DYNAMIC SEAT CUSHION

By

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Abstract

This final report describes the increased risk wheelchair users face of developing pressure sores, our proposed solution for a dynamic seat cushion that automatically readjusts seat areas experiencing prolonged pressure, and our implementation of the electronic components for this ECE 445 Senior Design Pitched Project. This report includes overviews and verifications of our electronic subsystems, design considerations and tolerance analysis, and cost metrics for the implementation.

Contents

1. Introduction

1.1 Problem

Pressure sores are ulcers that break down skin and underlying tissue in body areas that experience prolonged pressure. Approximately 3 million people worldwide develop pressure sores every year, with over 500,000 cases requiring extended hospitalization [1]. Wheelchair users face a higher risk of developing pressure sores and their best solution today is to manually adjust every 15-30 minutes. However, those with limited mobility and/or sensation may struggle with manual readjustments and/or with feeling when a readjustment is needed. As such, this group of wheelchair users faces an even higher risk when it comes to pressure sores.

While conventional cushions provide some relief, the solution they offer is static, limited, and does not eliminate the risk of pressure sores due to its inability to adapt to the user. Moreover, research into dynamic solutions is limited and no commercially available dynamic solution exists.

1.2 Solution

Our solution uses a combination of resistive force sensors, a programmable pneumatic pump, and an inflatable thermoplastic polyurethane bladder to create a dynamic seat cushion that will relieve pressure for wheelchair users. The sensors will be used to create a high-resolution pressure reading map to detect areas of prolonged high pressure. When time and pressure thresholds are both met, the microcontroller signals to the pneumatic controller for inflation or deflation of cushion bladders surrounding detected pressure points.

Throughout this pitched project, we collaborated with Dr. Golecki's research group to implement the electronic subsystems, which are the sensor array, user interface, microcontroller, and communication to the pneumatic controller. With these subsystems, we will develop a high-resolution sensor array that detects high-pressure areas on the seat over time and relieves pressure through selective inflation or deflation of cushions in the bladder. Our design is optimized for efficiency, compactness, and effectiveness.

1.3 Visual Aid

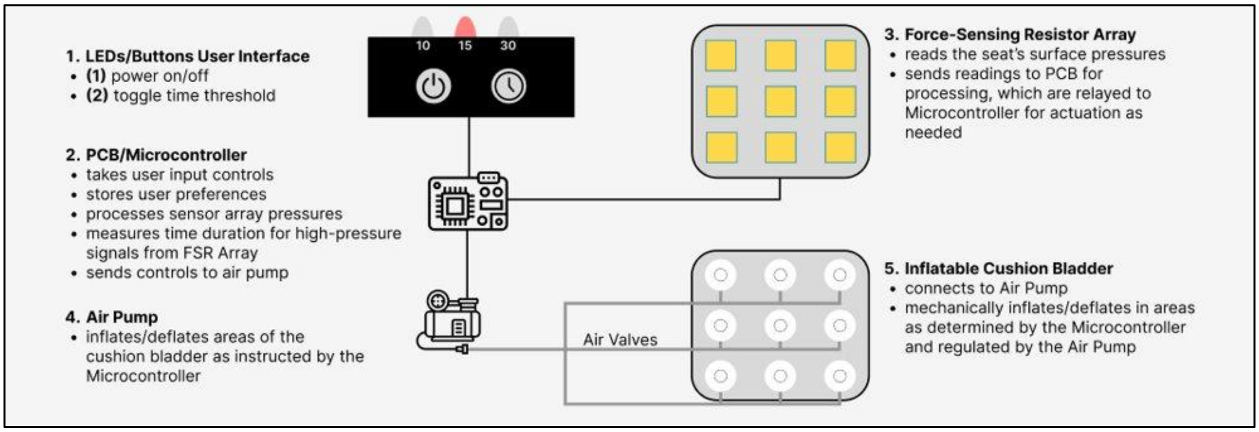

Figure 1 Dynamic Seat Cushion Functionality Overview

1.4 High Level Requirements

The primary success criteria for our project are as follows:

1. The dynamic seat cushion fits within the dimensions 12in. Wide x 14in. Deep x 4in. High, which is suitable for standard manual and electric wheelchairs [2].

2. The microcontroller reads sensor array signals to determine when a target area exceeds the pressure threshold. The microcontroller times the duration of the signal to determine if the target area also meets the time threshold, which can be set by the user.

3. When both thresholds are met, the microcontroller signals for inflation to areas surrounding a target such that the target drops below the pressure threshold.

2 Design

2.1 Block Diagram

The block diagram consists of our three main subsystems: user interface, sensor array, and pneumatic controller. All three subsystems are connected through the microcontroller. As such, the microcontroller is a component of all subsystems.

The user interface subsystem consists of four LED lights and two buttons for user interaction. The sensor array subsystem is an array of force-resistive sensors whose voltage outputs vary with applied pressure. These voltage values are repeatedly scanned by the microcontroller. The programmable air subsystem takes instructions from the microcontroller to inflate the bladders around corresponding areas of high pressure. The microcontroller interfaces with all subsystems.

In our block diagram, dark green arrows represents 5V, light green arrows represent 3.3V, and orange for data lines. Button 1 is a power button in charge of turning the device on and off. Button 2 is a soft button that will toggle the time thresholds.

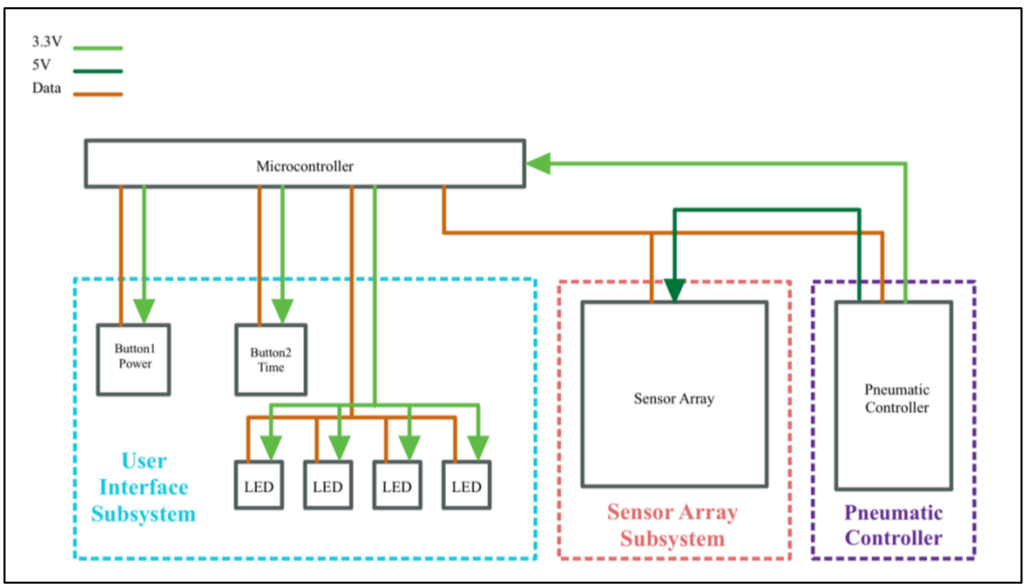

Figure 2 Block Diagram

2.2 Physical Design

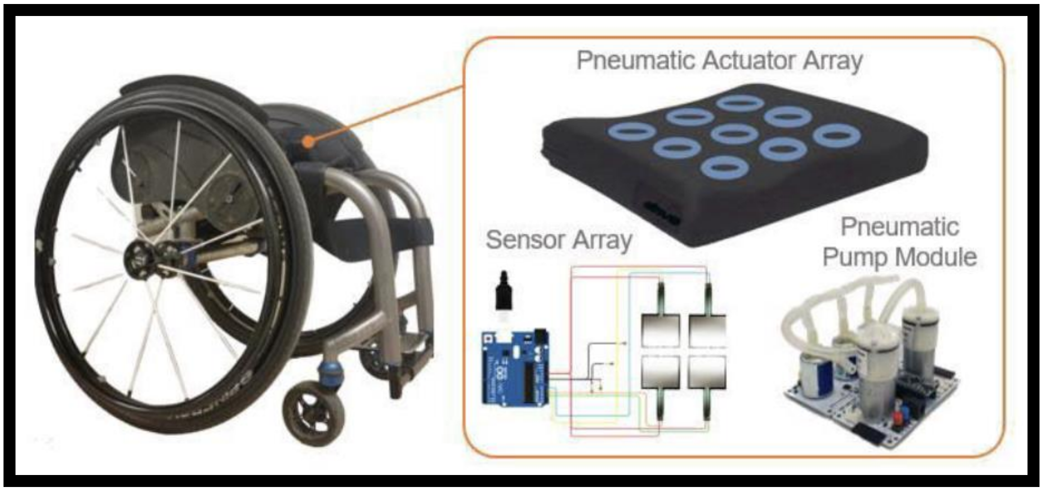

Figure 3 Physical design provided by Dr. Golecki's group [1]

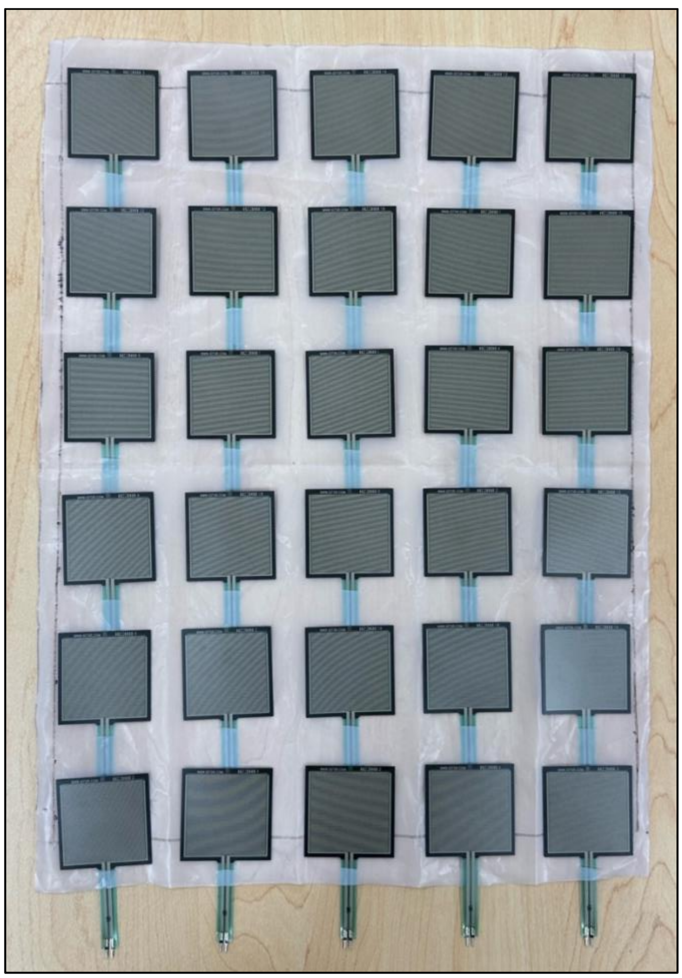

Figure 4 Array of Sensors on PDMS

2.3 Subsystem Overview

2.3.1 User Interface Subsystem

The user interface subsystem houses four LEDs and two buttons. Only one LED will be on at a time to display the current time threshold setting; this setting is stored by the microcontroller between power cycles. Button 1 (switch) allows the user to switch the device power on or off. Button 2 (soft) bounces instruct the microcontroller to toggle to the next time setting, turn off the current LED, and turn on the next LED.

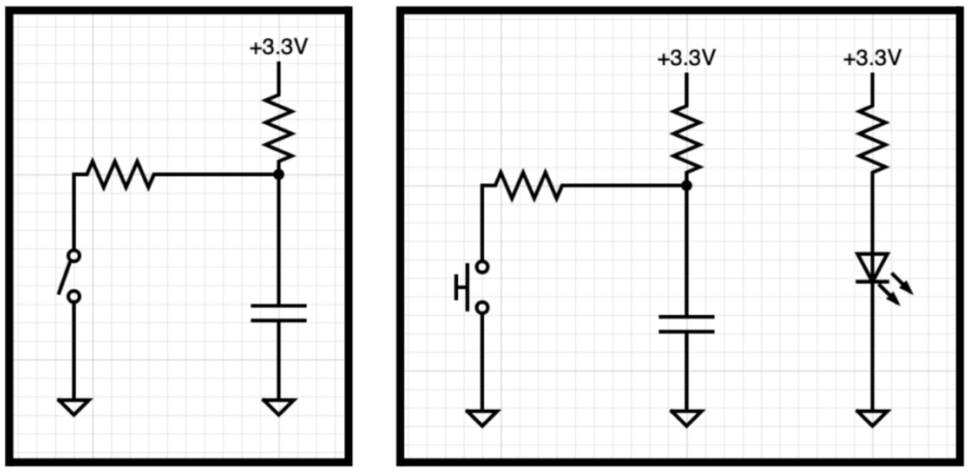

Figure 5 Button 1 Switch Schematic (Left) and Button 2 (Soft) with LED Schematic (Right)

2.3.2 Sensor Array Subsystem

The sensor array subsystem will consist of 30 square force-sensing resistors to provide a high-resolution image of pressure distribution on the cushion. The microcontroller will read its data to handle control functions to the pneumatic controller subsystem. The sensor array subsystem will receive power from the pneumatic controller's battery, which is routed through pins on the PCB.

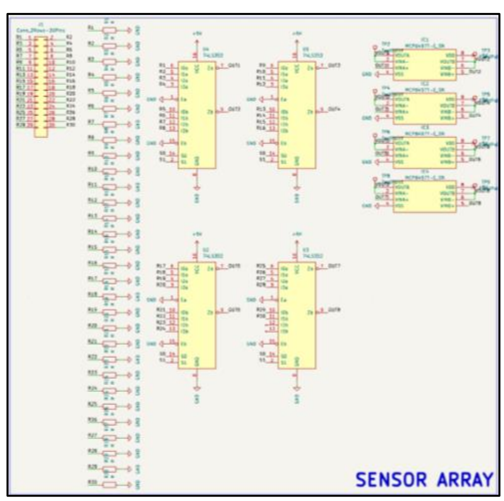

Figure 6 Sensor Array Schematic

2.3.3 Pneumatic Controller Subsystem

The pneumatic controller subsystem will operate the air pump and read instructions from the microcontroller to inflate and deflate the bladders. It will inflate or deflate the bladders depending on the signals received from the microcontroller. It will also monitor bladder pressures to prevent overinflation and popping of the bladders.

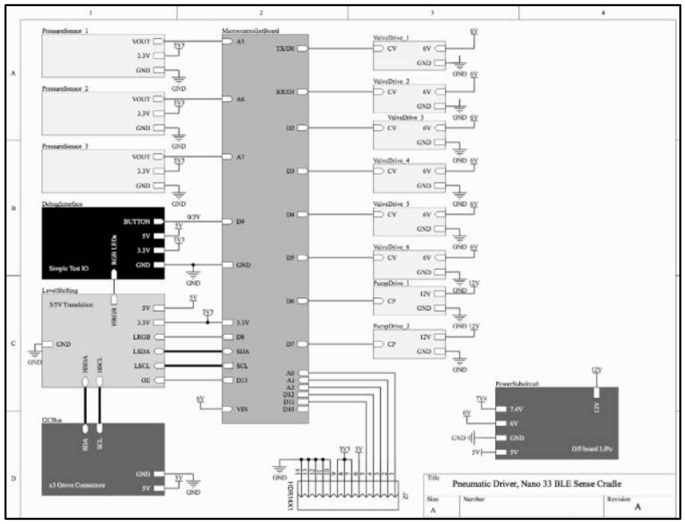

Figure 7 Pneumatic Controller Schematic

2.4 Tolerance Analysis

Our design utilizes multiple Square Force-Sensing Resistors (FSRs) over the wheelchair seat cushion to obtain a high-resolution image of the seat's surface pressure. The model we will use is the FSR UX 406 by Interlink Electronics. Its sensing range is 0.10 N to 100 N over an active area of 1.5 in^2 [3].

Assuming an average user mass of 70 kg, the maximum gravitational force exerted on their seat is 686 N or ~155 lbs. While the seat surface is 12 in W x 14 in D, most of the user's weight will be concentrated in a 12 in x 6 in area centered along the width and positioned to start at the very back of the seat [2]. As such, we are focused on obtaining a high-resolution pressure reading within a 72 in^2 area.

For an average user, an equally distributed surface pressure in this 72 in^2 area would be 155 lbs/72 in^2 or ~2.15 PSI. High-resolution readings from highly sophisticated and expensive systems, such as the TACTILUS, often tolerate up to 200 mmHg (3.87 PSI) [4], although the average user would rarely exceed 130 mmHg (~2.50 PSI) anywhere on the seat [1]. Thus, we should be concerned with measuring up to 2.15 PSI for an FSR grid area.

Recall that our selected FSR model can measure up to 100 N over an active area of 1.5 in^2 which translates to 66.67 N / in^2 and equivalently ~15 PSI. As such, we can confidently incorporate multiple FSR UX 406s into our design to create a high-resolution discrete pressure mapper by using an FSR array.

3. Design Verification

3.1 User Interface Subsystem

3.1.1 Requirements
The user interface subsystem's main purpose is to allow the user to power on the entire device and toggle through the different time threshold settings. The process to verify these functions is shown in Appendix A Table 6. **All requirements were met.**

3.1.2 Design Decisions
The user interface was designed with simplicity and ease of use in mind. We limited it to the minimum necessary components to operate the device. This required a physical switch for the power line connection, a soft button to toggle time settings, and display LEDs to inform the user of the current setting. With these choices, this system has the simplest design for developers and device users.

3.2 Sensor Array Subsystem

3.2.1 Requirements
The sensor array subsystem's main purpose is the collection of the seat's pressure distribution data for the microcontroller to processing. It is crucial that the individual sensors reliably measure this data as well as changes to this data. To ensure this, we verified that the sensors do not saturate during prolonged use with a 2kg of weight and a delta weight of 100g. The process to verify these functions is shown in Appendix A Table 7. **All requirements were met.**

3.2.2 Design Decisions
With regards to the sensor arrays, our design choices were geared towards reliability and cost effectiveness. The requirements and verifications below were created to ensure the reliability of the 30 sensors we chose to affordably cover the entire area described by our first high-level requirement.

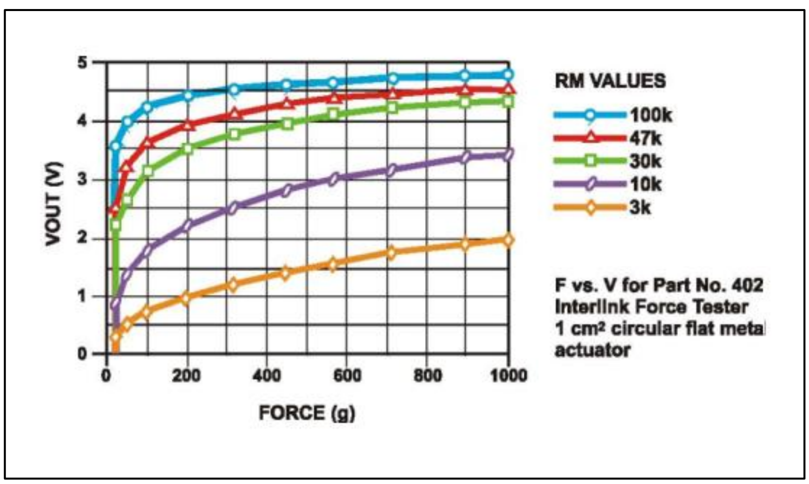

Figure 8 FSR Datasheet Graph with 2V Output Near 1000g with 3k Ohm resistor

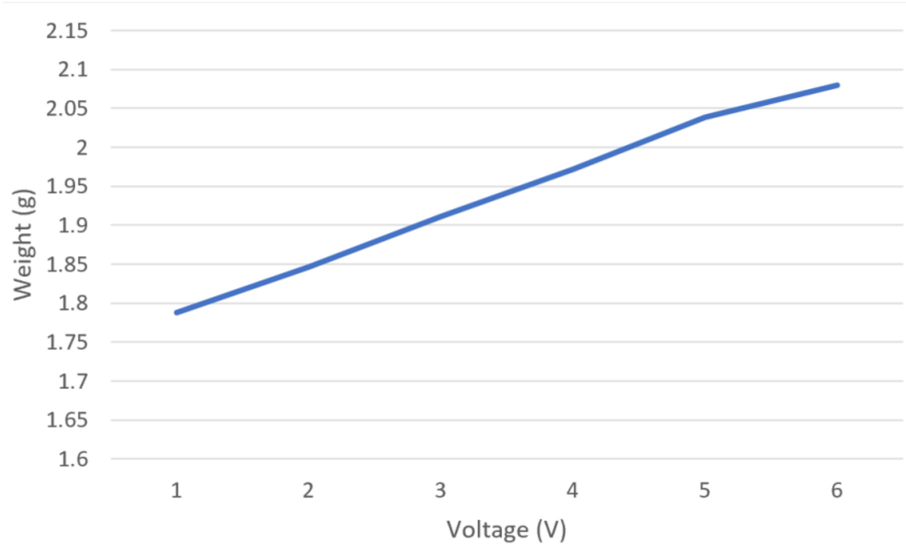

Figure 9 FSR Voltage Output Reading Near 2000g

3.3 Pneumatic Controller Subsystem

3.3.1 Requirements

The pneumatic controller subsystem is responsible for bladder inflation and pressure management. It is also responsible for power delivery to the other subsystems. Therefore, the main verification will be making sure that inflation is happening in a timely manner, overinflation is being prevented, and power delivery is stable. The process to verify these functions is shown in Appendix A Table 8. **All requirements were met.**

3.3.2 Design Decisions

Upon starting the project, we were given a choice between two air pump modules to apply to our project: the Programmable Air and the Pneumatic Controller. We ultimately decided to work with the Pneumatic Controller. Both modules came with a programmable Arduino but had several differences. These differences are outlined in Table 1 below.

Table 1: Pneumatic Controller vs. Programmable Air

	Pneumatic Controller	**Programmable Air**
Power Delivery	10,000mAh 3.3V / 5 V	Need external BMS 3.3V / 5V
Pump Characteristics	Two air pumps Noticeable internal gas leakage	One air pump
Versatility	3 Programmable Valves	2 Programmable Valves
Size	Bigger and heavier	Compact
Communication and Time Threshold management	I2C + Digital	Digital only
Pressure Control	Individual valve pressure readings	Central pressure readings (no dual options)

The biggest aspects behind our decision to adopt the Pneumatic Controller instead of the Programmable Air were power delivery, pump power, versatility, and pressure control. The Pneumatic Controller provided a 10,000 mAh lithium-ion battery with a battery management system while the Programmable Air would have required these external components. Thus, the Pneumatic Controller was easier to use and also saved space on our PCB. Moreover, the Pneumatic Controller had two inflation pumps compared to Programmable Air. Power was an important factor since we needed the pumps to be powerful enough to pump bladders under the weight of the user. The Pneumatic Controller had an additional programmable valve for gas output compared to the programmable air, which made the device faster at inflating multiple regions. We were told by our sponsor that the final bladder would have six gas intakes. Choosing the Pneumatic Controller with three gas valves would only require a total of two modules while the Programmable air would require three modules. The decision to use the Pneumatic Controller was not only cost effective, but also spatially efficient. Lastly, the Pneumatic Controller had a more versatile pressure reading environment. With pressure sensors on each valve, we would be able to monitor each bladder's pressure reading and prevent over pressurization. The Programmable Air adopted a central pressure reading environment which was less ideal for our implementation.

With this rationale, we decided to implement the Pneumatic Controller module for our project.

Table 2: Power Delivery Stability Requirement for 5V Supply

Resistor (kΩ)	Trial 1 (V)	Trial 2 (V)	Trial 3 (V)	Mean (V)
1	4.952	4.959	4.953	4.954
2.5	4.968	4.969	4.974	4.97
10	5.002	4.995	4.995	4.997

Table 3: Power Delivery Stability Requirement for 3.3V Supply

Resistor (kΩ)	Trial 1 (V)	Trial 2 (V)	Trial 3 (V)	Mean (V)
1	3.302	3.311	3.308	3.307
2.5	3.308	3.303	3.311	3.307
10	3.311	3.318	3.328	3.319

4. Costs

4.1 Parts

Table 4: Parts and Costs

Part	Manufacturer	Retail Cost ($)	Bulk Purchase Cost ($)	Quantity	Actual Cost ($)
FSR UX 406	Interlink Electronics	4.99	4.99	30	149.70
3kΩ SMD Resistors	Stackpole Electronics Inc.	0.10	0.17	30	5.10
Dual Op Amps	Microchip Technology	0.63	0.63	4	2.52
Dual 4-1 Mux	NTE Semiconductors	1.72	1.72	4	6.88
2x15 Connector	Samtec	6.58	6.58	2	13.16
2x15 Cable	Uxcell	7.99	7.99	2	15.98
Button	C&K	1.24	1.24	5	6.20
Screw Terminal	Phoenix Contact	0.38	0.38	2	0.76
2x3 Connector	3M	0.75	0.75	1	0.75
5x2 Connector	3M	0.75	0.75	1	0.75
100kΩ SMD Resistor	Stackpole Electronics Inc.	0.10	0.10	3	0.30
10kΩ SMD Resistor	Stackpole Electronics Inc.	0.10	0.10	2	0.20
1μF SMD Capacitor	KEMET	0.35	0.35	2	0.70
100nF SMD Capacitor	KEMET	0.35	0.35	5	1.75
0.354.7μF SMD Capacitor	KEMET	0.35	0.35	1	0.35
0.01μF SMD Capacitor	KEMET	0.35	0.35	2	0.70
STM32F103C8	STM	5.99	5.99	1	5.99
Total					**211.79**

4.2 Labor

The average starting salary for an electrical engineer UIUC graduate is $87,769 in 2021-22 and for a computer engineer UIUC graduate, it is $109,176 [6]. Since there are electrical and computer engineers in our group, we will take the average of that, which comes out to $98,473 and equates to $49.2/hour.

Table 5: Estimated Hours

Category	Estimated Hours (Angelica, Anthony, Eric)
Circuit Design	(17, 6, 17) = 40
Board Layout and Design Check	(10, 10, 10) = 30
Soldering and Assembly	(6, 7, 7) = 20
Software Component	(5, 10, 5) = 20
Signal Interpretation	(5, 0, 5) = 10
Debugging	(30, 30, 30) = 150
Documentation and Logistics	(34, 33, 33) = 100
Total Hours	**370**

The project's total labor costs comes out to a total of:

$$2.5\ (overhead\ multiplier) * \frac{\$49.24}{hour} * 370\ hours = \$45,547.00$$

4.3 Total Cost

The total cost of this project is:

$$(Parts + Labor) = \$45{,}758.79$$

5. Conclusion

5.1 Successes and Failures

Overall, our project was able to function and fulfill requirements with the development board. This meant that our design was successful and correct; however, because we were not able to get our microcontroller on the PCB to be working, so we had to resort to using a development board. Our sensor array was functioning and able to reliably output voltage readings that correspond to different levels of pressure. However, the 4-1 multiplexer that we ordered only outputted a digital signal of inverted HIGH or LOW. This meant that although we were able to generate a signal of whether to inflate or not, the discrepancy between different levels of pressure was lost in this process. This was due to the fact that we ordered the wrong multiplexer, and switching to a non-inverting part should resolve the issue. The pneumatic controller was able to accurately respond to the microcontroller signals and detect pressure readings. However, there was gas leakage in the valves, which led to deflation when the device was not inflating. This can be easily fixed by switching the current gas tubing into something smaller and with a thinner inner diameter.

5.2 Learnings

Throughout our design process, we learned more about PCB design and routing on KiCad. This involved using tools to draw the schematic and route. Through this process, we also gained experience choosing the right components depending on our requirements. This meant looking through many data sheets and comparing the power, current, and voltage ratings among other specifications. We also learned to work with a research group, which was like a client relationship. They provided us with general knowledge about the project and we then worked following an agreed-upon timeline. We had many discussions about expectations and whether they were feasible for us to accomplish in one semester.

During the build phase, we got to experience the different ways to solder, including the regular technique using a soldering iron as well as using the oven with a stencil and solder paste. We also had to work together to integrate different parts. Throughout the project, we divided the subsystems between us; in the end, when we had to put everything together, it was a learning process where we had to rely on each other to make the connections and interfaces work properly. This involved many knowledge transfer. Most importantly, using isolation, we spent most of our time debugging our hardware and software portions.

Overall, we went through the process of creating a project from start to finish, which none of us had experienced before. We were able to gain technical writing and presentation skills as well.

5.3 Ethical Considerations

5.3.1 Relevant IEEE Code of Ethics

Our group will abide by the IEEE Code of Ethics adopted by the IEEE Board of Directors. Our device can be dangerous if not designed carefully. We will hold ourselves to the highest ethical standards in which some are listed below.

1. **To seek, accept, and offer honest criticism of technical work, to acknowledge and correct errors, to be honest and realistic in stating claims or estimates based on available data, and to credit properly the contributions of others [5]**

   We will be collaborating with Dr. Golecki's research group. They have extensive knowledge of the project's subject matter compared to our group members. Thus, we will regularly ask for their feedback on our work. Strong communication with our sponsor is crucial to their own objectives, as well as our ability to fulfill their expectations. Most importantly, we will properly credit their contributions as they relate to our work.

2. **To maintain and improve our technical competence and to undertake technological tasks for others only if qualified by training or experience, or after full disclosure of pertinent limitations [5]**

   The Golecki Group is the originator of the project/product and they are collaborating with us due to our specialization in electronics engineering. As such, our work also serves to improve our own technical competence in this field. Moreover, we will not act as primary contributors to mechanical design decisions since we are not qualified by training or experience to do so. By dividing tasks based on our respective strengths in this way, we are more likely to succeed in the development of this project.

3. **To treat all persons fairly and with respect, and to not engage in discrimination based on characteristics such as race, religion, gender, disability, age, national origin, sexual orientation, gender identity, or gender expression [5]**

   Our project aims to serve users who rely on wheelchairs for daily life. This necessitates collaboration and testing with target users. Treating all persons fairly, with respect, and without discrimination is a golden rule, and it is especially relevant in the context of this project since our members do not hold the relevant personal experiences that our target users do. As such, we must strongly value and consider their feedback for our project to make progress in extending the target users' access to a comfortable lifestyle and preventative healthcare measures.

5.3.2 Safety Concerns and Precautions

With regards to safety regulations that are relevant to this project, we consider the following:

1. **Battery Failures**

   We will examine dangers associated with batteries being close to a person's body, as well as the risks of lithium-ion batteries in general. We aim to address the risk of overheating by researching prevention methods and deliberating on appropriate precautions. From this, we will strongly consider and deliberate on the best location for the battery. In addition, we will be including a safety manual for our device, with an emphasis on mitigating dangers associated with reusable batteries. For example, procedures that promote safe use include storing the device in a cool, dry, and well-ventilated area and warnings that minimize risks include not replacing the included batteries.

2. **Air Pump Failures**

   We will be considering the accuracy of cushion inflation, especially with regard to the risk of the air pump overinflating a cushion which could lead to popping and potential injury. We will also take precautions with regard to setting appropriate limits to the level(s) of inflation that are available to the user.

3. **Circuit Failures**

   We will be extremely cautious with configuring the circuitry within the cushion itself. If a short-circuit were to occur, it could cause injury to the user so we aim to minimize this risk by researching and following best practices for our equipment, mainly with regard to PCB component placements.

5.4 Future work

We plan to continue working with Dr. Golecki's group. We are planning to polish and redesign the PCB to optimize functionality. This includes re-routing the board so that the connections are cleaner, redesigning the microcontroller circuitry so that it works properly without the need for a development board, and finding a new multiplexer to suit our analog needs. We also plan to professionally package the circuit parts for user experience when we attain both pneumatic controllers from the sponsoring research group. We will also be doing the final assembly with the bladder seat cushion from the mechanical team. Lastly, we will be collaborating with the research group to write the research paper.

References

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Appendix A Requirements and Verification Tables

Table 6: User Interface Subsystem Requirements and Verification Table

Requirements	Verification
On/Off functionality through the user-controlled switch.	1. Using an oscilloscope, probe the output of the voltage regulator and ground. 2. Click the button. 3. Verify if the system is on by probing areas and checking for voltage.

User is able to cycle through the default time thresholds with Button 2 and the time is correct.	1. Turn the power on.
	2. Click Button 2 and visually see if the time setting increases (LED light for next time is on from 5, 15, 30, 45 one after the other and then back to 5).
	3. Double-check each time setting is accurate to the time by using a timer.
	    1. Place a heavy object on a sensor.
	    2. Wait the duration of time with a timer.
	    3. Check if the output of the microcontroller (inflate/deflate signal) is HIGH.
	    4. Place a heavy object on a sensor .

Table 7 Sensor Array Subsystem Requirements and Verification Table

Requirements	Verification
Force Sensing Resistors (FSRs) in the array can have their data individually read by the microcontroller without interference to other FSRs in the array.	1. Using a voltmeter, probe V_{out} of the FSR voltage divider referenced to ground. 2. Place a 1kg weight on a single FSR with all others free of any weight. 3. Verify 2V (±0.1V) on probe reading (see Figure 8 below). 4. Probe all unweighted FSRs and verify readings less than 0.5V. 5. Move weight to new FSR and repeat process for each FSR in the array.
FSR array avoids saturation up to 2kg per FSR in normal use.	1. Using a voltmeter, probe V_{out} of the FSR voltage divider referenced to ground. 2. Place a 2kg weight on FSR, with all others free of any weight. 3. Record FSR's probe reading. 4. Place a 100g weight on top of the 2kg weight. 5. Record new probe reading and verify a difference of at least 50mV. 6. Move weight to new FSR and repeat process for each FSR in the array.
The three microcontroller pin-outs that handle instructions for bladder inflation operate within 100ms of each other.	1. Using the oscilloscope, probe the three wires transmitting the bladder inflation opcode (3-bit) from the microcontroller referenced to ground. 2. Reset the microcontroller's opcode outputs to 000. 3. Place weight on FSR array to initiate opcode change to 111. 4. Record and verify the time from the initial bit change to the last bit change is under 100ms. 5. Reset the opcode to 000. 6. Record and verify the time from the initial bit change until the last bit change is under 100ms.

Table 8: Pneumatic Controller Subsystem Requirements and Verification Table

Requirements	Verification
The system must provide a stable supply of 3.3V (±0.1V) and 5V to the microcontroller, sensor array, and the user interface subsystems.	2. Connect the output of the voltage regulator to a load on a separate test breadboard which is also connected to the ground. 1. These are the loads that will be used for verification: 1kΩ, 2.5kΩ, 10kΩ resistors 3. Probe the output of the voltage regulator and ground using a voltmeter. 4. Record voltage drop readings across the load.
Air pump draws less than 10mA of current when not in operation	1. Add weights to initiate air module pumps. 2. Reset opcode to 000 by removing all weights. 3. Use a multimeter to measure and verify current through the pump resistor is less than 10mA. 4. Record results
Air pump stops within 100ms of when desired pressure is achieved in the bladder.	1. Using the oscilloscope, probe V_{out} of the pressure sensor. 2. Also probe the opcode outputs and ground. 3. Record and verify the time delay between pressure sensor V_{out} reaching 18 PSI and the opcode output falling below 0.2V (±0.1V).
Air pump activates within 1000ms of the opcode high signal.	1. Reset opcode to 000 by removing all weights. 2. Using the oscilloscope, probe the opcode output for voltage and pump power line for current. 3. Record and verify the time delay between opcode high and increase in pump current draw.