DESIGN DOCUMENT

GROUNDED ROPE MANAGEMENT SYSTEM FOR BELAYING

Team 24

Team Members: Abhyan Jaikishen, Chris Zhang, Daniel Hsu

TA: Jason Paximadas

09/29/2022

ECE 445

1. Introduction

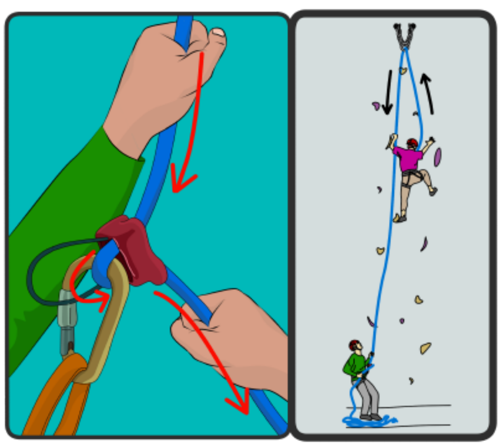
1.1 Problem & Solution

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)

Pictured above: Rough sketch of the belay system. Black stick figure is the climber, blue lines are the rope, and red represents force directions.



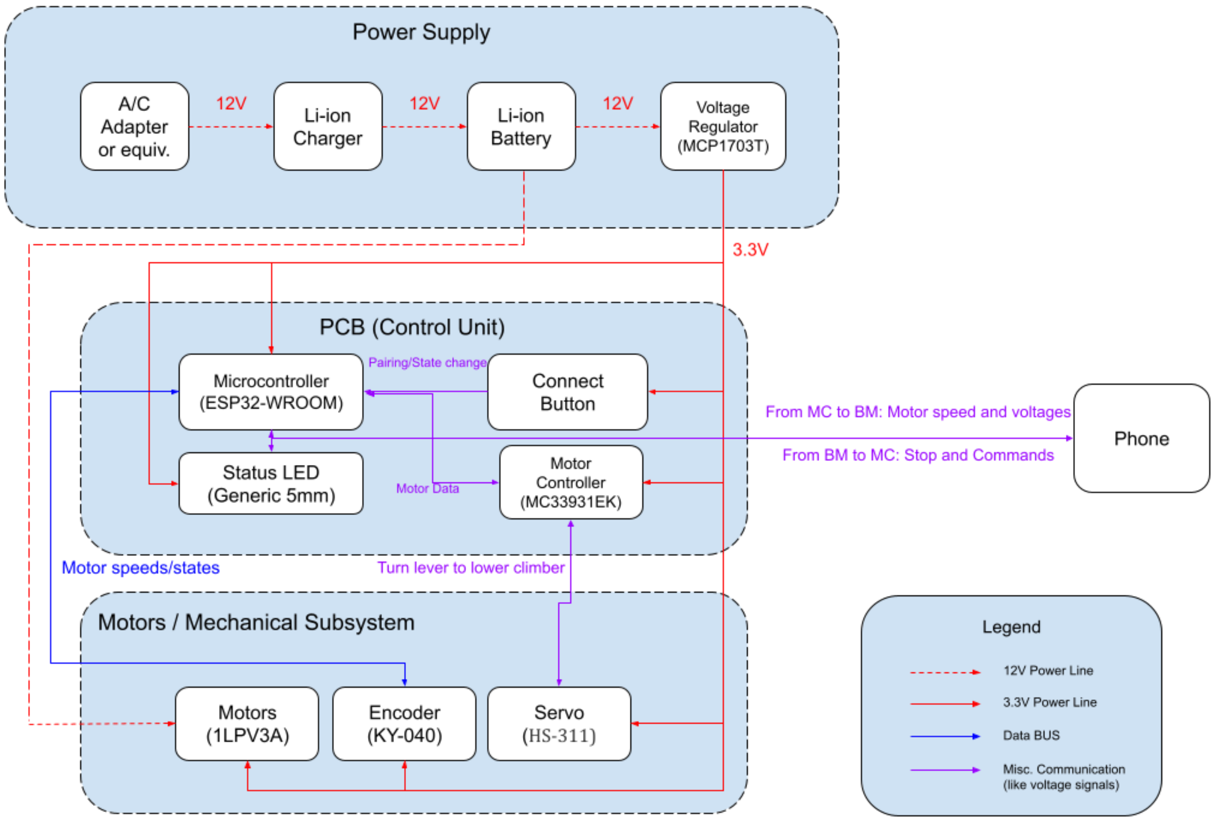
Pictured above: Typical top-rope climbing setup. In this example the belayer is using an ATC instead of a grigri, but the same principles apply.

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



Pictured above: Block Diagram for the belay system. Note: SPI protocol is being utilized for the data BUS.

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 encoders, and use that to control the motors. The microcontroller will handle the data from the motor system as well as the wireless communications, and determine the behavior of the mechanical system based on that. 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 reduction in speed, the microcontroller can be signaled off of these cues to slow or stop the motors. The motor we use is DC Dayton Gearmotor (model: 1LPV3A), 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. Motor controllers must be able to accurately send voltages for motor control within ± 0.1V	1. A multimeter will be utilized to ensure motors are receiving sufficient voltage for turning speed and amount. An encoder will also be utilized to confirm position and speed data sent/received from motor controllers.
2. The voltage has to stay stable with the installment of the voltage regulator.	2. The voltage regulator enables the unregulated power supply to provide consistent power (3.3V throughout the systems) regardless of the amount of current.

2.4.2 Control Unit

RV Table:

Requirement	**Verification**
1. When the rope runs out of slack, the system should detect it and indicate so (through motor speed or LED).	1. Turn system on and in climb mode. a. Let rope run through while applying opposing force (at least 20LBs) to climber-side of the rope. b. Continue until the rope runs out of slack. c. Microcontroller detects lack

2. The system can enter the different modes: a. Climbing start & stop (motors on or off) b. Lowering start & stop (servo pulling or not pulling lever)	of slack and toggles indicator LED. 2. Start system a. Select climb start in app i. Verify correct LED response and data response in app, as well as motors' movement b. Select climb stop in app i. Verify correct LED response and data response in app, as well as motors' stoppage c. Select lower start in app i. Verify correct LED response and data response in app, as well as no motor activation, and servo pulling back grigri lever d. Select lower stop in app i. Verify correct LED response and data response in app, as well as servo releases lever of grigri

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 2±0.2 ft/sec . 2. System must be able to handle the	1. Drive motors at rated voltage (12V) to pull rope through gri-gri, measure rate by length of rope. Monitor the current draw of motors with a multimeter/oscilloscope to check if stalling. 2. Procedure:

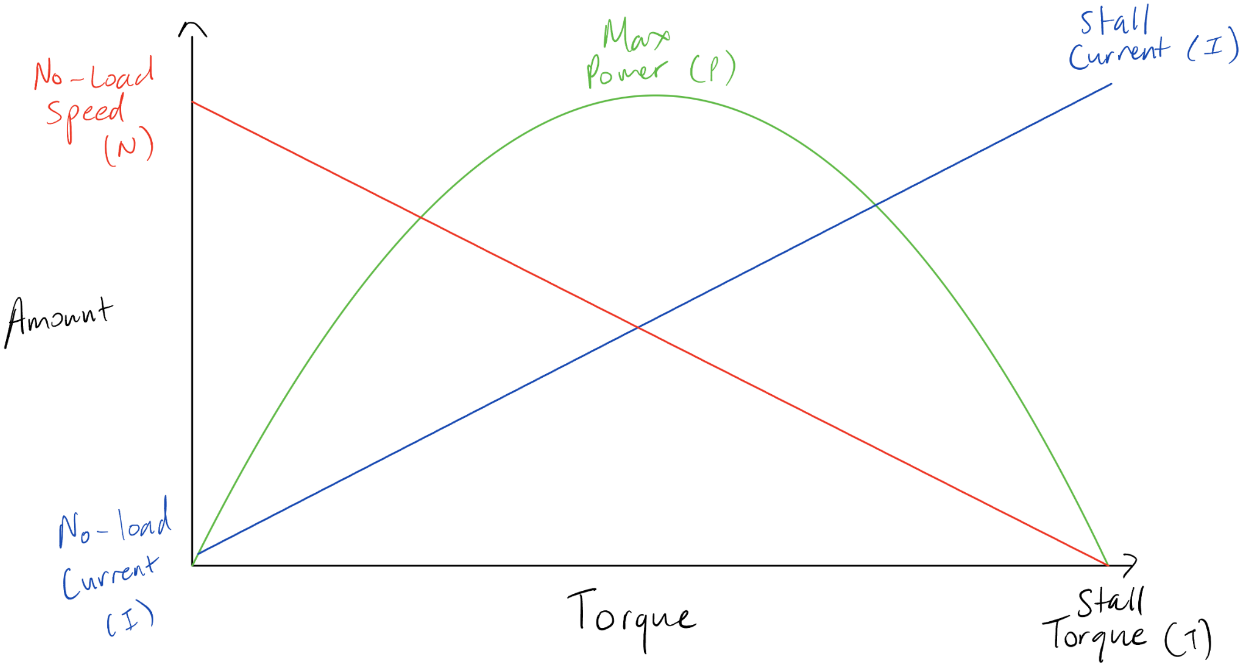
force of a climber's fall. a. Handle any back-emf of motors' backspin (current should not exceed 0.5A) b. Motors' external temperature should not exceed	a. Monitor current between power source and motor system using a multimeter or oscilloscope. b. Monitor external temperature of the motors with an IR gun or similar. c. Simulate fall by dropping weight from the end of the rope.

2.4.4 Communications and Software

RV Table:

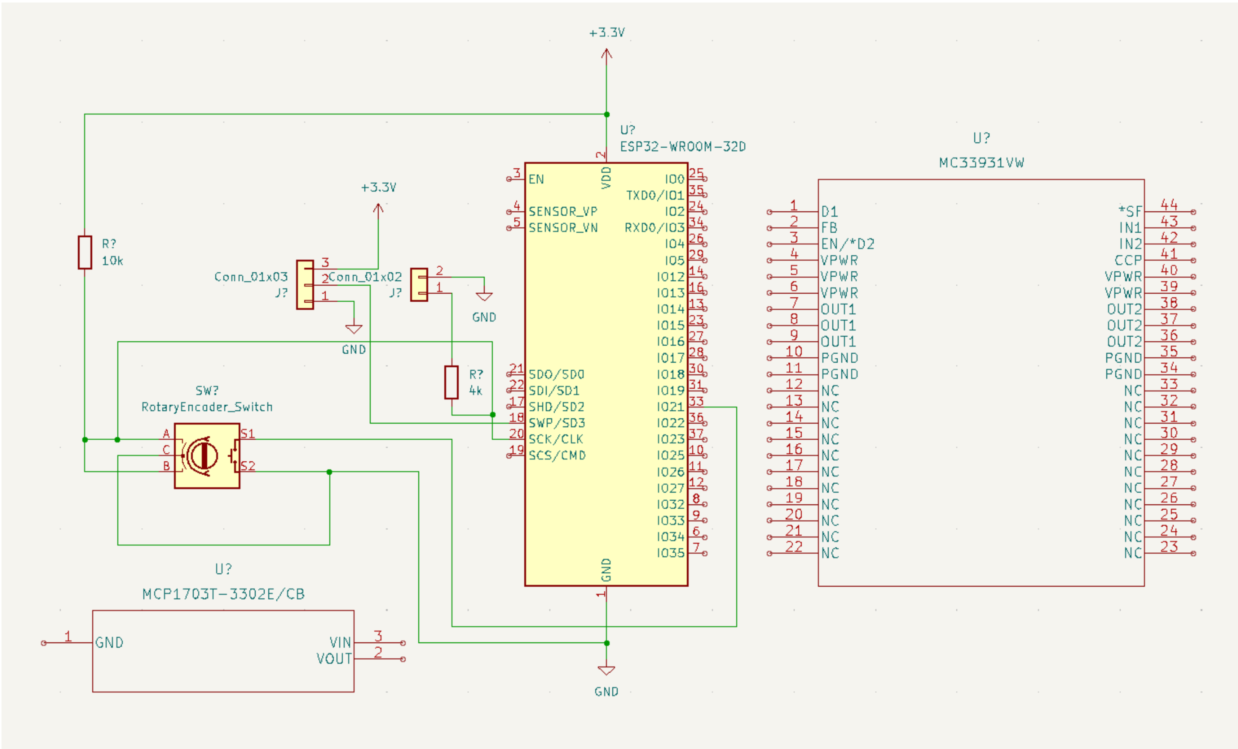
Requirement	**Verification**
1. Wireless communication range should work reliably within 50 feet.	1. Procedure: a. Stand at ranges of 10, 20, 30, 40, and 50 feet from the system. b. Issue commands from app c. Verify correct command was executed based on LED response and app display
2. Wireless commands sent to the system should be responsive within 0.2 seconds.	2. Testing will be performed by sending commands from phone to belay system motors. Receipt of command is measured either through LED turning on. Elapsed time will be determined through the use of slow-motion video (t_0 = issue command from app, t_1 = visible LED response)

2.5 Plots



Pictured above: Diagram depicting the relationship between motor torque and current. Constructing this graph (or finding it) for the chosen motor will enable us to perform calculations for important sensing thresholds.

2.6 Circuit Schematics (For PCB)



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

2.7 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

* 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 Above: Tentative Schedule for the semester

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

[3] G. E. O. of M. and Communications, "Salary Averages," *ece.illinois.edu*. [Online]. Available: https://ece.illinois.edu/admissions/why-ece/salary-averages

[4] "UIAA | Safety Standards UIAA," *UIAA*. [Online]. Available: https://theuiaa.org/safety/safety-standards

[5] VDiff, "How To Belay: Top Rope Basics - Learn To Rock Climb - VDiff Climbing," *VDiff*, Jan. 03, 2018. [Online]. Available: https://www.vdiffclimbing.com/basic-top-rope-belay/

[6] S. built by: Salary.com, "Machine Shop Tool & Die Maker III Salary in Illinois," *Salary.com*. [Online]. Available: https://www.salary.com/research/salary/alternate/machine-shop-tool-and-die-maker-iii-salary/il

[7] "TRUBLUE iQ Auto Belay," *Head Rush Technologies*. [Online]. Available: https://trublueclimbing.com/trublue-iq-auto-belay

[8] "Climb Safe: How to belay with the Grigri," *www.youtube.com*. [Online]. Available: https://www.youtube.com/watch?v=BAxY-BBSlGc

Images:

1. https://www.tradeinn.com/trekkinn/en/petzl-grigri-belay-device/137053801/p
2. https://www.grainger.com/product/DAYTON-DC-Gearmotor-24V-DC-52JE56
3. https://www.climbingnewheightswv.com/
4. https://www.vdiffclimbing.com/basic-top-rope-belay/