1. PROBLEM STATEMENT

A study of the prevalence and pattern of weightlifting injuries found that 27% of lifters in Taif City, Saudi Arabia received an injury from weightlifting in the last six months [1]. Proper spotting plays a major role in injury prevention.

1.1. Need Statement

According to a cross-sectional and meta-analytical narrative review, performed by the School of Sport Sciences at Umeå University in Sweden, bench press related injuries represent anywhere from 18–46% of obtained injuries whilst lifting, depending on demographic [2]. The demographics were separated into categories based on both experience levels and training styles that included inexperienced, sub-elite, and elite. The study then categorizes them into training styles such as CrossFit, Olympic lifting, bodybuilding, Highland Games, etc. The review outlines the intrinsic risk factors, which are improper technique, fatigue, and high loads [2]. Monitoring and minimizing these risks are ultimately the responsibility of the lifters; however, another party acting as an experienced and impactful spotter would prove beneficial in minimizing the risk of injury. Another systemic review, performed by Bond University in Australia, concluded that in the category of lifters not involved in professional circuits, the rate of injury is around one to two injuries per year, across twenty different studies [3]. With the statistic that 40% of Americans work out in a home gym setting [4], the need for improved gym safety is clear. This culmination of information underscores the point that weightlifting is a substantial injury risk, no matter the experience level of the lifter. Therefore, the development and implementation of a procedure to serve as a suitable precautionary measure against weightlifting-related injuries, specifically in the domain of bench pressing, is crucial.

1.2. Objective Statement

The Auto-Spotter is a device that makes bench pressing safer without interfering with the effectiveness of the workout. The device has cables connected to the barbell with minimal tension in them initially. An accelerometer connected to the device monitors the speed and orientation of the barbell. If the acceleration is too high or the orientation of the barbell is titled, the barbell is stopped by a pulley. After stopping the weight from falling, the machine pulls the weight back up to allow the user to rerack the weight easily. The Auto-Spotter also includes a machine health monitoring system. This system serves as a precaution and notifies users of the Auto-Spotter whether there may be faults in the lubrication, stress, or wear of the individual components.

1.3. Background and Related Work

Many people who go to the gym do not have someone to spot them. There are numerous reasons not to have a proper spotter, and the result is an escalated chance for an injury while benching. Machines do exist that attempt to help those who do not have a spotter. Smith machines are the most common and utilize a design where the barbell is in a fixed path between two railings. This assists the user in performing the repetition without a spotter present. However, the limitation that the user is required to have a restricted range of motion is counteractive against developing optimal form. The Smith machine’s guided path also prevents the development of stabilizing muscles making it a less effective workout [5]. The Auto-Spotter's pulley system is different. It minimizes any tension on the bar while keeping the bar from falling on the user. It also lifts the bar back up in the case of a failed rep. The emulation of free-weight bench press can give lifters a more effective bench press experience while keeping them safe.

2. DESIGN REQUIREMENT SPECIFICATIONS

The following sections explain the requirements and constraints of the Auto-Spotter. The design decisions made cover what goals the Auto-Spotter meets within the marketing and engineering requirements, as well as outlining some constraints and engineering standards the design team is following.

2.1. Requirements

The Auto-Spotter meets marketing and engineering requirements that takes into consideration the customer and the design of the system.

2.1.1. Marketing Requirements

There are five marketing requirements of the Auto-Spotter:
1. The device is safe to use.
2. The device is easy to use.
3. The device promotes proper bench press form.
4. The device prevents lifting when powered off.
5. The device detects mechanical failures.

Figure 2-1 shows the objective tree, a visual representation of the marketing requirements of the Auto-Spotter.

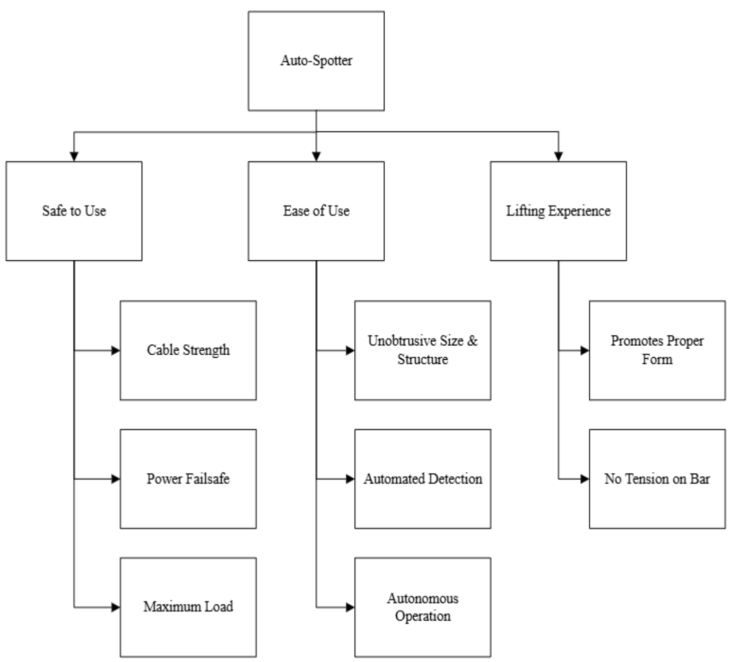

Figure 2-1: Objective Tree for the Auto-Spotter

The objective tree outlines the hierarchical needs of the Auto-Spotter. Requirements for the technical performance of the Auto-Spotter are outlined in the next section and are derived from the marketing requirements.

2.1.2. Engineering Requirements

Table 2-1 lists all of the engineering design requirements of the Auto-Spotter and explains how each relates to the marketing requirements.

Table 0-1: Engineering Design Requirements

Marketing Requirements	Engineering Requirements	Description
2, 3	The Auto-Spotter has less than 3 lbs of tension in the pulley system before the user is about to drop it.	The amount of tension is less than the weight of the clamps on the barbell so that it does not affect the user's workout.
1	The Auto-Spotter catches the barbell within 0.345 seconds.	The Auto-Spotter catches the barbell before it lands on the user. With the barbell at user's maximum reach the machine would have approximately 0.345 seconds to react.
1	The Auto-Spotter has a weight capacity of at least 220 lbs.	The pulley system lifts the average bench press weight. The average weight used for bench pressing is 220 lbs for men and 104 lbs for women [6].
1, 2	The Auto-Spotter catches the barbell if it is accelerating at a rate of 9 m/s^2 or greater.	The accelerometer detects when to activate the pulley by comparing the barbell acceleration to the acceleration due to gravity (9.81 m/s^2). This acceleration is rounded down to 9 m/s^2 as an extra safety precaution.
5	The Auto-Spotter's pulley mechanism does not vibrate more than 8.9mm/s (7.5mm/s+1.4) [7].	Vibration sensors connected to the pulleys measure the vibration within a 19% margin of error [8].
4, 5	The Auto-Spotter locks the pulley system when the winch's power consumption falls below 20% of the listed maximum.	The lock prevents people from using the Auto-Spotter while it is not powered on for safety.
5	The recess of the pulley and cable connections maintain a temperature at or below 62.7°C (52.7°C+10) [9].	An infrared pyrometer measures the temperature by reading the temperature of the surface where the cable makes contact. The desired temperature is within a 19% margin of error of the desired value [8].

Marketing Requirements:

1. The device is safe to use.

2. The device is easy to use.
3. The device promotes proper bench press form.
4. The device prevents lifting when powered off.
5. The device detects mechanical failures.

The pulley system reacts within 0.345 seconds of a drop to catch the barbell. This number is based on how long it takes to hit the user, after being dropped from the user's maximum reach, accelerating at 9.81m/s^2 (the acceleration due to gravity). The maximum reach is equal to the arm length of the user. The average arm length is 23 inches [10]. This information was used to calculate the time the barbell is falling, using equation (1):

$$time_{react} = \sqrt{\frac{reach_{user}}{\frac{1}{2} \cdot acceleration_{gravity}}} \tag{1}$$

The Auto-Spotter also detects when the barbell is dropped by using an accelerometer. The accelerometer keeps track of the acceleration and orientation of the barbell and catches it when it is moving too fast or if it is tilted. Then, it pulls up the barbell to be reracked easily.

The Auto-Spotter's pulley system also requires a high enough weight capacity to catch a barbell with a maximum weight of 220 lbs in total. The weight limit of 220 lbs was decided since this value is the average weight to lift on the bench press [6].

A machine health monitoring system adds a layer of reliability and safety to the Auto-Spotter. It acquires data and compares that data to safe baseline values and serves as a prevention method for machine failure related injuries. The machine health monitoring system prevents injuries to the user from machine failure and signals when the machine requires maintenance.

2.2. Constraints

In the design process of the Auto-Spotter, many constraints restrict its build specifications. These constraints inform the design decisions pertaining to the Auto-Spotter. External factors include nonnegotiable constraints such as budget, time, size, and durability.

Table 2-2: Constraints

Type	Name	Description
Economic	Cost	Team Bacon has been given a budget of $1000 granted to them by Mississippi State University's electrical engineering department.
Economic	Time	The design team has a deadline of November 2024 to have individual subsystems working and ready to be integrated into one machine. A final, fully integrated, and operational machine is expected by April 2025.
Health and Safety	Safety	The Auto-Spotter prevents injuries from the dropping of a barbell, as well as getting stuck under a barbell. It contains proper signage and warning to indicate to users the dangers of operation and maintenance.

Operation	Maximum Load	To meet American Society of Testing and Materials (ASTM) Standard Specification F2277-17a [7], the machine holds six times the listed weight limit for a duration of five minutes.
Manufacturability	Structure	The Auto-Spotter is durable enough to handle catching weights up to 220 lbs easily and remain out of the user's way.
Reliability	Durability	The Auto-Spotter is durable enough to be used daily by multiple people. It maintains its function despite possible damage from outside sources.

The base of this machine is made of durable metal to support the pulley system's weight limit. The machine is accommodating for any bench to be used while remaining out of the user's range of motion. The Auto-Spotter is accessible to people of various body sizes and shapes.

For the Auto-Spotter to meet the team's standard for safety, the combination pulley system and weight movement detection system sufficiently perform the task of preventing a bar from dropping and raising the weight to a position where the barbell is easily reracked. The Auto-Spotter detects when a bar has been stationary on a lift for an extended period. The period is determined by observational testing performed by the design team.

According to ASTM safety standards, the Auto-Spotter possesses the proper signage indicating how a machine is utilized and potential hazards. A graphic illustrates the muscle groups targeted whilst the Auto-Spotter is in use. A detailed explanation of how the workout is to be performed is presented with pictures [12]. The maximum weight allowance for the Auto-Spotter is required to be listed as well. The weight allowance is determined by testing for the maximum load the pulley system holds for a five-minute duration. Equation (2) gives the maximum weight allowance of the Auto-Spotter [11].

$$load_{safe} = \left(\frac{1}{6}\right) \times load_{max} \tag{2}$$

2.3. Standards

To ensure safe operation and machine health, the Auto-Spotter abides by engineering standards listed in Table 2-3.

Table 2-3: Engineering Standards

Specific Standard	Standard Document	Specification / Application
ASTM F2277-17a	The product follows ASTM Standard F2277-17a specifications [11].	The listed weight allowance for the Auto-Spotter is restricted to one sixth of the maximum load that is held for five minutes.
ASTM 1749-15	The product follows ASTM Standard F1749-15 specifications [12].	Warning and instructional signage is required to be placed on the Auto-Spotter. Graphics that show targeted muscle groups and a diagram of how to use the machine are required. Other

		warnings for maintenance and moving parts are also necessary.
ASTM F2216-17a	The product follows ASTM Standard F2216-17a specifications [13].	The cable around the pulley does not become dislodged when 4.5 lbs of perpendicular force is enacted upon it.
ISO 17359:2011E	The Auto-Spotter adheres to the International Organization of Standard's (ISO) guidelines presented in document 17539:2011E [14].	The Auto-Spotter's machine health monitoring system follows strict testing, data acquisition rate, and parameter limitations for implementation. This process requires extensive and feasible baseline data testing.

The ASTM Standard F2216-17a specifications detail how to test if a pulley system for a machine to prevent the rope or belt from disengaging with the pulley enclosure. Section 6.6 details the testing as applying 4.5 lbs of force perpendicular to the direction of travel without the rope falling out of the enclosure during the full range of motion [13].

According to the ISO-17359 safety standard, a litany of tests and calculations are performed to set baseline data for the machine health monitoring system. Firstly, the machine health monitoring system checks a series of faults for each component. Each mechanical component in the Auto-Spotter is tested for specific mandated parameters. This standard also mandates certain guidelines for the data acquisition rates and feasibility of data collection. Data acquisition rates are required to be faster than the rate at which the environment changes [14]. Feasibility is defined as the ability for the data necessary to be recorded in a precise and accurate manner. The proper recording of the system data enables efficient machine health monitoring, which prevents injuries and improper use due to mechanical failures.

3. DESIGN APPROACH

This section is about Team Bacon's approach to creating the Auto-Spotter, meeting all engineering and marketing requirements, while also working within the constraints and standards listed in the previous section. This section includes three different design options, an explanation of how the Auto-Spotter and each of its subsystems operate, a comparison of parts that can be used to make it, and a description of the final prototype.

3.1. Design Options

The Auto-Spotter works by tracking the movement of the barbell to detect if the barbell is about to be dropped and catching it, using a pulley system connected to each end of the barbell. Three different ways to track the movement of the barbell were considered. These options include using a camera and image processing software to track the speed and balance of the barbell, a wheel encoder in the pulley system to track the barbell's position, and using an accelerometer to monitor acceleration.

3.1.1. Design Option 1: Image Processing

The first idea the design team had for how to make the Auto-Spotter work was to use image processing. A camera connected to a microcontroller tracks the barbell's movement, monitoring the speed and balance of the barbell to detect when the barbell is dropped. If a drop is detected, the microcontroller activates the pulley system to catch the barbell. The advantage of image processing is that it tracks the movement without impacting the lift.

While this design option works, it is not without its drawbacks. A tripod and camera would make the Auto-Spotter's setup take up more space, and the design team has limited experience with testing and implementing image processing, especially within a short time frame. For these reasons, the team decided against this approach.

3.1.2. Design Option 2: Wheel Encoder

Another approach that was considered was using a pulley system that has a wheel encoder, allowing the pulley system itself to track the barbell's movement. It would track the position of the barbell based on the length of the cable coming out of the pulley. However, the only way to prevent the cable tension from interfering with the user's workout is to have some slack in the pulley before a drop is detected. The extra slack would cause the wheel encoder's data not to be accurate, so the team decided against this approach.

3.1.3. Design Option 3: Accelerometer

Alternatively, an accelerometer is used to track the barbell's movement. The accelerometer, also connected to a Raspberry Pi, detects tilts and tracks acceleration, allowing the Auto-Spotter to catch the barbell when it is unbalanced and when the barbell's acceleration is close to the acceleration due to gravity (9 m/s^2). The accelerometer data is also used to calculate the position of the barbell so that the machine knows how high or low it is. This data is used when the pulley system is lifting the barbell.

The team decided that this was the best approach for the Auto-Spotter because it is significantly easier to program than image processing due to the accelerometer not requiring as much data for testing. It also takes up less space than the image processing system because the accelerometer is small and is on the barbell.

3.2. System Overview

The Auto-Spotter is designed to use a 120V AC wall outlet for power and take inputs from the accelerometer and machine health sensors to send a signal to the electric hoist. The signal tells the hoist either to brake completely to catch the weight during a lift, not to activate at all to prevent a dangerous lift, or to lift the weight back up after a user's failure during the set. A basic overview of this system is shown in Figure 3-1.

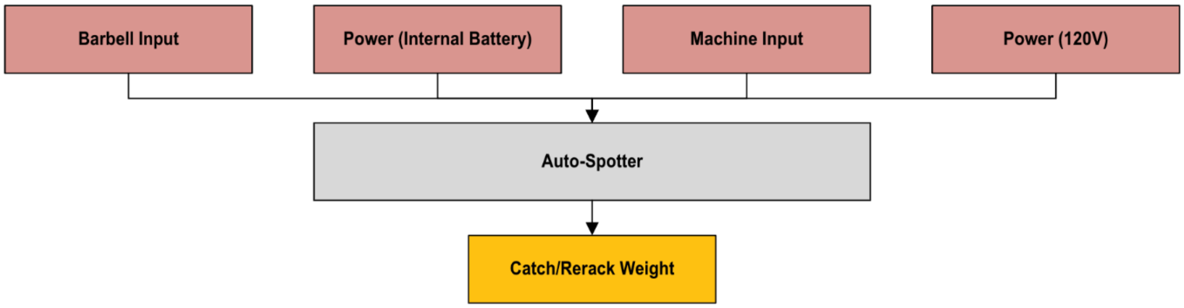

Figure 3-1: Auto-Spotter System at a Glance (Level 0)

Figure 3-1 is a high-level diagram for explaining the basic inputs and outputs of the Auto-Spotter. A more detailed diagram that explains these inputs and outputs and how they are connected to the system is shown below in Figure 3-2.

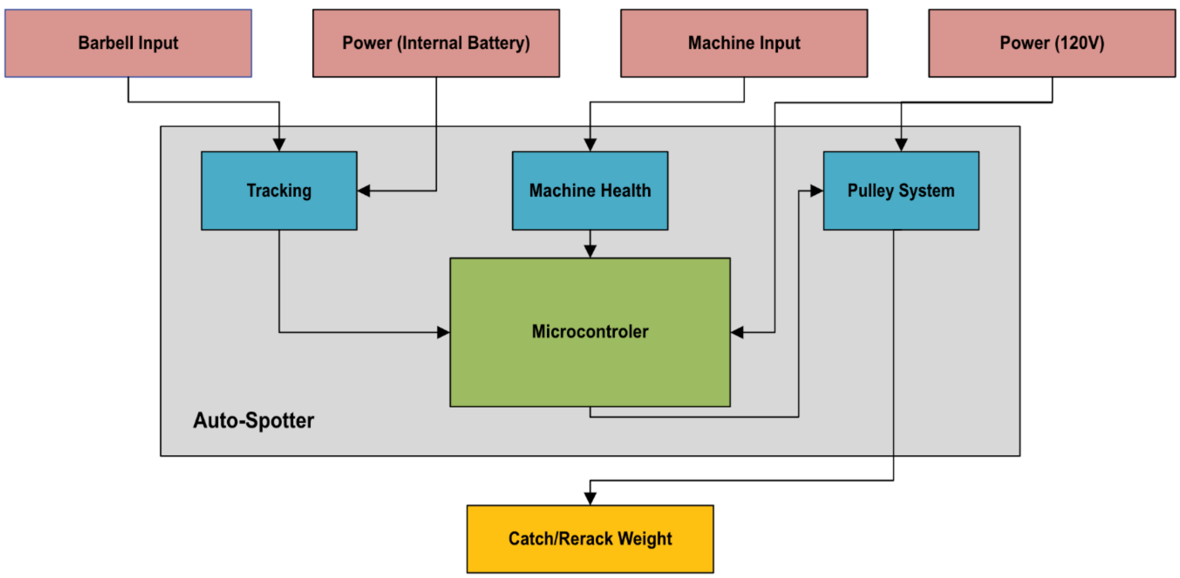

Figure 3-2: Auto-Spotter Functionality (Level 1)

The Auto-Spotter is comprised of a series of subsystems that share the end goal of the bar being secure in the rack position. The bar is lifted back up by the electric hoist in case of a failed rep, or the electric hoist does not allow the bar off the rack at all if a problem has been detected by the machine monitoring system. The accelerometer is used to send data to the Raspberry Pi, which then checks to see if the barbell must be stopped by the electric hoist. The infrared pyrometer and vibration sensor all determine if the machine's health is up to standard by sending data to the Raspberry Pi. The system would then not allow the barbell to have any slack and prevent bench pressing if damage has been found.

3.2.1. Microcontroller/Integrated Circuit

The design team has adopted the Raspberry Pi 4 Model B, as it is the most accommodating microcontroller for the Auto-Spotter. The Raspberry Pi's task is to measure the data given from the various sensors, as well as facilitating the safety locking and shutdown protocols.

Table 3-1: Microcontroller Options

Product Name	Software Complexity	Accessibility of Sensor Components	# of GPIO pins
Preferences	Easy – Medium	Very	> 24
Arduino UNO R3 [15]	Easy	Very	14
Raspberry Pi 4 Model B [16]	Medium	Very	26
Digilent Basys 3 FPGA [17]	Hard	Moderately	24-32

As a measure to integrate all the subsystems present in the Auto-Spotter, the use of some form of micro-controller or integrated circuit is critical. The chosen hardware's compatibility with an array of various sensors and their functionalities is paramount. The Raspberry Pi 4B, seen in Figure 3-3 below, meets this criterion; a wide variety of sensors under the Raspberry Pi brand and from other electronics manufacturers are compatible and fit within the budget constraint. Moreover, simplicity regarding software components allows the various subsystems to interact, in the code uploaded to the microcontroller, fluidly. This is achievable because individuals overseeing software integration on the design team have experience in Python coding, which is one of the inherent languages for the Raspberry Pi. Another metric to weigh the plausibility of the design team's choice is the amount of digital input pins present.

Figure 3-3: Raspberry Pi 4 Model B [18]

The Auto-Spotter is comprised of four different sensors that make up the barbell movement detection and machine health monitoring system hardware. Each sensor type may be implemented numerous times to account for each of the mechanical components present. Included in the design are accelerometers, vibration sensors, infrared pyrometers, and a current or power sensor. The Raspberry Pi handles the load of sensor input with its twenty-six GPIO pins, which is two more than the minimum requirement.

3.3. Subsystems

The Auto-Spotter has three subsystems. These subsystems are the pulley system, tracking, and machine health monitoring. The pulley subsystem's purpose is to catch the barbell when the Auto-Spotter detects a drop. The tracking subsystem achieves this by monitoring the acceleration and orientation of the barbell using an accelerometer. Lastly, the machine health subsystem monitors temperature, vibrations, and power to identify any mechanical errors and ensure the user's safety.

3.3.1. Pulley System

The pulley subsystem primarily focuses on the winch used to rerack the weight and the overall structure of the product ensuring the Auto-Spotter's durability. The winch is responsive enough to follow the barbell with an equivalent amount of slack no matter where the barbell is located within the workout. This is done so that the barbell can react quickly no matter where the barbell is located within the rep. With the winch operating at a maximum capacity of 220 lbs, the structure of the Auto-Spotter is durable enough to control this weight for repeated drops of the barbell. Table 3-2 describes the winches Team Bacon researched in order to work with the Auto-Spotter.

Table 3-2: Pulley Options

Product	Cable type	Weight capacity	Remote type	Cost
Preferences	Steel cable	>1000 lbs	Wired	< $250
Stegodon Jungle Explorer [19]	Steel cable	2500 lbs	Wireless & Wired	$89.99
Zostera ATV/UTV/trailer winch [20]	Synthetic rope	2000 lbs	Wired	$79.90
RENGUE Electric Hoist [21]	Metal Cable	1320 lbs	Wireless	$139.99
VEVOR Electric Hoist [22]	Steel cable	1320 lbs	Wired	$139.99

When looking at possible winches to wind up the barbell the design team narrowed the choice down to two types. Team Bacon's first option is to use a winch similar in design to those attached to the front of trucks often used to tow other cars. The second option is an electric hoist used in mechanical garages to assist workers lifting heavy mechanical components. The design team ultimately chose the VEVOR Electric Hoist due to two main advantages the VEVOR Electric Hoist had over the other winches. Firstly, it comes with an emergency stop button, which aligns with the function of the Auto-Spotter. This emergency stop function can be activated the moment the system realizes the barbell is moving too fast. Having this button makes the machine easily adjustable. The second main reason is the power that is used for these devices. A winch attached to a car draws its power from the car’s battery, which is dealt with by the car's alternator. The design team saw this flaw and decided to avoid it completely by using a device that is powered directly by a wall outlet. Figure 3-4 shows the selected electric hoist Team Bacon is using for the Auto-Spotter.

Figure 3-4: Pulley Selected [21]

The system has two clips that attach to the barbell. Using the clip at the bottom attached to the pulley allows the machine to have the cable double back for more support. The second clip can be removed from the motor and used on its own. The bottom right shows the remote control used, which Team Bacon can modify to communicate with the Raspberry Pi.

3.3.2. Tracking

Accelerometers measure the acceleration of an object in the x, y, and z directions with consideration to free fall. Free fall occurs in one direction only. Therefore, an analysis of the measurements made in all three directions yields tilt data. The Auto-Spotter has an accelerometer attached to a barbell so a determination of the speed and orientation of the barbell can be made. Table 3-3 shows different design choices made for the accelerometer used in the Auto-Spotter.

Table 3-3: Accelerometer Options

Product	Power	Interface	Cost
Preferences	DC & Built-in	Wireless	< $100
HiLetgo 680727635251 [23]	5 V	Arduino	$6.49
WT901B [24]	3.7 - 5 V	WIFI, USB	$33.90
BWT901CL [25]	3.7 V, 4-hour battery life	Type C, Bluetooth	$45.99
BerryIMUv3 [26]	3.3 or 5 V via Raspberry Pi	I2C, SPI, Raspberry Pi, Arduino	$38.00
WT9011DCL [27]	5 V, 8-hour battery life	Type C, Bluetooth	$57.99

In the selection of an accelerometer for the Auto-Spotter, the following was considered: wireless capability, powering, accuracy of measurements, sampling rate, and the accelerometer attachment to the system. In Table 3-3, the criteria are chosen based on the factors that vary for the five different accelerometers. All the accelerometers in the table perform acceptable g-force acceleration measurements, record and send data to the Raspberry Pi in milliseconds, and output data in 3-axis format. Acceptable g-force acceleration measurements entail a high g-force range for quick movements and having a low g-force range for slow movements. During bench pressing, the g-force range is important because several different kinds of movements occur, and the accelerometer needs to cover the spread of different accelerations.

The HiLetgo accelerometer has the lowest cost but is not compatible with a Raspberry Pi; it interfaces well with Arduino instead. The HiLetgo accelerometer requires a physical connection to a 5-V power supply. The BerryIMUv3 and WT901B also require physical connections to their respective power supply values. For the Auto-Spotter interface, a Bluetooth connection was desirable to prevent wires from disturbing the lifting experience. Therefore, even though the cost increases for the Bluetooth models, either the BWT901CL or WT9011DCL have the best power constraints. Both models have finite battery life from a built-in battery.

The WT9011DCL has double the battery life of the BWT901CL and five times the range (50 meters compared to 10 meters). The WT9011DCL is also smaller in size than the BWT901CL. The two models are also from the same company and thus have similar interfacing and coding needs. Due to these factors, the WT9011DCL is the ideal accelerometer and is displayed below in Figure 3-5.

Figure 3-5: WT9011DCL Accelerometer [27]

The left half of Figure 3-5 shows the actual accelerometer that performs the measurements, while the right side is the USB chip for Bluetooth operations. The size of the WT9011DCL is 1.26 x 0.96 x 0.45 inches. The accelerometer data feeds into the software as later displayed in Figure 3-6. The USB chip is inserted directly into the Raspberry Pi and the code handles data interpretation.

3.3.3. Machine Health Monitoring

The machine health monitoring subsystem measures the vibration and temperature of the pulleys, as well as the power the winch receives. These measurements serve as indicators to potential mechanical faults of the Auto-Spotter and provide insight into the safety and operating conditions. To perform measurements, the design team is using vibration sensors and infrared pyrometers. The vibration sensors indicate whether the wheel of the pulley is improperly connected or not functioning properly. Use of the infrared pyrometers informs the system if too much friction is present and relubrication or replacement of worn parts is necessary. Under these hazardous conditions, a user is unable to use the Auto-Spotter.

The following tables and paragraphs categorize and provide insight into the criteria that inform the selection of hardware components. Table 3-4 shows the vibration sensors and Table 3-5 shows the infrared pyrometers. The largest concerns for Team Bacon in the selection process of choosing a suitable vibration sensor are size, cost, and triggering threshold adjustability. The sensor must be able to fit into small spaces to read the values of an enclosed pulley. Also, the sensor triggers at or is able to read 9.8mm/s to be compatible with the Auto-Spotter, meaning that adjustable thresholds values are necessary. Lastly, the team prefers the chosen sensor to output digital values. The three sensors the team considers for implementation are listed along with the aforementioned preferences in Table 3-4 below.

Table 3-4: Vibration Sensor Options

Product Name	Analog/Digital?	Adjustable Threshold?	Size	Cost

Preferences	Digital	Yes	25x25x25mm	< $10 each
SW-420 Vibration Sensor Switch [28]	Analog	Yes	40x20x10mm	$5.99 each
Walfront Piezoelectric Vibration Sensor [29]	Digital	Yes	20x20x10mm	$8.77 each
Adafruit Medium Vibration Sensor Switch [30]	Analog	No	5x23x11mm	$0.95 each

Ultimately, Team Bacon is selecting the piezoelectric vibration sensor from Walfront, seen in Figure 3-6 below. The sensor fits within the size preference making it ideal for placing alongside the enclosed wheel of the pulley. The piezoelectric sensor is adjustable, allowing the team to adjust a potentiometer to calibrate the sensitivity. Lastly, the piezoelectric sensor is the only option in the table with digital outputs. Digital outputs make it possible for the team to closely monitor the values, calibrate, and debug during implementation due to receiving digital values, rather than flagging successes and failures.

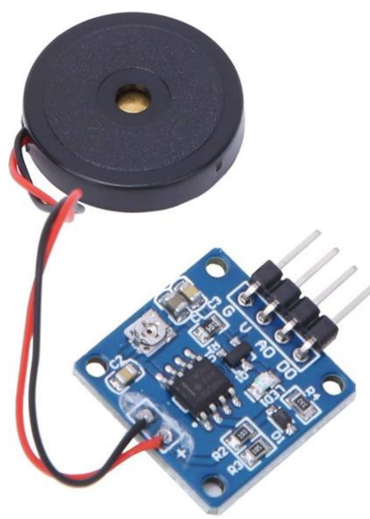

Figure 3-6: Walfront Piezoelectric Vibration Sensor [29]

The design team is including an infrared pyrometer in the Auto-Spotter to monitor the heat from friction on the pulley wheels. The most decisive criteria for the infrared pyrometers are the cost, and three criteria that attribute to constraints in implementing the sensors. These constraints are the maximum distance the sensors allow the read surface to be, the heat resistivity of the sensor, and the size or compactness of the sensor. The infrared pyrometer is placed in an enclosed chamber with the pulley wheel. This causes narrow margins for the sensor to fit into and the sensor is situated in close proximity to the surface that is being heated from friction. The sensors being considered and their metrics in relation to the preferences are listed below in Table 3-5.

Table 3-5: Infrared Pyrometer Options

Product Name	**Measuring Distance**	**Heat Resistance**	**Size (cm)**	**Cost**
Preferences	5cm	> 170°C	5x5x5	< $25 each
SHILLEHTEK Infrared Temperature Sensor [31]	0.5 cm	>380°C	8.5x6.5x1	$16.49 each
The Pi Hut Infrared Temperature Sensor [32]	2 cm	>380°C	2.8x1.6x2	$25.52 each
HiLetGo Infrared Temperature Sensor [33]	0.5 cm	>380°C	8.9x6.4x0.8	$15.99 each

Team Bacon concluded that the Pi Hut infrared sensor is the most suitable, seen in Figure 3-7 below. Specifically, Pi Hut's sensor is more expensive, but is capable of being up to four times the distance away compared to the sensors from SHILLEHTEK and HiLetGo. The Pi Hut infrared pyrometer sensor is also a more compact sensor, making implementation easier. These features contribute to the Pi Hut infrared pyrometer being more flexible in design capacity.

Figure 3-7: The Pi Hut Infrared Temperature Sensor [32]

3.3.4. Software Diagram

The machine health monitoring system code, illustrated below in Figure 3-9, runs alongside the drop detection code. Firstly, the Raspberry Pi monitors the accelerometers, ensuring that the barbell is neither tilted nor falling at too great of an acceleration. After monitoring the accelerometers, the code moves to monitoring the machine's health. This includes checking the values of the infrared sensors and the vibration sensors. If either is above the allowance, the locking mechanism engages and waits for the power, vibration, and temperature values to all return to below the accepted thresholds. After the values reach below the threshold, the system disengages the locking mechanism and the cycle loops. The constant acquisition of the data and sensors run on permanent loops.

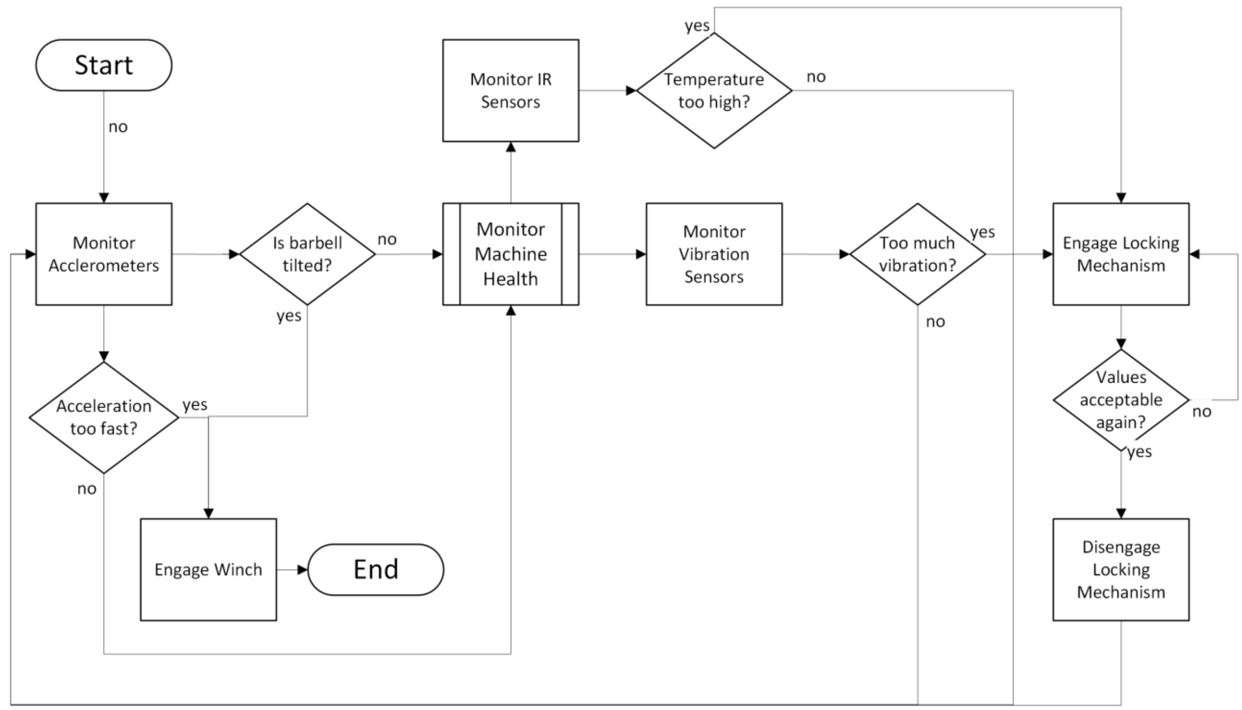

Figure 3-8: High-Level Software Flowchart

The code and the concepts illustrated in Figure 3-8 appear in the core structure of the level 2 design. This provides a clear mapping between foundational ideas and the more advanced structural elements of the system. This code encapsulates the work in achieving a robust final design, highlighting the progression from conceptual components to a fully integrated and functional model.

3.4. Level 2 Prototype Design

The design team's Auto-Spotter prototype uses a modified power rack as a structure that can carry the device's sensors and pulley system. Two electric hoists are located at the bottom of the rack and behind the bench press. Attached are two pulleys mounted to the sides of the rack that unreel and reel the pulleys as needed. To avoid possible damage from outside sources on the sensors and subsystems, the team runs wiring and power through protective panels on the rack and barbell. A control panel for shutting on and off the device altogether is also provided. The evaluation phase is mostly about testing subsystems and the full system of the Auto-Spotter to make sure the device meets the standards and requirements that were previously detailed.

3.4.1. Level 2 Diagram

The Auto-Spotter is built around a gym cage that includes all of its parts. The power for each winch is delivered from a wall outlet. The sensors communicating with the winches are mounted to the barbell out of the way of the user's grip, which allows the product to work seamlessly. These mounted sensors communicate wirelessly with the rest of the device notifying the winches of the barbell's speed, location, and balance. If any of these recorded data sets fall out of a desired threshold the winches lock and wind the weight up to allow the user to rerack the weight safely. Figure 3-9 shows all of the parts in each subsystem and how they work together as a whole.

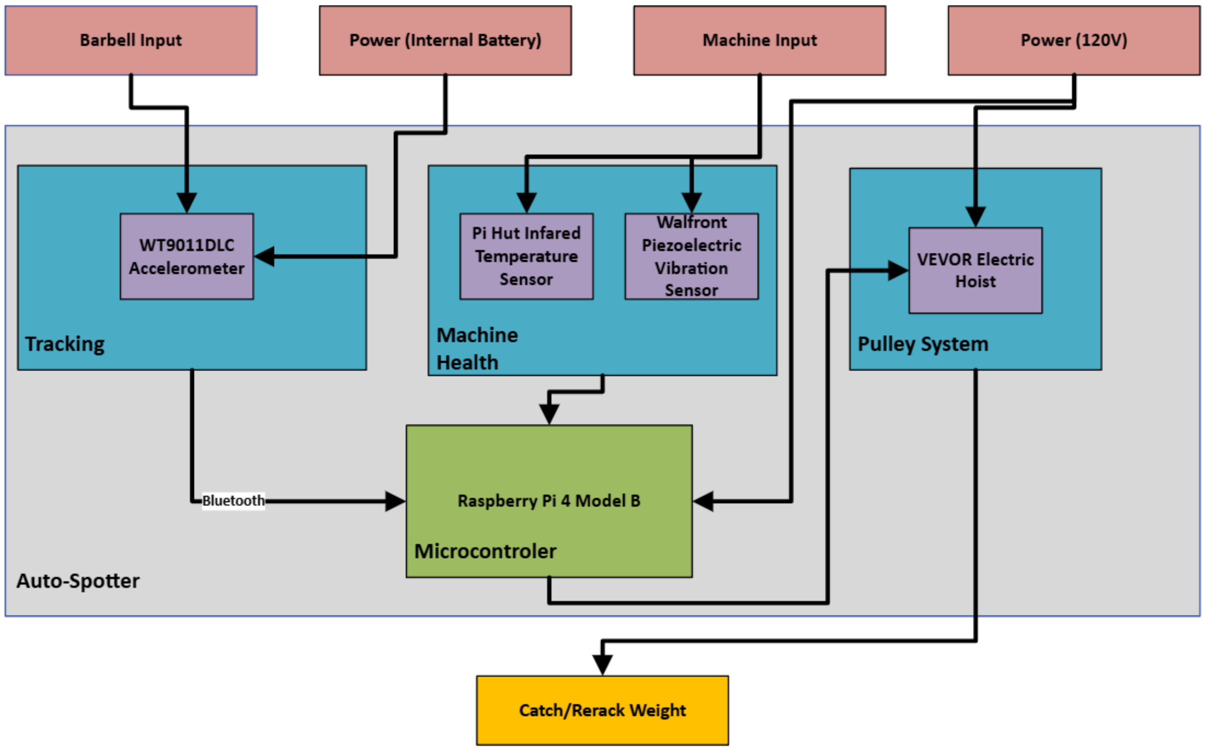

Figure 3-9: Diagram for Auto-Spotter (Level 2)

The above sections detail the design team's approach and the specifications that informed it, with each graphic detailing the flow of communication through the device as well as the logic it uses. The testing and refinement of the Auto-Spotter's subsystems are crucial to the safety and performance of the device.

REFERENCES

[1] H. Bukhary, N. Basha, A. Dobel, R. Alsufyani, R. Alotaibi, and S. Almadani, “Prevalence and Pattern of Injuries across the Weight-Training Sports.” *Cureus*, vol. 15, no. 11, Nov. 2023, doi: https://doi.org/10.7759/cureus.49759. [Accessed Sep. 19, 2024].

[2] V. Bengtsson, L. Berglund, and U. Aasa. “Narrative review of injuries in powerlifting with special reference to their association to the squat, bench press and deadlift.” *BMJ Open Sport & Exercise Medicine* 2018; doi:10.1136/ bmjsem-2018-000382 [Accessed Sep. 20, 2024].

[3] J. Keogh, P. Winwood, and G. Coast. “The Epidemiology of Injuries Across the Weight-Training Sports: A Systematic Review.” *Sports Medicine*, vol. 46, no. 6, pp. 773-795, Jun. 2016, doi: 10.1007/s40279-016-0492-2. [Accessed Sep. 20, 2024].

[4] CivicScience, “More Americans Work Out at Home than in Gyms, Citing Convenience.” [Online]. Available: https://civicscience.com/more-americans-work-out-at-home-than-in-gyms-citing-convenience/. [Accessed Sep. 20, 2024].

[5] Published as: “Adam L.”, “Smith Machine vs. Free Weights: Pros, Cons, and How to Choose for Your Fitness Goals 2024.” *NutroOne*, [Online] Mar. 14, 2024. Available: https://nutroone.com /en/2024/03/14/smith-machine-vs-free-weights/ [Accessed Sep. 22, 2024].

[6] StrengthLog, “Bench Press Strength Standards for Men and Women (lb).” [Online]. Available: https://www.strengthlog.com/bench-press-strength-standards-lb/. [Accessed Oct. 3, 2024].

[7] G. Sandwell, “Basic Understanding of Machinery Vibration.” *Vibes Corp*, [Online]. Available: https://www.vibescorp.ca/learn-about/basic-understanding-of-machinery-vibration/ [Accessed Oct. 20, 2024].

[8] Infinite Uptime, “Understanding Machine Health Score and Its Importance in Asset Reliability.” [Online]. Available: https://www.infinite-uptime.com/understanding-machine-health-score-and-its-importance-in-asset-reliability/ [Accessed Oct. 20, 2024].

[9] Bilco Group, “Crane Wire Rope Pulley.” [Online]. Available: https://www.bilcogroup.com/wire-rope/crane-wire-rope-pulley [Accessed Oct. 20, 2024].

[10] Misfit Athletics, “Case Study: Lifting Numbers Part 2 – Deadlift.” [Online]. Available: https://misfitathletics.com/articles/case-study-lifting-numbers-part-2-deadlift/. [Accessed Oct. 20, 2024].

[11] *Standards Test Methods for Evaluating Design and Performance Characteristics of Selectorized Strength Equipment,* ASTM F2277-17a, [Online] Available: https://www.astm.org/f2277-12.html [Accessed Oct. 18, 2024].

[12] *Standard Specification for Fitness Equipment and Fitness Facility Safety Signage and Labels,* ASTM F1749-15, 2020 [Online] Available: https://www.astm.org/f1749-15r20.html [Accessed Oct. 18, 2024].

[13] *Standard Specification for Selectorized Strength Equipment,* ASTM F2216-17a, [Online] Available: https://www.astm.org/f2216-12.html [Accessed Oct. 18, 2024].

[14] *Conditions monitoring and diagnostics of machines — General Guidelines,* BS ISO 17359:2011E, [Online] Available: https://www.iso.org/obp/ui/#iso:std:iso:17359:ed-2:v1:en [Accessed Oct. 18, 2024].

[15] Arduino Documentation, “Arduino Uno Rev3,” [Online]. Available: https://docs.arduino.cc /hardware/uno-rev3/ [Accessed: Oct. 31, 2024].

[16] Raspberry Pi, “Raspberry Pi 4 Model B Specifications,” [Online]. Available: https://www. raspberrypi.com/products/raspberry-pi-4-model-b/specifications/ [Accessed: Oct. 31, 2024].

[17] AMD, “AMD University Program: Digilent Basys3.” [Online]. Available: https://www.amd.com /en/corporate/university-program/aup-boards/digilent-basys3.html [Accessed: Oct. 31, 2024].

[18] KB-3D, “Raspberry Pi 4B Single Board Computer – Multiple RAM Sizes.” [Online]. Available: https://kb-3d.com/store/controllers-displays-drivers/670-raspberry-pi-4b-single-board-computer-multiple-ram-sizes.html [Accessed: Oct. 31, 2024].

[19] Stegodon, “2500 lb. UTV/ATV Electric Winch.” Amazon. [Online]. Available: https://www.amazon .com/dp/B09B9ZBXC7 [Accessed: Nov. 13, 2024].

[20] Zostera, “2000lb Winch for ATV,Small Electric Winch 12V with Steel Cable.” Amazon. [Online]. Available: https://www.amazon.com/dp/B0C2HBWVZ4 [Accessed Nov. 13, 2024].

[21] Rengue, “RENGUE 1320LBS Electric Hoist, 110V Winch with Wireless Remote Control.” Amazon. [Online]. Available: https://www.amazon.com/dp/B0CBPTD5XJ [Accessed Nov. 13, 2024].

[22] Vevor, “VEVOR Electric Hoist with Remote Control, 1320LBS Electric Winch.” Amazon. [Online]. Available: https://www.amazon.com/dp/B0C499CS78 [Accessed Nov. 13, 2024].

[23] HiLetGo, “HiLetgo GY-521 MPU-6050 MPU6050 3 Axis Accelerometer Gyroscope.” Amazon. [Online]. Available: https://www.amazon.com/dp/B01DK83ZYQ [Accessed Oct. 23, 2024].

[24] WIT Motion, “[Arduino Accelerometer Sensor Inclinometer] WT901.” Amazon. [Online]. Available: https://www.amazon.com/dp/B07GBRTB5K [Accessed: Nov. 13, 2024].

[25] WIT Motion, “[Bluetooth Accelerometer Inclinometer] BWT901CL MPU9250.” Amazon. [Online]. Available: https://www.amazon.com/dp/B01N99BUMR [Accessed: Nov. 13, 2024].

[26] Ozzmaker, “BerryIMUv3-10DOF.” Amazon. [Online]. Available: https://www.amazon.com/gp /product/B072MN8ZRC [Accessed Oct. 23, 2024].

[27] WIT Motion, “[Bluetooth 5.0 Accelerometer+Inclinometer] WT9011DCL MPU9250.” Amazon. [Online]. Available: https://www.amazon.com/gp/product/B0BQ9QTS4D [Accessed Oct. 23, 2024].

[28] SunFounder, “SW-420 Vibration Switch Sensor Module.” [Online]. Available: https://www. sunfounder.com/products/sw-420-vibration-switch-sensor-module [Accessed: Oct. 31, 2024].

[29] Walfront, “Vibration Switch Module Piezoelectric Tapping Sensor.” Amazon. [Online]. Available: https://www.amazon.com/Vibration-Switch-Module-Piezoelectric-Tapping/dp/B08254BM7X Accessed: Oct. 31, 2024].

[30] Adafruit, “Piezo Vibration Sensor – Large.” [Online]. Available: https://www.adafruit.com /product/2384 [Accessed: Oct. 31, 2024].

[31] SHILLEHTEK, “Pre-Soldered Non-Touch Temperature Sensor for Microcontrollers.” Amazon. [Online]. Available: https://www.amazon.com/SHILLEHTEK-Pre-Soldered-Non-Touch-Temperature-Microcontrollers/dp/B0CNM72R4L [Accessed: Oct. 31, 2024].

[32] The Pi Hut, “Contact-less Infrared Temperature Sensor.” [Online]. Available: https://thepihut.com/products/contact-less-infrared-temperature-sensor [Accessed: Oct. 31, 2024].

[33] HiLetgo, “MLX90614ESF Non-contact Infrared Temperature Sensor.” Amazon [Online]. Available: https://www.amazon.com/HiLetgo-MLX90614ESF-Non-contact-Infrared-Temperature/dp/B071VF2RWM [Accessed: Oct. 31, 2024].