances to maintain the device's stability and proper ground clearance. Variations in wheel diameter could lead to uneven loading and potentially cause the device to tip or fail during operation. Material tolerances are also significant; the wheel material must consistently provide sufficient durability and wear resistance under the load and environmental conditions expected. The locking mechanism’s tolerances are particularly critical, as they must reliably engage and disengage to allow movement or provide stability when locked, without failing under stress.

2.4.3. Sensors

Sensor accuracy is paramount in the robotic limbs system, as they inform the control system's responses to user movements. Tolerances for sensor placement and alignment must be tight to ensure accurate readings of limb positioning and user intent. Sensitivity variability among sensors must be minimized to avoid discrepancies that could lead to inappropriate adjustments by the actuators, affecting the system's responsiveness and the user's comfort and safety. Ensuring that sensors deliver consistent outputs across various operational conditions is key to maintaining the effectiveness of the device.

2.4.4. Battery and Electrical Connections

The power system’s reliability depends on maintaining strict voltage and current tolerances within the batteries and electrical connections. Any deviation could result in insufficient power delivery or potentially hazardous overloads. Connector tolerances are also critical, as poor connections can lead to intermittent power supply, reducing the reliability and safety of the device. Ensuring robust, secure connections that can withstand the physical demands of the device's operational environment is essential for consistent performance.

2.4.5. Frame and Wearable Mounting System

The frame and mounting system must be designed with adjustable dimensional tolerances to accommodate various body types while ensuring the device remains secure and comfortable during use. Tolerances in material strength and flexibility are vital to withstand the stresses of operation without deforming or breaking. These tolerances must be carefully managed to ensure that the frame supports the device’s functionality without compromising user safety or comfort, particularly under dynamic loads and movements typical in a workplace environment.

3. Ethics and Safety

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.

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.

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