DESIGN OF AN AUTO-BELAY DEVICE FOR LEAD CLIMBING

ELEN4000A/4011A EIE Design – Capstone Project

Joshua Schwark – 2118091

Supervisor: Dr Nicholas West

Submission Date: 26th August 2024

Abstract:

This report presents the design and development of a lead auto-belay system aimed at enhancing safety in lead climbing. The device is engineered to arrest a climber's fall regardless of the height ascended, accommodating climbers weighing between 30 kg (294 N) and 150 kg (1470 N). The core fall arrest mechanism relies on a friction-based system, supplemented by a motor-assisted locking device that increases friction by amplifying the bending and squeezing forces on the rope. To manage slack, the system integrates two brushless DC motors with rubber-sleeved wheels, allowing for efficient retraction of excess rope. A sprag clutch enables the motors to operate in reverse without adverse effects.

Given the critical importance of safety, a backup cam-style brake is incorporated, which activates automatically in the event of a power failure and can only be manually disengaged. Additional safety features include a "buddy-check" mechanism that verifies the integrity of the climber's knot through torque measurement. The system is securely mounted to the climbing wall using chemically bonded anchors and rubber shock absorbers to ensure stability. Powered by municipal electricity, the device is equipped with an uninterruptible power supply (UPS) to safeguard against voltage drops and blackouts, and a switching power supply converting power to 24 V DC for operational consistency.

This project underscores the significance of rigorous engineering practices and safety-centric design in climbing equipment. Future work will focus on further refinement through advanced simulations and real-world testing to validate long-term durability. The successful implementation of this system has the potential to set new benchmarks in climbing safety, influencing industry standards and improving the overall safety of the climbing community.

UNIVERSITY OF THE WITWATERSRAND, JOHANNESBURG

SCHOOL OF ELECTRICAL AND INFORMATION ENGINEERING

ACADEMIC MISCONDUCT DECLARATION

I, **Joshua Schwark** (student name and surname), **2118091** (student number), hereby declare that:

1. I have read the Student Academic Misconduct Policy [1] and I understand that: "*Academic Misconduct includes any action which gains, attempts to gain, or assists others in gaining or attempting to gain an unfair academic benefit. It includes Plagiarism, collusion, cheating, copying, contract cheating, fabrication of data, the use and/or possession of unauthorised materials or devices during an assessment; and falsification or misrepresentation of information including, falsification of a medical certificate, and/orchanging a script after it has been marked*" [1].
2. I know that any act of academic misconduct is unacceptable, and carries a penalty as prescribed inthe Student Academic Misconduct Policy [1].
3. This assessment/submission for the course ELEN4000A/4011A is my own work, andI have not engaged in any act of academic misconduct in the completion of this work.

Signature: ____________________ Date: 26 August 2024

[1] University of Witwatersrand, Student Academic Misconduct Policy G-C-2022-029,2023.

ACKNOWLEDGEMENTS

I would like to acknowledge the assistance from the staff at City Rock Johannesburg as well as the Wits University Mountain Club for explaining the background and method of lead climbing. I would additionally like to thank the Wits University Mountain Club for opening up their practices for first hand experiences in watching lead climbing examples and of climbers taking falls.

List of Figures

List of Tables

TABLE OF CONTENTS

1. INTRODUCTION

Rock climbing is a sport and recreational activity that necessitates robust safety systems to prevent injuries and fatalities. These safety systems include proper education in climbing techniques, the correct gear (such as ropes, shoes, and harnesses), and a belayer—a second person responsible for handling the rope that the climber is not on. Rock climbing is (for the purpose of this project) broken up into two categories, namely top-rope climbing where the rope is secured to a "pulley" at the top of the route, and lead-climbing where the climber takes the rope up and clips in as they ascend the route.

Manual belaying involves a second person controlling the rope to catch the climber if they fall and to lower them down from the top of the climbing route. A mechanical braking device is typically used to stop and release the rope on the belayer's end. This device either automatically locks or increases friction when the climber falls to prevent further descent.

Auto-belay devices are designed to automatically arrest a climber's fall without the need for a second person. These devices allow the climber to ascend the route independently and, in the event of a fall, the device automatically locks the rope and then allows a slow, controlled descent. Currently auto-belay devices are widely used for top-rope climbing.

Lead climbing presents a different set of challenges to top-rope climbing. A manual belayer in a lead climbing scenario must pay out slack for the climber to clip into the next quickdraw and then manage the rope to ensure it locks in the belay device if the climber falls.

This project involves designing an auto-belay device specifically for lead climbing for a climbing gym. Like auto-belay devices used in top-rope climbing, this device must arrest a climber's fall without allowing them to hit the ground. Additionally, it must be capable of paying out slack and taking up slack as needed to ensure the climber's safety. The device will comprise a slack management system, a fall arrest system, and two measurement systems to monitor falls and the status of the other systems. The focus of this project is the system design and conceptualisation rather than the in-depth design of specific components or building a final product. This device is to be design with the climate and environment of a climbing gym in Mpumalanga in mind.

This report will review relevant literature on the topic and detail the design specifications, decisions, and functionalities of the proposed device.

2. LITERATURE REVIEW

Auto-belay systems for lead climbing are mostly novel and undocumented systems. Research will need to be done to investigate components of the system and possible solutions to develop the auto-belay device.

2.1 Mechanics of Classical Rope Braking

Dynamic rope braking is classified by rope sliding through a brake, which reduces the deceleration of the climbers fall and the force with which the climbers fall is arrested [1]. The mechanics of dynamic rope brakes are discussed in a paper by Fuss and Niegl, 2010

[1]. In the paper, various dynamic braking techniques are modelled to fully understand the mechanics behind them. The frictional coefficients of the braking are also investigated in this paper. This would assist the investigator into understanding which frictional coefficient would be best suited for a braking system in the lead auto-belay system.

This paper compares the ATC, Figure-of-Eight (Fo8), and HMS (Munter hitch) rope brakes. The brake factor is calculated in this paper which is described as the brutality of the arrest when comparing brakes tested at exactly the same maximal hand force [1]. The static belt friction, $e^{\mu\theta}$, where μ and θ are the static friction coefficient and the contact angle respectively is calculated in this paper. This value across the three braking methods is seen to be very close to one another. As mentioned above, the contact angles (angles of rope on metal) are seen to be an aspect of the braking and static friction coefficient. The last factors that are mentioned in this paper are slip velocity, v and viscous rope friction, η.

In summary, the paper shows that the HMS and ATC produce higher high viscous friction coefficient η than the Fo8. This is said to be due to the rope-on-rope contact of the HMS and the ridges on the ATC's rope outlet on the belayer's hand side. The paper also states that at increased fall heights and velocities, the window for friction coefficients between no slip and critical braking extends to higher friction coefficients and becomes sufficiently large for efficient braking. The reduced window size as small velocities are said to be "not necessarily a disadvantage", where the fall energy is entirely absorbed by the visco-elastic rope. This would be useful to the investigator as it would assist in determining the optimal braking method for the auto-belay system.

The above explains various methods of non-assisted braking devices. A more modern and more trusted device is the assisted-braking device (ABD) [2]. These devices come in both active and passive variations. Active ABDs use moving parts to apply braking force to the rope (such as a camming mechanism), whereas passive ABDs use the geometry of the device. ABDs make it less tiring to catch and hold a climber after a fall and also allows for a very controlled decent for the climber [2].

2.2 Sensor and Monitoring Technology

Detecting the fall to arrest is an integral part of the auto-belay system. A paper by Tonoli *et al*, presents the use of a Kalman filter-based method to identify fall events during rock climbing [3]. This technique uses the acquisition of three-axis acceleration and altitude from a data logger integrated into the climber's harness. The use of the Kalman filter can be explained as a two-step mechanism, firstly, being the integration of the acceleration signal mitigates low-energy events, and secondly, the fusion of acceleration and altitude measurements favours the rejection of the occurrences that are not associated to altitude drops. This method was validated by equipping the device onto eight professional climbers, who were asked to log their falls into a notebook. This study would prove helpful to the investigator as it would allow for a reference into methodologies used to detect falls that need to be arrested by the auto-belay device.

A concern when designing a system that would be required to arrest the fall of climbers is the time-critical decision making that would need to occur in the system. A paper by Oppel and Munz details an analysis for Time-Critical Decision Systems with Applications on Sports Climbing [4]. This paper describes the use of a Convolutional Neural Network to classify whether the climber is falling and additionally manages the feature engineering. This studies models predicted the fall of a climber within up to 91,8 ms. This system uses two modules, one attached to the harness, and one attached to the belay device of the belayer. The system attached to the harness is an Inertial Measurement Unit and the system attached to the belay device is a magnetic Hall switch and six circularly arranged magnets which changing poles to record information about the rope running through the device.

Fall Factor is defined as a relationship of fall length to rope length. In an article by well-known climbing brand Petzel they explain the forces around different Fall Factors [5]. This article shows how the impacts of different falls are felt by a climber and the force that the climber feels. It also states that fall factors above Fall Factor 1 are rare in the field but are possible. Fall Factor would be a good metric to use as a key performance indicator when assessing the effectiveness of a device, if the maths is not too complicated.

3. High-Level Design

This design intends to solve the problem of human error in lead and sport climbing. This design is to be implemented in a climbing gym in Mpumalanga. The final device would need to arrest the fall of the climber and prevent them from falling on the floor despite which draw the climber is on. The environment in which the device is installed would be controlled.

Table 1: Contextual Specifications of the Design.

Category	Specifications	Details
User	Weight Range	30 kg to 150 kg
Environment	Temperature Range	-20°C to 60°C
	Humidity Range	67.36 %
	Humidity & Dust Resistance	IP65
	Province	Mpumalanga
Load Specifications	Load Type	Linear Loading: Sprag Clutch; Stopping Mechanism. Torque: Moving Arm
	Load Characteristic	Shock (fall)
Mounting & Integration	Mounting Configuration	Plate mounted
	Max Wall Height	18 m
Compliance & Standards	Safety Standards	UIAA, EN 341:2011
Maintenance	Maintenance Interval	Annual
	Maintenance Downtime	< 3 days
Rope	Rope Type	Dynamic
	Diameters	9,6 mm to 10,3 mm
	Length	> 50 m
Cost	Initial Cost	R 37 200
	Maintenance Cost	R 1000

Table 2: Technical Specifications of the Design.

Category	Specifications	Details
Slack System	Motor type	Brushless Dc Motors
	Measurement System	Rotary Encoder
	Wheel Diameter	15 cm
	Wheel Material	Steel wheel with Rubber sleeve
Fall Arrest System	Motor type	DC Stepper Motor with Gear System
	Measurement System	Torque Sensing Load Cell
	Fall Arrest device	Friction based assisted braking device
Free-Wheel Mechanism	Mechanism Type	Sprag Clutch
	Pull Force	300 N (hand force)
Torque Sensing Load Cell	Placement	Moving arm of the fall arrest device
	Input Range	0 N.m – 120 N.m
Rotary Encoder	Placement	Slack wheel
	Input Range	0 $m.s^{-1}$ – 7$m.s^{-1}$
Mounting	Load coupling	L-shaped steel plate
	Attachment	Chemical anchors
Power Supply	Switching Power Supply	240 V AC to 24 V DC
	Uninterrupted Power Supply	1.5 kW rated power supply
Logic Control	Processing Unit	Raspberry Pi

3.1 Design Overview

The system is set-up by placing the rope through the slack wheels and correctly around the fall arrest device. The rope also needs to be placed through the guide d-ring at the climber's end. An illustration of the device can be seen below in Figure 1. As the climber ascends the route, a sprag clutch is used to allow slack to be paid out freely as the climber needs. Motors will be attached to the slack wheels to retrieve any slack that the climber does not need to clip into the next point. Falls are arrested at the fall arrest device which mimics a traditional assisted braking belay device but is motor assisted. Climbers will be lowered by using the motor to release the fall arrest device slowly and let the rope slide through slowly. The device will be controlled by a controller (such as a Raspberry Pi) with a Robotic Operating System and would allow users to select a 'project' or 'competition' mode which will arrest falls and lower climbers differently.

Measurement Systems will be placed on the slack wheel and the fall arrest device. Falls are detected as the rope pulls the fall arrest device closed on itself using a torque load cell, which triggers the motor to close the rope in the catch. The measurement system placed on the slack wheel is a Rotary Encoder that measures the amount of rope that passes it by measuring the number of turns the wheel makes along with the speed rope is being let out or taken in. This is used, in conjunction with the fall arrest system, to control the speed at which the climber is lowered from the route.

The device will be built on a solid steel L-shaped plate and mounted to the wall using chemically activated raw bolts to ensure no amount of force exerted by the falling climber will be able to pull the device from the wall.

Due to the friction-based stopping mechanism, none of the components will be extremely power extensive. The device will be powered with 220 V wall power and consist of transformers to adjust the voltage to that required by the motors and measurement systems. A battery back-up and uninterrupted power supply (UPS) will be installed in the device to ensure no voltage drops and a regulated supply to the device. The battery would also be able to power the device in the event of a power blackout or loadshedding, allowing for a safe decent.

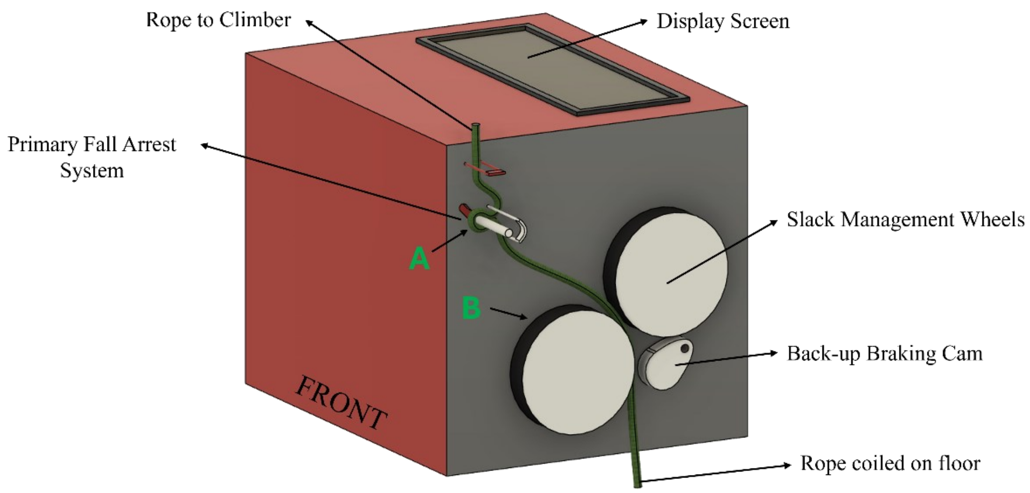


Figure 1: Annotated diagram of the complete system.

4. Technical Design

The full lead auto belay system is made up of multiple sub-systems. All these systems are required to make the device work as intended. These sub-systems are detailed below and broken into the components of each sub-system, including the justifications of the choices made when designing these sub-systems.

4.1 Fall Arrest System

The fall arrest system is made up of two stainless steel components, an outer "tube-style" guide and a moving bar. The moving bar is attached to a motor and controls the amount of bend angle and squeezing force on the rope around the device. Increasing the bend angle and squeeze on the rope around the device controls the amount of friction and therefore the stopping force the device exerts on the rope [6]. The moving bar is also attached to a torque load cell detailed in Section 4.3.1. Figure 3 below shows an illustration of the system.

Rope elasticity is taken into account in the design and seen as an additional safety method ensuring softer falls due to the stretch in the rope. Without the stretch climbers falls would be abrupt and cause physical harm [1], [7]. Maximum dynamic elongation is seen to be 40% of the rope length [8]. A graph showing the amount of rope stretch that would be present in the system depending on the amount of rope that has passed through the system is shown in Figure 2.

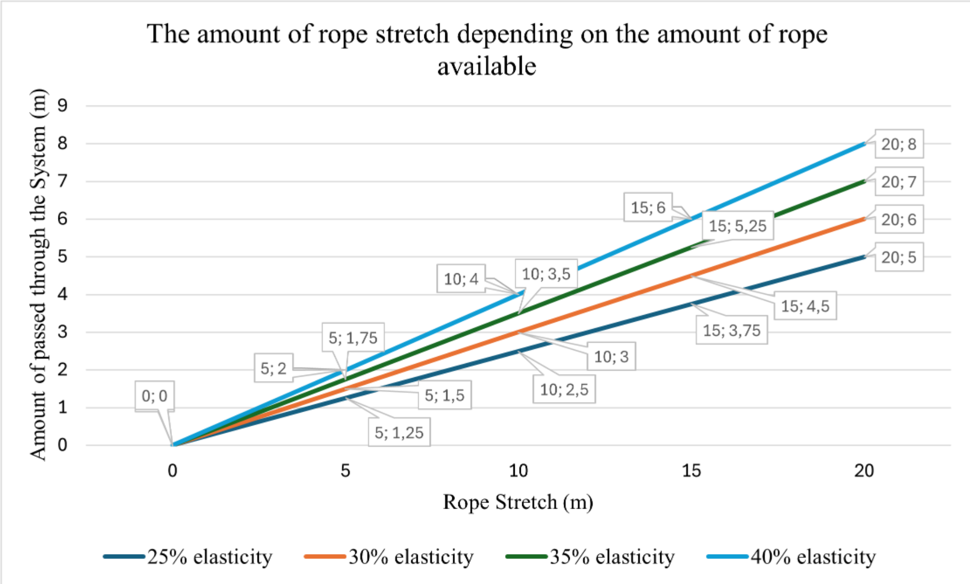


Figure 2: Graph showing Rope Stretch against the amount of rope passed through the system.

The fall arrest system needs to be able to arrest forces from 294 N (a 30 kg person in freefall) to 1470 N (a 150 kg person in freefall). Calculations show that a person who has just clipped into a draw (0 m slack) would fall with 0 $m.s^{-1}$ velocity before the fall arrest system is engaged, and similarly, 4.43 $m.s^{-1}$ for 1 m between draws and a maximum of 6.26 $m.s^{-1}$ for someone just about to clip into the next draw. There are three main forces that play a part in arresting a fall. The force of the rope being bent around the moving arm and through the device, the frictional force of the rope against the stainless steel, and the squeezing force exerted by the moving arm on the rope which inherently increases friction [6]. Response times for this are difficult to predict without physical testing but the mechanism has proved effective through traditional climbing belay devices.

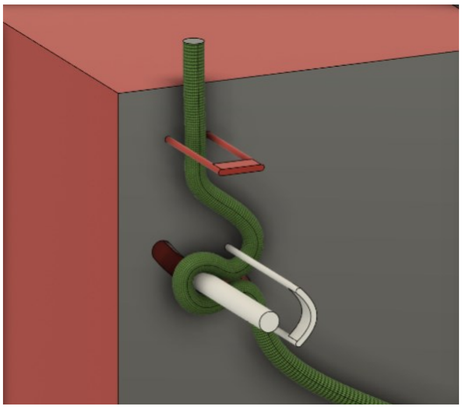


Figure 3: Close-up illustration of fall arrest system

To calculate the force due to bending the modulus of elasticity and friction between all the threads in the rope, as well as a measure of the degree the rope is flattened by [6]. This becomes too complex to calculate, but research has shown that an increase in the wrap angle increases the force until roughly 180° of bend and then force levels out. Bending forces are less effective for ropes with smaller diameter.

To calculate the force due to friction, the methods of using the normal force and coefficients are not accurate for ropes that slip. A Eulerian formula for friction is needed.

$$T_2 = T_1 e^{\mu\beta} \tag{1}$$

Where T_2 is the faller force, T_1 is the initial (hand) force of the belayer, e is the exponential function, μ is the coefficient of friction and β is the angle in radians [1]. The force that a human hand can pull ranges from 150 N to 400 N, with 300 N used as a good estimate for an average belayer [6]. The dynamic coefficient of friction is not a constant and varies with pressure. At higher loads (a human falling) it is noted to be 0.16 for nylon against stainless steel [6].

Stainless Steel is chosen due to it being hard and durable enough to withstand wear from the nylon rope rubbing against it. Stainless Steel has a lower thermal conductivity (16 W/m.K) than aluminium (250 W/m.K) but is more durable than aluminium and would therefore last longer in the system. Stainless steel, however, still has a higher thermal conductivity than nylon (0.25 W/m.K), which means the heat would transfer away from the rope and not cause damage, but would not dissipate the heat as well as aluminium [9], [10].

A DC stepper motor is used in this subsystem with a gear system to increase the torque due to its high torque and ability to release the lock-up on the device after a fall with precision, allowing the climber to decent slowly. Releasing the lock-up would require the motor to turn with enough force to move a maximum of 1460 N (heaviest specified climber) which would be 117.6 N.m of torque using an 8 cm moving arm length.

4.2 Slack Management System

The slack management system is comprised of two brushless DC motor-controlled wheels, and an electronically engageable sprag clutch on each wheel. Each wheel would be made of rubber with groves on them as shown in Figure 4, which would allow a close fit with different rope diameters without affecting the rope. The rope would be placed through the wheel so that the grooves catch the rope. The sprag clutch ensures that the motors only

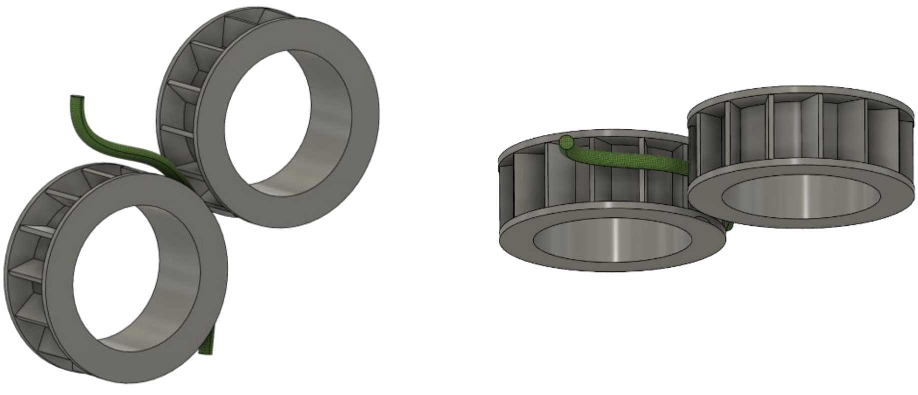


Figure 4: Two Isolated views of the Slack Wheels.

retrieve the rope in one direction, allowing for slack to be pulled freely in the other direction so that the climber can ascend freely. This uses a ratchetting type system which would introduce a linear loading onto the ratchets when slack is pulled out.

In the simulations (mathematics) below, the motor pulling force is seen to be the same as that of a human hand. This is shown to be important in the paper by Jim Titt [6]. The wheels will each have a 15 cm diameter including rubber gear grooves. A torque of 22.5 N.m would be needed to output the required 300 N of force that a belayers hand would produce. Equation (2) below shows how the torque required for the hand force to be achieved is calculated.

$$\tau = N \times r \tag{2}$$

A brushless DC (BLDC) motor is chosen for its high speed and low torque. The motor will be supplied with power as soon as the climb is started to constantly take up slack that the climber may pull through the sprag clutch. A BLDC motor is extremely wear-resistant due to it not having brushes and would require less maintenance than other motors.

This slack management system, that constantly keeps a set tension on the rope, mitigates the drastic differences falls at the beginning of the climb. The constant tension on the rope is a design aspect to prioritise safety on lower attachment points. Due to the amount of slack remaining constant as well as the fall arrest system automatically engaging after a fall, the climber should be at no greater risk of hitting the ground in the beginning of a climb.

4.3 Measurement Systems

In order to control and monitor the climber and subsystems that make up the auto-belay device, measurement systems need to be developed and put into place to measure crucial decision-making information. A Torque Load Cell (Point A on Figure 1) and a Rotary Encoder (Point B on Figure 1).

4.3.1. Torque Load Cell

A torque load cell is used on the moving bar of the fall arrest system (4.1). This load cell measures the force the rope exerts on the moving bar. A small force on this bar will not warrant the gear to lock up and arrest a fall but can be seen as the climber taking up slack to progress further up the climb. A larger force will cause the fall arrest system to lock up and for the motor to engage.

This torque load cell will be placed on the shaft of the motor connected to the moving bar. The readings from this measurement system will be used in the decision logic for the slack management system, fall arrest system and climber decent. The torque load cell has an expected range of inputs from 0 N.m to 117.6 N.m, which is calculated by relating the force of the climber and the length of the moving arm. A torque load cell such as an axial torsion load cell could be used for this application.

The torque load cell could also be used to signal when the slack management motors should be turned on and off to prevent them from overloading.

4.3.2. Rotary Encoder

A Rotary Encoder is placed on the wheel of the slack management system. This is to measure the speed at which rope is passing through the wheels and to measure how much rope is passed through the wheels to monitor how far up the route the climber is. This is critical for decision making on how different systems in the design should engage.

The rotary encoder will detect the rotation of the wheel as the rope passes through. As the wheel turns, the rotary encoder generates a series of digital pulses corresponding to the angular movement of the wheel. The number of pulses per rotation is used to calculate both the speed at which the rope moves (by measuring the rate of pulses over time) and the total distance the rope travels (by counting the total number of pulses and converting them to linear distance based on the wheel's circumference). This provides precise, real-time monitoring of both speed and distance. These functions of the rotary encoder will allow the processor to detect the speed of climbs and falls as well as the distance that the climber has climbed on the route. The rotary encoder would have expected speeds of 0 $m.s^{-1}$ to 7 $m.s^{-1}$ which would equate to 14.85 rotations per second of the wheels.

The rotary encoder will allow for the processing unit of the system to determine the speed at which a climber would take out rope to advance on the route, as well as the speed and acceleration at which the climber is falling. The tracking of distance would allow the processing unit to determine an estimate of where the climber is on the route and would enable the processor to change settings on the fall arrest system accordingly.

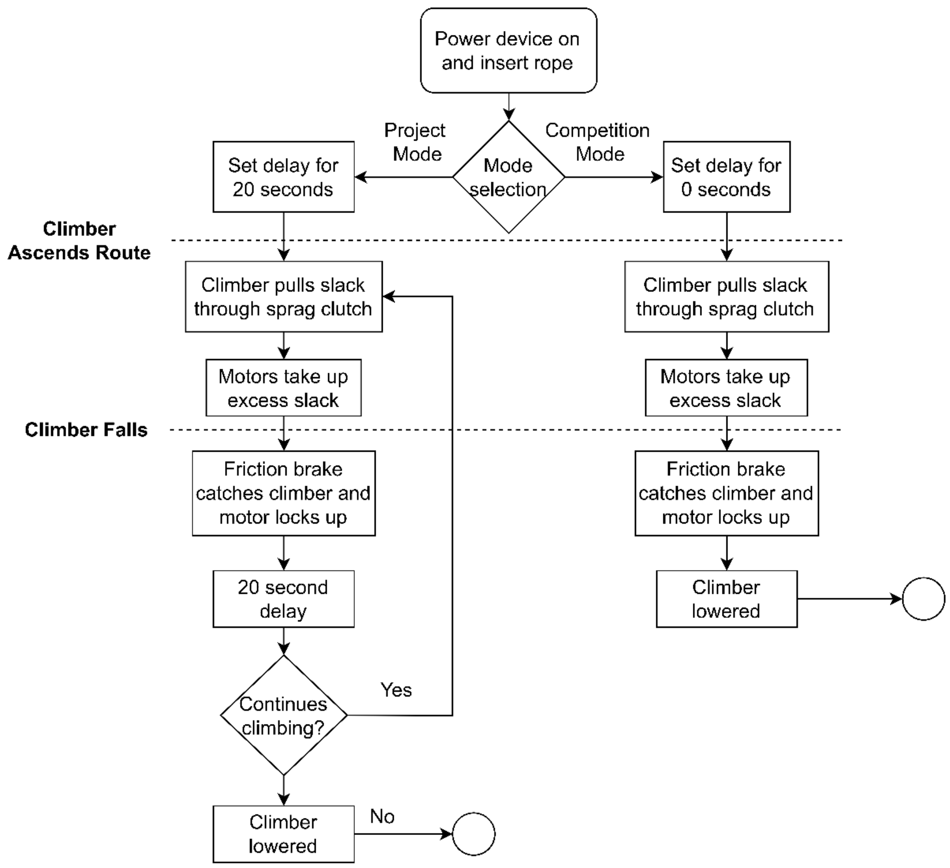


Figure 5: Figure showing logic overview for the system (Section 4.4)

4.4 Control System

A processing device (such as a Raspberry Pi) will control the decision making, displays and communication throughout all the systems. A Linux based Robotic Operating System (ROS) will be used to interface screens and control button presses and inputs from the measurement systems [11]. Figure 5 above shows the complete logic of the full system.

4.4.1. Catching Logic

Climber's falls would be arrested when the rope is pulled taught in the fall arrest device with enough force for the moving arm to pinch the rope against the outer "tube-style" guide bar. The torque load cell will measure the amount of force the rope pulls the moving arm into the guide bars, which would signal the motor to apply a torque to assist the breaking and locking of the device.

4.4.2. Descent Logic

Once a climber's fall has been arrested, the climber would be lowered by using the motor to release the moving arm in the fall arrest device and speed of the decent would be controlled by monitoring the speed rope passes through the Rotary Encoder and adjusting the friction through the moving arm motor accordingly. This is explained in Figure 6 below.

In 'projecting mode', the decent logic will suspend the climber for 20 seconds giving the climber enough time to re-attempt the climb from the point they fell to. Once the climber is back on the wall after the 20 seconds the moving arm will release and the measurement from the torque load cell will dictate if the climber has continued climbing or is being lowered.

In 'competition mode', the decent logic will immediately start lowering the climber after a fall giving the feel of an extremely soft catch and not giving the climber the opportunity to re-attempt the route from the position they are at.

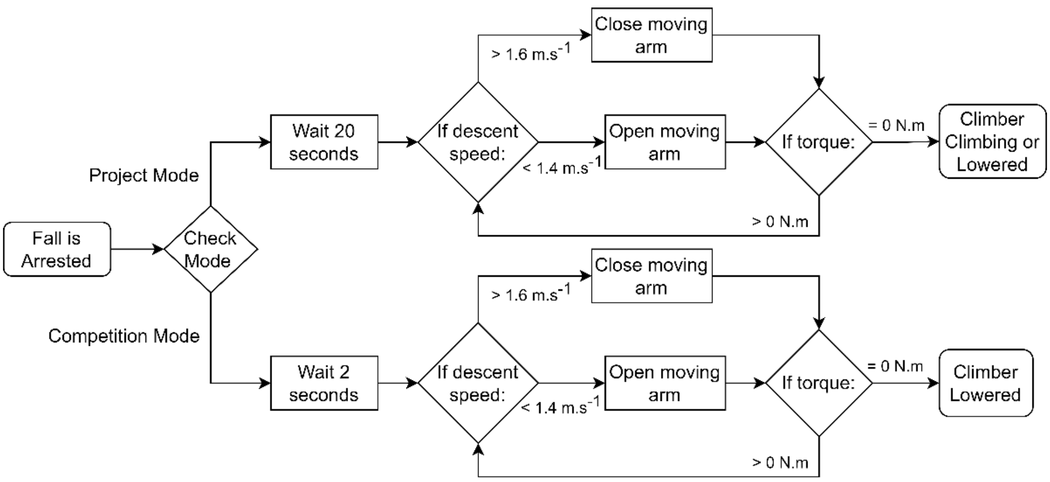


Figure 6: A flow diagram illustrating the descent logic.

4.4.3. Slack Management Logic

Slack Management is controlled by the motors and rubber wheels in the system, along with the torque load cell. The motors always run in the direction that retrieves the rope with a sprag clutch to allow freewheel in the opposite direction to pull slack.

When a fall is detected on the torque load cell, the sprag clutch is electronically disengaged to stop any additional slack being let out and to allow for the full "brake-hand" force to be used from the motors. The sprag clutch is re-engaged after the 20 second wait in 'project mode' and immediately after torque is constant in 'competition mode' to allow for decent.

4.4.4. Modes and Mode Selection

The system is designed to allow for two modes to be selected which affect the decent and slack management logic of the system. Project mode will give the climber the opportunity to re-attempt the climb from the point they are at or start lowering them down after 20 seconds. Competition mode will not allow the climber to re-attempt the climb and will lower them immediately after a fall. This mode would also be useful if the device is installed on a route with an overhang where softer catches than normal are preferred.

4.4.5. Displays and External Input

The main display for the device is a touch screen that would allow users to interact with the device. This allows users to change modes and receive error messages from the device and operating system. The external display will also have prompts to respool the rope for the climber once a climb is completed and the climber is lowered. The screens can be seen as dummy terminals to take in user inputs and display error messages.

The external inputs (from measurement systems) will act as separate nodes in the ROS software, each being read and allowing for decisions to be made based on the inputs they provide [11].

4.5 Mounting System

The system will be mounted to the base of a climbing route. The motors and fall arrest device will be secured to an L-shaped steel plate with the other side of the L being secured to the wall using chemically bonded anchors and dead bolts. Rubber Shock absorption washers are places between the wall and the device to ensure the force of a climber falling does not damage the climbing wall in any way.

4.6 Power System

A switching power supply will be used to convert 240 V AC municipal supply to 24 V DC supply that will be used to power the electronics in the device. Various buck converters will be used to supply precise smaller voltages to electronics such as 12 V rails for the motors and 5V for the processors (Raspberry Pi) [12].

An uninterrupted power supply (UPS) is installed in series with the municipal supply with a battery back up to ensure the device is not affected by any municipal power cuts or trips to ensure no one is ever stranded on a climb without the ability to be lowered down [13].

With an estimated 400 W per BLDC motor and 600 W for the geared stepper motor, as well as 50 W for other small electronics, the device will use 1,450 kW or power per hour. This would allow for a 1.5 kW UPS to be sufficient to power the device during a power outage as a back-up supply [14].

4.7 Fail-Safes

A trip switch is installed in the system which controls a back-up braking system. This ensures that climbers will be stopped if power is cut to the device and the UPS and battery back-up system also fails. A cam is placed alongside the slack management wheels and will engage with a solenoid jamming the rope up in the wheels. The cam will engage when the solenoid loses power. This system can only be disengaged manually and will serve as an additional safety measure for the device.

Once the climber is tied in, the device will "take up slack" using the slack management system until a torque of 24 N.m is detected on the torque load cell which would be equivalent to 300 N.m of force (the hand force of the motors). This is to ensure the knot is tied securely.

5. SYSTEM EVALUATIONS AND IMPROVEMENTS

This section evaluates the current system's performance, identifies limitations, and proposes improvements to enhance safety, efficiency, and reliability. Through the design of the system, it was noted that simulations that are purely based in mathematics are difficult to accurately represent the kinematics of the system. Many equations need to be combined and evaluated to have a fully mathematical model of the system, especially the fall arrest system. This led to assumptions being made and only partial equations being used to simulate the effects of certain sub-systems. In future, industry specific engineers who understand the mathematics and kinematics at a deeper level could implement simulations that are more comprehensive.

The readings from the torque meter could be used as an indication of when to power down the slack management motors when they are not in use to prevent them from burning out. This was not explored in depth in this design iteration as it would introduce complexities within the fall arrest logic as motors might not be able to produce the hand force required from a standby state.

Overheating due to friction is considered when choosing materials by looking at thermal conductivities, however more heat dissipation calculations could be implemented by professional engineers to determine whether increased cooling would be needed in any of the sub-systems.

A future problem could be encountered by the rope coiling on the floor of the gym while the climber ascends the route. If the rope becomes knotted or tangled the rope could get stuck in the device. This could be improved by implementing a spool or coiling mechanism.

6. SOCIAL, ENVIRONMENTAL, ETHICAL AND ECONOMIC CONSIDERATIONS

Designing and developing a device with safety as the primary objective will impact social, environmental, ethical, and economic aspects in various ways. Many considerations have been considered during the design process. This section highlights the considerations made and fully evaluates the design.

6.1 Social Impact

Climbing is an extremely social sport, where safety measures are often reliant on another climber to be present such as "buddy checks". Climbers also require a second person to belay them on climbs. This device would enable people who do not have another person to belay for them or perform these safety measures to still climb safely. This could also encourage more beginners to the sport without needing someone more experienced to belay them.

This device would provide standard catches across the board no matter on who the climber is. This could be useful for competition settings where fairness across climbers is important to keep in mind. Implementing this device in competition settings will take out the human bias of belaying and skill differences in different competition belayers.

6.2 Environmental Impact

The lead auto-belay device is to be placed in a climbing gym in Mpumalanga. Design choices have been made to reduce the power consumption of the device without impacting the reliability of the device with low power rating motors being chosen. Rubber shock absorbers have also been implemented in the mounting system to reduce any damages on the climbing wall, which acts as the immediate physical environment.

When developing circuitry, the environmental concern of mining the precious metals for circuit boards and processors needs to be factored in as these materials are being depleted increasingly quickly in the fourth industrial revolution.

6.3 Ethical Considerations

This device would be implemented to save lives during falls in an extreme sport. This comes with ethical considerations and responsibilities to ensure the device meets safety standards set by the UIAA and EN 341:2011 [15], [16]. Meeting safety standards helps ensure the device will not fail and would be reliable for the weights it is specified to be used for.

Another ethical consideration for the current design is that it lacks the input from professional engineers that would make up the multidisciplinary team involved in designing a device such as this. Mechanical engineers would be required to develop intricacies in the mechanical systems such as the calculations for the fall arrest system and the specific type of sprag clutch needed. Materials engineers would be needed to ensure the correct and most environmentally friendly materials are considered. Electrical and Information engineers would be required to design power and logic systems of the device.

6.4 Economic Analysis and Considerations

This device is estimated to cost R 37 200, which is further broken down in Appendix B. Given the critical role this device plays in ensuring climber safety, cost was not one of the main design priorities, but was still considered. This ensures a safe device that is still cost-effective within the design criteria.

The design process and materials would need capital invested into it, as well as the funds needed to apply for accreditation to the various standard compliance bureaus.

7. Sustainability Analysis

Throughout the design, sustainability has been prioritised within all the design decisions. Brushless DC motors are chosen over brushed motors for increased longevity. Stainless steel is chosen over aluminium for the fall arrest system, despite the lower thermal conductivity as it will have less wear over time and last longer in the system. A secure and robust mounting system has been proposed to ensure the components are not damaged during daily use of the device.

The device will be serviced once a year and inspected every 3 months for the first year of use to ensure correct usage and functionality. During the service motors and moving parts would need to be correctly lubricated ensuring safe future use. The device is equipped with a removable case (coloured red in Figure 1) with a detachable screen to make moving parts accessible when being serviced. The display will also have warnings appear when the device requires servicing or when problems are detected with buddy-checks and battery levels.

While the current design addresses many sustainability aspects, future versions could investigate components that are more energy efficient and could incentivise renewable energy sources to the gyms this product is sold to. Research on more sustainable materials could be performed by industry specific engineers to reduce the environmental impact of the product as well as implementing a recycle programme for devices that are no longer in service.

8. Conclusion

Through the process, a lead auto-belay system has been designed. Simulations and calculations have been performed to ensure that the device will arrest a climbers fall without letting them hit the floor regardless of the distance they have climbed. The device is designed to arrest falls of climbers from 30 kg (294 N) to 150 kg (1470 N). The fall arrest system is friction based with a motor that acts as an assisted locking device to increase the bending and squeezing forces on the rope. These forces allow the dynamic stretch of the rope to aid in providing a soft catch for the climber.

Slack will be managed by two brushless DC motors and wheels with rubber sleeves to retract rope when too much slack has been pulled out. The method of continuously maintaining a small amount of tension on the rope mitigates the risk of falling to the floor at early stages of the climb. A sprag clutch allows for these motors to be pulled in the opposite direction without any negative effects. As safety is a priority, a back-up cam style brake is designed. This brake is activated as soon as the device loses power and can only be manually disengaged. Additionally, a "buddy-check' is performed by the device by applying tension to the climber's knot and measuring the resultant torque. The device is securely mounted to the climbing wall using chemically bonded wall anchors and rubber shock absorbers as to prevent damage to the climbing wall due to falling force and to provide stability.

The device is designed to be powered by municipal power and is equipped with a UPS to prevent issues due to voltage drops as well as blackouts. Municipal power is converted to 24 V DC power through a switching power supply.

Future work could involve further refinement through advanced simulations and real-world testing to validate long-term durability and performance across various environmental conditions. The successful implementation of this device has the potential to set new benchmarks in climbing safety, contributing to the evolution of industry standards and enhancing the overall safety of the climbing community. Ultimately, this project highlights the paramount importance of safety-centric design in climbing equipment, reinforcing the necessity of rigorous engineering practices in the development of such critical systems.

REFERENCES

[1] F. Fuss and G. Niegl, “Understanding the mechanics of dynamic rope brakes,” *Procedia Eng.*, vol. 2, pp. 3323–3328, Jun. 2010, doi: 10.1016/j.proeng.2010.04.152.

[2] CityROCK, “Assisted-Braking Belay Devices,” GoodBETA. Accessed: Aug. 02, 2024. [Online]. Available: https://goodbeta.co.za/assisted-braking-belay-devices/

[3] A. Tonoli, R. Galluzzi, E. Zenerino, and D. Boero, “Fall identification in rock climbing using wearable device,” *Proc. Inst. Mech. Eng. Part P J. Sports Eng. Technol.*, p. 1754337115592749, Jul. 2015, doi: 10.1177/1754337115592749.

[4] H. Oppel and M. Munz, “A Time Window Analysis for Time-Critical Decision Systems with Applications on Sports Climbing,” *AI*, vol. 5, pp. 1–16, Dec. 2023, doi: 10.3390/ai5010001.

[5] “Forces at work in a real fall - Petzl Other.” Accessed: Aug. 24, 2024. [Online]. Available: https://www.petzl.com/INT/en/Sport/Forces-at-work-in-a-real-fall?ActivityName=Rock-climbing

[6] J. Titt, “Belay Device Theory, Testing and Practice”.

[7] goodBETA, “Everything Ropes,” GoodBETA. Accessed: Aug. 24, 2024. [Online]. Available: https://goodbeta.co.za/everything-ropes/

[8] “Elongation - Petzl USA.” Accessed: Aug. 24, 2024. [Online]. Available: https://www.petzl.com/US/en/Sport/Elongation?ActivityName=Multi-pitch-climbing

[9] “Comparing the Thermal Conductivity of Stainless Steel to other Metals.” Accessed: Aug. 23, 2024. [Online]. Available: https://www.stainless-structurals.com/blog/comparing-the-thermal-conductivity-of-stainless-steel-to-other-metals/

[10] “Plastics - Thermal Conductivity Coefficients.” Accessed: Aug. 23, 2024. [Online]. Available: https://www.engineeringtoolbox.com/thermal-conductivity-plastics-d_1786.html

[11] “ROS: Home.” Accessed: Aug. 21, 2024. [Online]. Available: https://www.ros.org/

[12] R. P. Ltd, “Raspberry Pi 4 Model B specifications,” Raspberry Pi. Accessed: Aug. 23, 2024. [Online]. Available: https://www.raspberrypi.com/products/raspberry-pi-4-model-b/specifications/

[13] “1.5 kVA / 1,350 Watt Power Conditioner, Voltage Regulator, & Battery Backup UPS,” Battery Backup Power, Inc. Accessed: Aug. 23, 2024. [Online]. Available: https://www.backupbatterypower.com/products/1-5-kva-1-350-watt-dsp-tower-ups-uninterruptible-power-supply-and-power-conditioner-for-sensitive-electronics

[14] “BLMR6400SK-GFV-B | Oriental Motor Brushless DC Motor, 400 W, 24 → 48 V dc, 22.9 Nm, 3000 rpm | RS.” Accessed: Aug. 23, 2024. [Online]. Available: https://za.rs-online.com/web/p/dc-motors/2822077

[15] admin, “EN 341:2011 EN 341:2011,” Pacific Certifications. Accessed: Aug. 23, 2024. [Online]. Available: https://pacificcert.com/en-341-2011-personal-fall-protection-equipment-descender-devices-for-rescue/

[16] “Safety Standards - UIAA.” Accessed: Aug. 23, 2024. [Online]. Available: https://www.theuiaa.org/safety/safety-standards/

APPENDIX A

The pseudocode below shows the logic that would be implemented for the lowering system of the device. This is a form of logic-based control with a conditional statement so ensure the descent speed remains constant between a small range of speeds.

Pseudocode: *Conditional Logic for Descent System*

```
#   Result: Controlled descent speed for lowering of climber

If fall is detected then:
    If mode is 'projecting mode' then:
        Suspend climber for 20 seconds
        Check if climber is back on the wall
        If climber is on the wall then:
            Release moving arm
            If torque load > threshold (climber is climbing) then:
                Maintain position (do not lower climber)
            Else (climber is being lowered) then:
                Calculate descent speed based on rope speed
                Adjust friction accordingly
    Else if mode is 'competition mode' then:
                Immediately start lowering climber
                Calculate descent speed based on rope speed
                Adjust friction accordingly
```

APPENDIX B

The cost of the device is important to consider during the design process. A cost breakdown is performed and tabulated below. Costs in this table are estimates from various sources and suppliers of the components.

Table 3: Cost breakdown of the design

Qty	Component	Cost
2	DC Brushless Motor	R 10 000
1	DC Stepper Motor and Gear System	R 6000
1	Torque Load Cell	R 8000
1	Rotary Encoder	R 100
1	Raspberry Pi	R 2000
1	Steel Case and Mounting	R 4000
1	Switching Power Supply	R 1100
1	Uninterrupted Power Supply and Battery	R 5000
1	Circuitry	R 1000
Total		R 37 200

APPENDIX C

An easy way to explain the system and allow a reader to understand and place items visually is with a detailed diagram or illustration of the system. Below shows a further annotated illustration of the system showing components and finer details as well as a close-up image of the rubber wheel sleeves used to grip onto ropes of different diameters. These figures were design in Autodesk's Fusion 360.

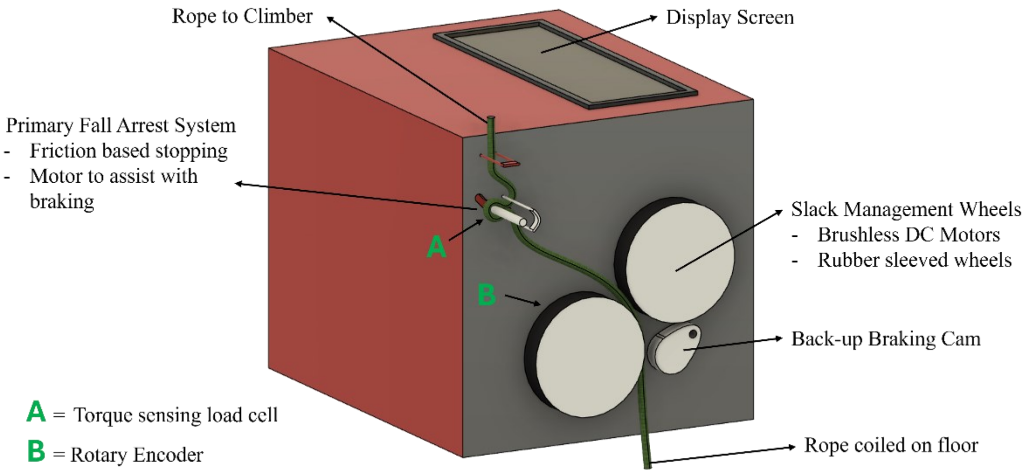


Figure 8: Fully annotated illustration of the design

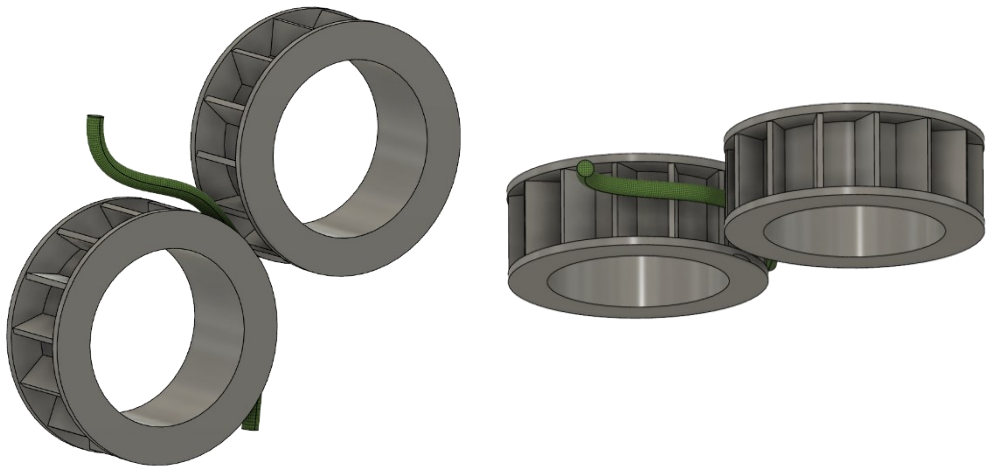
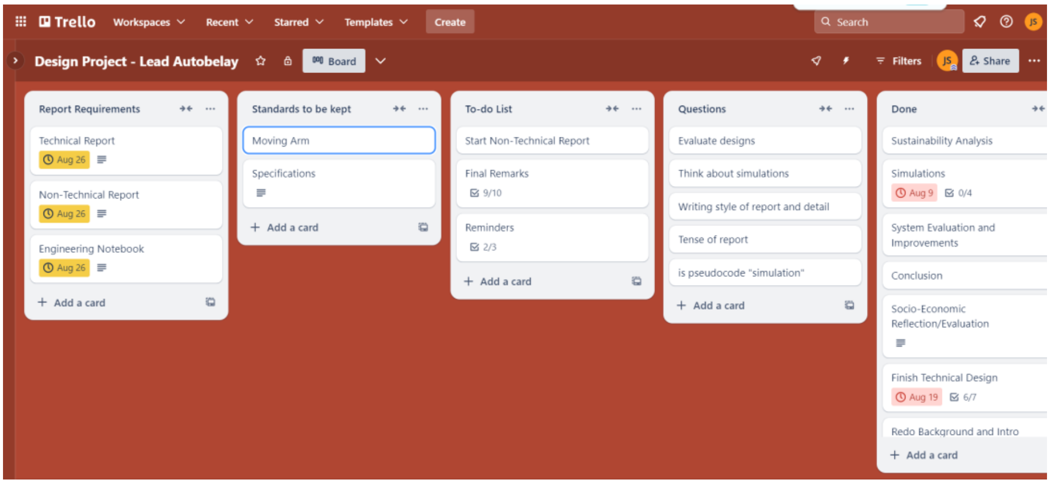


Figure 7: Illustration of the rubber wheel sleeves

APPENDIX D

Time management is an import part of systems design. For the duration of the project, a project management tool (Trello) was used to keep track of important deadlines that were set and to keep track of questions and points that needed to be kept standard throughout the project.



A week-by-week breakdown is also included to show how the project progressed through its duration. This is shown in the table below.

Table 4: Work Breakdown of the design process

Week	Progress Made
Week 1	Mainly involved research and problem understanding. Familiarisation with lead-climbing was done by attending Wits University Mountain Club practices and visiting City Rock Johannesburg.
Week 2	Conceptual thinking of sub-systems required, and brainstorming ideas was done. Background research stemming from ideas was performed to inform design decisions.
Week 3	Introduction and Literature Reviews were done, further informing design decisions as a deeper understanding of the project developed.
Week 4	Two final potential high-level designs were investigated, and design decisions were researched. The final design was solidified, and simulations were done to ensure the design was sustainable and verify it would be functional.
Week 5	Further simulations and investigation into possible components of the design were done. This included the documentation of the technical design in a report.
Week 6	The design was analysed for social, ethical and environmental impacts as well as overall sustainability. A non-technical report was also documented.

APPENDIX E

A table detailing the location of the Graduate Attributes is included in the report as a personal check to ensure that all of the Graduate Attributes have been met and additionally for the ease of locating the Graduate Attributes for the reader.

Table 5: Description of Graduate Attributes (GAs) and location in the report.

GA	GA Description	Location in Report	Page Number
GA 3	Design a component, system, product or process, the achievement of which requires engineering knowledge and constitutes a complex engineering problem.	Technical Design	5 - 12
GA 1	Solve problems using analysis, synthesis and evaluation at various levels, including complex engineering problems.	Technical Design	5 - 12
GA 2	Use specialist and fundamental engineering knowledge, supported by mathematics and natural sciences, in the solution of engineering problems, including a complex engineering problem.	Technical Design	5 - 12
GA 5	Select, use effectively and evaluate the results produced by appropriate tools and methods for the problem at hand.	Technical Design & System Evaluations and Improvements	5 - 12
GA 7a	Identify and address social, economic or environmental impacts during the course of engineering activity.	Social, Environmental, Ethical and Economic Considerations	13
GA 7b	Identify, analyse, and evaluate the sustainability of an engineering solution.	Sustainability Analysis	14
GA 8a	Work effectively as an individual in the planning and execution of a project.	Full Technical Report	
GA 6a	Report on an engineering activity in the form of a long technical report or paper that meets stated format requirements.	Full Technical Report	
GA 6b	Communicate with non-technical and affected parties on impacts of an engineering solution and amelioration of negative impacts in a short report.	Full Non-Technical Report	