Kate Gleason College of Engineering
Rochester Institute of Technology
Rochester, New York 14623

Project Number: P21009

Pediatric Test Mannequin - Sensing and Communication

Rhiannon Jimenez
Project Manager
Biomedical Engineer

Chris Abajian
Lead Engineer
Computer Engineer

Aharon Sebton
Validation and Test Engineer
Electrical Engineer

Thomas Sosa
Electrical Integration Engineer
Electrical Engineer

Rebecca Reich
Software Engineer
Computer Engineer

Abstract

A pediatric stander kit has been developed to modify a manually controlled pediatric stander to enable motorized movement controlled by the child who is secured in the stander. The idea of motorizing a pediatric stander has been pursued by a series of MSD projects at RIT. We are not currently able to collect data that characterizes the performance of the motorized kit and the experience of the human rider on the stander. Although some prior teams did testing, the data was limited and for limited scenarios. A system (PSPAS) that can be used to measure and record data relevant to the stander and a human subject secured to the stander is the main purpose of this project. A stretch goal is that this system might be easily adaptable to similar projects (e.g., a wheelchair) that involve devices that facilitate mobility of a human subject.

Background

It is important to create a safe way to test the functionality and efficacy of the motorized pediatric stander. Lack of proper testing protocols is a problem amongst other medical devices which target children with cerebral palsy or muscular dystrophy. In the future, this system would ideally be compatible with similar devices that aid patient mobility to ensure children with physical disabilities do not experience discomfort while riding and controlling pediatric standers.

The goal of this project is to develop a robust pediatric test mannequin with an untethered autonomous system that represents a patient the stander is designed to support. The data collected will be in regards to the stander's performance and patient experience. Collected data will allow us to map out areas of concern and identify how a patient's range of motion is restricted while being supported by the stander. Raw transmitted data would include acceleration, velocity and applied forces which would then be easily retrieved and visualized. The pediatric test mannequin must match the physical characteristics of a child, be compatible with the pediatric stander and similar devices, and have a power duration of roughly 9 hours.

Overall Goals

Customer Requirements

The pediatric test mannequin must be robustly developed, the device should be untethered and autonomous, the data collected should represent the stander's performance and patient experience, the data should map out areas of concern for a rider using the stander: it must be able to identify limited range of motion, areas of discomfort, and areas lacking support, the raw data that must be transmitted include acceleration, velocity and applied forces, it must match the physical characteristics of a child and be compatible with the pediatric stander and/or similar devices, and the mannequin must have a power duration of roughly 9 hours.

Engineering Requirements

Engineering requirements were developed to fulfill the customer's requests. As for the battery, the requirements were untethered, having a battery operation time over 8 hours and a charge time of less than 5 hours. The sensors had to be able to reach a velocity of at least 6 mph, an acceleration of greater than 5Gs, an inclination greater than 15 degrees, and a cumulative force greater than or equal to 440N. The data storage size had to be at least 32 GB.

Constraints

Constraints were derived from the structural side of the project as well as the customer. The weight and size of the sensing system had to match the physical dimensions and internal cavities provided by the structure team. The mannequin also must have the constraint of having an untethered power delivery during usage and the sensors must be versatile and adaptable to other models of the standers.

Description of Design

In order to fulfill the customer and engineering requirements, assumptions had to be made and implemented into an overall design. The design had to keep the problem definition in mind, begin a system level design, create a preliminary detailed design, form a detailed design, build and test the idea, build and test the subsystems, and finally integrate the system. The description of the design includes the prior assumptions and explanations on the microcontroller, raspberry pi, prototype board, sensor description/placement/mounting, wiring, and user interface chosen, built and tested.

Assumptions

In identifying the distinct forms of discomfort that a child may experience while using the stander, a team of experts were involved including our customers, a physical therapist, and prior MSD team documentation. The key concern from the physical therapist was the abrasion on the back of the knee caused by the leg straps on the stander. With that in mind, other areas of concern included the contact between the stander's chest and hip pads and the user, and the contact between the user's forearms and the control panel. The experience of whiplash stood out to the customers as an area of concern. Whiplash would primarily be affecting the neck and head movement. Prior MSD teams working on the stander documented the results of users interacting with the stander. It was found that other forms of discomfort still involve the rapid displacement of points in the body such as the hips swinging back while the chest remains still. This information allowed the sensing software to be developed for a few, discrete points with an option of expanding to more in the future. Another assumption made was that the head represented enough variability in movement to need detailed measurements captured by sensors. A final assumption that was made was that zeroizing would be allowed in any state because the value of sensors will not always reflect the same initial values due to differences in securing of the mannequin, previous displacement of any sensors, and

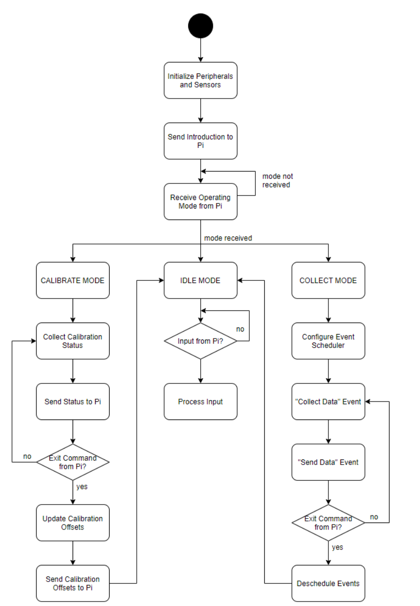


Figure 1: Microcontroller Software Block Diagram

Microcontroller

The NXP FRDM K64F microcontroller was selected as it contains several digital and analog interfaces. The K64F has a very high-speed central processor (ARM Cortex-M4 120 MHz) with several low power modes. The microcontroller also features two onboard ADC's.

The total input bandwidth of all of the sensors is determined to be 191.296 kbps. Assuming a 15% cycle overhead for I2C addressing and control bits, the total I2C bandwidth is 217.046 kHz. This easily falls below the 400 kHz maximum I2C clock frequency specification. The main program for the microcontroller consists of an initialization phase, calibration phase, and sensing event loops. Each sensor type has its own independent event that can be scheduled in unique periods to correspond with the specified sensor's sample rate. This reduces the workload of the microcontroller and will result in small power efficiency improvements.

Raspberry Pi

In order to optimize the processing speed on the Microcontroller, a Raspberry Pi 3 B+ with Wifi was included in the system. This additional processor was used to control the touchpad GUI interface, as well as all log saving functionality. By separating the labor across two devices, the NXP could solely poll sensor data without being slowed down by arduous file saving and transfer methodologies. As well, log parsing and GUI development was simplified in using Python over C. UART and Ethernet were used to communicate between the Pi and the Microcontroller. The specific model of Pi includes more features than were used for this project, however, these additional utilities allow for future development to expand upon its current capabilities –such as on-board Wi-Fi, Bluetooth, ethernet, and multiple USB ports.

Prototype Board

In order to improve the granularity of force measurements read from the FSRs, an amplifying op-amps with 3kΩ resistors were required between the sensor and the microcontroller. Additionally, the microcontroller did not support enough DACs to handle all planned 8 FSRs. In order to switch between limited analog inputs on our microcontroller, MUX was required. A support board, which contained both aforementioned components, were designed and implemented on altium. This module would be placed between the sensors and the microcontroller in the system. Theschematic included 8 op-amp blocks that fed into two, 4-to-1 MUXES as shown in Figure 2. Once fully designed digitally, the circuit was implemented as a protoboard which will be included in our subsystem.

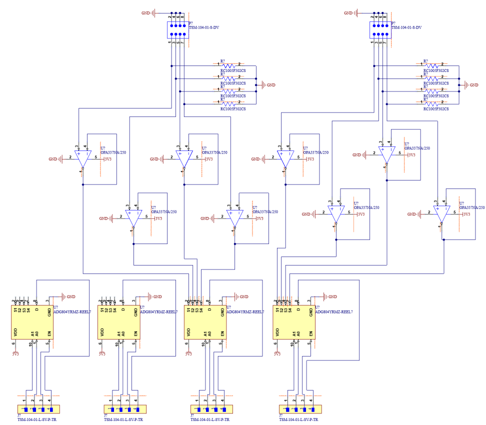


Figure 2: Prototype Board Schematic Design

Sensor Description, Placement, and Mounting

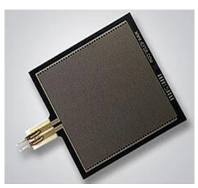
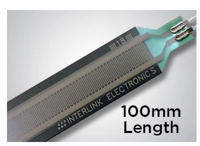
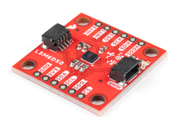
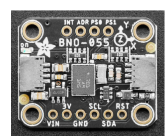
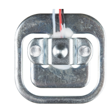
A major aspect of our design was deciding the sensor types and applications. There were four different types of sensors that suited our goals: the Orientation Sensor, Force Sensitive Resistor, Inertial Measurement Unit, and Load Sensor. Starting with the Orientation Sensor, this sensor is dedicated to the displacement of the Mannequin's head relative to a starting position. The BNO-055 Absolute Orientation Sensor from Adafruit is used. This sensor is a combination of three different sensors: an accelerometer, a gyroscope, and a magnetometer. A proprietary sensor fusion algorithm processes the sensory data using an onboard ARM Cortex-M0 processor. The result is a suite of high-accuracy, interpretable data that can easily be used to track the orientation of the structure the sensor it's attached to. The most difficult aspect of determining the sensor types was undoubtedly the force sensors. Unfortunately, most force sensors on the market are either hobbyist grade that are inaccurate or industrial grade that are too expensive or large. To measure the pressure of the mannequin against the stander pads, we opted to use Force Sensitive Resistors (FSR's). As the name implies, these sensors are simply resistors that are sensitive to the force applied to the area of the sensor. As the applied force increases, the resistance decreases. The biggest drawback to these is that support circuitry is required to obtain an analog output and they are not very accurate. For areas where the forces against the mannequin are not constantly changing and do not need to be precise, these sensors are applicable. The forearms, sides of the torso, sides of the hip, and the back of the knees are ideal locations for FSR's since prolonged exposure to a high force in these areas is what we're trying to measure. These sensors come in two form factors: a square pad and variable length strips. An IMU is similar to the Orientation Sensor described previously, however, it is only an accelerometer/gyroscope breakout board that does not apply sensor fusion algorithms. IMU's will be used where absolute orientation will not be necessary but data pertaining to the movement of this body part may be important, such as the legs. For parts of the body where greater, instantaneous forces are expected (such as the chest), FSR's are not a viable solution. They are not accurate enough, do not provide a high range of force detection (the FSR's listed above have maximum force ratings of 150 N), and they do not cover a large

Copyright © 2021 Rochester Institute of Technology

surface area. The chest of the pediatric test mannequin will be in contact with pads affixed to the stander. Sparkfun Load Sensors will be used to measure these forces in combination with supporting circuit boards.

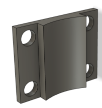
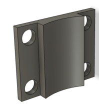
Sensor placement was an important part of the design process which helped target the relevant data needed. After speaking with a physical therapist and the customer, the ideal sensor placement was solidified. The key concern from the physical therapist was the abrasion on the back of the knee caused by the leg straps on the stander. In this case, a force sensitive resistor would enable us to detect how much pressure is being applied to the back of the knee during usage of the pediatric stander. With that in mind, other areas of concern included the contact between the stander's chest and hip pads and the patient, and the contact between the patient's forearms and the control board. For these reasons, we chose to place FSRs on sides of the torso (on the chest and hip area), and the bottom of the forearms. Because one of the customer requirements was to ensure that whiplash could be detected, we discovered that the orientation sensor would be best to determine the contrasting acceleration between the chest and the head. Therefore, one orientation sensor was placed in the chest and one in the head. Another customer requirement was to ensure that the child is comfortable. A detected issue was the movement of the hips and an increase in inclination of the feet. An inertial measurement unit was inserted into the top of the thigh right below the hips to see if the hip is moving at a different velocity than the torso. This also helps determine the angular acceleration of the legs.

Table 1: This table shows the sensor information such as the interfaces used, sample rate, sample size, data rate, data size, etc.

Sensor Information					
Sensor Types	Force Sensitive Resistor (pad)	Force Sensitive Resistor (strip)	Inertial Measurement Unit	Orientation Sensor	Load Sensor
Image					
Interfaces	Analog (ADC)	Analog (ADC)	I2C, SPI	I2C, UART	Digital
Selected Interface	Analog (ADC)	Analog (ADC)	I2C	I2C	Digital
Sample Rate	Up to 300 kHz	Up to 300 kHz	1.6 - 52 kHz	100 Hz	10 or 80 Hz
Sample Size	12 or 16 bits	12 or 16 bits	16 bits	272 bits	24 bits
Data Rate (Hz)	5	5	833	100	80
Data Size (Bytes)	2	2	12	18	3
Number of Devices	8	8	2	2	1
Total Input Bandwidth (kbps)	0.640	0.640	159.936	28.800	1.920

Mount Designs were another part of the design process that helped with safely securing the sensors to the mannequin. There were four main mounting designs: a knee brace for the FSR to securely attach to the back of the knee without interference from the mannequin, a 3-D printed chest scale design consisting of four load sensors attached in the front and the back with two rectangular surfaces to create a single pressure dispersed upon the four of them to provide more accurate pressure measurements similar to a bathroom scale, four 3-D printed mounts- two for the inertial measurements and two for the orientation sensors, and respective sized velcro straps for the force resistive sensors mounted on the forearms and the torso.

Table 2: This table shows the sensor types with the ways that they were hypothetically mounted to the doll.

Mounts					
Sensor Types	Force Sensitive Resistor (pad and arm strip)	Force Sensitive Resistor (back of the knee strip)	Inertial Measurement Unit	Orientation Sensor	Load Sensor
Mounting Technique Chosen					

Wiring

The wiring chosen was the 22 AWG wire with a 0.0254 inch diameter. In the thighs, the wires route through the hip alongside elastic and exit through the hold drilled near the top of the endoskeleton's thigh. It attached to the IMU directly, and was zip tied to the endoskeleton for organization. There were four different wires: red, black, blue, yellow which were 30" long each. To cover the wires we used faux skin. In the torso, there was a hole drilled near the base of the spine for leg wire egress. All wires were routed along the endoskeleton on the outside, and secured to the endoskeleton via zip ties. For the arms, the wires were routed down outside of the steel pipe, then entered the arms at the shoulder alongside elastic. It was ingressed from elbrow hole and immediately separated from the elastic (the elastic goes inside the pipe and the wires route along the outside. Zip ties were used on the wires on the outside of the endoskeleton. As for the forearms, holes were dropped at the top of the endoskeleton to extract wires from the pipe to keep it separate from elastic as much as possible. A hole was drilled in the medial side of the forearm to pull wires out of the doll for pressure sensor attachment. There were 2 wires: black and red which were 40" long; these were also covered with faux skin. The head had wires zip tied to the endoskeleton that was fed up into and back down the neck to the chest. The four wires were red, black, blue, and yellow that are each 38 inches long.

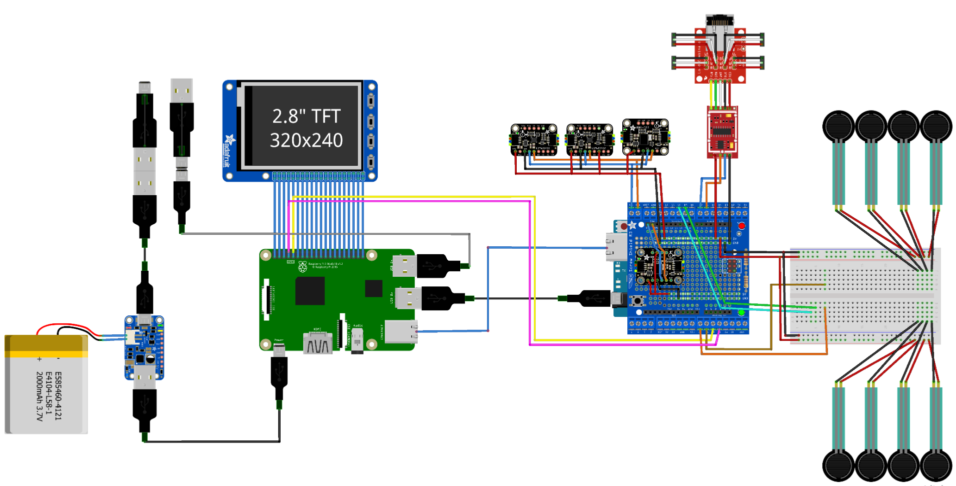


Figure 3: This figure shows the torso's wiring diagram including the battery, raspberry pi, NXP, load combinator, etc.

Copyright © 2021 Rochester Institute of Technology

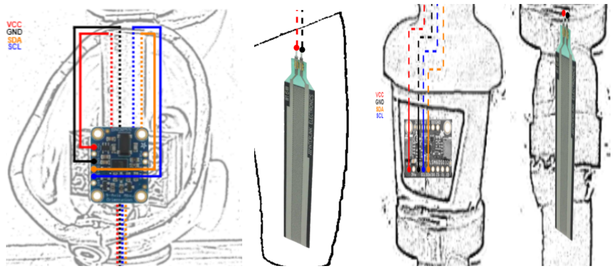


Figure 4: This figure shows a combination of different wiring diagrams including the arms, legs, and head.

User Interface

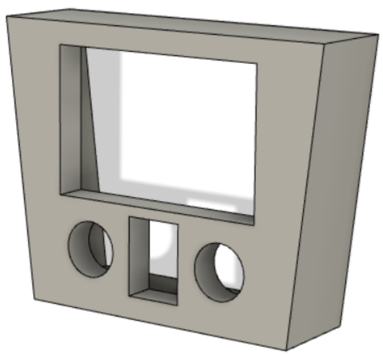


Figure 5: This picture shows the control panel's 3-D design. It is intended to have the LCD screen and two ports, and a power switch attached.

The control panel mounted to the back of the mannequin includes a 3-D designed and printed encasement that holds a power switch, USB A to Micro B Panel Mount for data extraction, USB Micro B to A Panel Mount for charging, and an LCD screen to display the User Interface. The interface follows a color scheme derived from the customer's colors, RIT's Liveability Lab.

The Home Menu allows for navigation to one of three options: Configuration Menu, Collection Menu, Export Data to USB. The first is the configuration menu where components can be zeroed, enabled, or disabled. The next is the collection menu where an operator can control the start, stop, or pause of measurement data. Finally, the export to USB sends a report to a removable disc drive. All menus have an option to return to home.

The Configuration Menu provides the user the option to enable or disable a group of sensors, as well as zero the data. The former option issues a command to the microcontroller to stop collecting data from the specified group of sensors. This feature helps reduce the overall power consumption of the sensing system, as well as filter out any unwanted data to reduce storage overhead. The Configuration Menu also provides the ability to zero a sensor's data such that an offset is calculated on the microcontroller to produce sensor readings with values of zero. This feature is useful when the orientation of the mannequin is independent of a test and should be disregarded, such as an acceleration test on an incline. In such a scenario, the acceleration vector can be zeroed to remove the gravity-induced acceleration vector. Finally, the Collection Menu simply contains two buttons: one to initialize data collection and another to stop collecting data. These commands tell the microcontroller to send data samples over ethernet connection where the Raspberry Pi then collects, processes and stores these samples.

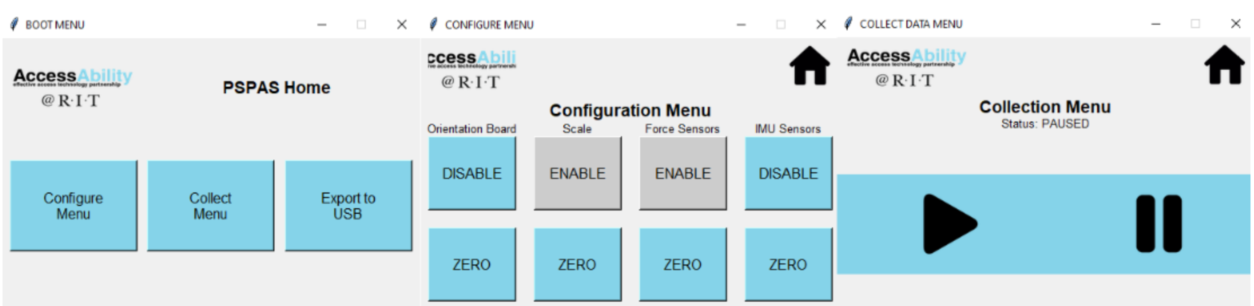


Figure 6: The GUI menus. From left to right: the Configuration Menu, the Home Menu, and the Collection Menu.

Design Process

Risks Explained

There were a few risks associated with this project. One of them being in the beginning we weren't positive about how COVID-19 would affect our ability to complete the project. Another risk we encountered was the risk of not being able to complete the project due to not integrating our sensing system with the structure's design. Next, we had the risk of the pediatric stander not being able to be used because of the motorized kit left undone.

Problem Tracking

A problem that occurred during the subsystem build and test phase was the difficulty with altium that occurred. Originally, a PCB was in the workings however with the delay of ordering and given time constraints the PCB was scrapped and the prototype board was added to the project. Another problem which occurred was the pediatric stander not being able to be used because of the motorized kit left undone. A student on the previous MSD team was able to assist our team in getting the standard working. This resulted in the ability to use the standar for testing for the future teams.

Test Results

The first test is the orientation board and inertial measurement unit feasibility testing. Results were able to show that small values would spike to a max of 1.0 whenever excessive pressure was introduced to the sensors.

The next test was the FSR feasibility test in which Mbed Studio was used to write and execute a code that would return the values of the FSRs every second. This was done via a *while* loop that would iterate selects from 00 to 11. Each of the selects would correspond to two outputs of a multiplexer. We used the two outputs to represent left and right as the Multiplexer IC's COM B and COM A outputs, respectively. Results were able to show that small values would spike to a max of 1.0 whenever excessive pressure was introduced to the FSR. A user was able to see that, on a given select, two FSRs were able to report changes.

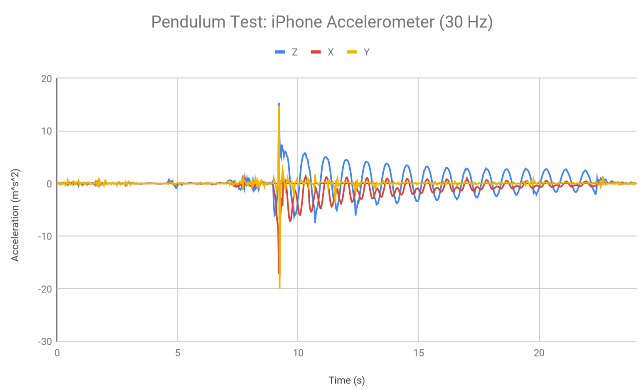


Figure 7: This figure shows the data collected from the accelerometer on an iphone. This provides data to check our sensors against.

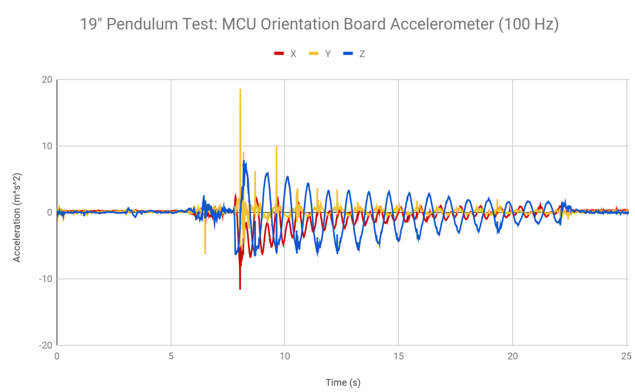


Figure 8: This figure shows data collected by the Orientation Board's accelerometer with a pendulum length of 19".

After the feasibility testing, ensuring that the sensors are reading data accurately and able to continuously collect and communicate data to the MCU was done. A recreation of a pendulum was built to allow us to see how the orientation board and the inertial measurement unit would pick up data and transmit it to the NXP. The same test was repeated three times with three different distances away from the x-axis: 19in, 25in, and 34 in. Afterwards, the results were graphed and a conclusion was made. The data is shown below and it was concluded that we see that the data from the MCU and the Iphone Accelerometer, our control, matched. While the devices were oriented differently, we altered the legends of each graph to match. As seen by the Blue data curve in the top two graphs, both devices measured a maximum, vertical, acceleration that corresponds to Gravity, 9.81 m/s^2. This is in the negative Z-direction. As seen by the Yellow data curve, we can see that the maximum acceleration measured by both devices was about twice that, but in the negative Y-direction. After reviewing the data, it was concluded that both the IMU and the Orientation Board yielded accurate data in real time. At no point was the data flow to the MCU ever disrupted. Data collection was continuous. This test was successful.

Copyright © 2021 Rochester Institute of Technology

There was also a gyroscope test conducted on the inertial measurement unit. The goal of this test was to obtain data from the IMU and compare the data with physical inclination. The intention was to determine the accuracy of the chosen sensors. An Iphone was again used to check the sensor data. The Iphone's inclinometer was verified with a digital protractor. There were six trials conducted with different angles at each one: 0, 15, 30, 45, 90, and 135. As seen in the chart, the IMU's gyroscope has an offset of 3-5 degrees up to an incline of around 90 degrees. However, it was observed that past 90 degrees vertical, or once it reaches obtuse angles, the displayed incline measurement did not match the actual incline. This is because the IMU provides angle measurements with respect to the x-axis. Therefore, we can conclude that the IMU is accurate up to the 90 degree angle, which then we must add an additional 90 degrees to the measurement to be accurate. However, our inclination goal was at least 15 degrees, so there should not be issues associated with going over 90 degrees. It is also producing negative results with an offset of 3-5 degrees that can be corrected during calibration.

Trial	Actual Incline [degrees]	Measured Incline [degrees]	Difference [degrees]
1	0	-4.4375	4.4375
2	15	-19.75	4.75
3	30	-33.75	3.75
4	45	-48.8125	3.8125
5	90	-86.25	-3.75
6	135	-41.5265	-93.4735

Figure 9: The above chart displays the data collected during inclination testing. The results are the physical inclination compared to the inclination captured by the IMU.

Final Deliverables

The final deliverables for the sensing system of the pediatric test mannequin consisted of a dismounted assembly of the sensing electronics system. The system was operational and allowed for a user to charge the system's batteries, power the system on, run the GUI, control sensor configurations, and collect sensor data. The validity of the sensor data was not determined due to the fact that the sensors were decoupled from the test mannequin and any results would be invalid. The team provided an Assembly Plan complete with wiring diagrams and sensor mounting procedures and CAD models, a User's Guide, a Programming Guide, and a PSPAS Status Report.

Going Forward

The PSPAS project is a great opportunity to utilize and validate the pediatric stander that has been created and modified over several MSD projects. The project required a broad scope of engineering backgrounds, however the scope of the sensing system was more than the team could achieve. In terms of the goals set out for the project, the team fell short of achieving an untethered system that was mounted to the mannequin, primarily due to the scale of the sensing system, the programming workload, and the limited space available in the mannequin. However, the team was successful in developing a functional prototype of the sensing system and serves as a strong base for a future iteration of the project.

If repeating this project again, we would collaborate more with the structure team so that the integration portion would be handled better. The inner diameter of the mannequin's torso did not provide enough space for the sensing system. The inner sensing components being mounts were too large to fit alongside the endoskeleton pole. Another option would be to have predefined dimensions to pass to the structure team. However, with the structure's system and dimensions being changed so frequently it was hard to determine how much room the sensing system would have to work with. With time constraints in mind, the sensing system had to make dimensional decisions before the structure was completely built and the structure was trying to produce their build based on their customer and engineering requirements and not so much on the sensing system. In conclusion, team integration should have been more prevalent in the beginning of the project to make sure both teams were on the same page.

As for future work, all of integration must occur. The mounting in the torso has to be redesigned and fitted properly with the thickness of the endoskeleton in mind. If possible, expand the stomach of the doll to create more space for the components to go into. More testing still needs to be completed such as for the FSRs, the chest scale, the orientation board and the IMUs. Testing has already begun on the orientation board and the IMUs connection from the sensors to the NXP. However, all of the results produced must be tested.

Acknowledgments

The team would like to acknowledge Dr. Carlos Barrios and Jennifer Indovina for their continual support and guidance throughout the project. The team would also like to acknowledge Dr. Steven Day and Dr. Dan Phillips for their support, advice, and considerations throughout the project. Finally, the team would like to thank Interlink Electronics for providing the Force Sensitive Resistor sensors used in the project.