DESIGN DOCUMENT

GROUNDED ROPE MANAGEMENT SYSTEM FOR BELAYING

Team 24

Team Members: Abhyan Jaikishen, Chris Zhang, Daniel Hsu

TA: Jason Paximadas

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ECE 445

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1. Introduction

1.1 Problem & Solution

When top-rope rock climbing, the climber is usually tied into a rope with a belayer on the ground for safety. While this does promote community and cooperativeness in the sport of rock climbing, this poses a problem for those who want to climb alone. While “bouldering”, (climbing shorter climbs at a safe enough height to fall directly onto crash mats), exists, it is a complete discipline of climbing. In fact, even within roped climbing, there exist several different variations, e.g. trad climbing, sport climbing, lead climbing.

We will design a ground rope management system that replaces the belayer. Although there are auto-belays on the market, they are expensive (>$2000) and pre-installed at the top of the wall which makes them less practical for outdoor climbers or spontaneous usage. The rope management system will combine a grigri (rope management tool for belayers) and operate it with sensors and motors that read data about the tensions to adjust the rope feeding. It will be grounded and battery powered, with wireless control to be ideal for solo, outdoor usage.

1.2 Visual Aid(s)

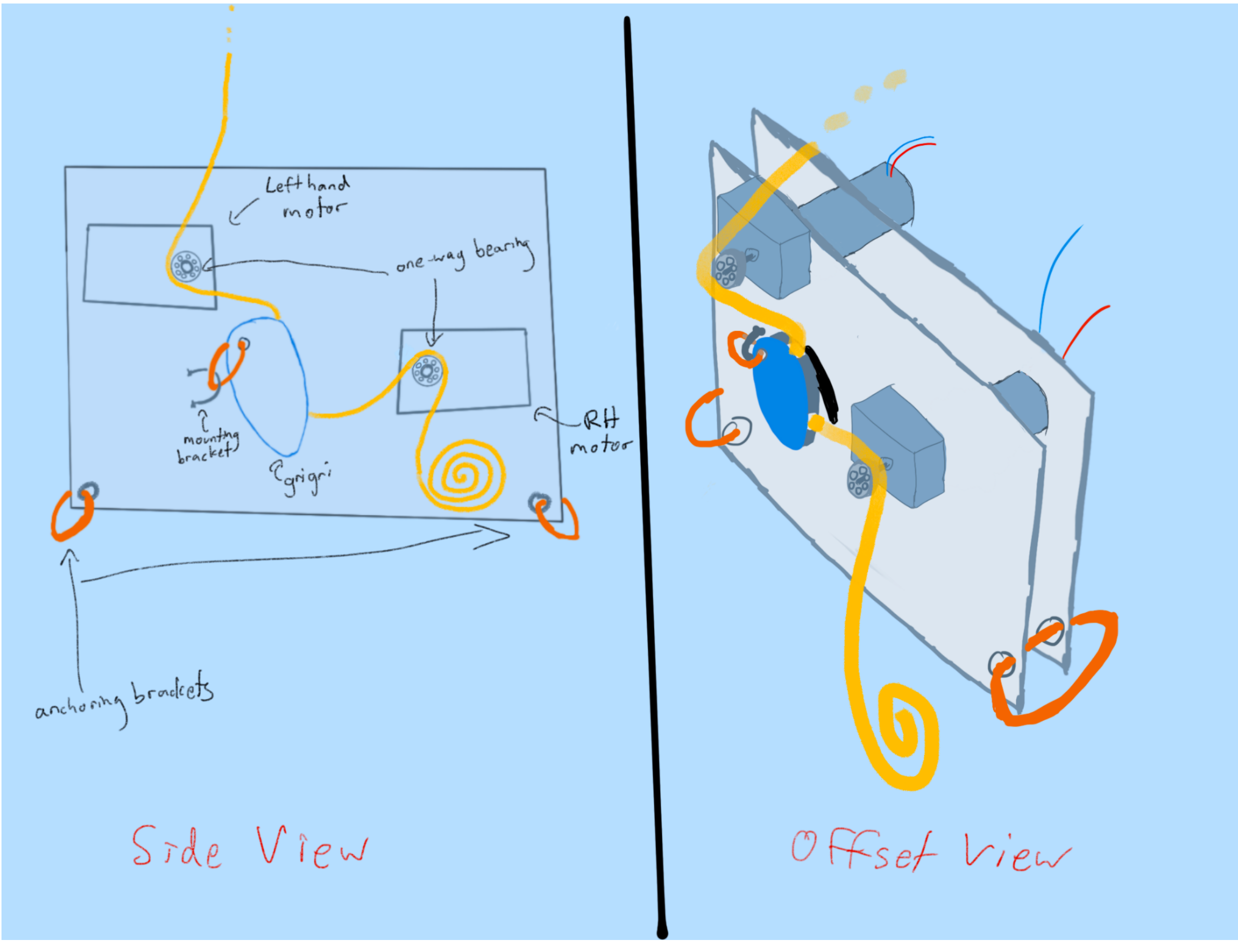

Figure 1: Rough sketch of the belay system.

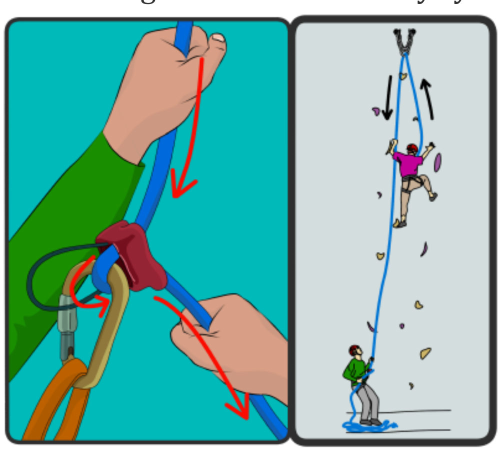

Figure 2: Typical top-rope climbing setup. In this example the belayer is using an ATC instead of a grigri, but the same principles apply.

1.3 High-Level Requirements

- Rope system must be able to maintain an acceptable level of tension (such that excess rope length is less than 4 feet) on the rope while the climber ascends without actively pulling the climber up the wall.
- The climber must be able to communicate with the rope system wirelessly (range of at least 50 feet) to give the following commands: stop, start, and lower.
- Rope system must be able to handle the climber's fall safely by catching the fall within ~4 feet.

2. Design

2.1 Block Diagram

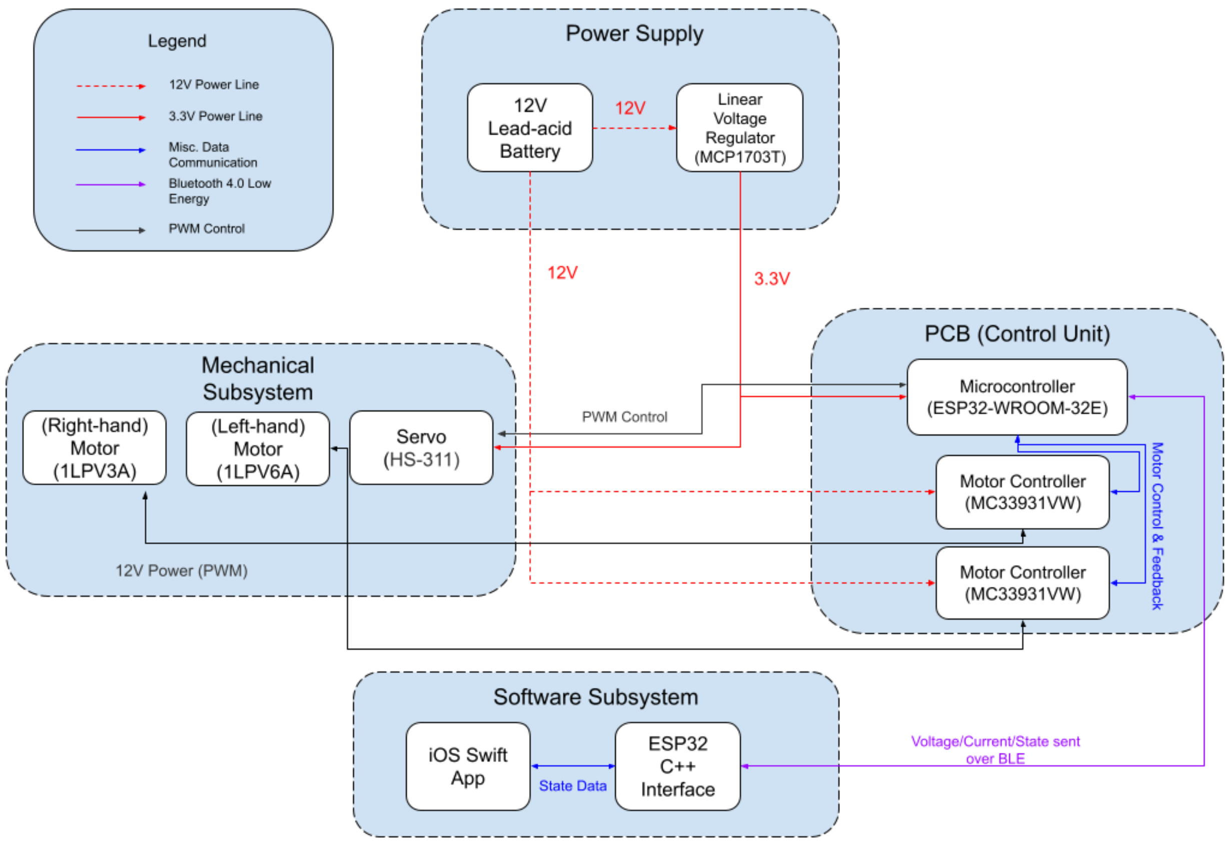

Figure 3: Block Diagram for the belay system. Note: The ESP32 uses I2C, but we are not utilizing it for this project.

2.2 Physical Design

This project requires a complex physical design that will be subject to change through the entire engineering process. The exact dimensions of mounts and motors will be determined after speaking with the machine shop in a more extensive manner. This will occur once all parts (motors, grigri, rope, etc.) have been acquired. For now, a brief overview of the mechanical design will be provided for reference.

Both motors will be mounted on the same plane to reduce unnecessary force and strain in other directions. The left-hand motor will be pull rope using a toothed spool and one-way bearing. The one-way bearing enables us to spin the spool in the other direction freely when lowering, without working against the motor and generating back EMF. The right-hand motor will require a similar setup.

2.3 Subsystem Overviews

Subsystem 1: Power Supply

The system will obtain power stored in the Li-ion battery, and the voltage regulator will adjust proper voltage for each subsystem. The battery will be rechargeable using an A/C power adapter, and be able to supply at least 12V at its maximum. More specifically, it will supply the full 12V to the motors themselves, and be stepped down to provide 3.3V to the rest of the system.

Subsystem 2: Control Unit

The ESP32 microcontroller will handle data from the phone, motor system, as well as the wireless communications to determine the behavior of the mechanical system. The ESP32 microcontroller that we will be using will run on the 3.3V stepped down rail.

Subsystem 3: Motors and Mechanics

Aforementioned, the motor system will supply data to the microcontroller using the encoders. When tension on the rope is detected, through back-emf, as well as a change in current, the microcontroller can be signaled off of these cues to slow or stop the motors. We are using 2 Dayton DC GearMotors (models: 1LPV3A, 1LPV6A), which uses at most 12V at 2.1A, and it will be combined with a servo (model: HiTEC HS-311) for releasing the lever that will be operable at 3.3V.

Subsystem 4: Communications and Software

The built-in bluetooth module in the microcontroller will operate at 3.3V. The user can input data from the graphical user interface on the App to control the rope feeding through the motor controller. This should have the ability to start and stop the auto-belaying, as well as start and stop lowering the climber. The commands given using the app will be reflected in LEDs on and around the PCB, as well as get a ping back from the microcontroller over bluetooth acknowledging receipt of the signal.

2.4 Subsystem Requirements

2.4.1 Power Supply

RV Table:

Requirement	**Verification**
1. The constructed diode protection circuit should prevent excess current from flowing back to the motor controller when the motor spins the other way during lowering.	1. A multimeter will be used to determine current and voltage before and after the protection circuit. If the current drops below 0.01A and the voltage is dissipated to below 1V, the circuit will be considered successful.
2. Internal Power Dissipation of the Linear Voltage Regulator must not exceed 1.006W.	2. A multimeter will be used to determine input voltage, output voltage, and output current. This can then be used to calculate the Internal Power Dissipation of the chip. The calculated value should not exceed 1.006W. The formula used is $P_{LDO(MAX)} = (V_{in(MAX)} - V_{out(MIN)}) * I_{out(MAX)} = (12V - (0.97*2V)) * 0.1A = 1.006W$.

Table 1: RV table of the power supply

2.4.2 Control Unit

RV Table:

Requirement	**Verification**
1. The control unit should be able to detect a fall and signal the app that a fall has occurred. A fall should cause an estimated current change from 1.8A to 2A.	1. This can be verified by utilizing the feedback pins on the motor controllers. 0.24% of the load current is the reference current the feedback pin provides. By running this current through a 100 Ohm

2. The system can enter the 3 states given commands from the mobile app: belay, lower, stop.	resistor, we receive a reference voltage. When the current changes from 1.8A to 2A, under a higher load, a difference in reference voltages (0.48 - 0.432 = 0.048V) can be identified. a. Normal: (0.24% * 1.8A) * 100 Ohm = 0.432V b. Load: (0.24% * 2A) * 100 Ohm = 0.48V 2. These states will be verified through the use of an LED and visual confirmation. a. Belay: Both motors spin at the same rate, pulling away excess rope b. Lower: The motors are stopped and the microcontroller is able to send a "lower" command c. Stop: The motors are stopped and the weight on the rope will not move.

Table 2: RV table of the control unit

2.4.3 Motors and Mechanics

RV Table:

Requirement	**Verification**
1. Mechanics must be able to pull rope through gri-gri alone without stalling at a rate of 3±0.2 in/sec . 2. System must be able to handle the force of a climber's fall. a. Handle any back-emf of motors' backspin (current should not exceed 0.5A) b. Mechanical subsystem should withstand fall force	1. Drive motors to pull rope through gri-gri, measure rate by length of rope. A simple mark on one point of the rope, combined with a reference point can show how much rope has been pulled through the system. Monitor the current draw of motors with a multimeter/oscilloscope to check if stalling. 2. Procedure: a. Monitor current between power source and motor

3. Both motors run at the same speed (given that they are different motors), maintaining an acceptable level of slack.	system using a multimeter or oscilloscope. b. Simulate fall by pulling rope with significant abrupt force (or dropping a weight). 3. This can be verified by measuring the RPM of each motor after determining the correct voltage to drive each motor at. RPM can be measured through the use of an encoder, or marking a point on the shaft and timing how long one rotation takes, which can then be converted to RPM. An acceptable level of slack can be visually verified. The required speed to belay at a rate of 3±0.2 in/sec will be found through trial and error.

Table 3: RV table of the motors and mechanics

2.4.4 Communications and Software

RV Table:

Requirement	**Verification**
1. Wireless communication range should work reliably within 50 feet (need a requirement because using bluetooth low energy).	1. Procedure: a. Stand at ranges of 10, 20, 30, 40, and 50 feet from the system. b. Issue commands from app c. Verify correct command was executed based on LED response and app display
2. The round-trip time of sending a signal from the phone and receiving a state-change notification back from the controller is under 1 second.	2. Testing will be performed by sending commands from phone to belay system motors. Receipt of command is measured either through LED turning on. Measured time only needs to be accurate to the tenths place to ensure that the round-trip time is under 1 second. Time will be measured by starting a

	timer at the start of a command and ending it once the phone shows a response.

Table 4: RV table of the communications and software

2.5 Circuit Schematics (For PCB)

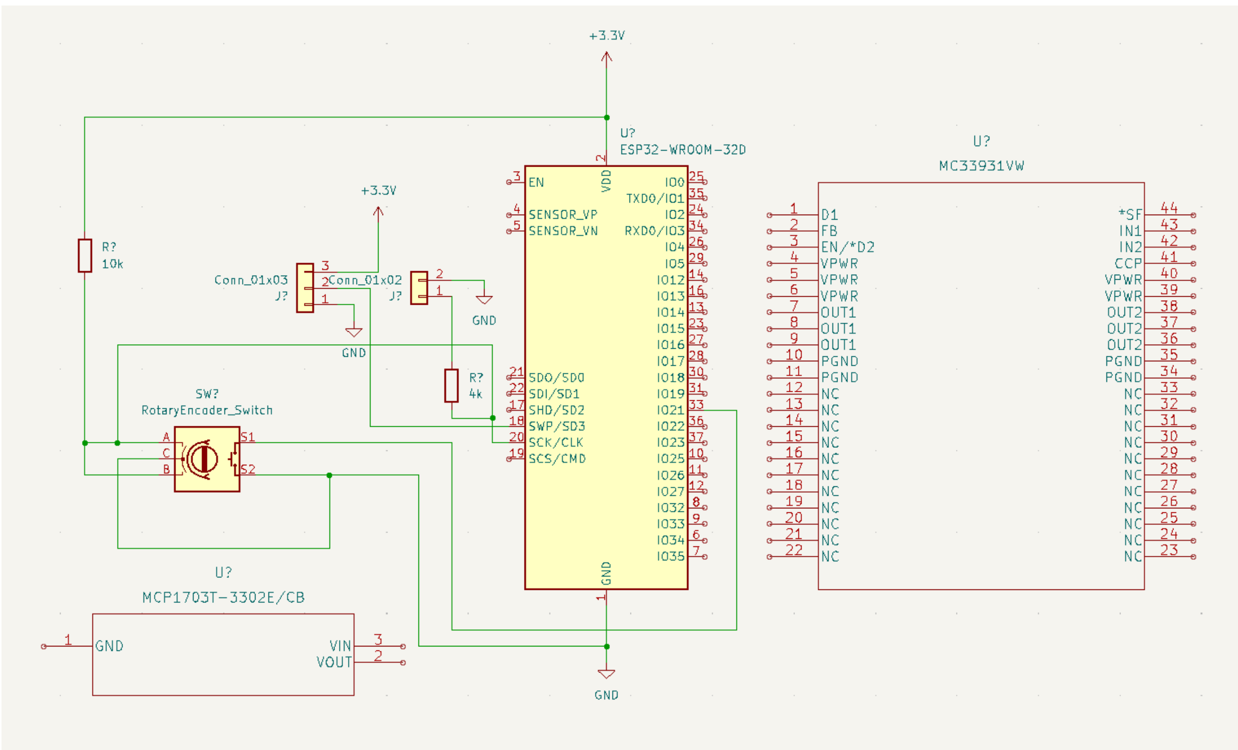

Figure 4: Schematic layout with planned components. In the process of designing and cleaning up the schematic for the PCB.

2.6 Tolerance Analysis

After speaking with Gregg Bennett at the Machine Shop and clarifying build ideas for the mechanical aspect of this project, we both agreed that the “left-hand” motor will likely be one of the most challenging aspects of this project. We are not overly concerned with the tension-sensing capability of the motor as we believe there are multiple ways to determine if an adequate tension has been reached (based on voltage, force sensors, etc).

However, we are concerned regarding the stopping force of this motor (or the mechanical mechanism needed to lessen the force the motor feels) during a fall. Although the rope is typically wrapped twice around a beam at the top of the climb (which in turn cuts the force the belayer experiences during a climber's fall in half), this is still a significant amount of force for a motor to experience. There is also the issue with fall detection using this left-hand motor.

> We would like to detect falls in a weight range of 50 lbs to 200 lbs, therefore meaning that our left-hand motor must be able to sustain and detect forces between [∼2500N, ∼10500N]. This was calculated by taking masses of 20 kg and 90 kg, dropping from a height of 4 ft (∼1.2m), and then finding half the average impact force (because of the looped system).
>
> Avg. impact fore * (0.05m traveled) = Change in kinetic energy.
> Change in kinetic energy = $0.5mv^2$, where we know v = $\sqrt{(2gh)}$.

We believe we can design a system that withstands these forces, especially using a high torque, low RPM motor. Furthermore, we will be able to detect tension changes, i.e. falls, depending on motor voltage spikes. A greater voltage indicates more work is needed to pull the rope, meaning the rope is taught.

3. Cost and Schedule

3.1 Cost Analysis

ECE Student Labor Cost: To estimate the student labor cost, we found the average starting salary of a CE undergraduate from UIUC to be ~$105,000 per year. Assuming the average graduate works 50 weeks per year, and 40 hours per week, the average hourly salary would be roughly $52.50/hr. Assuming each student in the group spends roughly 10 hrs per week, with 13 weeks in the project, the average labor cost per student would be . Given that there are 3 students, the total ECE student Labor Cost for this project would be 3 students * 10 hours/week * 13 weeks * $52.50/hr = $20,475.

Machine Shop Labor Cost: According to payscale, the median Machinist pay is $32.26/hr. We spoke to the machine shop and estimated that the machine shop will spend 40 hours building the motor mounts and flywheel mechanism. So the total machine shop labor cost will be 40 hours * $31/hr = $1240 .

Part Name	ID	QTY	Price
Microcontroller	ESP32-WROOM-32D	1	7.30
Left Hand Motor*	https://www.grainger.com/product/DAYTON-DC-Gearmotor-12V-DC-1LPV3	1	289.01
Right Hand Motor	https://www.grainger.com/product/DAYTON-DC-Gearmotor-12V-DC-52JE53	1	62.46
Grigri Lever Servo	https://www.servocity.com/hs-311-servo/	1	13.49
Motor Driver	https://www.digikey.com/en/products/detail/nxp-usa-inc/MC33931VW/2185657	4	24.28
LEDs*	https://www.ledsupply.com/color-5mm-leds	5	.50
Button*	https://www.amazon.com/Momentary-Terminal-Pushbutton-Breadboard-Electronic/dp/B09R3ZPWJ7/ref=sr_1_1_sspa	1	.30

Li-ion Battery	https://www.amazon.com/dp/B01M0LASUB/ref=twister_B083QF48NR?_encoding=UTF8&psc=1	1	51.99
A/C Adapter*	https://www.amazon.com/Belker-Universal-Adapter-Supply-Speaker/dp/B07N18XN84/ref=sr_1_5	1	15.90
Voltage Regulator	https://www.mouser.com/ProductDetail/Microchip-Technology-Atmel/MCP1703T-3302E-CB	1	0.82
Encoder	https://www.amazon.com/Taiss-KY-040-Encoder-15×16-5-Arduino/dp/B07F26CT6B/	2	10.00
Grigri*	GRIGRI® Belay device with cam-assisted blocking	1	99.95
Carabiner*	SPIRIT SCREW-LOCK Compact, ultra-lightweight screw-lock carabiner	1	16.95
Rope*	https://sterlingrope.com/slim-gym/	1	119.95
Cost Summary	Total Parts Cost (including items in possession)	$712.90	
	Total ECE Student Labor Cost	$20,475	
	Total Machine Shop Labor Cost	$1240	
	Total Cost	$22,427.90	

Table 5: Parts list and cost summary. Note: * Indicates items which are already in possession

3.2 Schedule

Dates	Task	Person
9/26-9/30	• Finish Design Document • Parts finalization	Abhyan
		Chris
		Daniel
10/3-10/7	• Preliminary testing of parts + Design Review	Abhyan

	• PCB design (Wiring and testing compatibility)	Daniel
	• Design Review + Help with PCB design	Chris
10/10-10/14	• Motor controller design + Work with machine shop on design	Abhyan
	• Finalize PCB Design for first round ordering	Daniel
	• Start writing phone app	Chris
10/17-10/21	• Motors/Mechanics system integration (Motor controller and motors connection) + help with assembling PCB	Abhyan
	• Work on assembling PCB	Daniel
	• Finish app + start writing microcontroller code + help with motor system	Chris
10/24-10/28	• Test individual systems + finish up PCB assembly	Abhyan
	• Fix any issues with PCB design / finish up PCB assembly	Daniel
	• Microcontroller integration with motor controllers	Chris
10/31-11/4	• Systems testing and debugging • Communication system integration + full test (App and bluetooth) • 2nd round PCB order (if needed)	Abhyan
		Daniel
		Chris
11/7-11/11	• Systems testing and debugging • Project finalizing for mock demo • PCB assembly (if needed)	Abhyan
		Daniel
		Chris
11/14-11/18	Mock demo	Abhyan
		Daniel
		Chris
11/21-11/25	Fall break - catch up on documentation	Abhyan
		Daniel

		Chris
11/28-12/2	Final demo Prepare for final presentation	Abhyan
		Daniel
		Chris
12/5-12/9	Final presentation	Abhyan
		Daniel
		Chris

Table 6: Schedule

4. Safety & Ethics

Rock climbing, especially rope climbing, is an inherently dangerous sport. Safety is of the utmost concern and several systems and techniques are used to mitigate risks. Using the correct equipment and taking extra precaution prevents injury and potential death.

When designing this rope-management system, we intend to follow climbing and mechanical industry standards, in addition to documenting the full process. Furthermore, when testing, we will take advantage of testing techniques currently used by professionals to completely eliminate excess risks. A belay-certified individual will always be operating a grigri behind the system in the event of failure, safely catching the climber. Therefore, the usage of our rope-management belay system will be no more dangerous than normal top-rope climbing is. To further eliminate risks, we will never climb above a height from which a freefall would cause injury. By strictly following these steps and rules we have defined for ourselves, we will confidently be able to climb and test with the system safely.

There are some ethical concerns regarding unintended usage of the system. However, we intend to be the only users of this system at all times, as we will be familiar with the controls and dangers. Under no circumstances will we allow any untrained or non-group members to use the belay system. When active, the system will be under supervision at all times to prevent any misuse and resulting damage. This is in accordance with IEEE Code of Ethics (section 7.8.I.1).

All group members have completed the lab safety training and understand that we must exercise caution when working in dangerous environments. When working in the machine shop, we will take adequate precautions to avoid injuries and accidents. This is in accordance with IEEE Code of Ethics (section 7.8.III.10). Using feedback from TAs, Professors, and the machine shop employees, we will work to alleviate concerns and pursue honest work (section 7.8.I.5).

5. References

Webpages:

[1] *"IEEE Code of Ethics."* [Online]. Available: https://www.ieee.org/content/dam/ieee-org/ieee/web/org/about/corporate/ieee-code-of-ethics.pdf

[2] "CEN - EN 15151-1 - Mountaineering equipment - Braking devices - Part 1: Braking devices with manually assisted locking, safety requirements and test methods | Engineering360," *standards.globalspec.com*. [Online]. Available: https://standards.globalspec.com/std/1540615/EN%2015151-1

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