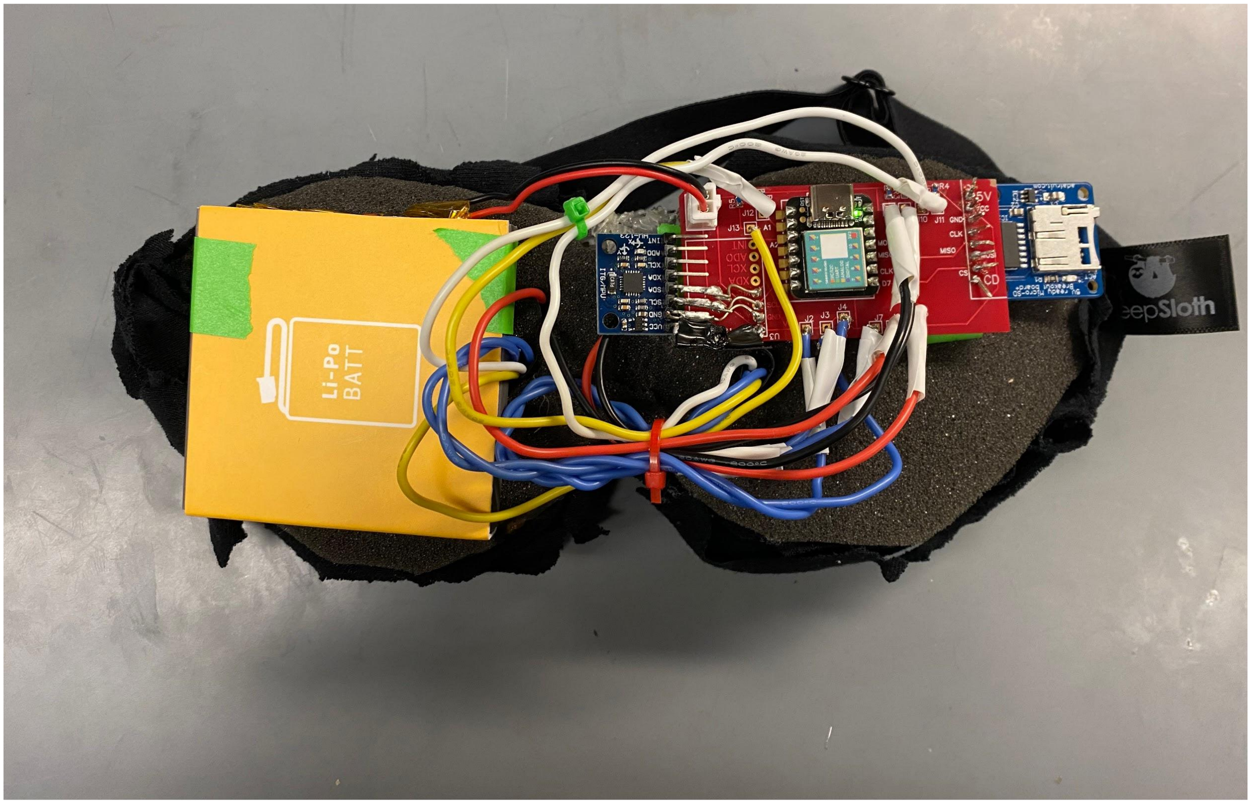
Method for Monitoring Rapid Eye Movement in Hospital Patients



Engineering Honors Capstone
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Abstract
Rapid Eye Movement (REM) sleep is linked with improvements in brain development and physical health. Previous works in the field of monitoring REM sleep have utilized electrical response from brain activity in order to categorize sleep stages (N1, N2, N3, & REM) with the 'gold standard' polysomnography (PSG) tests. PSG utilizes **extensive equipment,** has **large costs**, and can be **uncomfortable for patients** to achieve relaxed sleep. Additionally, consumer products such as FitBit categorize sleep based on correlated vitals and are not approved for use in a clinical setting. As such, there is a need for an improved REM monitoring system that can detect the amplitude and velocity of eyeball movement and the duration of REM sleep that is easy to use and accurate. A FA22 MECHENG450 team prototyped an eye mask with optical sensors to achieve this, and was verified with a phantom-eye model. However, before the prototype can be validated in an Institutional Review Board (IRB) approved sleep study, the prototype needs to become self contained within the mask (**cordless**), and be capable of **8 hours of data storage** for gyroscope and optical readings. This semester, the prototype was updated with the design of a custom printed circuit board (PCB), and selection of two new components: a rechargeable battery, and a microcontroller with smaller dimensions. With the finished assembly, the sleep mask will be usable to correlate optical sensor data to other sleep health metrics to determine the behavior of eye movement within a sleep cycle.

1 Project Background

1.1 Sleep and Rapid Eye Movement

When humans sleep, they cycle through four stages: N1, N2, N3, and REM (see Table 1). REM can occur multiple times throughout a night, and it has specific characteristics of body paralyzation with rapid lateral eye movement that is a key target in sleep studies to monitor the rest conditions of subjects. For example, sleep studies determined that patients with Lewy body dementia do not experience body paralyzation during REM and act out their dreams [1]. Additionally, sleep studies discovered that REM periods can shorten in duration as humans age [2]. Hence, REM is a stage of sleep with repeated clinical focus to diagnose patients and prescribe recovery plans for a variety of diseases.

Table 1. The various sleep stages that humans cycle through over the course of the night.

Stage	Description
N1	Initial transition to sleep, indicated by the slowing of brain waves
N2	Drop in body temperature with brief bursts of electrical brain activity
N3	Further slowing of brain waves aka "Deep sleep"
REM	Onset 90 minutes after sleep where there is rapid lateral eye movement Also characterized by temporary paralysis of leg and arm movement

1.2 Sleep in Hospitals

Outside of sleep medicine, hospital physicians are also motivated to understand the sleep cycle of their patients. REM sleep is linked with physical recovery, emotion processing, and brain development [2] as the onset of deep sleep will allow the body to do significant muscle repair as well as strengthen neural connections and memories. The brain activity observed is very similar to the activity observed during wakefulness so if a patient in a hospital is able to achieve REM sleep, a physician can use this information as a positive indicator of their care. If a patient is not able to achieve REM sleep in a hospital, that information can help inform the physicians of how their hospital care is working for that patient similarly to how taking the vital signs (blood pressure, temperature, oxygen saturation) of a patient tracks the recovery prognosis of a patient.

While sleep is a useful marker, patients in current hospital environments are not known for restful sleep cycles. From routine 24 hour nurse check-ins, to uncomfortable mattress beds, and mental stress from their illness, doctors state that patients qualitatively are unrestful at the hospital overnight. To support the claim of unrestful patient sleep, there is a need to monitor their sleep to gain a quantitative understanding of their recovery. REM detection could act as a quantitative marker for their sleep monitoring, of which current sleep medicine monitoring methods fail to be easily applicable in a hospital setting.

1.3 Current Sleep Monitoring Methods are Not Applicable to a Hospital Ward

There are few devices and techniques present in critical care settings that effectively measure eye movement, particularly rapid eye movement (REM), in recovering hospital patients. The current 'gold standard' technique used to measure REM in patients are polysomnography tests which are impractical in general ward settings (see Figure 1). In order to get accurate readings of brain activity during the different stages of sleep, up to 20 electrodes have to be placed on a patient's head for long periods of time [3]. The electrodes measure the voltage response of the nerve signals from the eye to the brain and this voltage is plotted in real time with its signal characteristics classified for the different sleep stages [3]. While the standard practice for sleep monitoring, it is impractical for use in the general ward as the proper placement of electrodes requires technical expertise which may not be readily available. Additionally, polysomnography tests are not feasible for long periods of time as they may interfere with other critical equipment such as life support systems or intrusive and invasive devices such as artificial airways and intravascular catheters [4,5]. Outside of the healthcare setting, using PSG for sleep studies requires subjects to sleep in a laboratory environment, incurring costs for personnel to watch the subject all night. The sleep studies in themselves are not analogous to the comfort of sleep in a home environment, so there is also a need for sleep studies to have a method to monitor sleep that is not PSG [6].

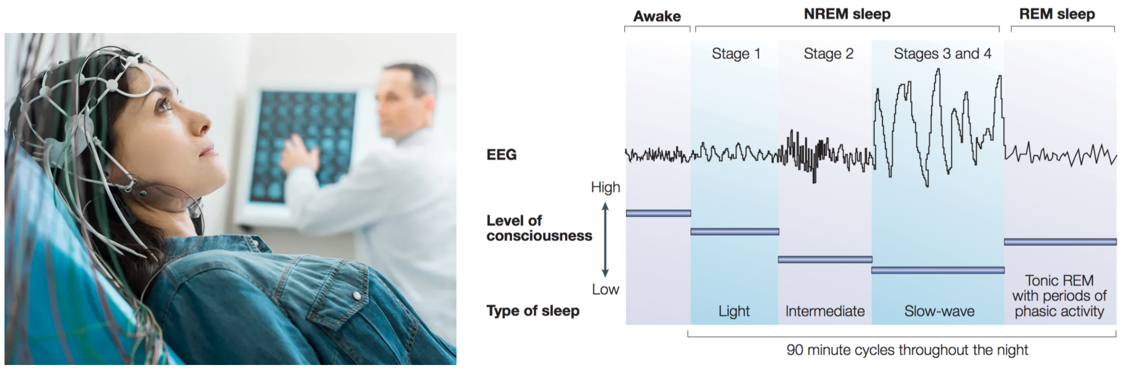


Figure 1. Polysomnography uses many electrodes to plot the brain waves of a subject, which are uncomfortable to sleep in and impractical to hook onto a hospital patient.

Between the commercial products and PSG technology described in section 1.4, there is a need to have a user-friendly method to quantify sleep at an affordable price (see Table 2 below). Commercial products such as smart watches are more affordable than PSG technology, ranging in price from $70 to $1500, but the devices use metrics correlated to sleep on not direct markers for sleep themselves. For example, Fitbits and Apple Watches measure a person's overall movement in their sleep and heart rate, which are vitals that are impacted from calm sleep, while REM in and of itself is a identifier of sleep. The commercial products can only qualify how someone's sleep was without a numeric measurement into how much REM vs non-REM sleep occurred.

Table 2. Benchmarks of current sleep monitoring methods.

Technology	Device Category	Sensing Technology	Use Case	Location	Cost (US dollars)	Sleep Stages	REM Detection Accuracy Percentage (Compared to PSG)
Polysomnography	Medical Monitoring	Brain activity, heart rate, breathing rate, body movement	Sleep Studies	Face, Chest, Abdomen, Hands	3000	Sleep/Wake N1,N2,N3, REM	-
Dreem 2 Headband	Sleep Monitoring in Clinical Research	Brain Activity, Heart Rate, Accelerometer, Breathing Rate	Clinical Sleep Studies	Head	Not Sold to Public	Sleep/Wake N1,N2,N3, REM	87.8 %
Tobi Pro Glasses 3	Consumer Electronics and Productivity	IR Light reflection	Open-eye Attention Monitoring	Head	10000	N/A	N/A
Oura Ring	Healthtech	Pulse rate, IBI, Optical Pulse amplitude monitoring	Consumer Sleep Monitoring	Fingers	300	Sleep/Wake, NI+N2, N3, REM	61 %
Apple Watch	Healthtech	Accelerometer, heart rate	Consumer Health Tracking	Wrist	530	Sleep/Wake, NI+N2, N3, REM	
Fitbit Charge 3	Healthtech	Accelerometer, heart rate	Consumer Health Tracking	Wrist	70	Sleep/Wake, NI+N2, N3, REM	62-69 %
SenseWear Pro 3 Armband	Healthtech	3-axis accelerometer, heat flux, skin temperature, galvanic skin response	Consumer Health Tracking	Arm (Tricep)	Discontinued	Sleep/Wake	-
AMI Motionlogger	Healthtech	Piezo Electric Accelerometer	Consumer Activity Tracking	Wrist	795	Sleep/Wake	-
Actiwatch2	Healthtech	Piezo Electric Accelerometer	Consumer Activity Tracking	Wrist	1500	Sleep/Wake	-

Previous sleep monitors in the market have varying levels of agreement with PSG - the 'gold standard' for sleep monitoring. However, some sleep monitoring technologies show promise. One particular wearable sleep monitoring device, the Dreem 2 Headband, uses dry electrodes to monitor brain activity as well as heart rate, actigraphy, and breathing rate. The headband can be seen below in Figure 2.

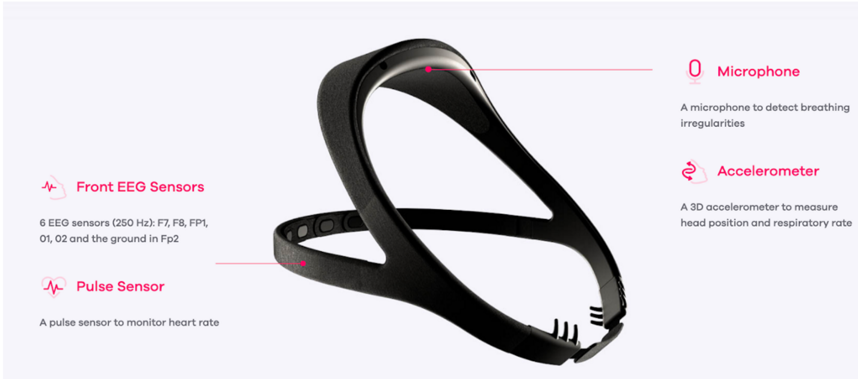


Figure 2: Dreem 2 Headband labeled with callouts showing its various sensing capabilities. Electroencephalogram (EEG) sensors are the electrodes used in PSG testing as well.

These parameters are combined and utilized in a deep learning algorithm to achieve high fidelity sleep staging [7] . The implementation of such deep learning algorithms allow for major strides to be made in the accuracy of data. According to recent research, the Dreem 2 Headband is reported to be just as accurate as PSG for breathing rate, heart rate, and respiratory rate variability. Most importantly, the Dreem Headband shows 84.5 ± 13.5 % accuracy for REM sleep staging compared to an 87.8 ± 13.6 % accuracy for REM sleep staging measured using a consensus for 5 scorers of automatic PSG [8]. This high level of agreement with PSG allows for Dreem to be utilized as a resource for research and clinical trials. The Dreem 3 Headband is currently registered as a Class II medical device in the US [7].

There are several other consumer products shown in Table 2 that have varying levels of agreement with PSG. The most important ones to note are sleep monitors that track sleep staging. Namely, Fitbit and other watch trackers as well as the Oura Ring show impressive agreement with PSG by tracking correlated vitals instead of the characteristics of rapid eye movement itself. However, these devices are commercially used for healthy consumers and have not been implemented or approved in a clinical setting where patients may have other health concerns that need to be taken into consideration (ventilators, IVY tubes, etc). Due to this, it is important to research sensing technologies that have a strong correlation to PSG tests and can be easily integrated into a clinical setting.

1.4 Problem Statement

There is a need for an improved REM monitoring system that can detect the amplitude, velocity, and rotation of eyeball movement and the duration of REM sleep that is easy to use and accurate.

2 Fall 2022 MECHENG 450

2.1 User Requirements and Specifications

To determine the high level priorities, specifications were organized based upon design requirements contingent to the success of the prototype in ME450 and are shown in Table 2. These include all metrics in relation to quantification of REM sleep metrics (such as rotation, velocity, period of time) as desired by the top stakeholders Professor Oldham and Dr.Ward, data storage and processing of REM sleep, and safety (of patients and physiologists.) Medium level requirements followed suit with a larger focus on patient compatibility. Although patient compatibility is crucial to the success of the product, these requirements are not high priority as successful measurement of REM sleep is independent of patient variability for a larger population size. Lastly, low priority requirements include sustainability and comfort. These requirements neither contribute directly nor indirectly functional aspects of our design and are therefore low priority requirements ("Good to haves.") This however, does not indicate that they have a low impact on successful integration of the project as sustainability and comfort can greatly impact the adoption of a product after the validation phase.

High Requirements. Quantification of monitoring duration and sleep metric requirements was done through academic research that correlated eye ball movement to PSG voltage readings, calibrated to physical eye movements [9]. Researchers Takahashi and Atsumi determined that the upper bound of continuous REM movement was 55 minutes, creating the one hour specification. Items such as eyeball rotation, velocity, and sampling rate were specifically isolated for burst of eye movements in comparison to total patient movements. Through this data on burst eye movements (BEM), it was determined a lower bound of 0.5 degrees and upper bound of 13.5 degrees. Similarly, a minimum eye velocity of 120 degrees per second was also derived from BEM research. Sampling rate of our device must be greater than 40 Hz, determined by doubling the largest frequency of BEM's across eight studies as outlined by Takahashi and Atsumi in order to account for aliasing during data collection.

To determine the device's period-of-use, project sponsors were surveyed in combination with sleep duration benchmarking of PSG studies to identify a 10 hour requirement of our device, as most sleep studies are monitored for 7-9 hours, typical of average sleep cycles. Throughout data collection with the device, it is important to distinguish between patient head movements and eye movements as a paralyzed head is indicative of REM sleep, while NREM contains head and body movement (see section 1). To do this, it was determined a sensitivity requirement of 0.5 degrees of minimum head movement [9]. Similarly, the device is required to report data in intervals of 1, 5, 10, and 20 second epochs as defined in current PSG standards [9]. To prevent unwanted noise in our data, there is a filtering eyeball requirement of values below 0.5 degrees movement and above 13.5 degrees. Lastly and most importantly, safety is crucial to any engineering project. As dictated by regulatory and medical standards, engineering ethics, and social context, safety is foundational to the design.

The requirement "System must be able to differentiate head from eye movement" the specification has been set to 20 degrees/sec as found in a study that monitored how fast participant's heads drifted while reading a passage on a computer screen [10]. The velocity and rotation of head movement of sleep is not documented as clearly due to the nature of sleep in individuals being un-uniform.

Medium Requirements. Focused on adaptability and integration, the population to use the product must be on individuals aged 18+. To determine the upper and lower bounds of head and pupillary distances, it was established that the lower and upper bound of women and men surveyants respectively to quantify the adjustable range of the product [11]. All ranges can be seen in Table 2. As there was a possibility for face contact with the product, there is a five pound minimum weight for comfort. Lastly, the device should be quick to set up both at home within ten minutes and in hospital environments within five minutes as desired by the nursing population.

Low Requirements. A notable low priority is comfort and sleep quality. In implementation of the product, it is desired to not negatively impact a patient's sleep cycle, and to quantify this, market technologies such as digital watches will be used to quantify sleep disturbance ("tossing and turning"), which is measured through accelerometer and gyroscope data.. Quantification of disturbance is determined through an individual baseline not using the product in comparison to the amount of sleep disturbance using the product. During use, the device should be non-invasive as defined by the CFR [12] and should be environmentally sustainable as there is no desire to source harmful components in our product.

Table 2. The user requirements and specifications met in the Fall 2022 Semester

Requirement	Specification	Verification Status in Dec 2022
Device must monitor the duration of REM sleep	Continuous REM movement > 1 hr Continous Eye movement for 10 hours	not tested not tested
System must quantify sleep characteristics	Eyeball Rotation: 0.5-13.5 degrees Eyeball Velocity: 120 degrees/sec Sampling Rate > 40 Hz	13.5 degrees met, 0.5 degrees not met, minimum 6 degrees detected 120 degrees/sec met, verified for 900 degrees/sec system samples at 220 Hz
System must be able to differentiate head from eye movement	exclude head movements > 20 degrees/sec	not tested
Device must be capable of data storage and output	report data in 1s, 5s, 10s, 20s intervals	data post processing filters in range of any size
Device must not be affected by electrical noise	Filter noise > 500 Hz	data post processing utilizes digital low pass filter
Device must be safe to use and operate	IEC 60601 and ISO 14971	not tested
Device should fit a variety of head sizes	weigh < 5lbs breaths: 147.6 to 167.1 mm lengths: 169.6 - 193.2 mm circumference 541.1 - 605.8 mm	final device weighs 0.25 lbs breadths from 142.24 - 246.38 mm lengths from 101.6 - 203.2 mm circumference range of 401.32- 701.04 mm
Device must be easy to use	Device set up time for medical staff < 5 min Device set up for at home use < 10 min	not tested not tested
Device must be suitable for diverse populations	patient age > 18 years old adjustable for pupil distance 54 - 77 mm	met automatically not met
Device must be comfortable during use	sleep disturbance less than control non invasive	not tested final device does not enter patient's body
Product should be environmentally sustainable	ISO 1135 - reusability ISO 11607 - material toxicity rechargeable batteries	not tested not tested not met

The requirements unmet during ME450 was the 0.5 degree rotation of the eye, the adjustable pupil distance, and the device being made of rechargeable batteries to be environmentally stable. The requirements that were not tested in ME450 was the device's ability to monitor the duration of REM sleep, how the system differentiates head from eye movement, how safe the device is, if the device is easy to use and comfortable to use. Here is version 1 of the prototype documented in the team's final report.

2.2 Tasks for MECHENG 490 Semester

From the unmet and untested user specifications, three user requirements were identified for editing and focus for the scope of this semester.

1. **Device must be comfortable during use**

This requirement was focused on being met by writing two new specifications for the requirement:

- All hardware is self contained in the mask (240 mm x 35 mm)
- Device is cordless

Hence, my focus was to look at the existing hardware for the device, identify the role of each component, and research for potential re-designs to contain less area in a cordless fashion. By eliminating the two cords on the first version of the prototype (cord from Arduino to Mask, code from Arduino to computer/wall outlet), and restricting the added hardware to equal the area dimensions of the device, the mask would be a wearable device comfortable for use, similar to the RENPHO Eye Massager Mask, which weight 1.52 lbs and has a face area of 201 mm x 106 mm.

2. **Device must measure the duration of continuous eye movement**

This requirement edited the specification from 10 hours down to 8 hours as that is the predicted time length of a sleep study night duration.

3. **Device must be easy to use**

This requirement added a specification that an instruction manual must be completed for user-testing to expand the range of personnel able to use this device for sleep studies. Hence, in conjunction with my version 2 prototyping job, it was imperative that I deliver an instructional manual for how the device works at the end of the Winter 2023 semester.

3 Version 2 Prototype

To allow all hardware to be self-contained within the mask and make the device cordless, all hardware that was not currently within the mask (the data storage, the power supply, the pull up resistors for all sensors, and the microprocessor) had to be re-specced and updated to meet the new specifications. The four changes to the prototype are displayed in Figure 3. The data storage method was fully integrated to be through a microSD card reader, the power supply was converted from wall outlet to a rechargeable battery, the microprocessor was switched from an Arduino IDE to a Seeeduino XIAO, and the circuit construction was converted from a breadboard to a custom PCB.

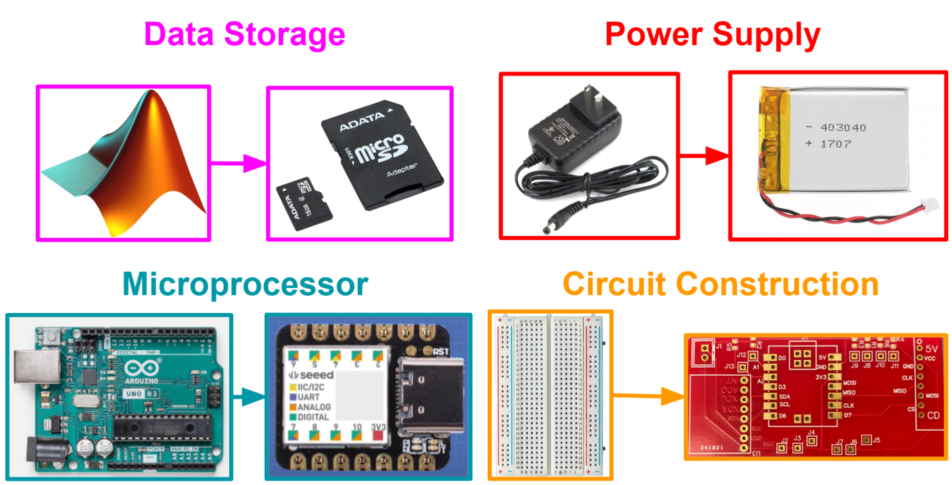


Figure 3: the four updated components during the Winter 2023 Semester

3.1 Data Storage
At the end of Fall 2022, the 450 team had preliminary coded and wired an SD card, but verification tests for its ability to collect data and sample at a fast enough frequency was not conducted. Using the wiring for Serial Peripheral Interface (SPI) communication for the microSD card reader, version 1 of the prototype ran 30 second trials to determine if the optical sensor and IMU data could be collected at an equivalent sampling rate as the MATLAB communication method. The result was very promising: the SD card creates a text file with a name chosen by the coder, and all data is saved to that text file at a rate of 220 samples/second.

For usability, the code needs to be updated for the text file name and how long to collect data for. The limitations of this method is that the name of the text file cannot be longer than 9 characters long, so for patient confidentiality and recognition - short, nondescript codes could be used to keep patient data or even have the time of day of the test be the name of the file. Additionally, this SD card microreader creates files that are "write-protected", meaning that no text files can be deleted off the SD card once they have been created. So, there is not unlimited storage with this method. For a 128 GB SD card, a new card will need to be purchased after conducting 3950 tests at 8 hour intervals.

By fully integrating the SD card into V1, the Arduino only had to be plugged in with a cord for power reasons. Hence, updating the power supply to a rechargeable battery was next in order to eliminate the power cord from the device.

3.2 Power Supply
To choose an appropriate battery, the voltage rating for all components had to be researched so that the battery would supply an appropriate constant voltage. Arduino had a built-in voltage regulator at which V1 of the prototype operated at 5 Vs. The lower the minimum voltage needed to be for the circuit, the smaller the size of the battery could be. From the spec sheets of the components, all voltage ranges were determined: MPU6050 needed 2.7 - 5 V, TCRT5000 needed 2.1 - 5 V, LEDs needed 1.2 - 5 V, and SDcard reader needed 2.7 V to 5 V. So the minimum voltage of the circuit was 2.7 V. As a verification experiment, V1 was ran at 3.3 V due to the other voltage regulator of the device to confirm that the sampling rate was unaffected. The result was confirmed that the sampling rate of 220 Hz was largely unaffected - around 214 Hz.

So, a battery with a minimum of 3.3 V would be able to power the device and not compromise the sampling performance. The next step was to determine the battery's power rating had to be for an 8 hour trial which was done by calculating the Amp-Hours rating of the battery. Using a *Keithley 2400* SourceMeter, the current draw of each component was measured in Amps under a 3.3 constant supply voltage. Then, the total current draw multiplied by 8 hours provided the Amp-hour rating to research the battery for.

There were two amp hour calculations found - one when the SD card was passive in the circuit drawing 200 mA, and another when the SD card was actively drawing 500 mA to collect the data as shown in Figure 4. The result was for a battery life between 2.3 Ahr to 4.7 Ahr, depending on how the final version of the code would write samples to the SD card.

	3.3	V
emitter	20.582	mA
detector	0.04	uA
LED bulb	22.037	mA
IMU	1.38	mA
SD Card	200	mA
Current	87.66808	mA
Power	0.289304664	W
Battery [Ahr]	**2.30134464**	**A hr**
Battery [Whr]	**7.594437312**	**W hr**

	3.3	V
emitter	20.582	mA
detector	0.04	uA
LED bulb	22.037	mA
IMU	1.38	mA
SD Card	500	mA
Current	87.66808	mA
Power	0.289304664	W
Battery [Ahr]	**4.70134464**	**A hr**
Battery [Whr]	**15.51443731**	**W hr**

Figure 4. The Amp-hour calculations for the entire circuit. A) the passive current consumption for when the SD card is not actively writing data. The minimum Amp-hour requirement is 2.3 Ahr if no data was to be collected the entire night while powering the SD card.B) the active current consumption for when the SD card is actively writing data. The maximum Amp-hour requirement is 4.7 Ahr if the SD card was the write data the continuously for the 8 hour trial.

With the Amp-hour rating and minimum voltage of 3.3 V, it was desired to find thin rechargeable batteries online that could conceivably be placed on the eye mask face. Two batteries were found: MIKROE-4475 6 Ahr (67 x 99 x 8.1 mm) and MIKROE-4474 3 Ahr (57 x 63 x 8.1 mm) to prototype with.

With the SD card and battery selected, there was now no need to have the arduino be plugged into a computer, eliminating the first chord in the prototype. Next step was to select components that removed the need for the 4 foot long cord connecting the mask electronics to the arduino & breadboard.

3.3 Microprocessor

The microprocessor had to be updated so that it was capable of all communication methods the Arduino was using in V1 of the prototype while minimizing its own area as much as possible so it could conceivably be constrained to the face of the mask. Additionally, a microprocessor that was able to interface with Arduino IDE was desired to eliminate the need for code rewriting. Arduino nano and Raspberry Pi Zeros were considered but ultimately Seeeduino XIAO (see Figure 5). was selected due to its small size of 21 x 17 mm (the size of US 25 ¢ quarter) while having at least 2 analog input pins for the TCRT5000 sensors, I2C communication pins for the MPU6050, and SPI communication pins for the SD card while being documented of operating at 3.7 Volts.Additionally, the Seeduino XIAO was 12 bits to increase the resolution sensitivity of the optical sensors in comparison to Arduino Uno’s 10 bit analog inputs.

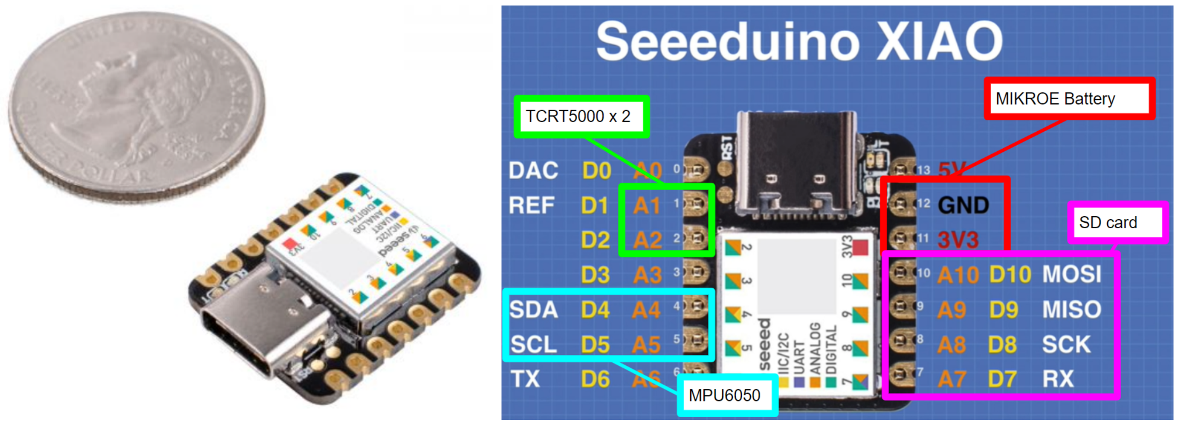


Figure 5. The Seeeduino XIAO set up. A) the Seeeduino has minimal size, fit for wearable device projects. b) a pin diagram for the Seeeduino XIAO in the sleep mask circuit application.

With the SD card, battery and XIAO the V1 circuit was recreated on the breadboard and tested (see Figure 6 for Wiring Diagram), of which from a few minor re-wiring corrections, all components worked as V1 expected and maintained a data collection sampling rate of 220 Hz. Hence, the last step was to update the circuit construction method itself.

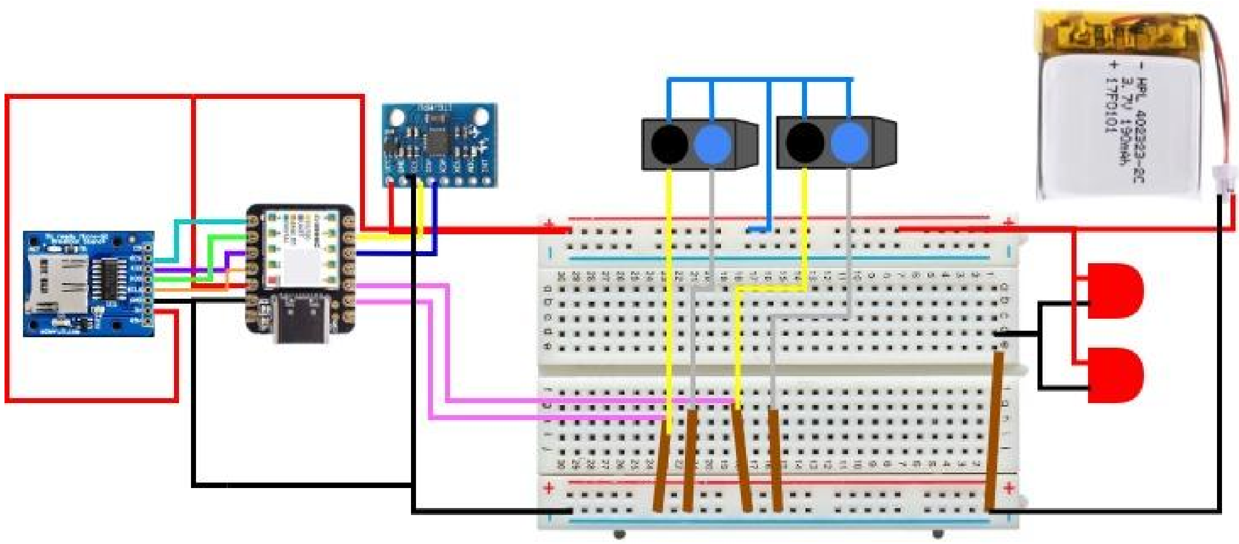


Figure 6. Wiring Diagram with the updated V2 components.

3.4 Circuit Construction

The new circuit construction method had to minimize the area the resistor and wire connections took on the face of the mask while making it larger. To do so, a custom printed circuit board (PCB) was designed on easyeda.com by creating the pin out diagram and tracing pin paths to follow the circuit path of the wiring diagram. For the connections of the TCRT5000 and LED bulbs, these were represented with J connectors because the manufacturing plan was to trim the existing wires protruding from the mask face and solder them to the PCB path. The first and second iterations of the PCB design are shown in Figure 7 with the pin labels described in Table 3. The first design mimicked the face area of the eye mask but this would've made the mask unnecessarily ridged and prohibit the mask for contorting to different head shapes. So, the second prototype focused on minimizing the area as much as possible for final dimensions of 33 mm x 65 mm.

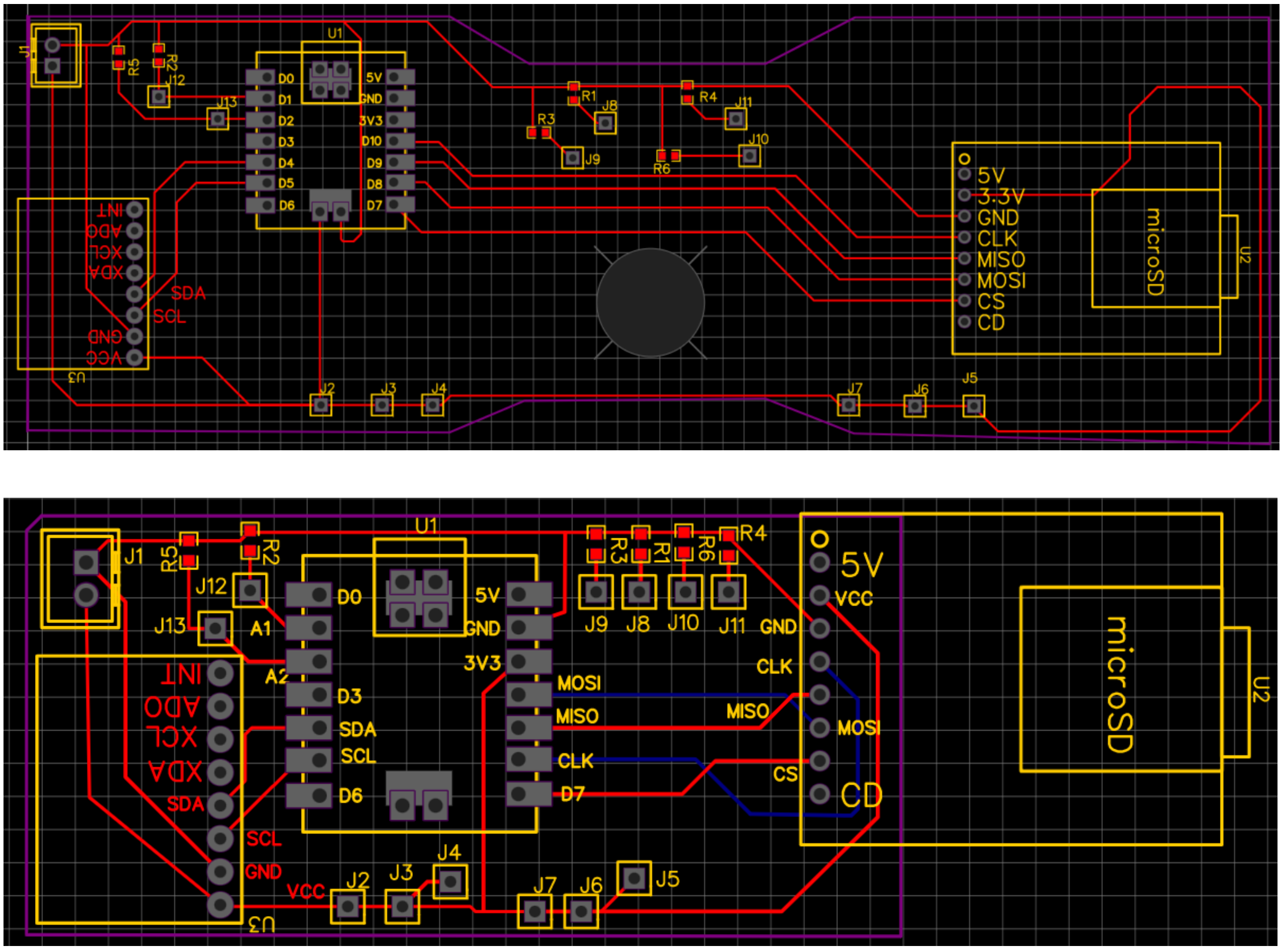


Figure 7. The PCB designs. The first design (top) would've restricted the mask's flexibility so the second design minimized area. Two backside tracings were needed for the SD card to MCU connections as shown in blue.

Table 3. Pin connections for junctions and resistors

Pin Label	Pin Connection	Resistor Label (0603 Package)	Resistor Value
J1	GND of battery	R1 R3	100kΩ
J2-J7	TCRT5000 light blue wires and LED red wires	R2 R5	10kΩ
J8, J9	LED black wires	R4 R6	100Ω
J10 J11	TCRT5000 white wires		
J12 J13	TCRT5000 yellow wires		

Hence, with the custom PCB, the components were soldered and then taped to the eye mask in Figure 8. The PCB and microprocessor allowed the need for the four foot cable to be eliminated as all components were able to be stored on the face of the mask.

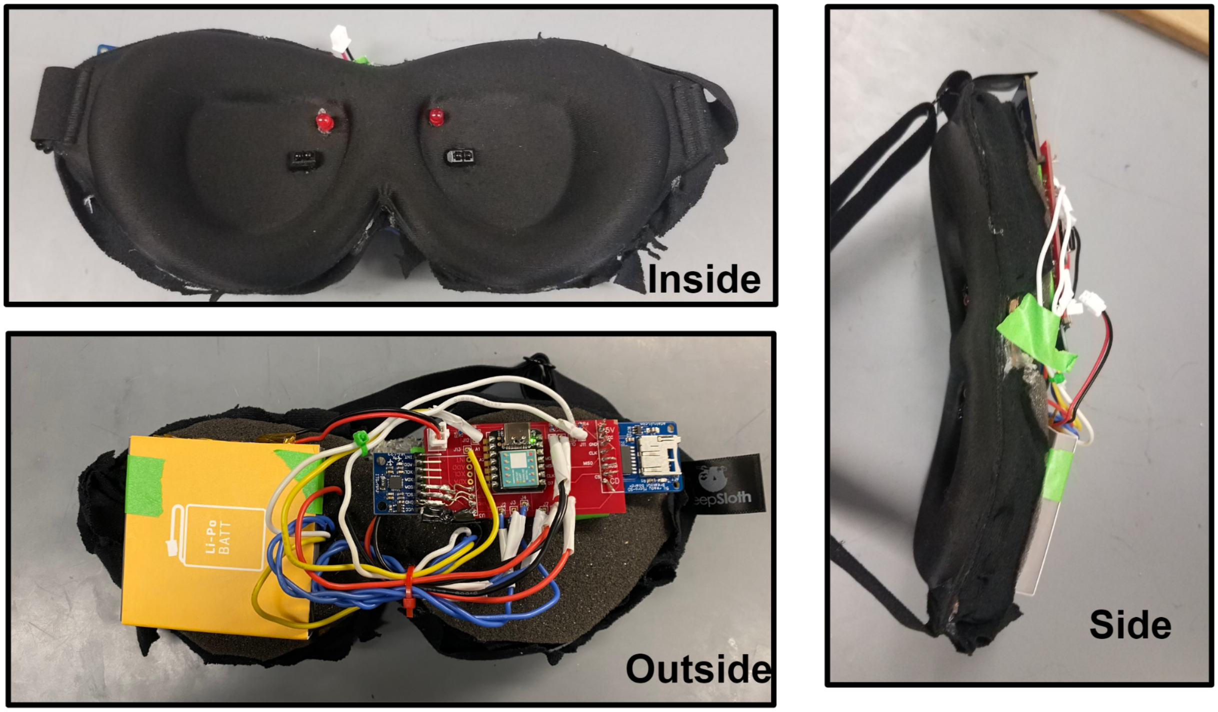


Figure 8. Multiple perspectives of the prototype. The 3 Ahr battery fit on the mask comfortably while the 6 Ahr battery dimensions were slightly too large for the mask dimensions. The thickness of the mask is now 2 inches. A future iteration of the prototype could rebuild the layers from scratch so the hardware is more embedded into the device and protected with a foam layer.

While exposed, the completed V2 prototype eliminated all cords and contained all hardware on the mask. The two battery types allow continuous eye motion detection to occur between 5.5-10 hours.

4 Results

With both versions of the prototype, tests were conducted to determine the limitations of sensing head and eye movement in the mask to prepare for potential hiccups in future user testing. With V1, head and eye movement are excluded incredibly well where there is a concern about the tightness of the mask strap. V2 currently has software issues communicating with the MPU6050 so head motion is currently not being detected.

4.1 Version 1 Prototype

Three tests were performed with V1:

1) eyes sweeping while the head is remaining still,
2) head sweeping while the eyes remain still
3) eyes sweeping while the head is resting on its side

Test 1: Eyes Sweeping with Head Still

When sitting straight and a participant moved only their eyes closed side to side while remaining as still as possible, mimicking "REM" sleep body paralyzation, the results prove promising for isolating eye movement from head movement. Figure 9 shows clear amplitude change in the optical sensor output while the rotation velocities of both pitch and yaw are near 0 deg/s. Hence, it is anticipated that for a threshold of head movements greater than 20 deg/s, the system can focus on eye movement to study sleep behavior.

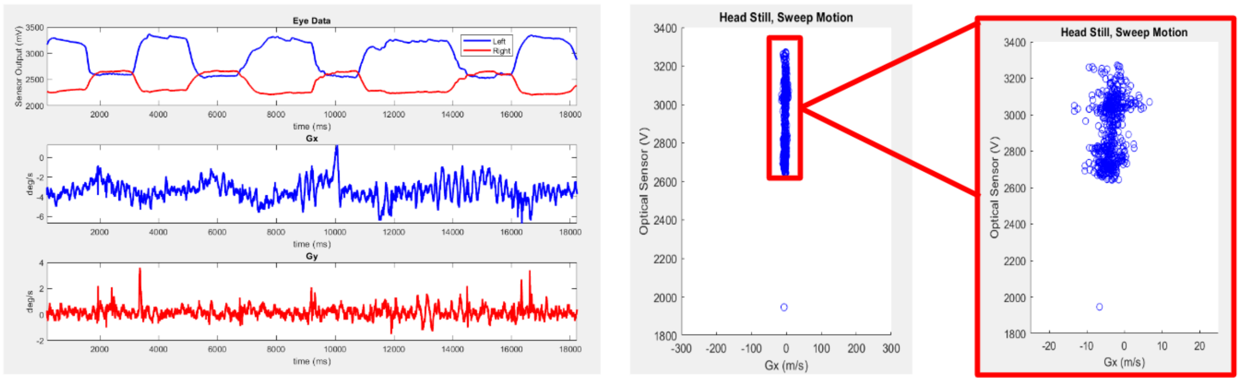


Figure 9: Time series and comparative data for still head and swept eyes

Test 2: Head Sweeping while Eyes Still

While the participant tried to keep their eyes as still as possible, they moved their heads at different speeds to see how much the optical signal “drifted” if at all. Figure 10 shows that as head rotation speed increases, the change in mV from the optical sensor is also of great amplitude creating phantom-looking eye data. Hence, the IMU data must be collected in order to ensure that eye movement data during periods of head rotation are not counted as “REM” sleep eye movements.

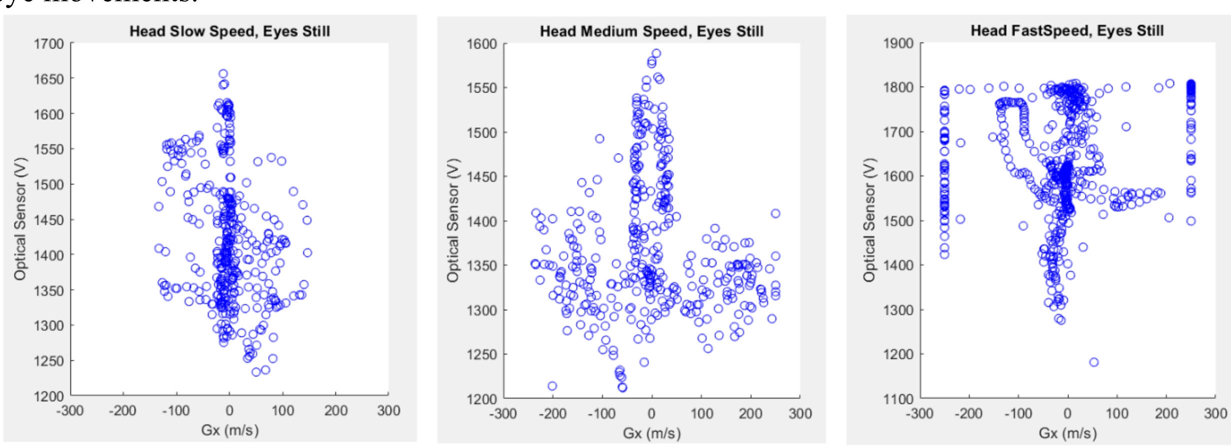


Figure 10: comparative data for still eyes and sweeping head at multiple speeds.

Test 3: Eye Sweep while Head Resting

Similar to Test 1, the eyes were closed and swept left to right while the head was rested on its side instead of the participant sitting up straight. Figure 11 shows the loose mask eye data flatlining with no motion detected. To re-test the mask was tightened and then able to observe the oscillation pattern. Hence, the fit of the mask could impact the capability of the optical sensor placement to observe eye movement and must be considered and corrected for user testing.

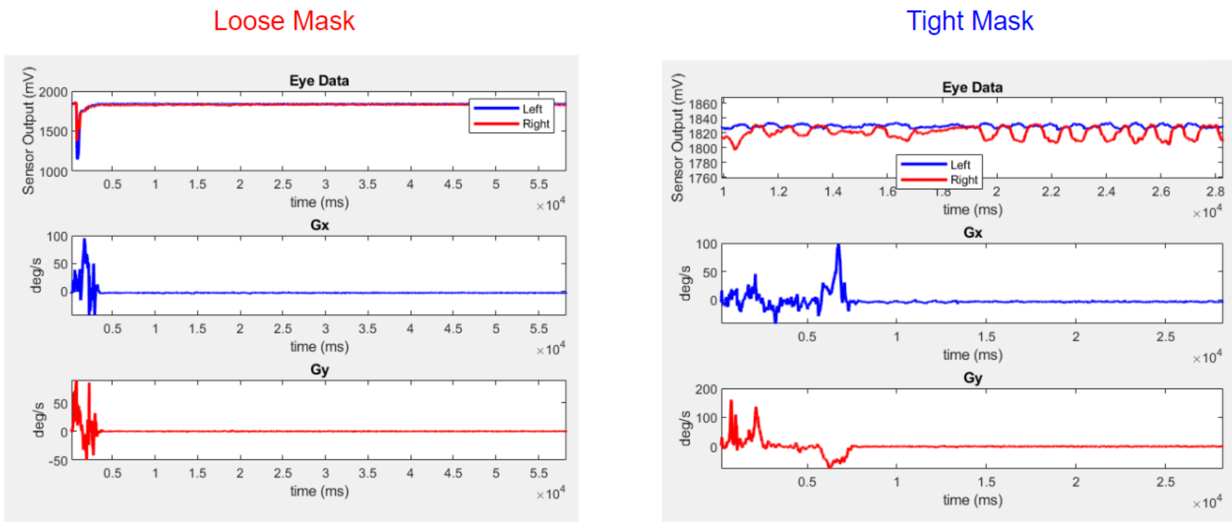


Figure 11: Loose and tight mask data collection comparison

4.2 Version 2 Prototype

For V2, only Test 1 was conducted because the MPU6050 connection was faulty and reported all measurements as zero. Hence, the participant kept the head still to determine if the optical sensors through SD card data collection worked. Figure 12 shows two different eye trials: one with swept motion and others with static, atypical motion. Both cases were detected by the optical sensors while the device operated cordlessly.

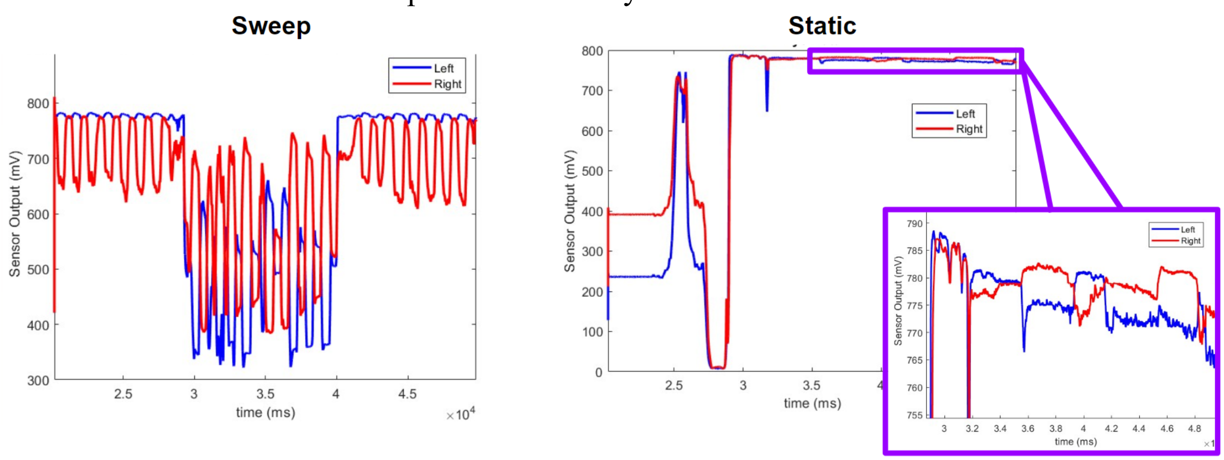


Figure 12: Swept and Static trials with the new prototype keeping the head as still as possible. The sweep test has closed eyes at the beginning and end of the test with the middle data being open eyes. The Static test has smaller amplitudes but still detects the asymmetric change.

5 MPU6050 Error

The MPU6050 error began once soldered to the breadboard, where the MPU would not initialize and stall all data collection by the XIAO processor. A spare IMU and XIAO were set up on a breadboard and the same error occurred. This evidence, along with the working circuit on V2 for the optical sensors and SD card hinted that the XIAO error was not a hardware issue but a software one.

The most likely cause is that the transfer of Arduino scripts to Seeeduino XIAO scripts was not properly understood. Arduino UNO uses a software architecture called "ATmega328P" while XIAO uses SAMD21. This means all software libraries and commands for ATmega328P must also be confirmed to work for SAMD21. V1 of the code used the <Wire.h> library that governs the sublibrary <MPU6050.h>. The sublibrary has built in helper functions to calibrate and initialize the MPU6050 specifically which was helpful for V1. However, this library assumes the MPU6050 the controller uses ATmega328P, and I2C communication with SAMD21 architecture has been reported as finicky when using Arduino IDE.

The best solution is to not use the <MPU6050.h> library but to try other code confirmed for SAMD21 softwares. Here are two forums that try to use the MPU6050 with XIAO to help debug: Xtronical uses an Arduino Nano which the Arduino forum said worked for his XIAO mpu6050 set up. If that does not work, rewrite the IMU code using only the <Wire.h> library commands with these resources as a starting point: I2C Communication for MPU6050, Arduino Guide for MPU6050

6 Instruction Manual

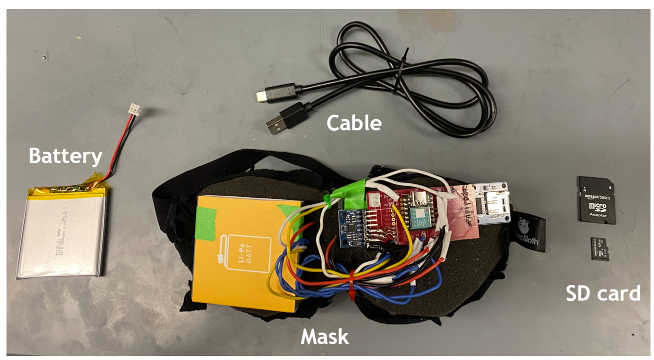
Once the IMU is debugged and working with the PCB, here is a set of instructions to initialize a set of data collection. The basic framework is to

- Setting Up the Mask
- Editing the Code & Starting Data Collection
- Uploading Data & Post Processing

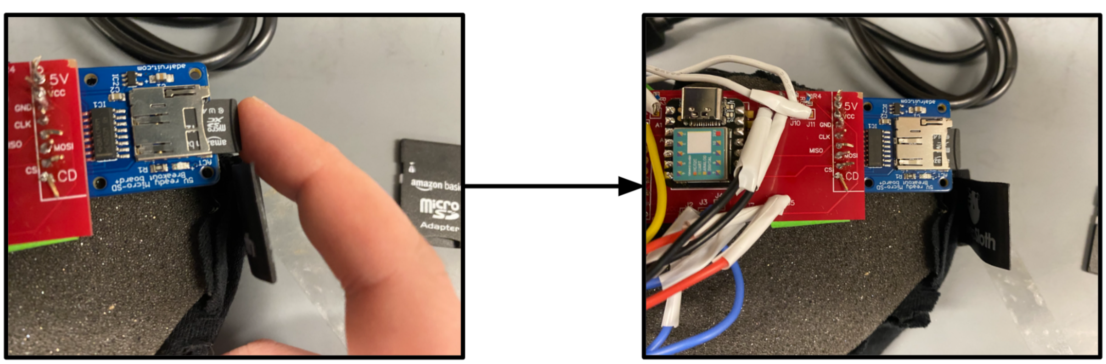
6.1 Setting Up the Mask

The materials you will need:

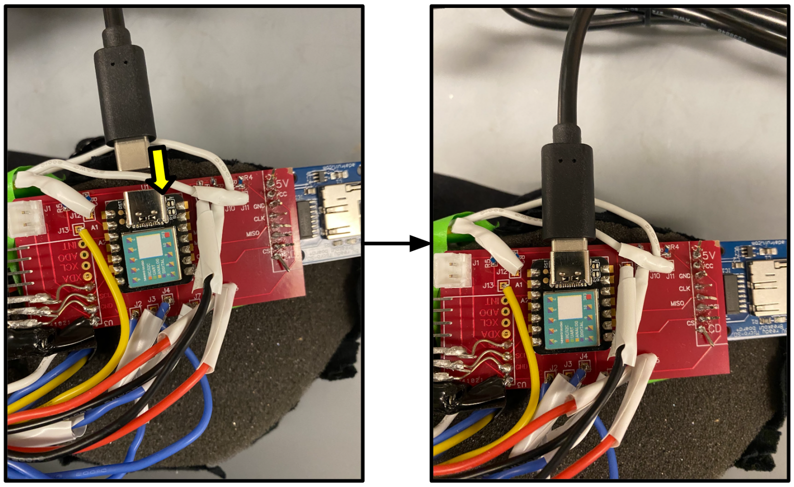
- the eye mask,
- USB C to A cable,
- 128 GB SD card & reader
- 3 Ahr MIKROE battery.
- Laptop with an SD card slot



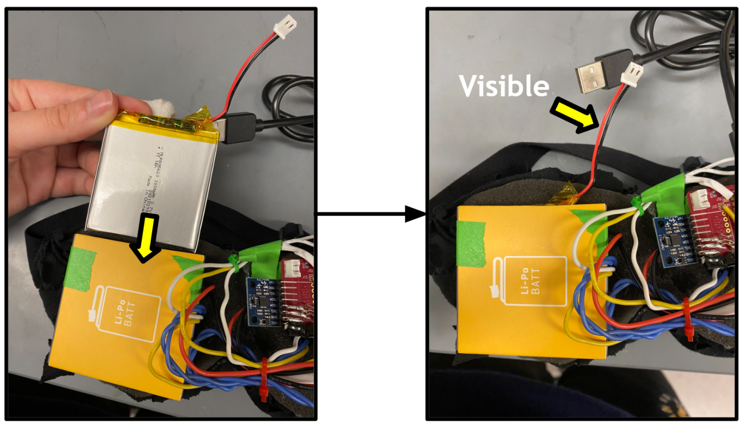
1. Load the SD card into the reader on the right side of the face mask. You should push the card gently until a faint click sound is heard



2. Plug in the USB C cable into the XIAO processor.



3. Slide the battery into the holder on the mask on the left side of the mask. Make sure the power wires are facing out.



4. Plug the USB A side of the cable into the computer where you will edit & load the code from

6.2 Editing the Code & Starting Data Collection

[This tutorial assumes you have Arduino installed with the following libraries: <TimeLib.h>, <SD.h>, <Wire.h> and - Please consult online documentation for instructions if you do not. Make sure that the Seeeduino XIAO is set up for Arduino IDE using [this tutorial]]

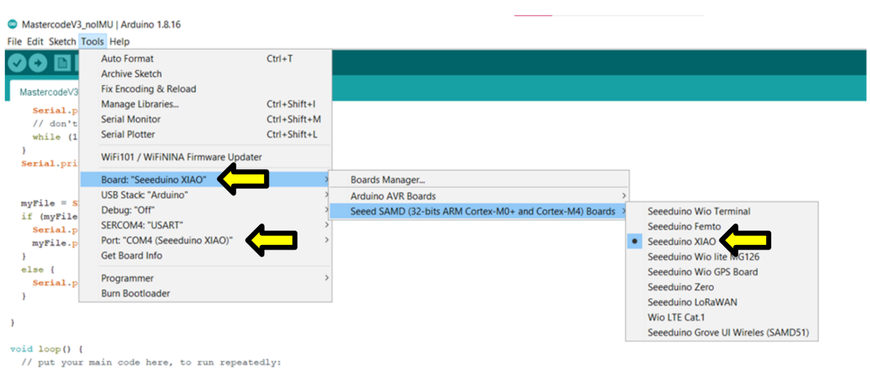
1. Open the "MasterCodeV1.ino" file.
2. Update `Filename` to be a trial-specific identifier less than 9 characters long in length.
    a. Note - if printing the date works in a future iteration of the prototype, this step will not be needed.

```
FileName = "APR18.txt"; lename for SD Card
Serial.print("Initializing SD card...");
// see if the card is present and can be initialized:
if (!SD.begin(chipSelect)) {
  Serial.println("card failed, or not present");
```

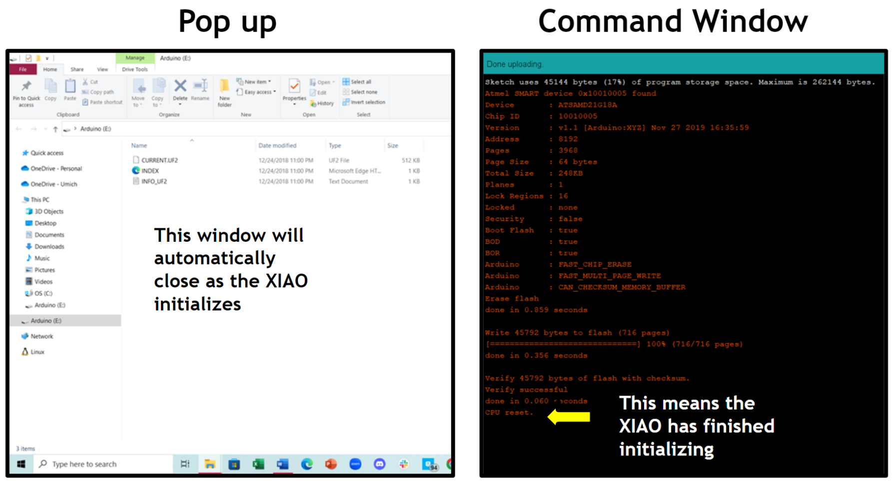
3. Check the `timerange` is for a trial time length desired by the user. Must be in units of milliseconds.
4. If desired, edit `timepause` that happens at the beginning of code initialization. This time is currently set to 20 seconds which the user can use to put on and adjust the mask during this time. The total length of data collection will be timerange minus timepause.

```
void loop() {
  // put your main code here, to run repeatedly:
  timepause = 20*1000;
  timerange = 50*1000;
  if( millis() >= timepause && millis() <= timerange && myFile) {
     varside1 = analogRead(A1)* 3300/4096;
```

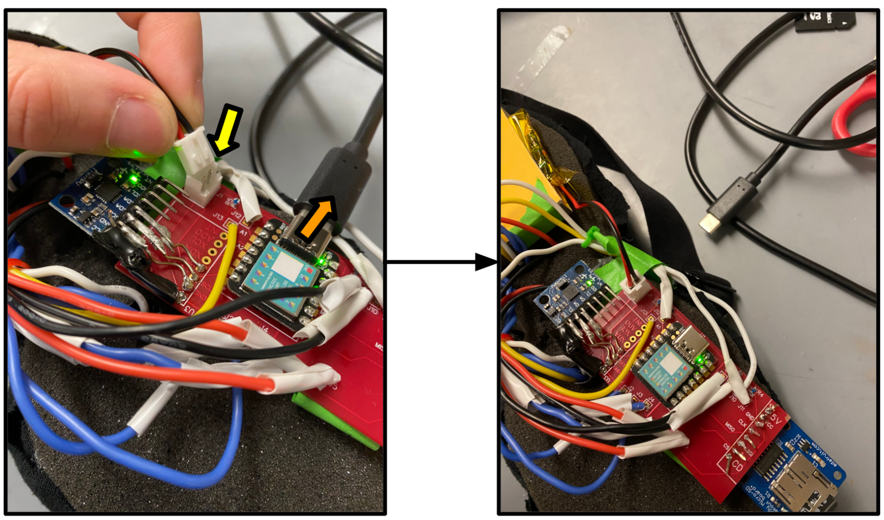
5. Make sure a Seeeduino port is selected and Board is set to Seeeduino XIAO. An error will arise otherwise.



6. Click Upload code and have the sound of your computer turned “ON”. Let the MPU reset itself and self close all pop outs. This may take a few seconds.



7. Once the MPU has reset itself and closed all pop outs, the computer should make the “plugged in” noise. At this time, plug the battery into the leads on the PCB. Then, unplug the USB C cable from the XIAO.

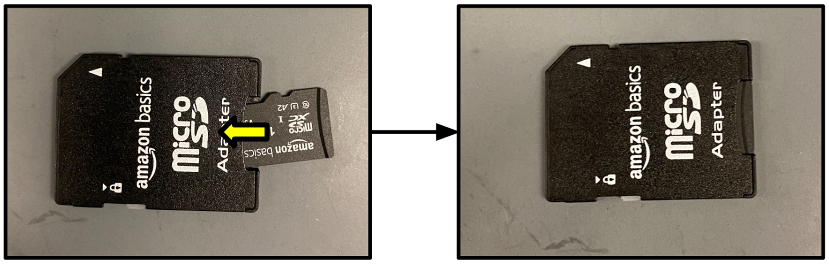


8. Set the mask on the participant and begin the trial. Set a timer separately for `timerange` on your phone or other device to know when data collection is complete.

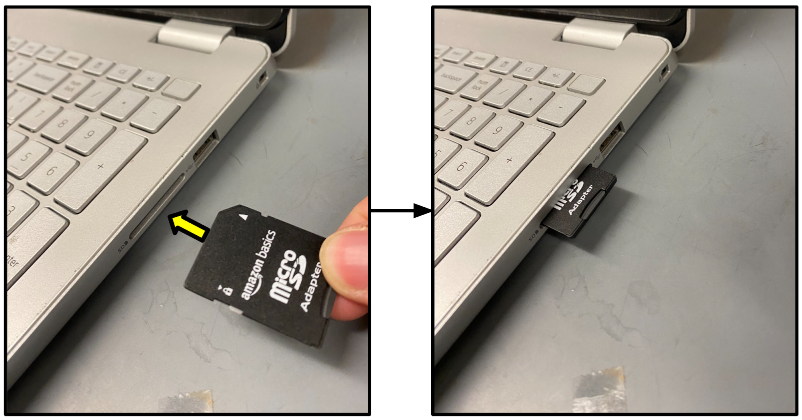
6.3 Uploading Data & Post Processing

1. Unplug the battery from the PCB leads
2. Remove the SD card from the reader. Push in slightly to hear the click and then pull gently

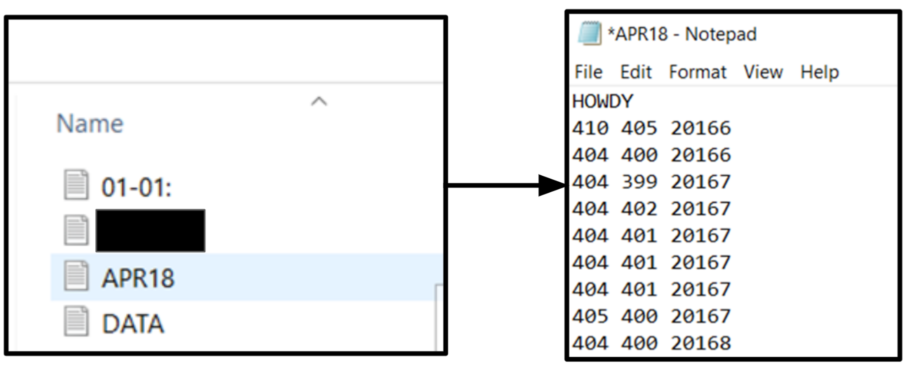
3. Load the SD card into the micro reader



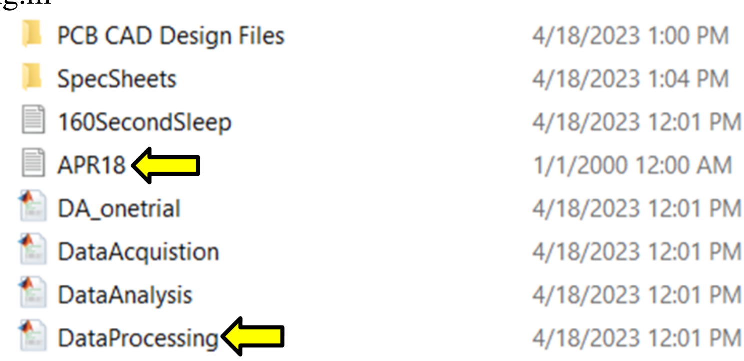
4. Load the microreader into your computer's SD card reader slot



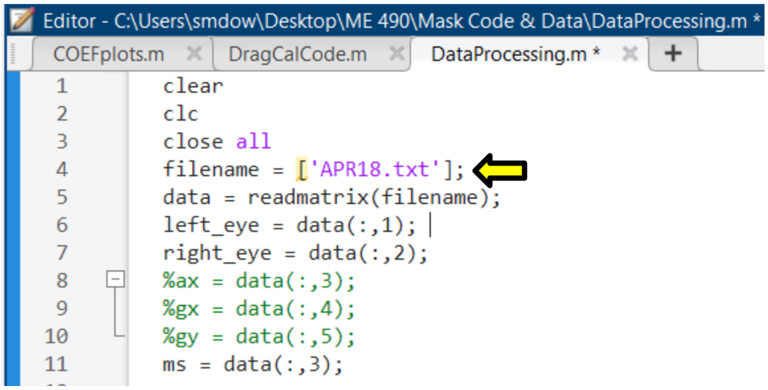
5. Open the SD card on your desktop and open to the text file from the trial to check that data has been collected.



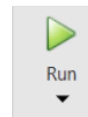
6. Copy this text file to the same working directory folder as the MATLAB script "DataProcessing.m"



7. Open “DataProcessing.m”. Edit the filename to the name of the text file from the SD card



8. Run the code. Two plots should be made - one that shows the eye readings and imu readings vs time, and another plot that compares the two.



7 *Manufacturing Manual*

Here are the bill of materials to create Version 2 of the mask from scratch and some instructions and suggestions to finalize the form factor.

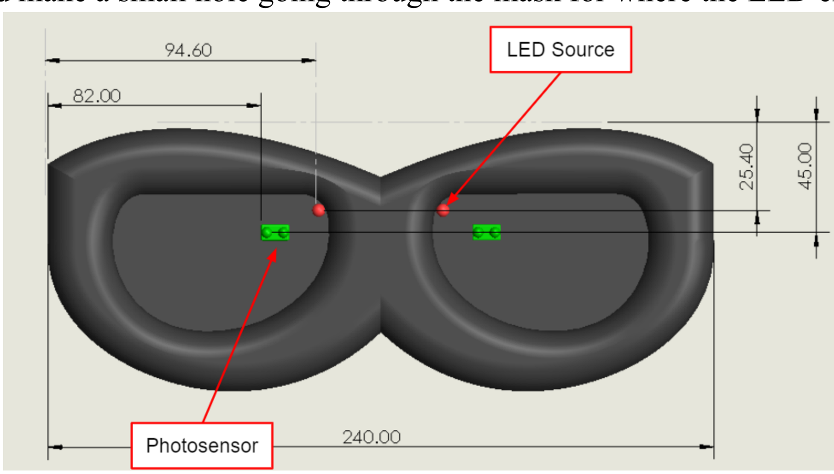
Bill of Materials

Item #	Name/Description	Qty	Cost/Unit	Total Cost	Source
1	Sleep Mask Variation 1	1 Unit	$6.99	$6.99	Amazon
2	TCRT5000L Optical Sensor	2 Units	$1.46	$2.92	Digikey
3	HiLetGo MPU Accelerometer	1 Units	$3.33	$3.33	Amazon
4	AdaFruit MicroSD card Board	1 Unit	$9.88	$9.88	Amazon
5	128 GB MicroSD Card	1 Unit	$14.40	$14.40	Amazon
6	3 Ahr MIKROE battery	1 Unit	$14.50	$14.50	Mouser
7	Battery Leads	10 Units	$0.118	$1.18	DigiKey
7	Ultra Bright diffused Red LEDs	1 Pack	$6.20	$6.20	Amazon
8	Custom PCB	5 Unit	$5.00	$26.50	DigiKey
9	Seeeduino XIAO	1 Unit	$10.90	$10.90	Amazon
10	USB C to A cable	1 Unit	$5.40	$5.40	Amazon
11	24 AWG gauge wires	N/A	N/A	N/A	Self-Source
12	0603 Resistors	1 Kit	$25.99	$25.99	Amazon
	Total			**$127.01**	

1. Solder 24 AWG wires to the two TCRT5000L sensors, two LED emitters, and the IMU. The tips of the wires should be hard core, not soft core. To match the wiring diagram, color coordinate the wires so that the two IMU power leads are blue, the detector is yellow and the emitter is white. The power of the LEDs is red and the other end is black.

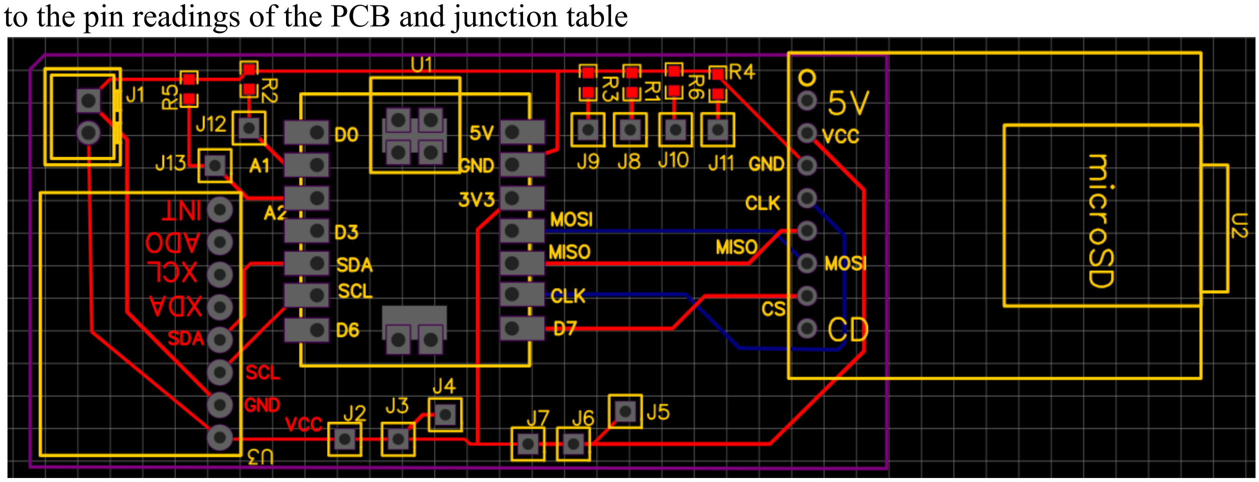
2. Take a pair of calipers and measure the distance across one socket of the eye mask. Divide that measurement by 3. Measure a third of the way from the edge of the eye socket and create an indentation. This is where one sensor will go. Repeat this process for the other eye socket. After making both indentations, confirm with calipers that these indentations are equally spaced from the center of the eye mask. Next, take an exacto-knife and cut a hole through the mask, just big enough for the wires to be able to fit.

3. For the LED emitters, measure 2 mm from the top inner corner of the socket on one side of the sleep mask, and create an indentation. Repeat this process on the other side of the sleep mask. After ensuring both indentations were equidistant from the center of the mask, take an exacto-knife and make a small hole going through the mask for where the LED emitters will go.



4. After creating holes for the LED emitters and sensors, thread the wires through the holes so that the sensors and LEDS are inside the mask, and the wires were hanging outside.

5. Solder the IMU, SD card reader, Seeduino XIAO, battery leads and 0603 resistors according to the pin readings of the PCB and junction table



Pin Label	Pin Connection	Resistor Label (0603 Package)	Resistor Value
J1	GND of battery	R1 R3	100kΩ
J2-J7	TCRT5000 light blue wires and LED red wires	R2 R5	10kΩ
J8, J9	LED black wires	R4 R6	100Ω
J10 J11	TCRT5000 white wires		
J12 J13	TCRT5000 yellow wires		

6. Trace a cardboard layer by placing the sleep mask on top of a sheet of cardboard, tracing it, and then cutting out the outline with scissors. Make a foam layer in the same fashion.Attach the soldered PCB, and battery container to the cardboard layer.

7. Use calipers and measure where the holes for the LED and sensors are on the sleep mask, and cut these holes out of the cardboard using an exacto-knife. Thread the wires from the mask through these holes. Cut the wires to appropriate length (not too bulky or too short) to solder to the PCB junctions. Hot glue the cardboard layer to the front of the mask.

8. Add protective layers (foam, fabric, etc). Allow slits to remove the battery, SD card, and hole for the USB C cable.

8 *Debugging Guide*

Here are some general instructions for debugging the device on both the hardware and software sides of the prototype.

8.1 Hardware

TCRT5000: a quick test to make sure that the optical sensors are detecting motion is to move your hand back and forth in front of the sensor and observe if a mV change is detected on the serial monitor. If the analog reading is unresponsive (0 or maxed out) the issue is with either the wiring of the TCRT5000 or the inner functionality of the sensor (replace with a new one).

LEDs: If the bulbs are wired without resistors, they tend to burn out super fast.

BATTERY: If no components of the circuit are turning on, or are all flashing on and off randomly, the battery has been drained or the soldering connections are not secure. Recharge the battery. Using the USB cable can also show if the battery power is inefficient or not - if the whole circuit is powered normally with the cable then the battery needs to be inspected.

SD CARD: the red LED is an indicator for if the SD card is actively writing data or not, it is not an indicator if it is passively receiving power.

IMU: the green LED is an indicator if it is receiving power or not. If it is flashing on and off there is not a strong power connection

XIAO: when the xiao flashes orange it is “resetting” its flash memory and happens whenever code is uploaded from Arduino IDE. When the xiao flashes blue it means it is executing code. The green LED indicates it is powered on.

8.2 Software

SERIAL MONITOR BLANK

- The baud rate coded into the Arduino must match the setting of the serial monitor
- Use delay() and Serial.println(“ “) to slow down code and give verbal descriptions of what lines of code execute and what lines of code cause the serial monitor to be empty

SD CARD PINS

- Between the XIAO and SD card, MOSI must match MOSI, MISO must match MISO, CLK must match SCK, but CS can be an digital pin as long as that pin number is correctly coded in the script

FILENAME

- If code is uploaded, the cable is disconnected and then the power supply is unplugged and replugged in, the code restarts and saves data to the same text file. It does not overwrite previous data, but continues to add to the same file. Hence, rewriting code must be done before replugging in the device

SD CARD BLANK

- Walk through the serial monitor line by line using delays and serial.prints to determine why the card did not open or initialize. It is most likely a hardware issue but online documentation could have other errors

Conclusion

REM, or Rapid Eye Movement signifies the onset of deep sleep in which the body of a patient is paralyzed and undergoing mental and physical recovery. In a hospital setting, ensuring that patients maintain good quality sleep is of utmost importance to promote quick and healthy recovery as well as to provide fast patient discharge rates. A better sensing tool is subject to investigation as current metrics for measuring REM sleep are complex. Sleep studies use the gold standard PSG tests which place over twenty electrodes in an observational setup to measure brain activity in relation to REM, which cannot be easily integrated into a hospital or home environment. There is desire for an alternate way of measuring REM as the direct source of tracking eyeball movement. Last semester, a MECHENG 450 team prototyped a sleep mask that utilized optical sensors to quantify the presence of eyelid and head movement.

This semester, I updated the MECHENG 450 prototype by making the device cordless and capable of continuous eye movement monitoring with a battery. There is currently a malfunction with the MPU6050 that must be corrected before user testing, and having the code correlate the UTC time to ease data collection is desired as well. This document includes instructions for how to manufacture and use the device. The next steps are to improve the form factor and debug the IMU software so that head motion can be detected again, and have the code report the correct time of day of the test.

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