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Prototyping Wearable Sensor Garment for Understanding Proprioceptive Changes in Microgravity

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Abstract

In a microgravity environment, the human body does not experience vestibular cues that indicate orientation in a 1-g environment. The constant gravitational cue on Earth informs the neurovestibular and proprioceptive systems, which are systems within the human body that control both interactions with the external environment and movement. Posture and limb movements rely heavily on gravitational cues, and aspects of movement have been shown to adapt over the course of a long-duration stay on the ISS. This study investigates proprioceptive adaptation in short-duration exposure to microgravity over the duration of a parabolic flight through a quantitative comparison of joint kinematics.

To gather data, a wearable sensor system garment has been designed and prototyped. The garment is equipped with twelve 6-degrees-of-freedom accelerometers, one on each limb joint, that gather linear acceleration and rotational motion data. Demonstration of this initial prototype took place in a ground-based human participant experiment and a parabolic research flight experiment involving locomotion tasks. A fluidity score can then be assigned to each ground experiment and each parabola of the flight based on the sensor data.

This wearable sensor system is an enabling technology for assessing proprioceptive adaptation to microgravity in short-duration exposures. Contributions to the body of knowledge regarding physical adaptations to microgravity are scientifically important and have applications in many human spaceflight fields, such as spacesuit and habitat design. With the rise of commercial suborbital flights, information about the short-term performance of the proprioceptive system is crucial for the ergonomic design of commercial capsules. This study also isolates microgravity as a confounding factor of the space environment for proprioceptive changes and adaptations.

This paper covers the design and prototyping process in detail and includes an assessment of the preliminary performance of the system in human participant experiments.

Keywords: biomechanics, parabolic flight, kinematics, adaptation

Acronyms/Abbreviations
DOF = Degree of Freedom
IMU = Inertial Measurement Unit
LED = Light Emitting Diode
RTC = Real Time Clock

1. Introduction

Microgravity poses a significant challenge to the proprioceptive system. The proprioceptive system is a complex system that is responsible for the awareness and control of movements. Since neural pathways that provide our internal knowledge of the location of our body parts were formed and evolved in 1-g, proprioception is gravity-dependent [1]. Especially for those without familiarization with the microgravity environment, understanding movement control and the adaptation of the proprioceptive system are important for injury and equipment damage prevention [2]. Prior work has shown evidence for adaptation within days of microgravity exposure for arm-reaching movements [3][4]. Stirling et al. have shown some kinematic adaptation within the length of a parabolic flight [5].

With the recent rise of commercial space tourism experiences offered by Blue Origin, Virgin Galactic, and more competitors pending, there is an influx of inexperienced passengers who may be at risk of injuries. Furthermore, the shortened flight time condenses high-risk critical events (such as launch and landing), where the passengers may not be ready to perform the needed movements during contingency scenarios. More data are needed on proprioception during short-duration microgravity exposure to address this knowledge gap. A parabolic flight of 20 parabolas, each at 20 seconds, serves as an appropriate analog to a two-to-three-minute suborbital flight. Therefore, we aim to characterize the response and subsequent adaptation of the proprioceptive system during short-duration microgravity exposure.

To characterize the proprioceptive adaptation process, we propose using fluidity as a metric. Fluidity is a biomechanical property derived from minimum jerk theory [6]. We are interested in comparing local kinematics at each joint between ground and flight, and between parabolas during microgravity flight. These comparisons will allow us to understand if fluidity changes upon introduction to microgravity and if it continues to change throughout the flight [7].

We developed a wearable motion tracking system to make this investigation possible under the constraints of a parabolic flight. A commercial-off-the-shelf motion tracking system was considered. However, after an initial demonstration, it became apparent that the system relied heavily on a ground reference, and drifted up to 1 m/s without a ground contact point. Additionally, the system required a computer and a relatively large empty area, which increased operational complexity. Thus, it was considered unsuitable for microgravity. This pushed us to prototype our own system designed for our experimental needs.

This project was part of the microgravity prototyping course hosted by the Space Exploration Initiative in MIT Media Lab.

2. System Design Requirements

The sensor system garment is designed for microgravity flight, which means it is self-sufficient, compact, wearable, and robust. For this particular project, self-sufficient is such that the garment package will

- power itself
- collect data without user management (except to power on)
- not require any attachments or additional accessories to use

The hardware should be sewn onto the garment with negligible interference to motion. We chose accelerometers to be placed at the following joints: shoulder, elbow, wrist, hip, knee, and ankle [8]. We selected SparkFun's 6 Degree-of-Freedom Accelerometer, LSM6DSO. The 6DOF accelerometer features an accelerometer and a gyroscope capable of measuring three degrees of linear acceleration and three degrees of rotational motion, which are necessary for the calculations of fluidity metric over time. Since each parabola was only 20 seconds in duration and we needed the rate of change of the collected acceleration data, we opted for a higher data collection rate. Johnson et al. collected three-axis accelerometer information at 32 Hz for parabolic flight, and Lee et al. performed gait analysis at 59 Hz with a self-developed motion tracking system [8][9]. Both of these served as references for our baseline target frequency. We chose a 3 x 32 Hz ≈ 100 Hz data collection rate for each sensor in order to have sufficient flight data for extrapolation, based on a three-point finite difference scheme anticipated for data processing. This rate also exceeds the 59 Hz used for ground gait analysis.

The sensors are attached via Qwiic connectors to a microcontroller. Qwiic connectors are 4-pin JST connectors that eliminate the need to solder individual connectors when the microcontroller and its peripherals (e.g. the sensors) are Qwiic-compatible. We chose this format due to the modularity and flexibility during the prototyping process. The data from the sensors are stored on a microSD card.

Additional design requirements for the Zero Gravity Corporation (Virginia, US) parabolic flight were having a manual power switch, flight-certified batteries, and the ability to be worn underneath a Zero Gravity Corp flight suit.

3. Prototyping Process

Two prototypes were designed and developed per the system design requirements. Both prototypes include sensors, microcontrollers, data collection capability, and an independent power source, but differ in form factor, capability, and manufacturability.

3.1 Prototype 1

The first prototype was designed and built in a three-month timeline due to the constraints of the project course. The course-provided materials served as a starting point for the hardware. This first system was comprised of four RedBoards. Each RedBoard had three LSM6DSO 6DOF accelerometers, an OpenLog, a 9V battery, and a multiplexer attached. The RedBoard is the microcontroller that interfaced with each component. The OpenLog is a RedBoard interface that allowed the reading and writing of data to a microSD card. The 9V battery provided the microcontroller with around four hours of battery power. The visual representation can be found in Figure 1.

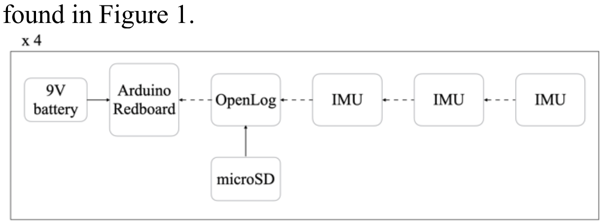


Figure 1: Simplified block diagram of prototype 1. Dashed lines represent Qwiic connections, solid lines represent other wired connections.

The Qwiic connector type, which all of the components shared, utilizes the I2C protocol. One of the benefits of I2C is that multiple peripherals can be connected to one I2C bus on the microcontroller, allowing components to be easily daisy-chained. The microcontroller communicates through the chain, identifying each component by its unique, factory-set hexadecimal addresses. However, this means that no two identical components can be on the same chain plugged into one I2C bus since the microcontroller will be unable to differentiate between identical addresses. One RedBoard only has one I2C bus. Each accelerometer is factory-set to one address (0x6A), or the back can be manually soldered to switch the sensor to the second address (0x6B). Therefore, two accelerometers can be connected on a single I2C bus, but not all three. Purchasing another two sets of RedBoards and peripherals was undesired due to cost, increased bulkiness, and the lack of placement options. The main workarounds we considered were:

1) Using a program to read two sensors off I2C and one sensor off SPI protocol
2) Using a multiplexer to introduce more I2C buses

Due to the complexity present with the programming option and the need to solder to the SPI ports, we decided to use a multiplexer. The multiplexer has eight I2C input buses and connects to the microcontroller on its one I2C bus. The function of the multiplexer is to cycle through the input buses, one at a time, solving the problem that identical components cause with address conflicts on a single I2C bus.

Each sensor provided the following datapoint to the microcontroller: time (in milliseconds since powering on), the linear acceleration in x/y/z axes in [g = percentage of 9.81 m/s^2], and the angular motion around the x/y/z axes in [rad/s].

This system (comprised of 4 smaller subsystems) was powered on by connecting the 9V battery with a battery clip and DC plug to the RedBoard. The RedBoard was loaded with a program and data collection started as power was provided. Therefore, all four independent subsystems did not start data collection at the same time and had asynchronous data timestamps. Each sensor operated at about 13 Hz (collecting 13 data points as described in the paragraph above, from each accelerometer every second). This was a constraint imposed by the processing power of the RedBoard.

The entire system was sewn by hand onto a black Capezio Ballet Makers Inc. (Totowa, NJ) unitard. The accelerometers' x-axes were aligned to be the body-x direction (pointing forward from the body). All accelerometers' z-axes were normal to the body surface. The placements of the multiplexer, OpenLog, RedBoard, and 9V battery for each subsystem were strategically chosen on the deltoids or top of the thighs to minimize obstruction to motions.

The main improvements we aimed to make with the second prototype were:

- The battery should have a smaller profile to limit protrusion from the garment. It should also be rechargeable to prevent financial and energy waste.
- The overall footprint (the surface area that is in contact with the garment), weight, and profile (height protruding from the garment) of the system should be reduced to increase mobility.
- Increase the data collection rate to 100 Hz from each sensor.
- Decrease the number of independent subsystems from four to two.
- Add a kill switch to lower battery overheating and component failure consequences during microgravity flight.
- Record absolute time since sensors won't be initiated simultaneously.

3.2 Prototype 2

Over the next three months, we performed a trade study to make the aforementioned improvements.

We conducted a battery sizing calculation to make the leap from 9V to a LiPo battery, which was rechargeable and had an 85% smaller profile. Reducing the footprint and increasing the data collection rate were compatible goals that resulted in the selection of a different microcontroller. The RedBoard imposed a low data rate, the need for an OpenLog (due to the lack of onboard microSD compatibility), and the need for a multiplexer (only one I2C bus for three identical components).

3.2.1 Microcontroller trade study

The trade study considered the following criteria: cost, footprint, number of I2C buses, data processing speed, and microSD card compatibility. We considered the Teensy boards and the Raspberry Pi boards, both popular microelectronics boards for parabolic flight that were recommended to us by an avionics expert. Of all Teensy models, we selected the Teensy 4.1 since it had microSD card compatibility and the highest processing speed.

Both options feature built-in slots for microSD cards and provide 3.3 V for the accelerometer, which was sufficient to power all twelve accelerometers [10][11]. The clock speeds of the Raspberry Pi's are higher (1 GHz – 1.5 GHz) than that of the Teensy 4.1 (600 MHz) [10][11]. The Teensy 4.1 has a 1000 kbit/sec I2C speed option contrasted with the Raspberry Pi's 400 kbit/sec maximum [12][13]. Finally, the Teensy 4.1 has three

I2C buses, and the Raspberry Pi has two at most, depending on the exact model [12][14]. This meant that each Teensy board could accommodate six (three 0x6A, three 0x6B) accelerometers for a total of two boards, while the Raspberry Pi would need three boards.

At $29, the Teensy is slightly more expensive than the Raspberry Pi at $25. The footprints were comparable, with the Teensy and Raspberry Pi at 10.8 cm^2 and 36.4 cm^2, respectively.

Table 1: Trade study criteria and scores for the Teensy 4.1 board and the Raspberry Pi.

Criteria	**Weight**	**Teensy 4.1**	**Raspberry Pi**
Cost	1	0.9	1
Footprint	2	0.8	0.4
I2C buses	3	1	0.5
Data speed	3	0.6	1
microSD	1	1	1
Total	10	**8.3**	7.3

The Teensy 4.1 was selected as the preferred microcontroller for prototype 2.

3.2.2 Battery Sizing

The Teensy 4.1 usually consumes 100 mA [10]. In high-performance mode, the 6DOF accelerometers consume around 0.55 mA each [15]. With six accelerometers per Teensy, this yields 103.3 mA. The microgravity flight is about three hours, and each system needs 309.9 mAh for a total of 619.8 mAh. We selected a 1000 mAh LiPo battery to provide a 1.5 factor of safety, a reduced profile from the 9V battery, and rechargeability. The LiPo battery was used to power both microcontrollers via a single power switch, providing an advantage over prototype 1, which required four manual power switches when powering on the system.

3.3.3 Software Design Update

Code rework was needed for a microcontroller with three I2C buses instead of one. With the Arduino Wire library, the I2C protocol for each bus was initiated via Wire, Wire1, and Wire2. To meet the criteria of the 100 Hz data rate, the clock frequency was set to 1000 kHz.

The code used in the first prototype provided time-since-program-start in milliseconds and did not provide information on when the microcontrollers started writing data relative to one another. This was an issue we also anticipated for the second prototype due to the lack of programming for data collection timing, since doing so would have caused more lag at 100 Hz. Our solution was the Real Time Clock (RTC) functionality, which obtains the time from the computer provided upon program load while the microcontroller is connected to a computer. After the microcontroller is disconnected from the computer, it relies on an external coin cell battery to keep the timekeeping function running, drawing current on the order of μA [16]. The capacity of a CR2032 coin cell is around 235 mAh, which should enable the RTC to run for months without issue [17]. With the RTC, both microcontrollers had accurate non-relative timestamps for the cross-comparison of data points.

3.3.4 Build

While the first prototype was plug-and-play, the Teensy did not use the Qwiic connectors. The sensors still used Qwiic connections, and the microcontroller end was spliced and soldered onto a solderable breadboard that held both microcontrollers and a manual power switch.

The Teensy microcontrollers were soldered onto the breadboard with break-apart headers. The wires from the Qwiic connectors all had plastic sheaths which were pulled apart and stripped, then passed through one hole on the breadboard before being soldered in another hole. This technique provided strain relief to the small solder joint.

The simplified block diagram for the second prototype can be found in Figure 2.

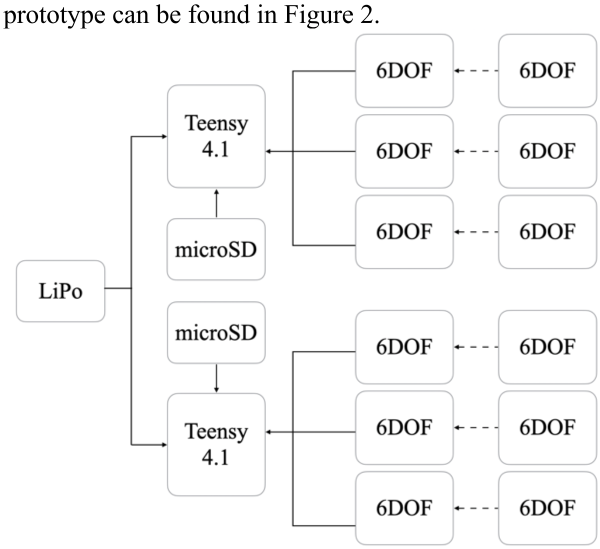


Figure 2: Simplified block diagram of prototype 2. Dashed lines represent Qwiic connections, solid lines represent soldered/plug-in connections.

4. Garment Integration

Hand-sewing was the only viable method of attaching components that provided the option of re-attachment since alternatives such as fabric glue were permanent. Sewing allowed for minute adjustments in the tension and placement of the wires to be performed after trying on the garment. The Qwiic wires we used comes in 50 cm, 200 cm, and 500 cm lengths. The connections between the sensors and between the sensors to the microcontroller both relied on these Qwiic connector wires. Since each wire path only had two sensors, and each microcontroller had six sensors, placement of sensors with respect to the microcontrollers was carefully considered to accommodate 500 cm as the longest length of wire. The prototype was built to fit a 165 cm, 50 kg female flyer.

The microcontrollers both connected to a solderable breadboard, which sat atop the chest. This breadboard position minimized the number of wire length adjustments. One microcontroller corresponded to the upper body, with three I2C wire paths: two shoulders, left elbow and wrist, right elbow and wrist. The other microcontroller corresponded to the lower body, with three I2C wire paths: two hips, left knee and ankle, right knee and ankle.

The following wires needed to be adjusted, since the 500 cm proved to be either too long (causing a tangle risk) or too short (connection easily broken with extreme movement). The sensors were sewn on first on the upper side of joints (on the forearm above the wrist, on the thigh above the patella, etc.) to avoid interference with the joints during movements. Each of the sensors had four solder holes in each corner, which we used to sew three passes on each external side, as shown in Fig. 3 below. The breadboard was secured in a similar fashion with the four corners sewn in as shown in Fig. 4, and the garment stretched underneath so it would be flush when put on. The electronics and wiring were left exposed throughout the prototyping process since LEDs on each sensor served as visual indications for electrical connections. The microcontrollers needed to be exposed since the power switch and SD cards needed to be accessible on flight day. Zero Gravity Corp required their flight suit to be worn on top of the garment, so the decision to leave the electronics exposed saved time and did not increase risk to the user or system.

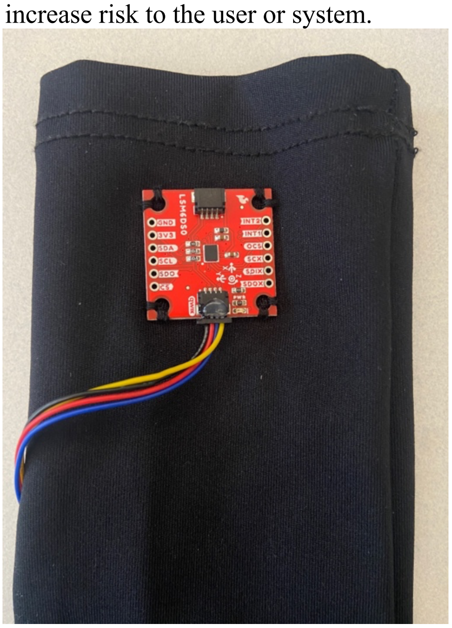
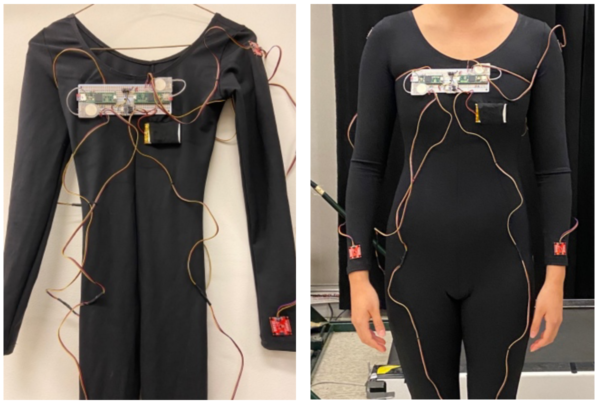


Figure 3: Sensor sewed in the wrist position with Qwiic connector attached.

We plugged in one side of the Qwiic wires and held the other side in place while performing movements that tested the range of motion. For any wire, we chose the maximum extended range of motion for that particular wire and set that as our wire length. A midpoint was chosen where the wire was secured to the garment with thread loops in order to create friction, but not attached so the wire was able slide back and forth as needed. The wrist-elbow and knee-ankle wires were wrapped around the forearm and calf respectively to reduce excess wire. For wires that needed modification, they were spliced and wrapped with heat shrink. The movements at the full range of motion were again conducted to ensure there was no excessive slack (more than 10 cm hanging from the body) or insufficient slack (wire tugging at the full range of motion). Once the wire lengths were verified, the connectors were secured with hot glue to ensure retention during movement. Hand-sewing proved to be time-consuming, requiring an estimated 20 hours throughout the project lifecycle.



Figures 4 & 5: Prototype 2 garment closeup and on-body.

5. System Characterization

First, we created a breadboard system and ran the program to ensure data collection. All of the components, including the LiPo battery, were represented and flight-like. After soldering, we laid out the garment and ran a three-hour "day in the life" static test to simulate the duration of the parabolic flight. We verified the test by checking for continuous data collection at 100 Hz from all sensors and ensuring all sensors were in absolute acceleration mode (one accelerometer axis stored ±1 g) instead of relative acceleration mode (all accelerometer axes reading ~0 g).

6. Results and Discussion

The sensor system garment was tested in parabolic flight, worn under a standard Zero Gravity Corp flight suit. Performance and data collection were nominal. In total, the prototyping cost was around $1500, and each final garment costed $350.

Prototype 2 had an improved data collection rate and reductions in footprint, weight, and profile, as compared to prototype 1. It also had a manual power switch, synchronized power, and RTC capability. The improvements are described in Table 2 below.

Table 2: Summarized improvements from prototype 1 to prototype 2.

Feature	**Prototype 1**	**Prototype 2**	**Improvement**
Footprint	515 cm^2	189 cm^2	63%
Weight	594 g	148 g	75%
Profile	17.5 cm	7 cm	60%
Power switch	No	Yes	--
Data rate	13 Hz	100 Hz	670%
RTC	No	Yes	--

6.1 Challenges

Most sensor systems similar to ours utilized Inertial Measurement Units (IMUs) instead of accelerometers. IMUs add a magnetometer that provides inertial acceleration with respect to the Earth's magnetic field. Supply chain disruptions due to COVID-19 affected the availability of IMUs. Although a magnetometer is not necessary for our purposes, IMUs usually have higher performance capabilities compared to accelerometers.

Supply chain disruptions also created shipping delays at the distributor level and the shipping service level, which made iterative prototyping significantly more challenging.

7. Future Work

The flight experiment associated with this work will be discussed in a future publication. The wearable system enabled data collection of kinematic data across the body to assess the adaptation of movement quality throughout short-duration microgravity exposure.

We hope this prototype development process can serve as a reference for others designing low-cost wearable systems for microgravity flight.

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References

[1] Peter Norsk. 2018. Physiological Effects of Spaceflight – Weightlessness: An Overview. Springer International Publishing, Cham, 1–9. https: //doi.org/10.1007/978-3-319-10152-1_126-1

[2] Leia Stirling, Karen Willcox, Philip Ferguson, and Dava Newman. 2009. *Kinetics and kinematics for translational motions in microgravity during*

parabolic flight. Aviation Space and Environmental Medicine 80 (6 2009), 522–531. Issue 6. https://doi.org/10.3357/ASEM.2356.2009
[3] Papaxanthis, Charalambos, Thierry Pozzo, and Joe McIntyre. "Arm End-Point Trajectories Under Normal and Micro-Gravity Environments." Acta astronautica. 43.3 (1998): 153–161. Web.
[4] Papaxanthis, C., T. Pozzo, K. E. Popov, and J. McIntyre. "Hand Trajectories of Vertical Arm Movements in One- G and Zero- G Environments." *Experimental Brain Research* 120, no. 4 (May 25, 1998): 496–502. https://doi.org/10.1007/s002210050423
[5] Stirling, Leia, Karen Willcox, Philip Ferguson, and Dava Newman. "Kinetics and Kinematics for Translational Motions in Microgravity during Parabolic Flight." *Aviation Space and Environmental Medicine* 80, no. 6 (June 2009): 522–31. https://doi.org/10.3357/ASEM.2356.2009.
[6] T Flash and N Hogan. *The coordination of arm movements: an experimentally confirmed mathematical model*. Journal of Neuroscience, 5(7):1688–1703, 1985.
[7] Shu-Yu Lin, K. Arquilla. "Quantifying Proprioceptive Experience in Microgravity." Space CHI Workshop, Association for Computing Machinery Conference on Human Factors in Computing. May 2022.
[8] Johnson, Kristina T, Sara Taylor, Szymon Fedor, Natasha Jaques, Weixuan Chen, and Rosalind W Picard. *Vomit Comet Physiology: Autonomic Changes in Novice Flyers*, 2018. https://doi.org/10.0/Linux-x86_64.
[9] Lee, Kevin, and Wei Tang. "A Fully Wireless Wearable Motion Tracking System with 3d Human Model for Gait Analysis." *Sensors* 21, no. 12 (June 2, 2021). https://doi.org/10.3390/s21124051.
[10] "Teensy 4.1." SparkFun, SparkFun Electronics, www.sparkfun.com/products/16771. Web. Accessed 3 February 2022.
[11] "Raspberry Pi Products." *Raspberry Pi*, www.raspberrypi.com/products/. Web. Accessed 3 February 2022.
[12] "Teensy® 4.1 Development Board." PJRC, www.pjrc.com/store/teensy41.html. Web. Accessed 18 March 2022.
[13] "enableI2C." *Mathworks*, www.mathworks.com/help/supportpkg/raspberrypiio/ref/enablei2c.html. Web. Accessed 3 February 2022.
[14] "Raspberry Pi I2C Interface." *MathWorks*, www.mathworks.com/help/supportpkg/raspberrypiio/ug/about-i2c-interface-on-the-raspberry-pi-hardware.html. Web. Accessed 3 February 2022.
[15] "LSM6DSO Datasheet." ST Microelectronics, Jan. 2019, cdn.sparkfun.com/assets/2/3/c/6/5/lsm6dso.pdf. Web. Accessed 10 November 2022.
[16] NXP Semiconductors. "Enabling Timekeeping Function and Prolonging Battery Life in Low Power Systems." *Digi-Key Electronics*, 14 Dec. 2011, www.digikey.com/en/articles/enabling-timekeeping-function-and-prolonging-battery-life-in-low-power-systems . Web. Accessed 14 March 2022.
[17] "Energizer CR2032 Product Datasheet." Energizer, data.energizer.com/pdfs/cr2032.pdf. Web. Accessed 14 March 2022.