Self-Adjusting Helmet

By

Minghao Liu

Shuhan Li

Yichen Gu

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TA: John Kan

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Abstract

This document introduces the background, the working mechanism and the design process of our senior design - the self-adjusting helmet. Two basic functionalities of this helmet are providing shading from rotatable brim according to the direction of the sunlight and detecting falling down accidents. This project combines mechanical, hardware and software designs. The mechanical design involves the CAD design of the helmet, 3D printing of the helmet and other mechanical components. The electrical design takes charge of designing the PCB. The software part deals with the control algorithms used to achieve the two functions as well as programs that the microcontroller implemented. Finally, the test results of different parts are documented, and accomplishments and problems are described.

Contents

1. Introduction

1.1 Objectives

Helmets are ubiquitous in our daily lives. We can see construction workers or bicyclists wearing them, and helmets prevent people from potential hurt. In many scenarios, the users are under strong direct sunlight, which can cause potential skin problems such as sunburn. Most helmets do not provide enough shade. Even if some do, they do not function well because the orientation of the brim does not always align with the sunlight. Besides, using hands to adjust the helmet is inconvenient, especially for people with both hands occupied. Therefore, we come up with a solution – a self-adjusting helmet.

The primary objective is to make the helmet brim rotate to the direction that shields most of the sunlight. Besides, we also consider the safety issue and extend its functionality by adding a safety alarm to it. In a dark environment, light indicators will be automatically turned on and flash at the normal mode. In the case of falling and possible injury (bone fracture, coma, etc.) after, the emergency mode will be triggered, and an alarm will keep ringing to notify people passing by in a range of 20 meters.

1.2 Background

Sunlight is critical to our lives, but too much ultraviolet exposure can cause serious diseases such as skin cancer [1]. For many people, such as construction workers, long exposure to strong sunlight can cause damage to their health. According to the American Academy of Dermatology, about 9500 Americans are diagnosed with skin cancer every day, and nearly 20 die from it every day [2]. Certain modification to their hard hats can be helpful to prevent overexposure.

At the same time, there are many accidents incurring construction workers. A 2017 article from Bloomberg, said that head injuries lead to the death of 992 construction workers from 2011 to 2015, and many accidents started from a simple fall [3]. On the one hand, we have to improve helmets to provide more protection. On the other hand, spotting accidents instantly ensure that the injured worker is rescued in time. This is critical to their treatment and recovery. Consequently, we develop the idea of installing an emergency system on the helmet.

The number of construction workers employed in the United States is over 8 million in 2017 [4]. Beneath this huge population is the need to improve the functionality of helmets by automating the sun-shielding function and adding an emergency system. Seeing little effort on this aspect, we feel it a good idea to be the first team to solve this problem.

1.3 High-Level Requirements

Our design must satisfy several basic requirements:

1. The designs function properly.
    1) Our controller should react to the light intensity properly. The mechanical system provides shadow for at least both eyes, while the movement should be limited at a reasonable speed and temporarily paused when the sunlight is weak.

2) In cases of falling, the system can detect them accurately. The emergency actuators (lights and speaker) should be triggered automatically until manually being reset.

2. The self-adjusting helmet must be free of safety issues. This means the mechanical parts should be shielded from human touch. There are protection circuits on the board to avoid battery overcharge.

3. The price should be low so that workers can afford the cost.

2 Design

This is a modular design, and it can be divided into the following modules: the power module, the sensing module, the control module, and the mechanical part. The power system contains AAA batteries and two LDO circuits that output two different voltages, one for the motor driver and the other for the control unit and the sensing module. The sensing module detects the physical signals, converts them to electrical signals and sends the data to the control unit. The control module contains a microprocessor with some peripheral circuits and sends instructions to the actuator, which is the mechanical part. The block diagram and physical design are shown in Figure 1, 2 and 3.

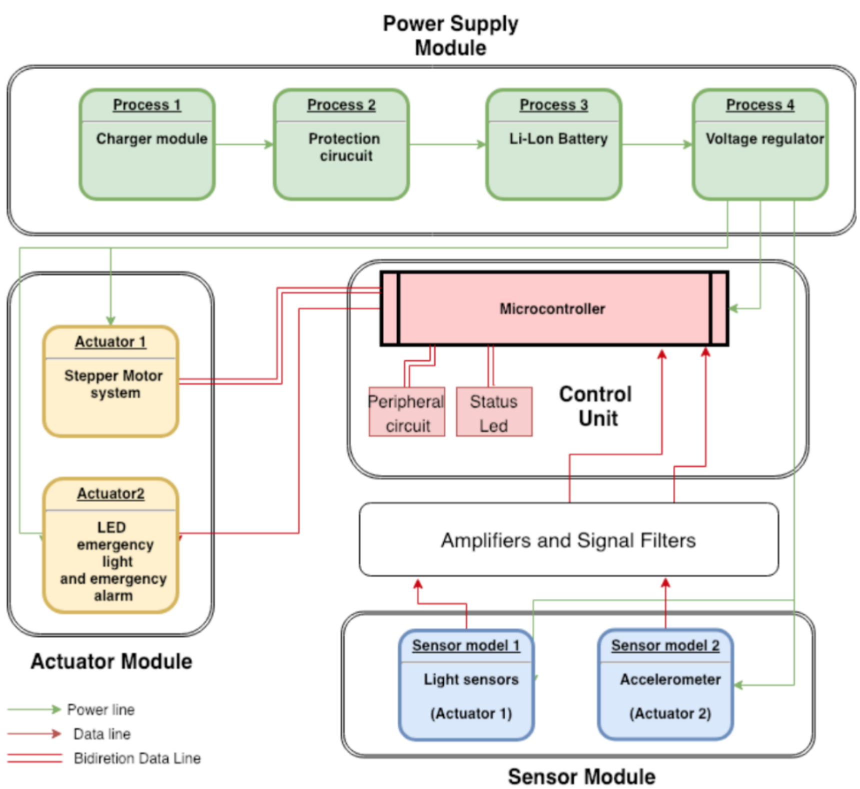


Figure 1 Block Diagram of the Self-Adjusting Helmet

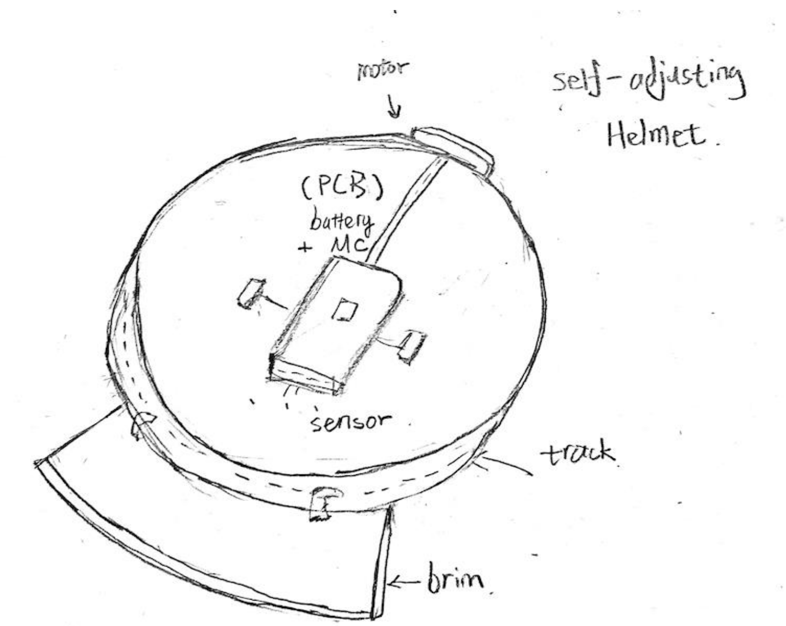


Figure 2 Physical Design of the Self-Adjusting Helmet (Sketch)

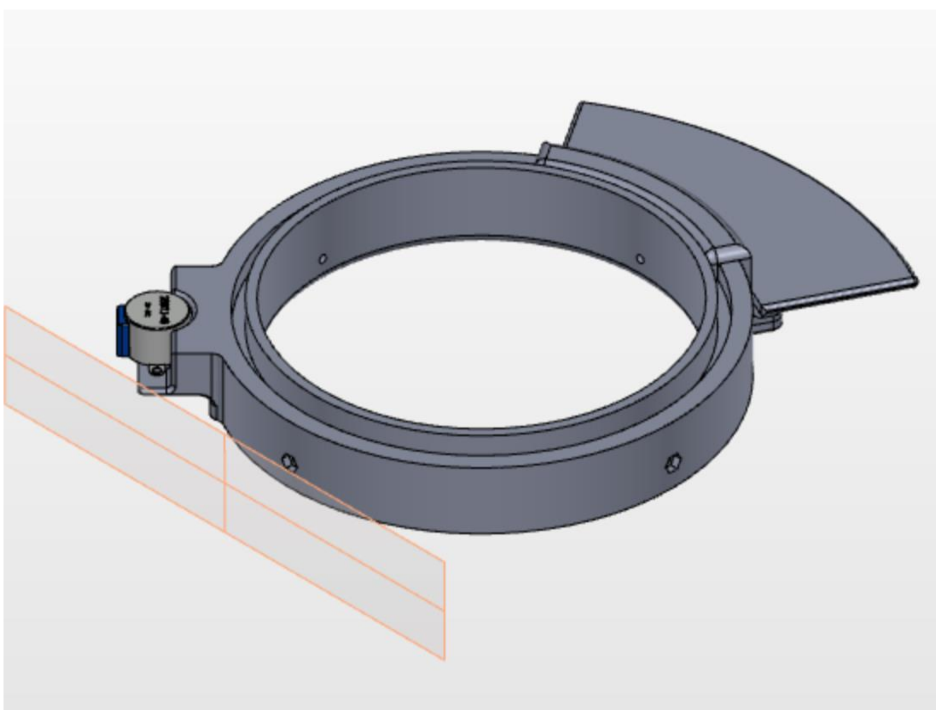


Figure 3 CAD Design of the Self-Adjusting Helmet (Isometric View)

2.1 Sensing Module

The sensing module is composed of sensors and connected to the microprocessor. In our design, we need ambient light sensors for light intensity measuring and an accelerometer for fall detection.

2.1.1 Ambient Light Sensor

The light sensors collect data of light intensity and send them back to the controller. They have I2C interfaces and can communicate directly with the microcontroller. According to Wikipedia [5], the light intensity of the brightest sunlight is about 120,000 lux, and it goes below 1 lux at night. The light sensor should detect a wide range of light intensity. The OPT3001 ambient light sensor has a wide range of 0.01 to 83,000 lux, supports four different device addresses and therefore fits the design.

The light sensor communicates with the microcontroller via the I2C protocol. Figure 4 [9] shows the circuit diagram. Since the chip is highly integrated, the only peripheral circuits we need are the bypass capacitor near the supply and pull-up resistors. A reasonable pull-up resistor is about 10 kOhm, and this gives a pin current of $3.3\mathrm{V}/10\mathrm{kOhm} = 330\mu\mathrm{A}$. According to the datasheet, a 100nF capacitor is recommended to filter out the noise.

2.1.2 Accelerometer

The accelerometer collects data about the motion of the head and sends them back to the controller. There are different types of accelerometers. We choose LIS3DH accelerometer from STMicroelectronics which has the interrupt settings. The sensor works under a supply voltage from 1.71 to 3.6V. Figure 5 shows the PCB design schematic.

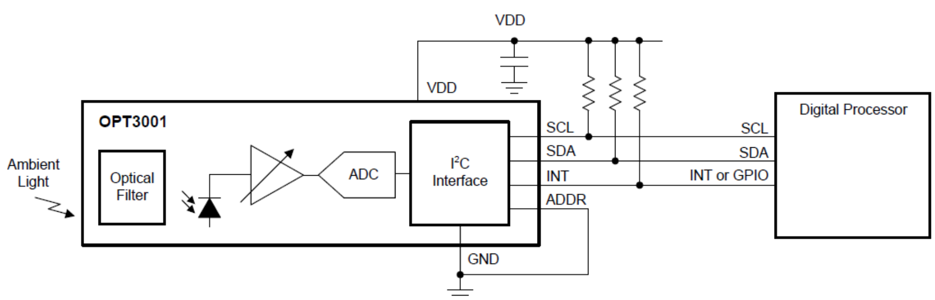


Figure 4 OPT3001 Ambient Light Sensor Circuit Diagram

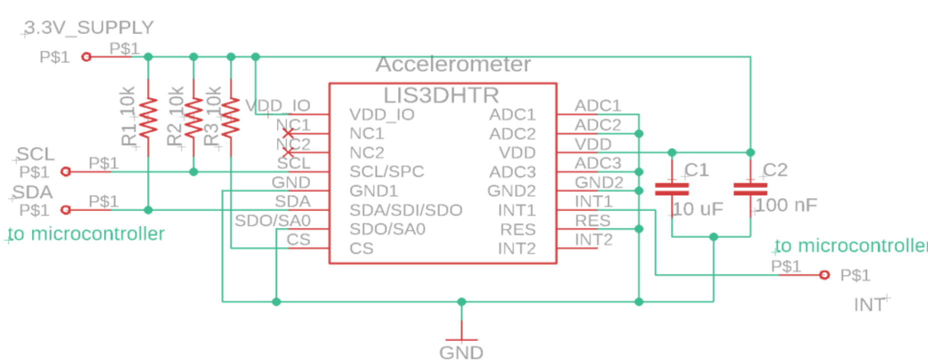


Figure 5 LIS3DH Accelerometer Circuit Diagram

The accelerometer has different detection ranges, and in our application, a range of 2g is enough because in free fall, the accelerometer reads an acceleration of 1g. We choose a 3.3V supply, and we need pull-up resistors for the CS (chip select), SCL (I2C clock line), and SDA (I2C data line) pins. Two capacitors are added next to Vdd to filter out noise. The unused ADC pins are connected to ground, as recommended by the datasheet.

2.2 Mechanical and Alarm System

2.2.1 Stepper Motor System

The stepper motor serves as the actuator that rotates the brim of the helmet. The motor is driven by the ULN2003 chip. There are two strings tied to a pulley mounted on the motor. The strings are wrapped around the pulley and tied to the left and right sides of the brim. In this way, when the motor rotates, the strings pull the brim to either side. The main source of friction is the one between the surface of the brim and the track due to the gravity of the brim. Here's a conservative estimate. We use the static friction coefficient of Polystyrene on Polystyrene as the upper bound of the sliding friction coefficient, which according to the Engineer's Book website [6], is 0.5.

$$f \approx \mu_{poly} m_{brim} g \approx 0.5 \times 0.1kg \times 9.8N/kg = 0.49N$$

The tension on the string should be larger than the friction and the pulley has a radius of 1cm. Therefore, we need at least $0.49N \times 0.01m = 4.9\ mN \cdot m$ The motor actually has a friction torque of at least 600 gf·cm, which is about 58.8 mN·m, and a pull-in torque of 300 gf·cm, which is about 29.4 mN·m. This fulfills our requirement.

2.2.2 Alarm System

The alarm system is composed of two LED light bars and a speaker. Each LED bar is a collection of 4 red LED in parallel. Figure 6(a) shows the I-V curve of the LED. The maximum current is 30 mA, and a working point at 1.85V and 20mA is appropriate. In this case, the resistance we need is about:

$$R = \frac{V_{DD} - V_{LED}}{I_{LED}} = \frac{5.0V - 1.8V}{15mA} = 213\Omega$$

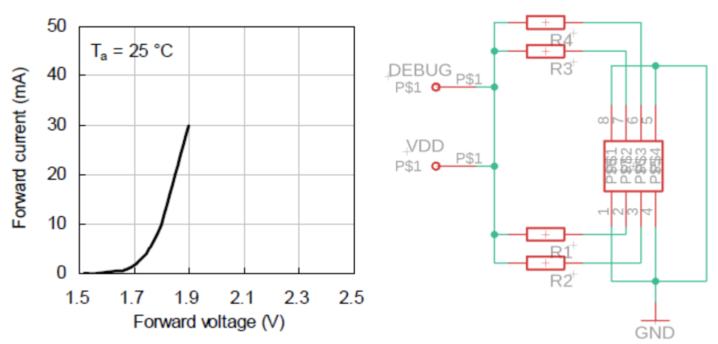


Figure 6 (a) I-V Curve of the LED Light (b) LED Bar Circuit Schematic

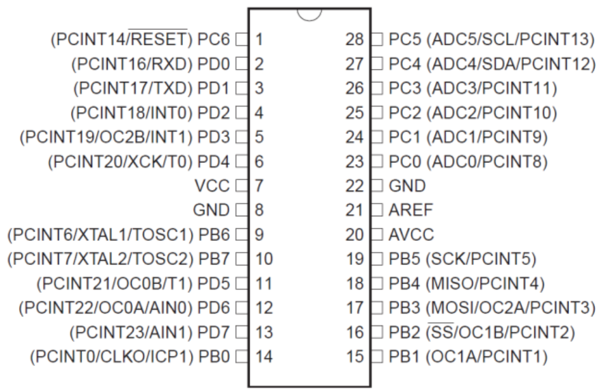


Figure 7 ATmega 328P Pin Configuration

2.3 Control System

The microcontroller is the "brain" in our design and critical to good performance. It receives the data from the sensing module, runs data analysis algorithms, recognizes different lighting conditions and cases of emergency, and finally sends instructions to the motor or the emergency system to react to the scenarios. The microcontroller Atmega328 is used to build the system for its affordability and reliable performance. Figure 7 shows the pin configuration. In this design, the peripheral circuits include a reset push button and pull-up resistor and a 16 MHz resonator to provide the clock. The chip works under a supply between 1.8 to 5.5V and supports I2C communication. It can be programmed through the Arduino platform.

2.4 Power System

The power supply offers enough power for the circuit to operate normally, but meanwhile, there are limits on its size and weight to make the product wearable. In the design, the sensors need a 3.3V supply voltage, while the motor driver needs a 5V supply voltage. As a result, there are 2 LDOs, and the battery voltage should be at least 5V.

2.4.1 Low Dropout Voltage Regulator (3.3V)

This voltage regulator supplies a 3.3V voltage for all the sensors, the microcontroller, and the alarm system. Table 1 gives the working voltage and current of each component in the design.

Component Name	Typical Supply Voltage (V)	Typical Working Current (uA)
Ambient Light Sensor (OPT3001)	1.6 – 3.6	Quiescent current: 3.7 Digital Pin (High): 330 Digital Pin (Low): 0.01
Accelerometer (LIS3DH)	1.71 – 3.6	Normal Mode at 50Hz: 11
Microcontroller (ATmega 328P)	1.8 – 5.5	I_{cc} at 3V, active: 1700
Linear Voltage Regulator (AP7331)	2 – 6	Quiescent Current: 6.5
Emergency LED	1.85	Forward Current: 15,000
Speaker	0.89	110,000

Table 1 Supply Current and Voltage of the 3.3V subsystem

The total current is:

$$I_{total} = (3.7 + 330 + 0.01) \times 4 + 11 + 1700 + 6.5 \times 2 + 15000 \times 2 + 110{,}000 \approx 153mA$$

The AP7331 regulator has an input range of 2 to 6V and provides an output current as high as 300mA. Therefore, it is sufficient for this subsystem. Figure 8 [11] gives the circuit diagram. Since this is an adjustable voltage regulator, we need to choose the resistors properly to get the ideal output voltage.

Figure 8 [11] shows the circuit diagram of the LDO. The output is calculated by this formula:

$$V_{out} = \left(1 + \frac{R_1}{R_2}\right) V_{ref} \Rightarrow \frac{R_1}{R_2} = \frac{V_{out}}{V_{ref}} - 1$$

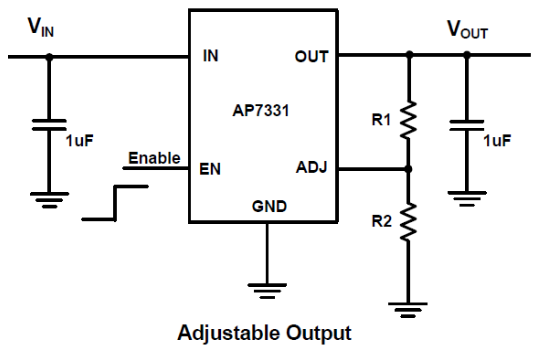


Figure 8 AP7331 Voltage Regulator Circuit Diagram

The input voltage is about 5 to 6V, due to a decrease in battery voltage over time. The output voltage for the sensing and control system is 3.3V. Therefore, we have $\frac{R_1}{R_2} = \frac{29}{4}$. According to the datasheet, R_2 should not exceed 125 kΩ for stability. To ensure a small quiescent current, we pick $R_1 = 29\ k\Omega$ and $R_2 = 4\ k\Omega$. However, no 29 kΩ or 4 kΩ resistors are available in the lab. Therefore, it is practical to pick $R_1 = 33\ k\Omega$ and $R_2 = 4.7\ k\Omega$. The theoretical output voltage is 3.208V, 2.78% off the ideal value. This is within our tolerance.

2.4.2 Low Dropout Voltage Regulator (5V)

This voltage regulator provides the supply voltage of the motor driver and the breakout boards (in case our 3.3V PCB boards fail to work). The circuit diagram is the same as Figure 8, and the choice of resistors is based on the same formula in section 2.4.1. Finally, we have $\frac{R_1}{R_2} = 11.5$. Using the available resistors in the lab, we pick $R_1 = 23.5\ k\Omega$ (as a parallel of two 47 kΩ resistors) and $R_2 = 2\ k\Omega$. In this way, the theoretical output voltage is 5.1V, 2% off the ideal value.

2.5 PCB Design

This project requires the main board, four ambient light sensor boards, and 2 LED boards. The main board, shown in Figure 9, contains 2 LDO circuits, the microcontroller, and its peripheral circuits, the accelerometer, and some output ports. We also include a USB B port for testing on a computer. The original design included a battery charger, but this was abandoned later due to the limited voltage of the lithium battery (3.7V). Figure 10 shows the light sensor board, which has four different configurations, corresponding to 4 different device addresses. There are also two LED boards

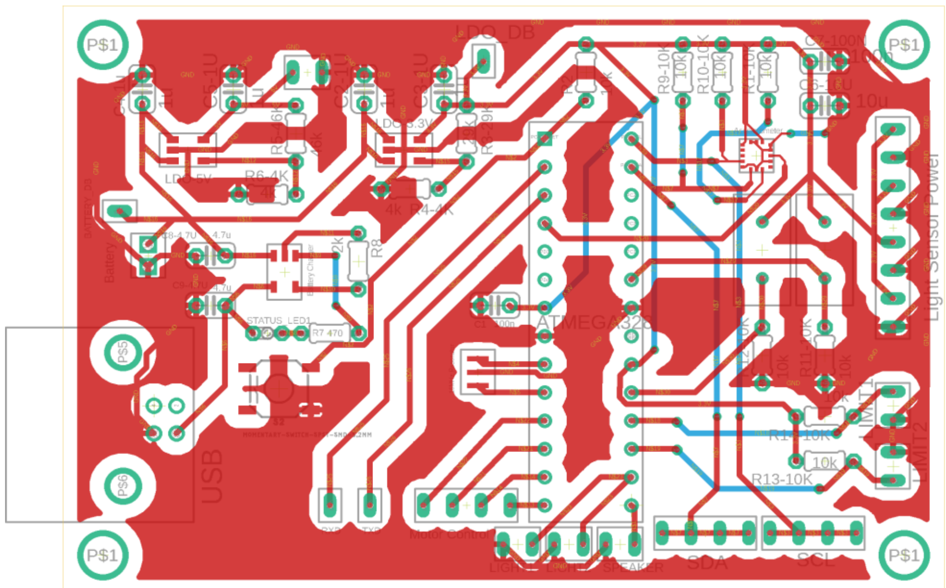


Figure 9 PCB Layout - Main Board

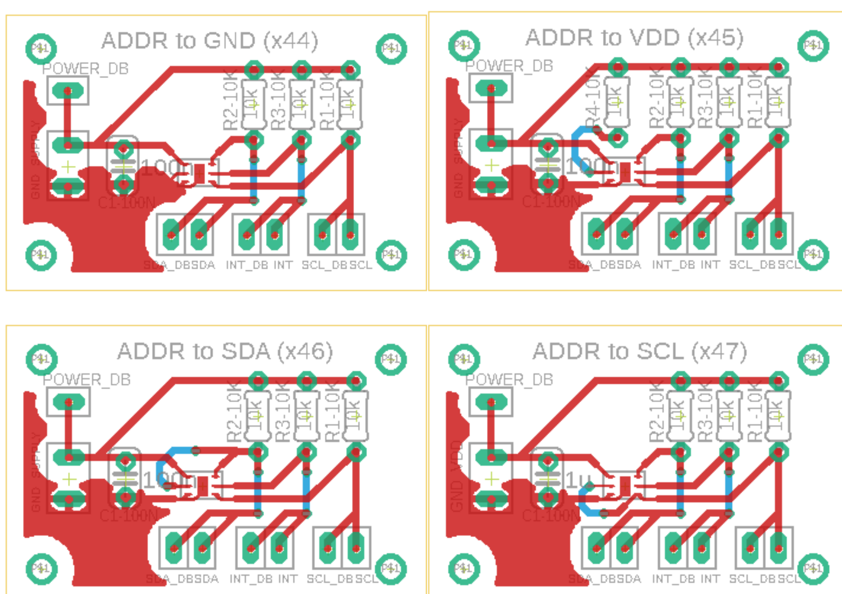


Figure 10 PCB Layout - Light Sensor

2.6 Software Design

The software design involves two part and the integration, the brim rotating algorithm and free-fall detection algorithm. Figure 11 shows the flow chart of the main program. The alarm is triggered by sending an interrupt signal to the microcontroller, so the main program will be paused until we reset the system.

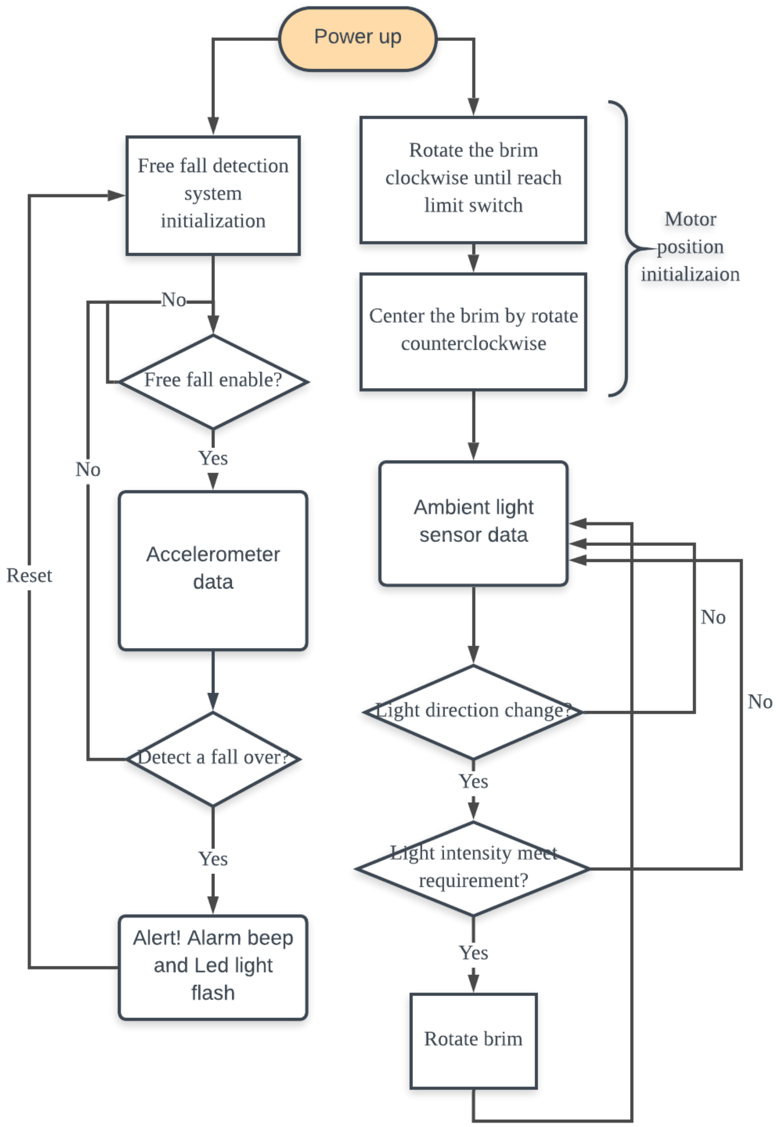


Figure 11 Main Program Flow Chart

2.6.1 Free Fall Detection

The free fall detection uses the built-in interrupt mechanism of the accelerometer. During a free fall, all three axes has an acceleration of zero, ideally. The accelerometer supports sending an interrupt event when certain conditions in the three axes are satisfied. In our case, the event is: (1) $a_x \leq 0x20(0.5g)$. (2) $a_y \leq 0x20(0.5g)$. (3) $a_z \leq 0x20(0.5g)$. The duration threshold of this event is about 0.2 to 0.3 second. All three conditions must be fulfilled to generate the interrupt signal.

2.6.2 Light Direction Detection

The light detection algorithm analyzes the data from the light sensors and computes the direction to which the brim will rotate. There are only four sensors and the self-adjusting function won't be very effective if we only allow the brim to rotate to just 4 positions. Therefore, we apply linear interpolation to get a more accurate output angle. Figure 12 shows the design of this algorithm.

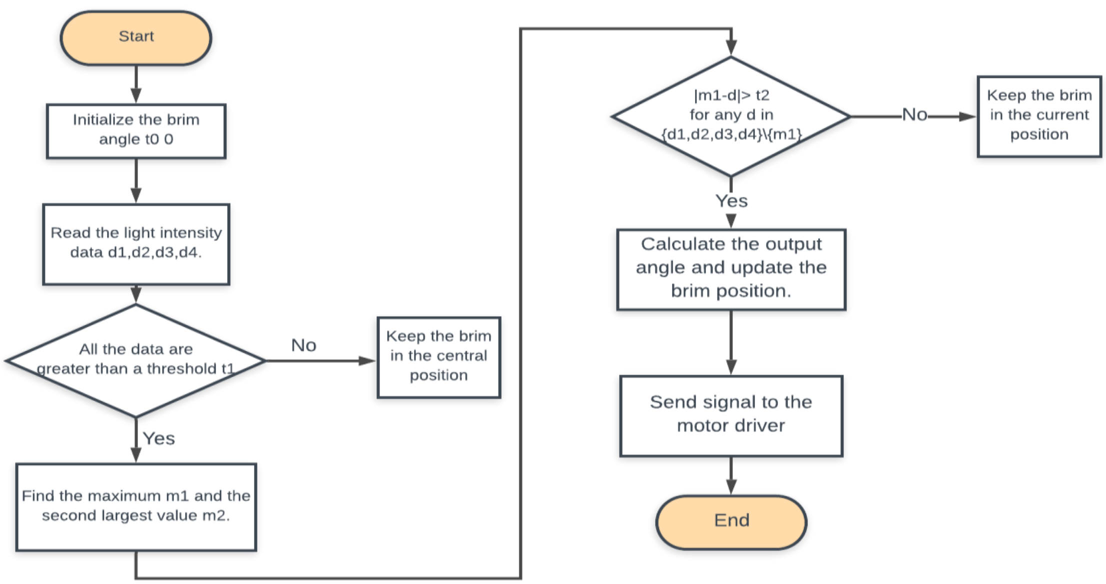


Figure 12 Light Detection Algorithm

Suppose l_1 and l_2 are the two largest light intensity values we've measured. The output angle is calculated by the following equations:

$$r = \frac{l_1}{l_1 + l_2}$$

$$Output\ Angle = r \times m_1 + (1 - r) \times m_2$$

This makes sense since when we have $m_1 \approx m_2$, the brim will rotate to the middle position between the two sensors. When a sensor data point dominates the four, $r \approx 1$ and the brim will just rotate to the position of that sensor.

3. Design Verification

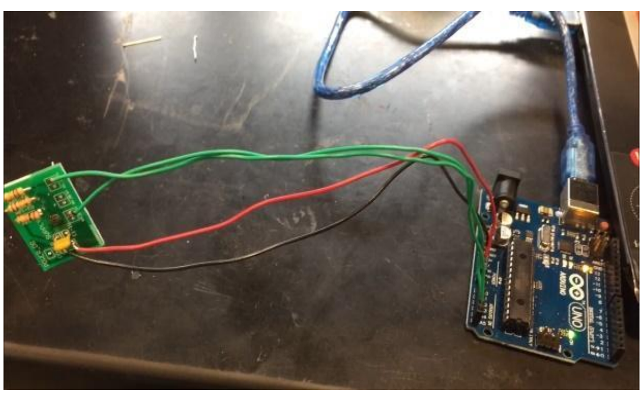
3.1 Sensing Module

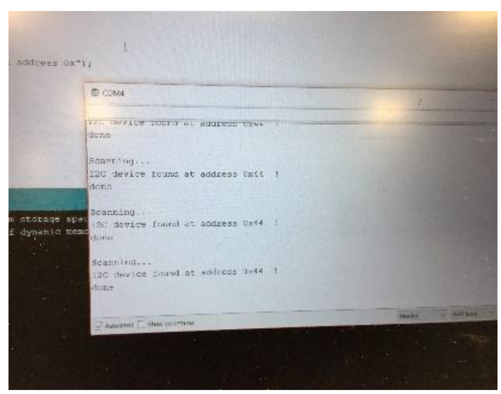
3.1.1 Light Sensor

The OPT3001 light sensor uses the I2C communication protocol. The purpose of the test is to ensure that the measured data can be transmitted to the microcontroller successfully and to get an idea of various light intensity in different light conditions. Figure 13(a) and (b) show the I2C communication test. Figure 13 (c) shows the light intensity outside during a single day. The light intensity is as high as 4000-5000 lux. We also measured the intensity indoors, it’s about 200-400 lux. Figure 14(d) shows the data measured by three light sensors at different incidence angles. Although the data measured is higher, the trend is about the same, meaning the data change simultaneously disregard of the incidence angle.

Requirement	Verification
The light sensor sends the data to the microcontroller successfully.	(1) Program the Arduino board with a program reading the data from the sensor. (2) Print the data on the monitor.
The light sensor detects a variety of light intensities in different light conditions.	(1) Put the light sensor in both indoor and outdoor environment for a whole day and save the measured data in an SD card. (2) Load and plot the data from the SD card. (3) Check if there are different intensity levels in different periods of the day. Find the thresholds distinguishing these environments.

Table 2 Requirement and Verification of the Light Sensor





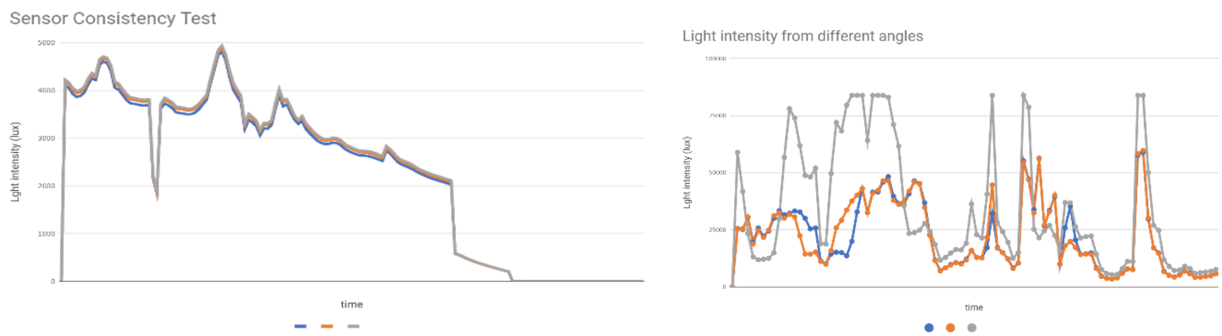


Figure 13 Light Sensor Test (a)I2C Communication Test (b) I2C Communication Test Result

(c) During a Sunny Day (d) Impact of Incidence Angle

3.1.2 Accelerometer

The LIS3DH accelerometer also uses I2C communication protocol. Similar to the previous test, this test aims at ensuring the correct communication between the sensor and the microcontroller.

Requirement	Verification
The interrupt event is triggered correctly.	(1) Program the ATmega328P with a program to receive an interrupt event of x being high. Connect an LED to an output pin. If the interrupt signal is received, then the LED should blink. (2) Shake the PCB board with the accelerometer in x-direction. (3) Check whether the LED blinks.

Table 3 Requirement and Verification of the Accelerometer

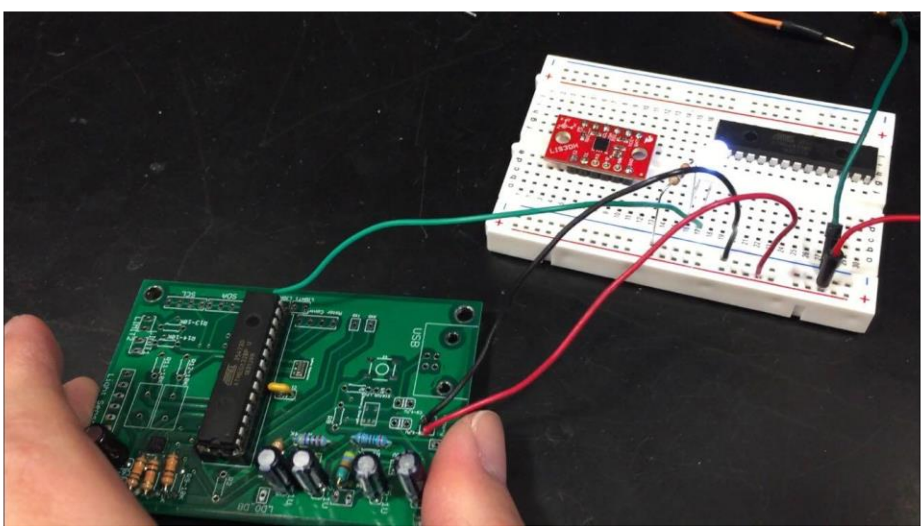


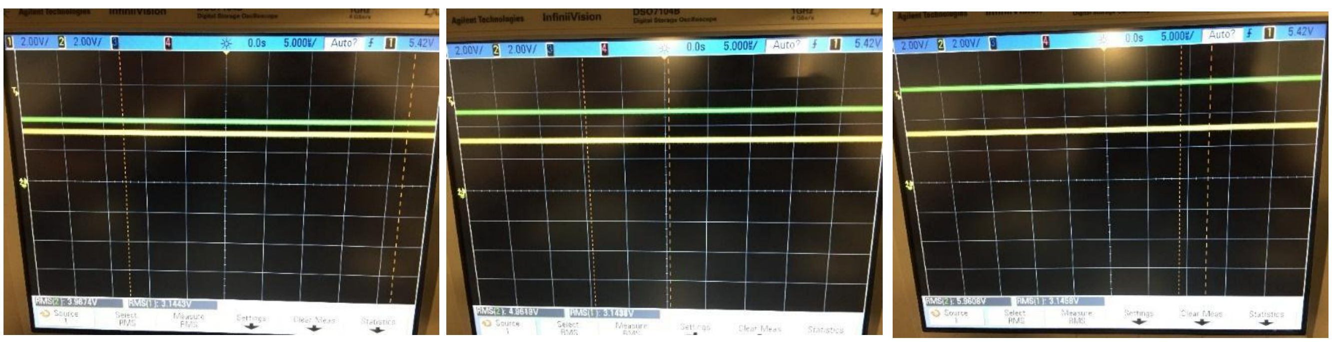
Figure 14 Accelerometer Test

3.2 Power System

The purpose of the test is to ensure that stable voltages supply all the other system. Therefore, the main contents of this part are the two LDO circuits. Table 4 shows the requirements and verification of the LDO circuits.

Requirement	Verification
The output of the first LDO should be stable at 3.3V +/- 5% when the input is at different levels.	Apply an input supply to the input pin, and use an oscilloscope to measure the output. Do this test for an input voltage of (1) 4V (2) 5V (3) 6V
The output of the second LDO should be stable at 5.0V +/- 5% when the input is at different levels.	Apply an input supply to the input pin, and use an oscilloscope to measure the output. Do this test for an input voltage of (1) 5V (2) 6V

Table 4 Requirement and Verification of the Power System



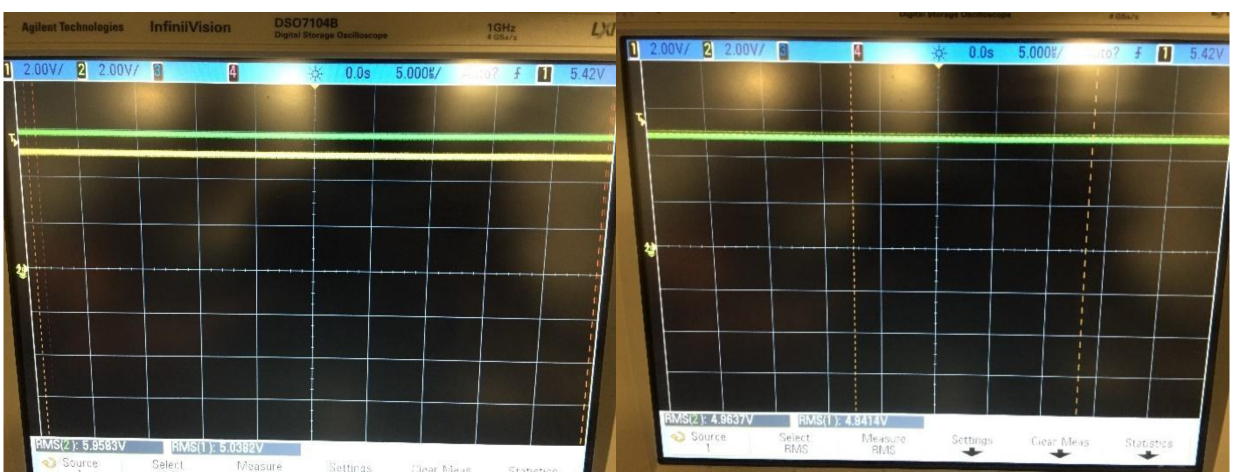


Figure 16LDO (3.3V) Output Waveform (a) 5V Input (b) 6V Input

Figure 15 and 16 shows the waveforms of the two LDOs at different input voltages. As the graphs show, the output is a stable DC voltage in each case.

Table 5 shows the actual test outputs and the error rate. All results meet our requirement, so the LDOs are supposed to provide the expected voltages to the other modules.

Input Voltage (V)	Actual Output (V)	Ideal Output (V)	Error Rate
4.0	3.144	3.3	-4.72%
5.0	3.144	3.3	-4.72%
6.0	3.146	3.3	-4.67%
5.0	4.941	5.0	-1.79%
6.0	5.038	5.0	1.15%

Table 5 LDO Test Results

3.3 Control System

The test of the control system mainly involves the test of the two algorithms – the light detection and free-fall detection algorithms.

3.3.1 Light Detection

The general requirement for this part is that the brim rotates to the position in the direction of the sunlight. To clarify our test, we first define some norms we use.

- The angle of the brim is 0 when its central line points to the front.
- The positive rotation direction is defined to be counterclockwise from the top view.
- The angle of the brim, θ_{brim}, is defined as the rotation angle from the zero position to the current position.
- Denote S1 as the sensor at 135 degrees, S2 as the sensor at 45 degrees, S3 as the sensor at -45 degrees, and S4 as the sensor at -135 degrees.

Requirement	Verification
$\theta_{brim} = 0° \pm 1°$	Place the helmet in a condition where light comes evenly from the space above.
$\theta_{brim} = 135° \pm 10\%$	Cover S2, S3, S4 with hand and check the rotation angle.
$\theta_{brim} = 45° \pm 10\%$	Cover S1, S3, S4 with hand and check the rotation angle.
$\theta_{brim} = -45° \pm 10\%$	Cover S1, S2, S4 with hand and check the rotation angle.
$\theta_{brim} = -135° \pm 10\%$	Cover S1, S2, S3 with hand and check the rotation angle.
$\theta_{brim} = -90° \pm 10\%$	Cover S1, S2 with hand and check the rotation angle.

Table 6 Requirment and Verification of the Light Sensing Module

Test No.	S1(x44) Data	S2(x47) Data	S3(x46) Data	S4(x45) Data	θ_{brim}	Error Rate
1	228.24	332.64	332.00	240.16	0.04°	N/A
2	260.08	2.02	1.12	0.74	134.31°	-0.51%
3	5.66	322.40	3.04	7.57	40.87°	-9.18%
4	2.52	1.04	342.56	3.83	-46.00°	-2.22%
5	4.35	3.56	4.17	226.32	-129.91	3.77%
6	7.27	1.42	296.08	260.40	-87.11	3.21%

Table 7 Test Result of the Light Detection Algorithm

Table 7 shows the test results. The brim angular positions are shown in the last column. This is the actual value calculated by our software program and it was printed on the monitor. All the results are accurate and fulfill the requirements.

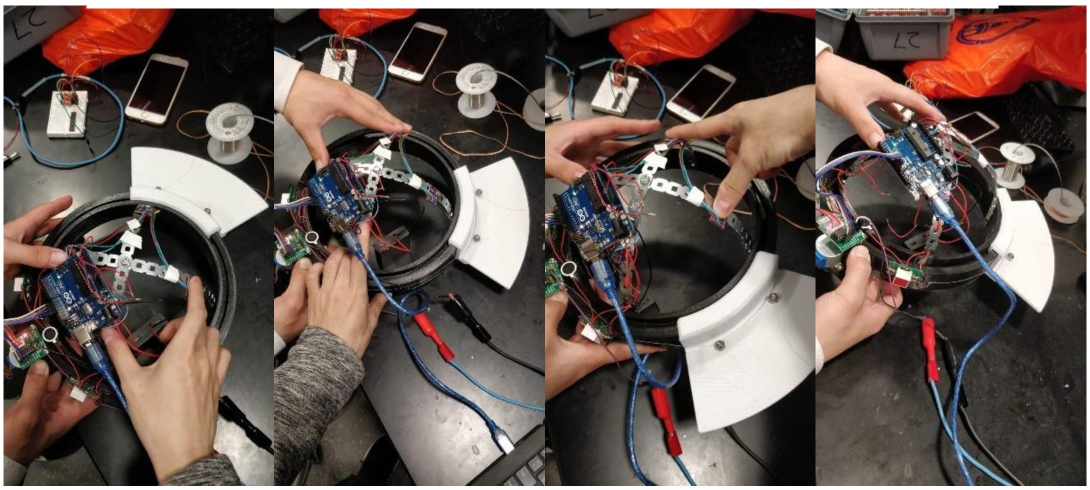


Figure 17 shows the actual test result. As the pictures show, the brim rotated to the correct position based on the light intensity measured by the four sensors. This verifies that the microcontroller controls the motor correctly. Thus, our light detection program gives us the desired behavior.

3.3.2 Fall Detection

Since it is improper to ask anyone to fall, the test of fall detection can only be simulated by squatting down to mock the free fall. According to IEEE code of ethics [7], we should "avoid injuring others, their property, reputation, or employment by false or malicious action". Therefore, it's not exactly what we want, but for ethical reasons, we didn't ask anyone to do so.

Requirement	Verification
The alarm system detects free fall successfully and reacts by flashing the emergency lights and ringing through the speaker.	Let the user wear the helmet and squat down very fast. Check whether (1) The LEDs flash (2) The speaker makes a sound.

4. Costs

4.1 Parts

Following is a starter table for parts costs. Add cell contents as well as rows and, if necessary, columns. Update the table number according to your sequence. Note that columns 1 and 2 are set up for centered text (words) and columns 3-5 (numbers) are set up for right-alignment so that decimal points align.

Part	Manufacturer	Unit Price (in USD)	Amount
AAA Battery	N/A	0.62	4
AAA Battery Case	N/A	1.0	1
0.8-5V Output LDO (AP7331)	Diodes Incorporated	0.58	1
Ambient Light Sensor (OPT3001DNPR)	Texas Instrument	3.35	4
3-axis Accelerometer (LIS3DHTR)	STMicroelectronics	1.53	1
8-Bit Microcontroller (ATmega328-PU-ND)	Microchip Technology	1.96	1
Stepper Motor and Motor Driver	ELEGOO	2.80	1
Alarm LED Bar (DE4SRD)	Kingbright	2.75	2
Speaker (SP-1605)	Soberton Inc.	1.64	1
16 MHz Oscillator (CSTNE16M0V530000R0)	Murata Electronics	0.29	1
3D printing (helmet structure)	N/A	10	1
Metal Bar	N/A	2.3	2
Total		**44.78**	**20**

4.2 Labor

Our fixed development costs are estimated to be $40/hour, 10 hours/week for three people. We consider approximately 60% of our final design in this semester (14 weeks), neglecting any testing and building tools used in the development process.

$$3 \times 40\ dollars/hr\ \times\ 10\ hours/week\ \times\ 14\ weeks\ /\ 0.6 \times 2.5\ =\ 70{,}000\ dollars$$

The total cost for labor would be 70,000 dollars for the group (three group members in total).

5. Conclusion

5.1 Accomplishments

1. Communications between MCU and 4 light sensors (4 address configurations) using I2C protocol successfully provide the light information of the environment.
2. After obtaining the rotation angle(phases) which calculated by our software algorithm, the stepper motor drives the brim to the correction position as expected.
3. Rotation function is properly interrupted once our accelerometer detects falling. Time and magnitude thresholds are deliberately set by our tests to avoid false alarms. LEDs flash and alarm rings right after the interruption signal.

5.2 Uncertainties

1. Soldering the SMD component (accelerometer) onto our main PCB caused a short circuit that we did not notice. Debugging the circuit took lots of effort.
2. The first version of light sensor PCB was not designed into four different configurations which make I2C only available for two sensors.
3. Lithium Battery and battery charger were abandoned when building the circuits. We found the charging was quite unstable and lithium battery did not have enough power to drive the stepper motor.

5.3 Ethical considerations

Considering that our product is a wearable device and closely attached to the head, safety is one of our highest priority. There are several potential safety hazards in our project. To prevent any potential hazards from circuit damage, we chose the LDO with short circuit protection so that the circuit will not blow out.

Besides, the IEEE code of Ethics, #7 states: "to seek, accept, and offer honest criticism of technical work, to acknowledge and correct errors, and to credit properly the contributions of others [7]." As electrical engineers, we should be honest in the whole design process and give credit to any reference or aid we get from others. The potential risk may cause defects in our final product, but we'll try our best to correct the errors and face the defects honestly.

Last, according to the IEEE code of Ethics, #9: "to avoid injuring others, their property, reputation, or employment by false or malicious action [7]. ", we should notify the latent risk of the device. Our device is not meant to operate in the raining or under high air moisture condition since such weather may cause circuit board shortage which may lead to damages of our product and cause potential injury. However, we will still provide some weather shield to add robustness of the system.

5.4 Future work

1. Modify the mechanical design. Currently, the string is placed outside the track which potentially makes string easily broken sometimes. Instead, the new version will use magnets to drive the brim. Around the track is a band that can change magnetic poles that will attract the brim.
2. Integrate the charging module and rechargeable battery into the design.
3. Rebuild the system to be a multi-threads application to enable more functionalities.

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