<u>UCF Senior Design II</u>

Powering Roller Coaster Sensors Via Piezoelectric Transducers

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1 Executive Summary

Many roller coasters do not have means to power onboard devices. Roller coasters that do have means to power onboard devices require complex and expensive solutions. Being able to implement power onboard the coaster can extend its functionality, such as using sensors for analytics. However, installing onboard power requires charging mechanisms or routine maintenance.

Sensors on roller coaster cars have nearly limitless applications and opportunities for data acquisition. Many parameters can be monitored such as noise levels, vibrations, acceleration, velocity, position, etc. This kind of information could provide critical safety and maintenance-related feedback to ride engineers. Some sensors require very little power during operation, so it is not necessary to install large and complex energy storage systems on the coaster.

Our team proposes the use of energy harvesting methods to power the onboard sensors of rollercoasters. The energy harvesting method under consideration is the use of piezoelectric transducers to generate electricity through the mechanical vibrations provided by the coaster. While piezoelectric transducers are not yet capable of producing large amounts of power, being able to power an accelerometer typically only requires a few microwatts. Our team designed and implemented an energy capturing device that intermittently powers a relevant diagnostic sensor in a simulated coaster environment.

Many roller coasters are located outdoors making durability an important factor for consideration. Extraneous environmental conditions, which include temperature, condensation, sudden acceleration, and vibrations will be exposed to the device, requiring the overall design to be robust. Pre-existing coasters are not designed to include this product. Therefore, size and weight must also be limited to make installation more feasible. The overall design should not interfere with the roller coaster's performance or increase the overall dimensions.

To provide sufficient amounts of data, the onboard sensor must be operating as often as possible. Sensor operation time will be limited by the transducers ability to efficiently convert power. While the sensors do not need to operate every time the coaster runs around the track, the transducers can still capture energy while the sensors are off. Therefore, the transducer's efficiency will limit the amount of time the sensors can be on. The efficiency of the power conversion will dictate the amount of data obtainable.

Typical customers and stakeholders would include amusement parks like Disney, Universal, Fun Spot, SeaWorld, Cedar Point, etc. While the applications of this study are focused on the energy harvested from roller coasters, this specific application for the use of powering sensors can be a much broader concept. Sensors powered in this manner could be utilized for diagnostic information in aviation, military vehicles, and other mechanical systems prone to vibrations.

2 Project Description

The final objective is to develop a sensor device that is easily installed and harvests 100% of its energy from mechanical vibrations using piezoelectric transducers. This sensory unit is to be mounted on a rollercoaster and provide meaningful data through sensors that require a very small amount of power. This device is not required to run continuously and will enter a low-power energy harvesting state between data collections.

2.1 Existing Projects

There are some projects that have been developed to use and evaluate the potential of piezoelectric transducers. These transducers are implemented in various form factors including pathways and speed bumps to harness energy and generate electricity through vibrations. This section highlights some of the projects that contain similar technologies found within our assignment.

2.1.1 Speed Bump

This platform based in Indonesia aims to reduce the speed of oncoming vehicles while generating electrical energy converted from mechanical vibrations by using a speed bump which houses the piezoelectric sensors. The design of the project used an inclined ramp that connects to a small section that houses the springs with two stacks of cantilevers with piezoelectric plates. The module uses the four springs as support for the cantilevers which contains piezoelectric plates that are attached with adhesive. With the plates being attached, it will produce electricity whenever the cantilevers vibrate while magnets placed inside will lengthen the vibrations to generate more energy.

***Figure 1**: Speed Bump Design*

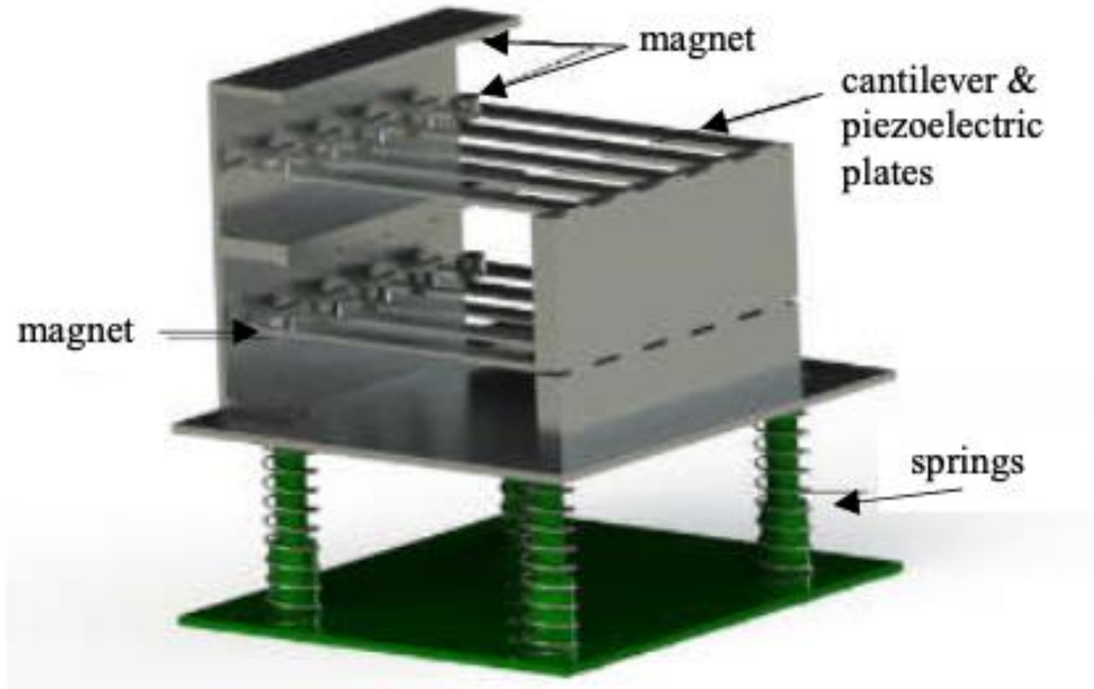


***Figure 2**: Piezoelectric Cantilever*

2.1.2 **Footstep Voltage Generator**

By using the non-conventional method of footsteps, piezoelectric transducers are placed in series to capture that energy. By comparing the two materials for the sensors (PZT and PVDF), the conclusion met was that PZT (Lead Zirconate Titanate) generated more than twice the voltage than PVDF (polyvinylidene fluoride). When pressure is placed on the tile containing the sensors, voltage is generated and supplied to the battery. Included in this design is an LCD that displays information like the voltage generated.

2.1.3 **Measuring Wheel-Rail Forces**

This project does not include any energy harvesting methods but utilizes the piezoelectric sensors to measure the actual forces acting upon the wheels of the roller coaster. By using the transducers onboard the roller coaster, the sensors measured force and torque upon the wheel, which the maximum amount of normal force that can be measured is 30 kN. The advantages proposed by this project is the integration of the transducer within the coaster that can provide information in real time about the status during operational hours. One part of our project is transmitting data from the sensors to display information about the movement of the vehicle to the ride operator or to anyone whole deems this information useful.

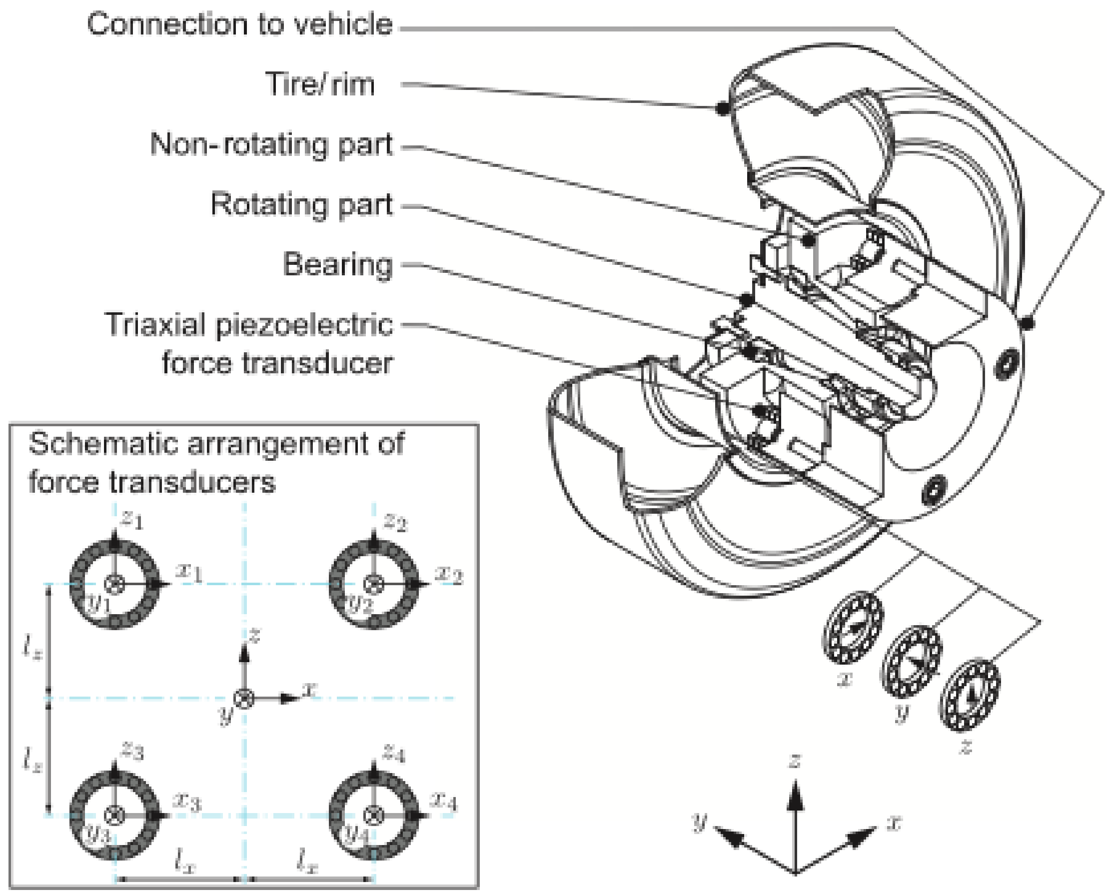


Figure 3: *Wheel Design*

A benefit that is highlighted within these various projects showcase the different usages of the piezoelectric sensors. These sensors have various applications and have a great potential in future use cases.

2.2 Selection of Vehicle

While this design may be applicable to numerous forms of vehicles in motion, rollercoasters were selected as they provide a highly controlled environment enduring many mechanical forces. With the abundance of mechanical vibrations present, the piezoelectric sensors are placed in an optimal setting for energy harvesting. Additionally, this sensor solves a very common problem for rollercoasters; many rollercoasters do not have onboard power that can be utilized. Therefore, while this device does have the capability to expand onto other applications, the application of this device on rollercoasters will be the scope of this project and our main focus.

2.3 Engineering Requirements

For this project, ten engineering requirements have been created. The first requirement being efficiency:

2.3.1 Efficiency

While this requirement will be difficult to measure, it will be estimated how much energy is presented to the piezoelectric transducers within the mechanical system. This amount of energy will be compared to the amount of power that is captured by the system. This ratio will dictate how efficiently the system is operating and will be one of the key factors dictating how long of a duration the sensors may operate between charges.

2.3.2 Dimensions

The dimension of the overall design is to be within the boundaries of $250mm^3$. This is to ensure the device may be easily installed onto a pre-existing rollercoaster, where room may already be scarce.

2.3.3 Transducer Quality

The quality of the transducers will be a prominent dictator of the efficiency of the system. Therefore, a Q factor of greater than 40 is required for the piezoelectric transducers. The electromechanical coupling factor must be efficient enough to power all components of this device. Having a low Q factor means the oscillation decays rapidly, therefore a higher Q factor is desired.

2.3.4 Battery Capacity

The capacity of the battery should not be too great, as to reach undesirable weights and dimensions, but should be great enough to sustain a microcontroller and all its peripherals.

2.3.5 Power Consumption

The amount of power consumed by the system cannot exceed the amount of power harvested by the system. This will be governed by experiments and application of runtimes and downtimes.

2.3.6 **Cost**

The overall project should cost no more than $700. This includes prototyping, fabrication costs, and all purchased components. Should the project approach the threshold, the budget will be adjusted to accommodate this.

2.3.7 **Weight**

To maintain the ease of installation and minimal footprint on the overall system, the weight is required to remain under 5 kilograms, or 11 lbs. This constraint will ensure that the weight of the sensor will not negatively impact the overall operation of the roller coaster, as they are designed to operate under varying weight loads.

2.3.8 **Runtime**

To ensure usability, the self-powered sensor unit must be capable of extracting data for at least one loop around the coaster track. With the average rollercoaster running for under 2 minutes and 30 seconds, this should be the established runtime the device should run for in order to send an accurate amount of data to the end user and ensure a confident charge.

2.3.9 **Charge Time**

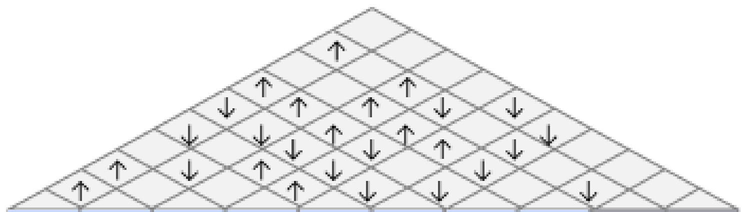
The amount of time that it will take for the device to fully charge is critical for being able to take proper data. The device cannot charge up too fast in risk of causing possible damage to the other components, nor too slow since there will be the need to use it multiple times throughout the day. Therefore the device should be able to charge within a 20 minute time frame to ensure efficiency and usability.

2.3.10 **Time of Data Transmission**

While data can be stored and collected during times when the rollercoaster is not operating, it would be more efficient to transmit the data during the loading phase of the coaster cars. While guests are getting off the ride, and more guests are being led into the coaster cars, the device will be capable of wirelessly transmitting all stored data within one minute to an offboard device located at the loading station. While this data transmission could take mere seconds, is an absolute requirement that all data is collected in less than one minute.

2.4 Decision Matrix

House of Quality



Marketing Requirements		Efficiency	Dimensions	Transducer Quality	Battery Capacity	Power Consumption	Cost	Weight	Runtime	Charge Time	Time of Data Transmission
Engineering Requirements		+	-	+	+	-	-	-	+	-	-
Durability	+		↑	↑↑	↑	↑	↓↓	↑			
Charging Capacity	+	↑↑	↓↓		↑↑		↓↓	↓↓	↑	↓	
Installation Ease	+	↑	↓↓				↓	↓			
Safety	+				↓	↓	↓↓	↓		↓	
Low Maintenance	+			↑↑		↑	↓↓		↑		
Cost	-	↓↓	↓↓	↓↓	↓↓	↓↓	↑↑	↓	↓	↓↓	↓↓
Targets for Engineering Requirements		> 30%	< 250x250x250 mm	< 40 (Q Factor)	> 1500 mAh	< 5 Watts	< $700	< 5 kg	> 2 minutes	< 1 Day	< 1 minute

Correlations Legend

↑:	Positive
↑↑:	Strong Positive
↓:	Negative
↓↓:	Strong Negative
+:	Positive Polarity
-:	Negative Polarity

***Figure 4**: Decision Matrix*

2.5 Responsibility Block Diagram

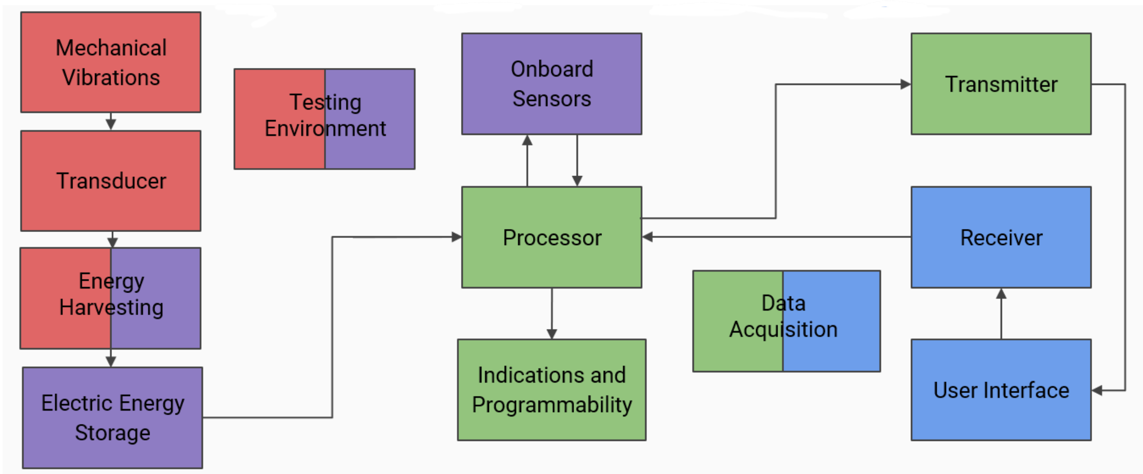


***Figure 5**: Block Diagram*

Legend:

- **Red**: Kristopher Walters
- **Blue**: Nicholas Villalobos
- **Green**: Juan Rodriguez
- **Purple**: Richard Klenotich II

Our main component block within the platform is the processor which allows the onboard sensors to send and receive data as well as using the energy from the electrical storage component. This processor (handled by Juan) is able to read information powered by the transducer (setup by Kris) and use onboard sensors (worked on by Richard) to gather more information regarding the position and movement of the ride. This information is then broadcasted with the use of a transmitter (implemented by Nicholas) onboard the vehicle, which is connected to the microprocessor, and sends data to the receiver. The receiver obtains this information with the use of another microprocessor or an interface that is implemented within the computer or on a mobile device.

3 Design Constraints and Standards

This section outlines the constraints and standards being placed on our project. These design constraints and standards apply to both hardware and software and will be addressed when creating the platform.

3.1 Constraints

These constraints placed on our project are implemented to create the platform that adheres to these limitations. With these limitations in place, our project sets boundaries that will help our development with a focused narrative. Within this chapter there are seven constraints that are expanded with more detail. Without these restrictions in place, our project will not succeed and will violate some rules. Also, these constraints are in place to know the limits provide in this project.

3.1.1 **Safety Constraints**

In the creation of this project, safety comes first to protect ourselves and others using the equipment for the platform. Our platform works by placing the sensors onboard moving vehicles such as a roller coaster car. By working on the stationary vehicle, all measurements will be calculated once the vehicle has completed the track and comes to a complete stop.

Another safety measure that will be taken is to protect our team members from an electrical shock or faultily power systems. This can occur if there is a lot of electrical current flowing with no ground implemented. To prevent this incident, a well-design system needs to be in place and thoroughly checked to inhibit human error. Another implementation for electrical safety is wearing the right equipment and using the correct tools for the project. Without these proper safety measures in place, an accident can occur and cause serious injuries.

3.1.2 **Environmental Constraints**

With the dynamic weather system that Florida contains, weather plays a big factor in the longevity of the device. One weather pattern that can ruin all the components is rain, which can short circuit the components causing the system to malfunction. This problem can be avoided by placing the components within a container protecting from external factors such as liquids.

Another weather condition that Florida faces is the extreme heat and humidity, especially during the summer months. The main way to combat high temperatures is creating a cooling system to prevent the board from overheating and damaging the electronic components.

One environmental and sustainable challenging faced with prototyping and testing miscellaneous components is the proper handling and disposal of wasteful materials. When purchasing materials, these should provide an extended life cycle and be compatible with our project. Research can mitigate this issue by selecting the correct part for the project and using datasheets to view details about the component. A harmful act on the environment is the disposal of electronic waste (e-waste) and this can be lessened by reusing functional units and properly maintaining the components found within the project. Our project aims to harvest energy safely and deliver a system that can generate and reuse the energy within the system. Using renewables and less disposable resources can craft our project into a more environmentally friendly system.

3.1.3 **Economic Constraints**

With this project, most of the funding came from our own contributions, however this does not mean that there is not a budget being enforced. This budget that was placed limited our spending and focus our cash flow to affordable and high-quality products. Tradeoffs occurred within the project since the platform needs to be affordable while keeping production cost low as well. We decreased our spending by researching and obtaining the correct materials for the project which also helps in the environmental effort as mention earlier.

One constraint that played a major effect on our budget is the pricing that is used by manufactures which dictate how expensive the material is. Even with competitors in place, most of the pricing for materials are consistent throughout the market. For example, piezoelectric materials are usually priced reasonable high compared to the other materials within our project. There are sections for cheap piezo disc, but these did not fit our project narrative and does not produce enough energy for the system. Our only research for these materials is through online resources which expands our scope but neglects the local vendors in place. A downside to obtaining products online is the extra fee of shipping and handling placed on the material. Many stores implement a shipping and handling fee especially on delicate materials such as an LCD and usually add about five dollars or more depending on the circumstance. Some storefronts such as Amazon do not charge shipping and handling if you are a Prime member. Regardless, the extra fees attached with the materials add up in our total budget.

3.1.4 **Ethical Constraints**

Our project did not infringe on any intellectual property (IP) or violate copyrights and trademark materials. Our design concepts that are inspired by other works contain proper citation and give credit to the authors of the material. These designs adhere to the standards placed and followed all the legal requirements imposed as well as engineering codes implemented. Disregarding these measurements such as copying work from other material will result in serious consequences from the university and other enforcing entity governing our work. It is important to review all standards and regulations for this project to comply with the Accreditation Board for Engineering (ABET) requirements. It is every team member responsibility to follow these standards and follow the legal requirements to not infringe on any other material of work.

3.1.5 **Manufacturability Constraints**

In the process of making this project, one important constraint that has affected all stock is the availability of components. Due to current events, some supply chains have decrease production of certain components which will make it harder to find. With the scarcity of some products, it was hard finding a reasonable price point for the component. These constraints tie with the constraints imposed by the economic budget being placed on the project as the manufactures can dictate the prices imposed and decide what materials are used within the product. Our scope for assemblers of piezoelectric materials is through online resources since there are no local vendors in the Central Florida area that works on piezo materials. The closest location that can produce piezo materials is in West Palm Beach and is too far of a reach for our location radius.

3.1.6 **Time Constraints**

The deadline for this project is at the end of Senior Design 2, which is in Spring 2021. The duration of this project consists of two semesters starting in Senior Design 1 in Fall 2020. These dates are established, and our team completed and accomplished the various tasks before the dates imposed. Many additional features were cut out due to the limited time but could be considered for future iterations of this project.

With these constraints in place, our team worked hard and allocated time from work or other activities to focus on the project. With the guidance of Professor Lei Wei, our paper was finetuned and our team focused on the important details to highlight within the paper. Having a mentor with experience and expertise guided our team to the right direction and we avoid major missteps within our system. We held periodic meetings which redirected the teams’ focus and we established short term goals for each team member. With established milestones early on, and our addition of short-term goals, our team moved quickly and efficiently to accomplish our tasks.

3.1.7 **Testing and Presentation Constraints**

Our testing environment was in an open space area with plenty of room for movement. Related to the safety constraint, our main priority is protecting the end user from the moving vehicle. The presentation showcased the work of the piezoelectric sensors and at the end the Android application displays information regarding the ride outcome.

3.2 Standards

Implementing standards within this project helped our group follow guidelines and regulations provided by establishments. These establishments include the Institute of Printed Circuits (IPC), Institute of Electrical and Electronic Engineers (IEEE), International Organization of Standardization (ISO), and the International Electrotechnical Commission (IEC). Standards are in place to provide a clear implementation of the device as well as provide safety along with proper handling. Protocols are also categorized under standards and are used for communication between devices.

3.2.1 Standards for Printed Board Design

The Institute of Printed Circuits (IPC) or now known as the Association Connecting Electronics aims to provide electronic industry standards through printed circuit board (PCB) design, manufacturing, and assembly. In the classification of electronic products, IPC has established three classes that organizes the definition of the electronic components. PCBs are classified under class 2 which are dedicated service electronic products which provide uninterrupted services and is integral to the general system. Class 1 products are general purpose electronic devices which provides a general function to the end user. The last class mention is class 3, which are high-reliable electronic products used in critical applications.

There generic standard on PCB is provided within the publication IPC-2221B which details topics associated with designing a PCB such as layout, materials, parts, thermal and electrical properties. IPC 2581 imposes the standard of the information being relayed from the PCB designer to the manufacturer. With this standard in place, the data for exchanging design is streamlined and incompatible formats are not an issue. IPC 2152 defines the design specification of the PCB to provide thermal stability and performance. This standard is important, so the PCB does not overheat and cause safety issues due to not adhering to the requirements imposed by the standards.

Another important standard is the IPC-TM-650 which are published testing methods to assess various aspects of the PCB. These testing methods entail ways of testing the propensity of surface electromagnetic migration on the board as well as measuring the resistance across the PCB. The manufacturer also contains standards in place by IPC to create the board that was specifically designed by the end user’s specifications. These guidelines were in place when designing the board using the CAD software used by our group. Following these design procedures eliminated errors and create a foundation for a functional board.

3.2.2 **Standards for Power Supply**

For the power supply, safety is the main priority when dealing with hazardous materials. The main source of guides for batteries that supplies this system is through the Institute of Electrical and Electronic Engineers (IEEE). The range of standards presented are listed under the standards of IEEE 1184-2006. This revision was approved in 2006 and superseded the one placed in 1995. This guide is presented to inform about the various batteries used for uninterrupted power systems (UPS) [34].

There are three different equipment classes associated with power supply as listed in the IEC 60950 and the newer IEC 62368-1. Class I classifies equipment that can achieve electric shock protection with the help of basic insulation and protective earth grounding. In this requirement, all conductive parts that could assume a hazardous voltage (definition will be explained later) in the incident of basic insulation failure to be connected to a protective earth conductor. Class II list equipment that provides protection with the aid of double or reinforced insulation, this means that no protective earth grounding is required for this equipment. Class III contains equipment that operates from a Safety Extra Low Voltage (SELV) supply circuit. The operation of SELV provides protection against electric shock and does not generate hazardous voltages.

With these standards provided, defining circuit definitions helps our group clearly understand the implications and terminology used within the regulations of IEC 60950. A hazardous voltage classifies any voltage that exceeds 42.2 Vac peak or 60 Vdc without a limited current circuit. Extra-Low Voltage (ELV) indicates a voltage that is in the secondary circuit and does not exceed 42.2 Vac peak or 60 Vdc. This secondary circuit is separated from the hazardous voltage by providing basic insulation. As mention earlier, the Safety Extra-Low Voltage (SELV) is in the secondary circuit and does not reach a hazardous voltage between any two accessible parts or between an accessible part and protective earth under normal operations or while experiencing a single fault. When a single fault is caused due to insulation or component failure, the voltage in accessible parts of SELV does not exceed 42.2 Vac peak or 60 Vdc for longer than 200 ms. The limit of this system is of 71 Vac peak or 120 Vdc and these limits should not be exceeded at any circumstances.

The standard also highlights the classification of Limited Current Circuits that are accessible regardless of the voltages exceeding the limit of the requirements listed in SELV. With this design, the limited current circuit ensures the current drawn is not hazardous under a fault condition. In containing frequencies less than 1 kHz, the steady state current drawn should not exceed 0.7 mA peak ac or 2 mA dc. When faced with frequencies that are more than 1 kHz, the current should not take up more than 70 mA. When accessible parts are not exceeding the limit of 450 Vac peak or 450 Vdc, the maximum circuit capacitance that is allowed is 0.1 μF. When the limit is increased to 1500 Vac peak or 1500 Vdc and the accessible parts are not exceeding this limit, then the maximum stored charge that is allowed in the system is 45 μC and the available energy should not exceed 350 mJ.

The last main definition is the Limited Power Source (LPS) which are designed with prescribed output voltage, current, power, and short circuit current limits. LPS contain reduced hazard of electric shock or fire caused by the system. LPS systems have an internal power limiting provisions or external devices that are limiting the current delivered to the load.

Regarding power supply, the five types of insulation that shield live components with hazardous voltage are listed in the standards. With the knowledge of understanding and implementing the standard, a safer work environment is fostered within our team. The five types of insulation are operational / functional, basic, supplementary, double, and reinforced. With operational / functional insulation, protection against electric shock is not provided and only serves the purpose of making the component fully operational to use within the system.

Basic insulation is applied to live parts and only provides basic protection to the user against electric shock. Supplementary insulation builds upon the foundation of basic insulation and applies an independent insulation on top of the basic layer. This type of insulation is a backup plan and protects the user against electric shock when basic insulation fails. Double insulation is a mixture of basic and supplementary insulation and provides double reinforcement. The last type that is mentioned is reinforced insulation which is a single insulation system that is reinforced and provides the same protection as double insulation.

3.2.3 **Standards for USB**

The universal serial bus (USB) is an industry standard that establishes a link between two devices. This standard can be used for connection, interfacing, power supply, and data transfer. USB-IF (IF stands for Implementers Forum) is the non-profit company that establishes and develops the specifications for this protocol. The classification of USB is divided within generation and type of connector. There are four generations involved in the protocol which dictate the transfer speed and there are three types of connectors sizes: standard, mini, and micro.

This platform does not utilize any mini-USB connections, only standard and micro. The developmental board for the microprocessor uses a Standard USB 2.0 Type B connector for interfacing and for writing code to be used by the MCU. The cable used to connect the developmental board to a laptop is with a Standard USB 2.0 Type B Male connector to a Standard USB 2.0 Type A Male connector that contains transfer speeds of 480 Mbps (megabits for seconds).

The Analog Discovery 2 provided in the Senior Design kit connects a Micro USB Type B connection which can be connected to a laptop with a micro–USB Type B Male connector to a Standard USB 2.0 Type A Male connector. The main point for the interfacing of the Analog Discovery 2 is to utilize the application (Waveform) provided on the host computer. This application provides the user an interface to interact with and provide functions such as an oscilloscope all through the connection of a USB cable.

Many computers whether desktops or laptops utilize a Standard USB Type A connection, usually a third generation which consists of 3.0, 3.1, and 3.2 with at least 5 Gbps (gigabits per second) transfer speeds. Since Type A has been the de facto standard for many devices ever since the introduction of the first generation in 1996, many manufactures still produce products with it even though it has been deprecated with the new fourth generation in 2019. Many modern devices have been adopting the USB Type C standard which provides some convenience to the user since it is reversable and contains 24 symmetrical pins.

3.2.4 I^2C Standard

This standard invented by the company Phillips is the Inter-Integrated Circuit protocol used for connecting low speed peripherals to a microcontroller. This connection only uses two wires to transmit data between the primary and secondary device unlike USB which only has one connection. There are two roles for the nodes to take which are primary and secondary. The primary node generates the clock and starts the communication with the secondary device. The secondary device receives the clock signal and responds when the primary device communicates with it. In our use case, the primary device is the microcontroller, and the secondary device are the peripherals implemented to extend the functionality of the unit.

There are two connections within the protocol which are the Serial Data (SDA) and Serial Clock (SCL). SDA provides a line for the two devices to send and receive data while SCL carries the clock signal. Listed in the specifications are the clock frequencies / speed for the protocol which the original implementation had 100 kbit/s in 1982. Each new version of the standard increases the maximum transfer speed along with new implementations and corrections. The newest version (version 6) was created in 2014 and add corrects and contains a maximum transfer speed of 5 Mbit/s. The first time 5 Mbit/s was listed as the maximum transfer speed was in the year 2012 with version 4 of the standard.

Within addresses in the protocol, every secondary device contains a unique 7-bit address when connected to the primary unit. Some devices contain 10-bit addresses but most of the devices implemented contain 7. Within the 7-bit address, (using binary) when bit 0 is set, this sends a single to primary unit to write to the secondary device. When the bit 0 is set to 1, then the primary device will read from the secondary device. Different from the secondary devices, the primary device does not contain an address since it is the device to generate the clock with SCL and is the main unit to address individual secondary devices.

The main benefit of using this protocol is the support for multiple primary and secondary devices that connect to each other. Even with this advantage, the slow data transfer speeds compared to USB are not suitable for multiple and large transfers between devices. Another disadvantage is within the limited size of the data frame which is only 8 bits and must divide up large data transfers. This protocol is more suited for low-speed peripherals as mention before and not for items that need to be updated quickly or for large data / file transfers.

3.2.5 **SPI Standard**

Like I^2C, the Serial Peripheral Interface (SPI) is another communication protocol that is implemented in these systems for short-distance communication. Developed by Motorola in the 1980s, this synchronous standard is used to interface microcontrollers and various peripherals. SPI is different from the I^2C protocol as it uses a full duplex system that can contain 3-wire or 4-wire, but the 4-wire is the most popular interface option.

The SPI contains for logic signals which are SCLK, MOSI, MISO, and CS which are found on the primary device. SCLK is the serial clock which is an output from the primary device. MOSI is the data output from the primary device and an input to the secondary device. MISO is the data input from the primary device and the output for the secondary device. CS stands for chip select which is an output signal from the primary device to select which secondary device to use. This signal is usually active low and when the secondary device is disconnected from the SPI bus, the signal will become high.

Compared to other connections, SPI is synchronous as mentioned before and uses the separate lines for the data and clock to sync up the signals. One advantage with using this method is that a shift register can be used for the receiving hardware which is simple and cheap to implement. The device that generates the clock signal is the controller or primary device and sends these signals to the peripheral or secondary device.

SPI interfacing has some advantage over the I^2C protocol such as being a full duplex model that can contain a higher throughput and is not limited to only 8 bits for data transfer. This means with this model; higher transfer speeds are achieved and can obtain speeds double the transfer rate of I^2C. Unlike the previous mentioned protocol, the secondary devices do not need a unique address, but with SPI, only one primary device can be implemented. A major disadvantage for SPI is within pin usage as more signal lines (wires) are required for this connection compared to I^2C.

3.2.6 **UART Standard**

UART stands for Universal Asynchronous Receiver / Transmitter and are usually part of an integrated circuit or integrated within the microcontroller chip. The main purpose of UART is handle serial data by transmitting and receiving it. UART is different to I^2C and SPI as it is not a communication protocol but a physical circuit. There is another device that is related to UART which is the Universal Synchronous and Asynchronous Receiver / Transmitter (USART) which can handle synchronous and asynchronous operations, but the focus will be on UART for this section as UART is more commonly used.

In communication, two UARTs communicate directly with each other with the usage of two wires to transmit data. In the UART that is transmitting, the Tx pin is used and connected to the Rx pin of the receiving UART. With the Tx line, the transmitting UART will create the data packet while appending the sync and parity bits. After this data packet is created, the UART will send this across the Tx line to the receiving UART at the correct baud rate. The receiving UART will pick out the sync bits at the baud rate and output the data all through the Rx line.

Found within the data packet are four components: start bit, a data frame, parity bit, and stop bit. The start bit is only one bit and initiates the reading of the bits when the UART detects the transition from high to low voltage. The data frame is composed of 9 bits if the parity bit is not used and 8 bits when used. The minimum size of the data frame is 5 bits, and the main purpose of the data frame is to store the data being transferred. The packet can contain 0 or 1 parity bits and it is used to indicate to the receiving UART if a change has been made during the transmission. The last part is the stop bit which can be 1 or 2 bits. The stop bit signals the end of the data packet.

As mentioned before, UART is asynchronously so the clock signal does not sync the transmitting and receiving of data between the two UARTs. For the UARTs to transfer data between each other, both need to operate at the same baud rate to function, which is at a specific frequency which is usually 9600 baud and max 115200 baud. The baud rates of these UARTs must be within a margin of 10 percent of each other or the transfer of data will not occur between the two systems.

One advantage that the UART implementation provides is the usage of only two wires to transmit data and not having a reliance on the clock signal which SPI contains more wires and using the synchronous function to operate. The major disadvantage in UART is not being able to support multiple primary and secondary devices as it is only limited to two UARTs communicating directly with each other. Unlike the other methods, multiple secondary devices can be used to interface with the primary device.

3.2.7 **C Programming Language Standard**

Our project used the C Programming Language that was implemented within the microcontroller unit. The current standard for this language is ISO/IEC 9899:2018 based on the revisions made by C18 and C17 (2018 and 2017 respectfully). The standards specify the representation, syntax, and sematic rules for C programs. The standard does not dictate the mechanism in which C programs are written and alerted. The guidelines are presented by the International Organization of Standardization (ISO) and the International Electrotechnical Commission (IEC).

There are four subdivisions found with the International Standard: preliminary elements, characteristics of environments, syntax and semantics, and library facilities. The most important standard that the user needs to know is the syntax of the programming language. The syntax is consistent throughout the whole usage of the language. Regardless of the type of the Integrated Development Environment (IDE) used, the syntax of the C language remains the same throughout.

3.2.8 **Soldering Standard**

The soldering standard imposed by IPC is the Requirements of Soldered Electrical and Electronic Assemblies implemented within IPC J-STD-001. The IPC J-STD series of standards are the Joint Industry Standards for soldering. These standards list the materials and methods used for producing soldered electrical assemblies. The main purpose of this implementation is to produce completed solder joints that conform to the acceptable requirements. With containing completed solder joints, connections between components can be complete and the error of faulty components can be minimized.

J-STD-002 is used for solderability test for component leads, termination, lugs, terminals, and wires. Assessing the standard includes the test as well as a test method for the resistance of dissolution of metallization. While J-STD-003 focuses on certain aspects of the board, J-STD-003 list the solderability tests for printed boards which assess the solderability on the whole PCB. This standard applies to the user and supplier and is used to verify the PCB fabrication process. Using this process of J-STD-002 and 003, our team can check the validity of the connections made and produce any adjustments to the board if needed. Implementing these thorough test does seem excessive but without performing tests the board can fail or components can be proven flawed.

4 Research

Energy harvesting is a developing field that includes various methods of obtaining power such as solar and wind. These various platforms provide energy for different functions that varies such as light sources for a home or powering a facility full of workers. Our focus was narrowing our platform to using piezoelectric transducers to provide power for sensors on board a roller coaster and/or various vehicles.

Keep in mind the following components you see were based on preliminary design and were researched before the prototyping phase. While some of these options do appear in the final design, such as the piezoelectric transducer options and the microcontroller options, there are other components mentioned here that were considered during the research stage but never made it into the final overall design.

4.1 Microcontroller Options

The system will use a microcontroller unit (MCU) to monitor the data that is transmitted through the sensors. The MCU will be on low power mode to consume less energy from the piezoelectric sensors.

4.1.1 **TI MSP430**

This controller was chosen as our first pick for analyzing MCU options since we have used this board during lab sessions in Embedded Systems and have gained experience developing for it. This family of 16-bit low cost and low power MCU created by Texas Instruments (TI) provides a lot of features for our project.

4.1.1.1 MSP430G2xx Series

The G variant of the MSP430 is one of the cheapest modules compared to the other variants. The G series is very similar to the F series, but the main different is the G series uses flash-based value line compared to the flash memory found in the F series. All the MCUs in the G series run up to 16 MHz and use 16-bit reduced instruction set computer (RISC) architecture. Providing more details will be described in the specific component section.

4.1.1.2 MSP430G2553

This version of the G series MCUs provide up to five power saving modes and consumes 0.5 μA on standby mode. This MCU has a low supply voltage range of 1.8 V to 3.6 V and contains up to 24 I/O pins. With regards to memory, up to 16 KB of flash memory is provided and has 500 B of RAM.

4.1.2 **AVR: ATMEGA328/P**

These range of MCUs are developed by Atmel which was acquired by Microchip Technology which also develops PIC. Being built on an 8-bit architecture, these MCUs provide low cost and power for a versatile unit.

This ATMEGA328 and ATMEGA328P are very similar but with one key difference is that the ATMEGA328P provides a lower power version hence the P suffix which stands for picoPower. The ATMEGA328P is a little bit more expensive that the base model but provides the benefit of using less power which is ideal for our project. These MCUs are commonly found within Arduino boards and are based on an advanced RISC architecture. Both provide flash memory up to 32 KB and 2 KB of static random access memory (SRAM). For performance, the ATMEGA328/P can achieve 20 million instructions per second (MIPS) at 20 MHz.

4.1.3 **PIC: PIC24F16KA102-I/SP**

Also developed by Microchip Technology, PIC original stood for Peripheral Interface Controller and contains various MCUs with multitude of features.

This 16-bit MCU contains eXtreme Low Power (XLP) which contains a sleep mode that consumes 20 nA and a deep sleep mode that consumes 9 nA. With the highest clock speed at 32 MHz, this is about double the speed of the MSP430G2xx Series with 16 MHz.

4.1.4 **Silicon Labs: C8051F98x**

This 8-bit MCU is created by Silicon Labs with the main advantage of being of the lowest power MCU. Consuming 150 μA/MHz while in active mode and lowering the rate to 10nA in sleep mode, this MCU provides less power consumption compared to other competitors. Even with a high clock speed of 25 MHz, the main drawback of this MCU is within the amount of flash memory and RAM provided within the unit. With the size of 4 KB and 512 B of RAM, this unit is not capable of multiple task and programs with a large size.

4.2 Microcontroller Comparison

4.2.1 **Clock Speed**

The PIC24F16KA102-I/SP has the highest clock speed at 32 MHz with the high price tag of $2.40. The C8051F988 contains the second-best clock speed at 25 MHz but contains many drawbacks that would consider this MCU to be the main component of our project.

4.2.2 **Cost**

For low end features available for the Silicon Labs MCU, the price is very reasonable for $1.11 for the size of flash memory and RAM. The most expensive MCUs are within the TI family, for the MSP430G2553 starting at $2.09 and with some MCUs within the family containing a price near $3.00. The PIC24F16KA102-I/SP is also priced at $2.40 with being based on 16-bit architecture and containing ultra-low power technology. The ATMEGA328 starts at $1.90, and with the addition of pico power being implemented, the price jumps to $2.08.

4.2.3 **Flash Memory**

The AVR MCUs provide the most storage compared to the other rivals, containing double the flash memory provided within the TI MCU (32 KB vs 16 KB). The AVR MCUs also contain the most amount of RAM with 2 KB to handle multiple tasks.

4.2.4 **Power Consumption**

The C8051F988 consumes the least amount of power among the microcontroller selection. Consuming 150 µA/MHz while on active mode is idle, the C8051F988 does not provide as many features compared to the other microcontrollers. The PIC24F16KA102-I/SP also contains a sleep mode that boast it can consume 20 nA which is impressive for a MCU that is based in 16-bit architecture.

4.2.5 **Microcontroller Selection**

Microcontroller	Clock Speed	Flash Memory	RAM	Manufacturer	Data Bus Width	Price
MSP430G2553	16 MHz	16 KB	500 B	Texas Instruments	16-bit	$2.09
ATMEGA328	20 MHz	32 KB	2 KB	AVR	8-bit	$1.90
ATMEGA328P	20 MHz	32 KB	2 KB	AVR	8-bit	$2.08
PIC24F16KA102-I/SP	32 MHz	16 KB	1.5 KB	PIC	16-bit	$2.40
C8051F988	25 MHz	4 KB	512 B	Silicon Labs	8-bit	$1.11

Table 1: *Microcontroller Comparison*

The microcontroller that was implemented in our project is the ATMEGA328P for its use of pico power and lower power consumption for the price point. This MCU provides the most amount of flash memory and RAM compared to the other options. With this expanded space, the program can be a larger size and execute faster than the other controllers.

4.3 Piezoelectric Sensors Options

Piezoelectric Sensors are classified by two categories of materials: single-crystal and ceramics. These sensors take mechanical stress / force to generate electrical energy.

4.3.1 **Quartz**

This is one of the main choices of piezoelectric sensors when it comes to single-crystal materials. Quartz was the first material used within piezoelectricity in the 1880s by Pierre and Jacques Curie.

4.3.2 **PZT (Lead Zirconate Titanate)**

Classified by for its ceramic material, PZT is the most used ceramic piezoelectric sensors. These ceramic disks are mostly cheaper than using single-crystal materials.

4.3.3 **Resonance Frequency**

For the use of piezoelectric in our system, the range of resonance frequency depends on the thickness of the material. The resonance frequency and the thickness of the material are inversely proportional, as increasing the thickness will decrease the resonance frequency. Identifying the resonance frequency can provide the most effective way to convert our mechanical input to electrical energy. As the cycling frequency increases, the impedance increases as well until it reaches the maximum impedance frequency which is about equal to the parallel resonance frequency. When the cycling frequency decreases, the minimum impedance frequency is obtained and contains approximately the same value as the series resonance frequency. As showcased in the image below from the source “Power Converters Design and Analysis for High Power Piezoelectric Ultrasonic Transducers “, in KHz the resonance and anti-resonance frequencies in the piezoelectric system.

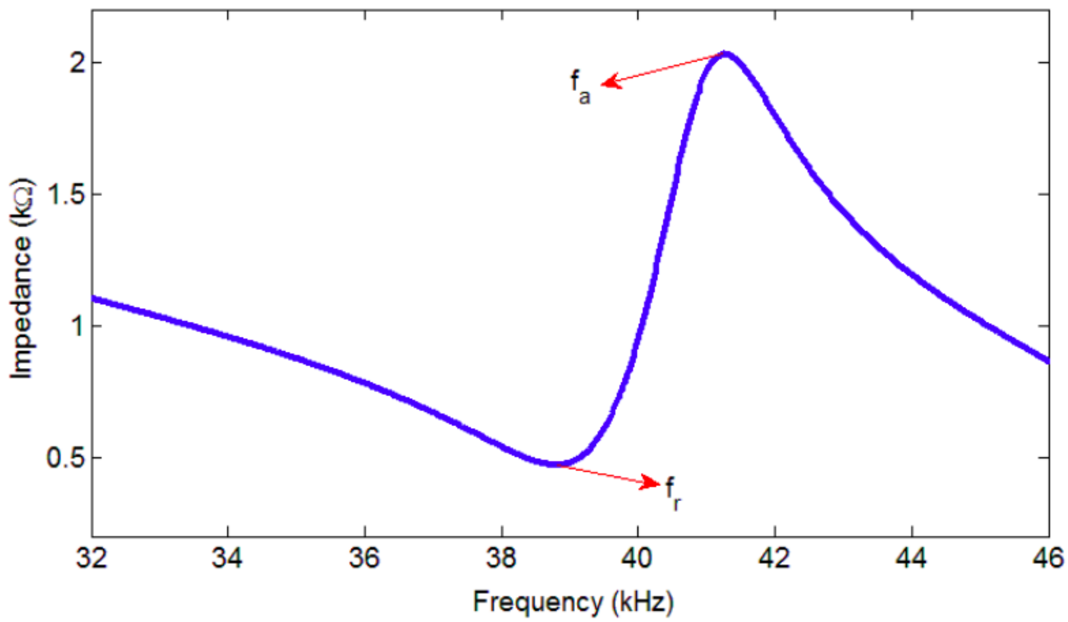


***Figure 6**: Resonance Frequency*

4.4 Battery

4.4.1 **Lithium-Ion**

Commonly used in mobile devices, this is the most popular choice for power that is identified by using liquid electrolytes. One downside of using these batteries is having the battery combust into flames and this can be caused by not applying appropriate safety rules to handle the battery. Compared with the other choices of batteries, lithium-ion is usually more expensive along with its counterpart Lithium-Po. These lithium batteries are priced higher than nickel-based ones.

4.4.2 **Lithium-Po**

This battery is also known as lithium-polymer in which it contains polymer electrolytes instead of liquid electrolytes found within its counterpart lithium-ion. This power source is safer than lithium-ion as it provides less chance of a leakage and is less prone to combustion. A major drawback of choosing this battery is that less power is stored and contains a shorter lifespan. Having less power is a major disadvantage for our energy harvesting project.

4.4.3 **Nickel-Cadmium**

Nickel-Cadmium (NiCD) is a rechargeable battery invented in 1899 to be an alternative to lead acid batteries. An advantage of using this power source is it contains a long shelf life and has a lower price point compared to other sources. With a high self-discharge, this power source contains a major limitation that affects its performance for this system.

4.4.4 **Nickel-Metal Hydride**

Also based on Nickel, Nickel-Metal Hydride (NiMH) can contain up to two to three times the capacity to its counterpart NiCd and builds upon the technology developed for NiCd. Just like NiCD, these batteries are often found with a cylindrical shape. The main benefit that NiCd and NiMH provides compared to Lithium sources are price as it cost less to produce. However, NiCd and NiMH are usually much larger and heavier than the lithium batteries and can take up valuable space within the unit.

4.4.5 **Battery Comparison**

Battery	**Cost Per Cycle**	**Load Cycles**	**Discharge**	**Energy Density (Wh/kg)**
Lithium-Ion	$0.14	500 – 1000	10%	110 – 160
Lithium-Po	$0.29	300 – 500	10%	100 – 130
Nickel-Cadmium	$0.04	1500	20%	45 – 80
Nickel-Metal Hydride	$0.12	300 – 500	30%	60 – 120

Table 2: *Battery Comparison*

In this comparison, all four types of batteries mention in the paper are evaluated with criteria such as cost per cycle, load cycles, discharge rate, and energy density which is measured in watt-hours per kilogram (Wh/kg). A battery cycle is categorized by a full charge from 0 to 100 percent. A cost per cycle is measured by the average cost of the battery divided by the estimated cycle life. A lower cost per cycle indicates that the battery is cheaper overall. The load cycle of a battery measures how many complete cycles it takes for the battery to reach about 80 percent of its original capacity. A higher load cycle demonstrates the longevity of the battery.

The discharge rate (self-discharge) measures how much the battery can discharge without any power being used. With a high discharge rate, the battery will drain a lot quicker and will not last long on a single charge. The last component being compared is energy density. Energy density shows how much energy the system can contain relative to its mass. A high energy density unit (Wh/kg) is favorable to our group as weight is an important engineering requirement.

In the table, out of the four batteries being compared, Nickel-Cadmium contained the lowest cost per cycle with $0.04 while Lithium-Po contained the highest at $0.29. NiCD also contained the highest load cycles with 1500 while Lithium-Po and NiMH contain only 300 to 500 cycles. However, with NiCD being the cheapest and containing a high load cycle that demonstrates its longevity, it contains the lowest energy density (45 to 80 Wh/kg) and discharges with 20 percent. With our energy harvesting platform, having a battery that cannot contain a lot of energy and discharges more than lithium batteries makes NiCD a poor candidate. NiMH contained to lowest load cycles and discharges the fastest, which means it does not last long and needs to be constantly recharged which is not ideal for our use case.

Lithium-Po is the most expensive and contains the least amount of load cycles and the only advantage it provides is the low discharge rate of 10 percent. Out of all these options, Lithium-Ion was the clear choice for our project since it contains one of the highest rated energy densities at 110 to 160 Wh/kg and has a low discharge rate of 10 percent. It contains about 500 to 1000 load cycles depending on the unit, which is at least better than the offering of Lithium-Po and NiMH. The only downside with this battery option is that the cost is a little bit more than NiMH, but it is cheaper than Lithium-Po.

4.5 Battery Chassis Options

Given that currently the best option for our design would ideally be a lithium-ion battery, since it can be recharged and even go through multiple cycles of recharging, we considered options for a chassis that can hold said batteries. Ideally the chassis was mounted to the board and attached to the board for ideal efficiency. Furthermore, the chassis was small enough to not interfere with overall footprint and size of the board, since we needed to minimize the size as best as possible. Options for supercapacitors as a power supply were utilized, which is further highlighted in the next section.

A benefit to including these chasses in our design was their flexibility in terms of size. Since Lithium-Ion batteries come in multiple different sizes, the chasses are able to come in different sizes that can accommodate for either larger or smaller sized batteries, making it efficient in terms of minimizing the overall footprint that it will take up. Furthermore, if a coin-based lithium-ion battery was to be considered, the overall footprint could be reduced even further given its size for the chassis and how it can even be placed in vertically.

Despite these obvious benefits, there were some slight drawbacks to the given options that are listed below. While these chasses are made to securely hold these batteries and not be easily removed by user hands, they could be exposed to forces on a rollercoaster that could dislodge them in a worst-case scenario, especially since the battery itself will not be soldered onto the board itself. This could prove detrimental to operation and even data collection when testing and even trying to make the board work.

Another issue that arises is simply the capacity for each lithium-ion battery, which averages around 3.7V. Should our board need more power to operate efficiently, more batteries will need to be added and, in turn, the footprint will be increased, which could prove inefficient to keeping out board as small as possible. However, as mentioned before, a coin-based option or even a supercapacitor could alleviate any stress or issues this may cause.

Options in terms of any researched battery chasses are listed below, along with a final comparison to determine which would be best for the design.

4.5.1 **Aokin Battery Chassis**

One of the options available for a possible battery chassis is the Aokin series from Amazon. This chassis is able to hold a 3.7V lithium-ion battery and has options between one slot to four slots. Given the amount of power we wish to generate for the board, an option between one to two slots would be ideal both in terms of charging and supplying power. In terms of how it will affect the footprint of our board, it will more likely than not cover a large section when mounted on, given it is around 2.95in x 0.75in. We will need to consider this factor if we wish to have an on board power storage. Another challenge that lays ahead is the fact that this is a series storage, which will require us to work around ideas on how to charge it as well as make it run the board itself.

Furthermore, on any issues that may arise, this option may require a specific lithium-ion battery to function properly, so we cannot use any type of battery with this chassis and making it more susceptible to failure. One final problem that presents itself is the cost. According to Amazon, these types of chassis only come in packs, whether they be a pack of single slots or a pack of singles, doubles, triples, etcetera, and they can range between $7-$8, making them not very costly, but pushing the limit since there will be left over parts. Overall, the chassis yields some promise, but size and its series functionality may present challenges for the design. A full rundown on the specs of this option is shown below.

- 18650 Battery Holder Wire Leads - All 18650 battery case holder with leads, they are tinned wire end, the black and red two wire design is great for easily soldering and connecting. Wire Length: approx 5.1inch.

- Multipurpose Battery Case Holder - 18650 battery holder with soldering pins is designed for 3.7V 18650 rechargeable batteries. Case for rechargeable battery; Simple DIY recharge power supply. Great for Arduino boards microcontrollers, led projects, toys, also replaces broken battery holders for many electronic devices.

- Design - Metallic spring with pin design for easy install and convenient for electric circuit DIY work. Battery holder is made of ABS plastic with nickel plated springs, holding the batteries tight in place.

- Material - Great items for keeping your standard or rechargeable batteries together and safe. Wire lead battery case holder for 18650 single battery, Durable plastic and metal. Note - For flat top 18650 Li-Ion batteries only, length 67mm max. (Battery is not included here).

4.5.2 **1042 SMT Battery Holder**

Another option that presents itself in terms of a lithium-ion battery holder is the 1042 series from Keystone Electronics. Unlike its competitor mentioned above, this chassis not only comes in one specific size, but also does not come with premade wires given that it is a surface mount component. This fact alone makes it easier to work around any design constraints with the chassis and modify it to be in parallel with the transducers and the overall board. The chassis also does not seem to require a specific type of lithium-ion battery to function, making it more feasible to have different options for the battery in the design that the board can recharge.

There are some slight issues that do arise with this option, though. Like its competitor, it doesn’t have a covering for the battery, making it more susceptible to possibly falling out or being environmentally affected, especially in the high g’s a rollercoaster would produce. Another issue that may arise is the presence of two plastic prongs underneath the chassis. While this more likely than not is to help keep it in place on the PCB, it is an important factor we must take into consideration for proper installation. The chassis is also slightly bigger than its counterpart, measuring in around 3in by 0.81in, making its footprint large on the board. This must be compensated for in the overall design if we wish to make it as small as possible.

One final issue that arises with this component is the price, which runs around $3.93 per chassis when averaged out by DigiKey. This doesn’t seem like an issue at first glance, but when compared with the Amazon option, it provides around 10 single battery chassis for $7, making the 1042 option slightly more expensive in terms of how many can be purchased. However, given its flexibility and efficiency in terms of being a surface mount component with no specific battery requirement, this option may prove to be more reasonable for our design. An overall list of its features are shown below

- Low profile surface mount holder for Cylindrical Lithium and alkaline batteries
- UL 94V-0 heat resistant nylon housing well suited for reflow soldering
- Battery installation and removal does not require tools
- Securely holds battery in place
- Accommodates cells with or without built-in PCB protection circuits
- Polarity clearly marked for orientation
- Polarized holders available for protection against improper battery installation

4.5.3 **1096/1098 SMT Battery Holder**

Another option available from Keystone Electronics is the 1096 series of battery holders. Like the 1042 series, it comes in its own size and is a surface mount component, making it more feasible to modify with our transducers and overall board. However, unlike the 1042 series, the 1096 is smaller and more compact that its counterpart. The component measures in around 1.7 inches versus the 3.3 inches that the 1042 measures at. This fact in hand means that the component will have less of a footprint when it comes to the overall design.

Given this fact, however, it must be taken into consideration that the smaller size of the chassis might mean less of an ability to store energy. The smaller size means the lithium-ion battery will need to be smaller and, in turn, may end up producing less power than the board requires. Should this prove to be an issue, the 1098 series can be used, which is a dual version of the 1096 series. The only issue that would arise with this decision would be a slightly increased footprint in terms of width, increasing from 0.63 inches to 1.56 inches.

The price for a single slot 1096 would run around $2.91 while the price for a double slot 1098 would run around $4.95, making these options slightly more expensive than the amazon option, but also both more and less expensive than the 1042 option, depending on the application and how much power it can provide. While the double slot option is definitely the most expensive out of the options presented, it might be worth it to invest in if it can decrease the footprint. A list of features for each item can be found below.

- Low profile surface mount holder for Cylindrical Lithium and alkaline batteries
- UL 94V-0 heat resistant nylon housing well suited for reflow soldering
- Battery installation and removal does not require tools
- Securely holds battery in place
- Accommodates cells with or without built-in PCB protection circuits
- Polarity clearly marked for orientation
- Polarized holders available for protection against improper battery installation

4.5.4 **2-1775485-1**

One final option for us to consider in our design for the board is the 2-1775485-1. This option presented is a coin-battery through hole chassis, which is much different than the previous cylinder style battery chasses that were presented before. However, with this variation in style, this option provides both pros and cons to the choice of using it in the overall design of the energy harvesting system. The battery chassis is much smaller than the other options, measuring out around only 20mm compared to the previous smaller option's 1.7in option.This means that the option's footprint will take up a much smaller space compared to its previous options. The options are also through hole compared to surface mount, meaning that the battery chassis could withstand more environmental stress compared to the surface mount options, since the through hole pins will be secured firmly inside the board and be able to withstand the constantly changing acceleration of the rollercoaster. Finally, the chassis only runs at $0.53 according to DigiKey, making it the cheapest available option when compared to the others.

It is important to note some of the flaws in the design as well. For example, the option is a coin chassis, which means that the options in terms of lithium-ion batteries are limited and can possibly only supply 3V worth of voltage. This could be an issue eventually if the board needs more than 3V to power it, especially when it comes to the data display and powering the microcontroller. Also given the device is much smaller and thinner than the other chasses, it could prove more susceptible to damage both in terms of repairing and environmental damage if proper caution is not used, compared to the less susceptible options previously mentioned. While a different path in terms of power supply, the option does seem to have potential. There are some issues with the possibly low power supply and the possibly fragility, the probability of reducing the overall footprint of the power supply could be integral to making our design close to ideal and feasible.

4.5.5 **Battery Chassis Summary**

Name	Manufacturer/ Supplier	Size	Type	Price
1096/1098 SMT Battery Holder	Keystone Electronics	1.56" x 0.63"	Lithium Ion Cylinder	$2.91-$4.95
2-1775485-1 Coin Battery Through Hole Chassis	TE Connectivity	23mm x 6.4mm	Lithium Ion Coin	$0.53
1042 SMT Battery Holder	Keystone Electronics	3" x 0.81"	Lithium Ion Cylinder	$3.93
Aokin Battery Chassis	Aokin/ Amazon	2.95" x 0.75"	Lithium Ion Cylinder	$7-$8

Table 3: *Battery Chassis Options Table*

When it comes to a selection of battery chasses, the current option that seems the best would be the 1096 battery chassis due to its footprint and power supply ability. However, if we were to save on space, the Coin battery chassis would be a close second. Both options have a small footprint and are cost efficient in the overall design. The 1042 option could be considered if we desire more power for our board and decide to go vertically with the footprint rather than horizontally. The Aokin option would be a last resort option in case none of the other options suffice and is the last option due to its cost.

4.6 Super Capacitor

In the subject of onboard power supplies, the use of a battery and chassis initially was the most pressing option due to its availability and convenience. However, given that the board will be on a rollercoaster and subjected to various forms of force, including acceleration, inertia, and other means that could prove difficult, the option remained but with some hesitation given that the battery inside the chassis could be subject to being dislodged or even damaged. Further research into energy harvesting as well as entities to hold any of said energy harvested, the subject of alternatives to batteries as power storages came up. One breakthrough in the research is using a super capacitor as a supply. With this breakthrough, we should be able to find a more efficient and overall better alternative for our design while trading off for overall cost.

Supercapacitors, otherwise known as ultracapacitors, are an alternative power source to batteries in which the capacitance is much higher than standard grade capacitors while also boasting lower voltage limits. Unlike its competitors in the lithium-ion battery area along with its chasses, the supercapacitor benefits in terms of energy harvesting by storing larger amounts of energy, can deliver and receive as much as a conventional battery, and can withstand more charging and discharging cycles than the standard battery, making it a more efficient and possibly better option when compared with the battery options.

However, despite the proven benefits of this component, the capacitor could prove to be more expensive than a lithium-ion battery, meaning a greater cost to the overall project if considered. Therefore, it might be beneficial economically to stick with a lithium-ion option in comparison to a supercapacitor option, even if the benefits of said supercapacitor are obvious. Another given downfall to the usage of a supercapacitor is the possibly thicker design than the average battery with certain models, meaning a larger footprint in the overall design with said certain models.

One final issue that comes up when it comes to a selection of supercapacitors is the availability. Given that our board will need a decent amount of voltage harvested, a supercapacitor will be needed that can handle that amount of voltage. The higher we go with the voltage amount, the larger, the rarer, and more expensive the item will be. Careful selection and consideration was put forward when selecting a proper capacitor, especially if it is to be the more expensive of the options. Highlighted below are two possible solutions to the debate over a supercapacitor in the design.

4.6.1 **FCS0H224ZFTBR24**

One of the first options available from researching various supercapacitors is the FCS0H224ZFTBR24. Manufactured by Kemet, this supercapacitor is advertised as a 220mF (EDLC) Supercapacitor, 5.5V, Radial, SMD 50Ohm @ 1kHz component and fits the description for a supercapacitor we are looking into. There are various pros and cons to including this component in our design and the tradeoffs must be considered if to be included. Whether a detractor or not, most of the specs within a given supercapacitor seem to reap greater benefits than the given batteries and chasses researched previously.

One of the first features that is initially attractive about the capacitor is its overall supplied voltage, which is a max of 5.5V. According to the datasheet, the capacitor can also supply as little as 3.6V as well, making it a versatile option in terms of supplied voltage. Another attractive feature is its relatively small size, measuring in around 0.421”x 0.335”, making it a much smaller option compared to the battery chassis options mentioned earlier. One final thing to consider as a benefit of the use of this option is the fact that is purely surface mount without any extra components. When compared with the options for the battery chasses, this makes the component less susceptible to possibly falling out or being damaged due to the rollercoaster’s inertia.

Despite the given benefits of this component, there are some downfalls to this option. For example, the equivalent series resistance, or ESR, for this capacitor is around 50Ohms, which may not seem initially wrong, but given that a lower ESR leads to less capacitance loss and more efficiency and stability, a 50Ohm ESR could prove inefficient, if not detrimental, to our design, especially of the ripple voltage is increased overall. This seems to be one of the few disadvantages to having the supercapacitor as our power supply.

According to DigiKey, the price for one of these supercapacitors is around $3.09, making it a slightly cheaper alternative to the previous options of the lithium-ion battery and chassis combined. While the high ESR may prove dissuading to the overall design, the other features, including the voltage supply and the overall size, may prove beneficial to our board and energy harvesting efficiency. Below is a given list of the main features presented with this component, according to the datasheet:

- Surface mount without holder
- Wide range of temperature from −25°C to +70°C
- Maintenance free

- Maximum operating voltages of 3.5 and 5.5 VDC
- Highly reliable against liquid leakage
- Lead-free and RoHS Compliant

4.6.2 **BZ12GA124ZLBA2**

Another option available to us when selecting from the supercapacitors is the BZ12GA124ZLBA2. Manufactured by AVX Corporation, the component is advertised as a 16V, BZ01, 3L Lead 160mOhm, 1000Hrs @ 70C supercapacitor in its initial description. There are quite a few features in this selection that make it both a better option and a slightly inferior option with given tradeoffs. Despite all the tradeoffs, it also proves to be a more efficient option than the battery options and their respective chassis options.

First and foremost is the 16V supply, which is more power supplied than the previous option, making it an attractive feature since it will be able to power our board without issue. Another great feature about this option is the through hole design, which allows for a more secure and sturdy component that will be less susceptible to damage from any extraneous forces it may be exposed to compared to its SMD option. One final metric for this option that makes it an appeasing component is the smaller ESR, measuring around 160mOhms and making it much more efficient and stable than its counterpart. All these metrics combined make this seem like it is the ideal power supply to have on the board.

Despite all the praises given for this component, there are a few factors that keep it from being an ideal choice. Firstly, is that given the better efficiency comes a greater cost to the component, coming in around $34.90 for a single capacitor. This makes it one of the most expensive options in terms of a power supply and makes it more difficult to replace in case of a failure. Another factor keeping it from being ideal is the overall size of the component, measuring in around 1.89” x 1.18”, which is around 2 ½ times bigger than the previous option given and leads to a bigger footprint overall for the design. To keep the design as small as possible, this option may not be the greatest for us both in terms of size and price.

Overall, the given specs for the capacitor are very attractive. The supplied voltage, the given overall lifetime of the component, and the overall ESR is either on par or much better than the previous option. However, cost and size ultimately hold back the option from being as ideal as possible. Despite cost and size, efficiency may be something to strive for in the design and may be beneficial to go with despite the overall cost. Furthermore, AVX Corporation seems to also provide other options in terms of voltage, which allows for a greater variety of options in terms of capacitors to choose from, according to the datasheet. Overall, a good option held back by its size and cost.

4.6.3 **BZ12GA124ZAB**

One final option to consider in terms of supercapacitors in our design would be the BZ12GA124ZAB. This is also an AVX Corporation style supercapacitor that is advertised as a 16V, 120mF capacitor. This option is both similar and different to the previous option in terms of name and functionality and with that comes some pros and cons to it as a choice in terms of supercapacitors. For starters, this option, like the BZ12GA124ZLBA2, boast itself with a 16V capacity, which is ideal for a power storage since it allows us to harvest and store more power created by the transducer. It also boasts a decent ESR of 160mohms, making it efficient in terms of storing the energy and not having leakage. One benefit to having this item compared to the previous option is the increased tolerance, which is at a max of +80% vs its +50%, meaning the capacitance can vary more without causing any issues.

However, with this option comes some downfalls. Like the BZ12GA124ZLBA2, it has the same dimensions and has a large footprint to it, meaning it will take up a large amount of space, but not as much as a group of battery chasses. Another downfall to this option is the price, coming in around $94.21 for the capacitor alone, making it single handedly the most expensive component in terms of a power supply and making it even more critical of a component should any possible damage ensue. If this option is selected, it should only be due to the increased tolerance and efficiency, but as it stands, this should be a last resort due to the cost. Overall, the option does provide some benefits in terms of tolerance and efficiency but will ultimately be held back by the cost of it, since the cheaper option does exist at the cost of tolerance.

4.6.4 **Supercapacitor Comparisons**

Name	Manufacturer/ Supplier	Output Voltage	Equivalent Series Resistance	Price
BZ12GA124ZLBA2 16 V Supercapacitor	AVX Corporation	16V	160mOhm	$37.90
BZ12GA124ZAB 16 V Supercapacitor	AVX Corporation	16V	160mOhm	$94.21
FC S0H224ZFTBR24 5.5 V Supercapacitor	Kemet	5.5V	50Ohm	$3.09

Table 4: *Supercapacitor options table*

Above is a table of the given two supercapacitor options that were researched for the design. As can be seen, the first option from AVX Corporation would be the best of the options given its amount of storage and its efficiency in terms of the ESR. While it may be more on the pricey side, it would be beneficial to have a component that has less voltage leakage compared to a regular power supply. The second option from AVX has similar functionality but has better tolerance at the cost of an increased price. The Kemet option should only be considered if we are resorting to a much cheaper option.

4.7 Accelerometer Options

For our design and the purpose of measuring a set of given parameters through the microcontroller, we have decided to include accelerometers in said design. The accelerometer is a device which will measure acceleration in any given fixed dimension. Accelerometers can be measured in spaces such as two dimensional or three dimensional depending on the necessary application of the component. Given that a rollercoaster is subject to various kinds of three-dimensional movement while in operation, the ideal accelerometer would be one with a fixed X, Y, and Z axis. Other key parts of the accelerometer include its measurement of the parameters, the amount of power consumption one component will have, and its durability on the board. The following options for accelerometers are highlighted below in the following sections.

4.7.1 **LIS2DH**

The LIS2DH is a three-dimensional MEMS digital output motion sensor developed by STMicroelectronics, boasting itself as a low-power, high performance femto accelerometer. From the specifications that can be found in the component's datasheet, the component has a very small supply voltage of between 1.7V to 3.6V, making it ideal for a low power consumption component.

The device also has a "ultra-low" current draw, which would be around 2μA, meaning even if the board is still active, it will have less of a chance to draw in and waste more power if the accelerometers are not currently in operation. Acceleration range is also ideal in the device, ranging from a minimum of $\pm$2g to a maximum of $\pm$16g, which is beneficial given the accelerometers will be dealing with intense movement in the rollercoaster. Finally, the package is relatively small for the component, measuring around 2x2x1 mm, meaning it will not take up a large, unnecessary amount of space on the board. The cost of a single accelerometer in this style would be approximately $1.53, averaging from Digikey's price. A full list of the functionality of this board are given below, according to its datasheet:

- Wide supply voltage, 1.71 V to 3.6 V
- Independent IOs supply (1.8 V) and supply voltage compatible

- Ultra low-power mode consumption down to 2µA
- ±2g/±4g/±8g/±16g dynamically selectable full-scale
- I2C/SPI digital output interface
- 2 independent programmable interrupt generators for free-fall and motion detection
- 6D/4D orientation detection
- “Sleep to wake” and “return to sleep” function
- Freefall detection
- Motion detection
- Embedded temperature sensor
- Embedded FIFO
- ECOPACK® RoHS and “Green” compliant

4.7.2 **LIS3DH**

Another option available from STMicroelectronics is another MEMS output motion sensor, only it is a “nano” accelerometer instead of a “femto” accelerometer. Most of the parameters, including voltage and current draw, acceleration range and sensitivity, and output type (I2C, SPI) remain the same. There are, however, some minor and major differences to consider when selecting between the two. For example, the bandwidth maximum is reduced to 625Hz in the LIS3DH vs its counterpart LIS2DH’s 672Hz maximum, which could lead to a slight decrease in data transfer between the accelerometer and the microcontroller. Both options contain I2C, SPI output, but the LIS3DH boasts itself with a 16-bit output with a 32 levels of 16-bit output data FIFO. It is mentioned in the block diagram for LIS3DH that a 32 FIFO exists, but it does not seem it be its priority.

The package for the LIS3DH is slightly bigger than that of the LIS2DH, coming in around 3x3x1 mm in its package, which isn’t too critical of a factor, but should be taken into consideration when designing the board. Finally, the average price for the component can be averaged around $1.49, which makes the device slightly cheaper than its alternative. A full list of the LIS3DH’s features are given below

- Wide supply voltage, 1.71 V to 3.6 V
- Independent IO supply (1.8 V) and supply voltage compatible
- Ultra-low-power mode consumption down to 2 µA
- ±2g/±4g/±8g/±16g dynamically selectable fullscale
- I2C/SPI digital output interface
- 16-bit data output
- 2 independent programmable interrupt generators for free-fall and motion detection
- 6D/4D orientation detection
- Free-fall detection
- Motion detection
- Embedded temperature sensor

- Embedded self-test
- Embedded 32 levels of 16-bit data output FIFO
- 10000 g high shock survivability
- ECOPACK®, RoHS and “Green” compliant

4.7.3 **ADXL327BCPZ**

This option for an accelerometer is presented by Analog Devices. It is advertised as a 3 axis, low power option for acceleration measurement. There are a few differences between this option vs the options given from STMicroelectronics. First and foremost is the adjustable and maximum bandwidth. Whereas the previous options have around 670Hz in terms of bandwidth, these options allow for a greater bandwidth of 1.6kHz for the x and y axis with a decrease in bandwidth to 500Hz for the z axis. The device also has a close voltage draw to the previously mentioned accelerometers, ranging between 1.8V-3.6V.

There are, however, some difference to keep in mind. First and foremost is its low power draw, which ranges around 350uA, which could push the limits of our system compared to the lower power draw. Another difference is its sensitivity, which can only go up to $\pm$2g. Depending on the rollercoaster, this may pose an issue to the design if the component cannot handle the g’s presented. The output is also in analog voltage compared to its previous options digital outputs, meaning that if this option is selected, there may be a need to research and use an analog to digital, or A2D, converter for proper programming. One of the final things to consider is the package size, which while small, also comes around 4x4x1.45mm, which is about twice as big as the first options 2x2x1mm option.

The overall price of this component is around $6.39 when averaging it out with DigiKey. This pricing makes it an expensive option when compared to the other two options presented, especially since they are only around $1 each. However, the benefits of greater bandwidth with data transfer of the acceleration may be worth the additional hassle, research, and expense this component brings. So, despite a list of obvious cons with this device, it would be beneficial to consider this an option in terms of accelerometers. A full list of the features of this component can be found below:

- 3-axis sensing
- Small, low profile package
- 4 mm × 4 mm × 1.45 mm LFCSP
- Low power: 350 μA typical
- Single-supply operation: 1.8 V to 3.6 V
- 10,000 g shock survival
- Excellent temperature stability
- Bandwidth adjustment with a single capacitor per axis
- RoHS/WEEE lead-free compliant

4.7.4 **MMA8453QT**

Another option presented to us in terms of useful accelerometers would be the MMA8453QT. This accelerometer is developed by NXP Semiconductors and is a three-axis component like the ones discussed before, with some tradeoffs that will be further highlighted, including acceleration tolerance, bandwidth, and pricing.

First and foremost is its acceleration tolerance, which can range from around ±2g to ±8g, which is a great sense of range, though slightly below the range given from one of the previous options. Given that a rollercoaster's maximum g's should be around 3, this shouldn't present too much of an issue. Another presented finding is the voltage draw, with only a minimum of 1.9V for operation. This is ideal for our energy harvesting device if the device can keep a low power draw, though it will ultimately depend on the strength of the power supply.

There are a few hinderances, however. The main issue with this option is the bandwidth, which is adjustable between 0.78Hz to 400Hz. In turn, this could cause any data output to be more delayed and less streamlined compared to the other options and could maybe even compromise any data we wish to discover and display on the user side. Another issue that arises is its I2C only compatibility, which makes it less adaptable than the other series that contained a SPI output as well, but more efficient that the option with an analog output.

The device is no bigger nor smaller than the other options and runs around $4 according to DigiKey, making it more of a middle of the road option in the grand picture of the design. It is definitely a component to consider in case the analog one falls through. A full list of features is detailed below:

- 1.95 V to 3.6 V supply voltage
- 1.6 V to 3.6 V interface voltage
- ±2 g/±4 g/±8 g dynamically selectable full-scale
- Output data rates (ODR) from 1.56 Hz to 800 Hz
- 99 μg/√Hz noise
- 10-bit and 8-bit digital output
- I2C digital output interface
- Two programmable interrupt pins for six interrupt sources
- Three embedded channels of motion detection
    - Freefall or motion detection: one channel
    - Pulse detection: one channel
    - Jolt detection: one channel
- Orientation (portrait/landscape) detection with set hysteresis
- Automatic ODR change for auto-wake and return to sleep
- Self-test
- Current consumption: 6 μA to 165 μA

4.7.5 **ADXL337**

Another accelerometer option presented to us that may prove to be beneficial to our design is the ADXL337. This accelerometer, produced by SparkFun Electronics, is a 3-axis sensor like the others we have discussed previously. However, the main difference between this option and the others is that this is a breakout board, with the accelerometer soldered onto a small red board with capacitors surrounding it to help its bandwidth. The board also has indicators, including for the axis, the voltage input, ground, and more to help with ease of installation and use, making it much more accessible than the previous options which are not soldered on.

One of the good features about this option is the fact that it only takes around 3.3V to operate, keeping within our specs of operation and remaining a feasible option. The current draw also ranges around 300uA, which is not the lowest of options available, but is still low enough to be reasonably efficient for our design. The range for the bandwidth also ranges up to 1600Hz for the x and y axis and up to 500Hz for the z axis, making it a great option in terms of data transfer. One final great thing about the option is that though it looks big in the visual above, the board is under the size of an American 25 cent quarter, making its footprint still relatively small and the accelerometer's footprint even smaller.

With this option does come some drawbacks though. For one, the breakout board comes to around $9.95 according to SparkFun's website, making it a slightly more expensive option compared to the others, though this may be due to the increased bandwidth and the included board and capacitors. Another issue that arises is the acceleration range, which only goes up to ±3g, making it slightly more efficient than the analog option, but not better than the others. While it may be able to take most forces of acceleration, it is hard to say if it can account for sudden jerks and turns on a rollercoaster. One final issue that becomes raised is the fact that this is a breakout board. While great for testing, the option will more likely than not only need to be the accelerometer alone. Further research on acquiring the accelerometer by itself and its pricing will need to be done if this is to be considered for the design.

Despite these given drawbacks, this option provides a great strength in terms of prototyping and allowing us to see the true functionality of the accelerometer without having to strenuously hook up a single accelerometer. A given list of features is given below and take from both the datasheet and SparkFun's website:

- Operating Voltage: 1.8V - 3.6V
- Typical Current: 300 μA
- Range: ±3g
- 3-axis sensing
- Bandwidth adjustment with a single capacitor per axis
- 1x Mounting Hole

4.7.6 **ADXL377**

Another option presented to us for our design in terms of accelerometers is the ADXL377. This accelerometer is another product of SparkFun Electronics and is a 3-axis sensor. This component is like the previous option but has a few major differences.

In terms of similarities, the option also comes on a red breakout board with some details added to it to make operation easier, including where Vin and GND go, the axis orientation, and given capacitors to help with bandwidth. The board also requires only under 3.6V to operate with a small current draw of 300uA, making it an efficient device in terms of operation and power and current draw. This breakout board also is around the same size as the previous option as well, which is just under the size of a quarter, making its footprint small and unintrusive.

One final similarity is the fact that they have similar bandwidths of 1600Hz for the x and y axis and 500Hz for the z axis. However, one major difference between the 337 and 377 series is that this option has a maximum acceleration range of ±200g, making it one of the largest ranges in terms of acceleration for our options. This increased range would compensate for any sudden turns and jerking the rollercoaster may exude on the component.

With the addition of this component also comes some drawbacks as well. Like the 337 series, the 377 series suffers from being on this breakout board, which could be mounted onto our final design, but it may be more for prototyping purposes than design integration. Another drawback to this option is the fact that due to the increased acceleration range and the breakout board addition, the cost according to SparkFun's website goes up to $25.95, making this a very expensive option and not as easy to replace should anything go wrong. Should this option be considered, it should be carefully utilized with upmost priority like with any expensive option.

Given the drawbacks, the increased acceleration would be beneficial to any sudden changes in acceleration and turning on a rollercoaster and would greatly benefit the efficiency of our design. A given list of features can be seen below and is take form the SparkFun website and the 377's datasheet:

- Operating Voltage: 1.8V - 3.6V
- Typical Current: 300 μA
- Range: ±200g
- 3-axis sensing
- Bandwidth adjustment with a single capacitor per axis
- 4x Mounting Hole

4.7.7 **Accelerometer Summary**

Name	Manufacturer	Bandwidth	Range	Output	Price
ADXL337 3 axis sensor	SparkFun	1500Hz	±3g	I^2C	$9.95
ADXL377 3 axis sensor	SparkFun	1500Hz	±200g	I^2C	$25.95
LIS2DH 3D Digital Output Motion Sensor	ST Microelectronics	672Hz	±2g- ±16g	I^2C, SPI	$1.53
LIS3DH 3D Digital Output Motion Sensor	ST Microelectronics	625Hz	±2g- ±16g	I^2C, SPI (16 bit)	$1.49
MMA8453QT 3-Axis sensor	NXP Semiconductors	0.78Hz- 400Hz	+2g- +8g	I^2C	$4
ADXL327BCPZ 3-Axis low power sensor	Analog Devices	1.6kHz	±2g	Analog	$6.39

Table 5: *Accelerometer Options Table*

From the options discussed in terms of accelerometers for our design, the best options so far are ideally the ADXL series mentioned, specifically the 377 in terms of bandwidth, output, and range. The 337 option could be considered if we wish to have a cheaper option, but the reduced g's could pose an issue. The LIS options could be considered as well if we wish to go with a cheaper option without too much expense to the Bandwidth amount and acceleration amount.

The NXP option could be considered if the first two do not meet our quota, but at the expense of a smaller bandwidth. The Analog Device option could be considered as a last resort if we need the extra bandwidth, but the analog output, decreased range, and current draw could pose issues for the design, especially if we need to consider an Analog to Digital Converter.

4.8 Diode Options

Given that our design will need to implement a rectifier, it is important to evaluate any diode options that can be used for said rectifier. Given that there are a variety of options that suite rectifier design, it is also important to minimize options in terms of size, application, and cost. The following options were found to be considered for implementation.

4.8.1 **1N4148WS**

One of the first options we have in terms of diode options specifically for rectification is the 1N4148WS. This component is a small signal diode manufactured by ON Semiconductor and may prove useful to our design. The diode also has a small amount of current rectified (around 150mA to be exact) with a speed around 200mA. Given this small amount of rectification, it might be ideal for our design.

Another benefit to having this option is both the cost and availability. When averaged on DigiKey, the Diode runs at only $0.16 each when ordered alone and cheaper when ordered in bulk, making it one of the cheapest components in our budget so far. This would make this option great in terms of cost efficiency and saving money. Another reason to consider it is that, also according to DigiKey, there are around two hundred thousand available for sale, making it widely available and not reliant on any detrimental lead times that may arise with other products.

However, with this option, there are some specs that do raise concern. For example, the maximum reverse voltage is around 75V. This reverse voltage might prove to be a bit too much for our design since we do not wish to use this much voltage. However, this is the maximum, so it may be possible to use less than what the spec is offering. Given that his option meets our requirements in terms of a rectifier, is cheap and available, and only has one main drawback, this is one of the more ideal diodes we could use for our design. The following details are labeled below in terms of features for this diode, according to the part’s datasheet.

- General Purpose Diodes
- Fast Switching Device (T_{rr} < 4.0 ns)
- Very Small and Thin SMD Package
- Moisture Sensitivity Level 1
- Matte Tin (Sn) Lead Finish
- Green Mold Compound
- Pb-Free Version and RoHS Compliant

4.8.2 **MBRS410ET3G**

Another viable option that is available to us in terms of diodes is the MBRS410ET3G Schottky Diode, also available from ON Semiconductor. Based on its given specs, the diode is more expensive than its given competitor, but also boasts specs that may aid our design slightly better than the previous. With this in mind, it is important to keep close detail as to what the specifications of our design will need.

To begin with, this option of diode advertises itself with a fast recovery speed of 500ns for any current greater than 200mA, which is an improvement on the unspecified speed of the previous diode, mentioning only that it has a small signal that must be under 200mA. The current that it can rectify is also much greater than the previous, measuring at 4A rather than 150mA. These factors alone prove the efficiency is greater in this option.

That being said, there is one slight drawback to this design. Despite the increased rectification current and the increased recovery speed, the diode option does have a smaller reverse voltage, which could lead to a smaller forward voltage and even greater chance of current leakage, which could impede the efficiency of the design since the previous option had a higher reverse voltage and less of a chance to incur this fault. Therefore, careful consideration must be made with the design to ensure how much voltage is required for certain sections.

The current option for this diode is slightly bigger than the option given before, however further inspection of the datasheet reveals that there may be an option to reduce the size, which would be beneficial to reducing the components footprint. The diode also runs at $0.56 each according to DigiKey, making it a slightly more expensive option that the previous ON Semi diode, though it is still under $1. Given its greater recovery and greater rectification, it may be ideal to include this diode in our design. Further features can be found below, mentioned in the datasheet.

- Very Low VF Accompanied by Low IR
- 1st in the Market Place with a 10 VR Schottky Rectifier
- Small Compact Surface Mountable Package with J−Bend Leads
- Rectangular Package for Automated Handling
- Highly Stable Oxide Passivated Junction
- Designed for Low Leakage
- Excellent Ability to Withstand Reverse Avalanche Energy Transients
- Guard−Ring for Stress Protection
- Pb−Free, Halogen Free/BFR Free and are RoHS Compliant

4.8.3 **S3M-13-F**

Another option available to use in terms of diodes for rectification is the S3M-13-F. This diode, manufactured by Diodes Incorporated, is a 1kV 3A diode as mentioned by the main descriptor. This option provides a variety of positive and negative tradeoffs that must be considered when discussing the selection of diodes available.

To start off, the recovery time for the diode, ideally, is around 500ns, which is similar to the Schottky's recovery time and faster than the other options, making it ideal for a proper design where recovery is needed. The current rectified also ranges to around 3A, which is less than the Schottky but much greater than the first option, which may prove ideal for our design given the application.

However, some issues to arise with this option if chosen. As mentioned in the description, the reverse voltage goes up to 1000V, which might prove to be too much for our design to handle given our device will need nowhere near 1000V to operate, especially safely. Another issue that arises is the current leakage, which is around 10uA at 1000V, but might prove different at lower voltages when applied. Further testing would be needed to know for sure.

The price for this component according to DigiKey would be around $0.40, making it more expensive than the first option but cheaper than the second option. Ultimately any of these Diodes could be used for our design, but it would ultimately depend on the rectifier that needs to be implemented. A full list of features for this device can be seen below and were pulled from the datasheet:

- Glass Passivated Die Construction
- Low Forward Voltage Drop and High Current Capability
- Surge Overload Rating to 100A Peak
- Ideally Suited for Automated Assembly
- Lead-Free Finish; RoHS Compliant
- Halogen and Antimony Free. “Green” Device
- Case: SMB/SMC
- Case Material: Molded Plastic. UL Flammability Classification Rating 94V-0
- Moisture Sensitivity: Level 1 per J-STD-020
- Terminals: Lead Free Plating (Matte Tin Finish). Solderable per MIL-STD-202, Method 208
- Polarity: Cathode Band or Cathode Notch
- Weight: SMB 0.093 grams (approximate)
- SMC 0.21 grams (approximate)

4.8.4 **Diode Summary**

Name	Manufacturer/ Supplier	Max Reverse Voltage	Rectification/Speed	Price
S3M-13-F Diode	Diodes Incorporated	1000V	3A/ 500ns	$0.40
MBRS410ET3G Schottky Diode	On Semiconductor	10V	4A / 500ns	$1.30
1N4148WS Small Signal Diode	ON Semiconductor	75V	200mA / N/A	$0.16

Table 6: *Diode Option Table*

For the given options available to us in terms of diodes, the S3M-13-F options seems to be the more ideal option given its rectification, max reverse voltage, and price, even if we won't necessarily utilize the entirety of the reverse voltage. The Schottky Diode would be a close second due to its 4A rectification, though the price is ultimately what keeps it from being the first choice. The 1n4148WS option is the last option since although it is the cheapest of the options, the rectification is only around 200mA, which may not be ideal for our design.

4.9 Operational Amplifier Options

The presence of weak electrical signals is bound to happen in our design if we are not careful. Therefore, the presence of operational amplifiers, or op amps, is integral to the safety and efficiency of our design. The following options to consider are listed below.

4.9.1 **UA741CDR**

One of the first options available to us that we can consider in our design is the UA741CDR Op Amp from Texas Instruments. One of the more attractive features about this component is its low current draw, running only at 1.7mA. Given our design is meant to be low power, this would benefit us greatly. The output is also low at around 25mA, which allows for an amplification of any current that will go inside the amp.

Although there are benefits with this design, there are some possible flaws that come with it. The voltage supply, for example, requires a minimum of 7V to operate, which may prove to be challenging depending on our supply, as we can only supply it with what it has. Another issue that may arise is the 25mA output, which is great for power consumption, but not necessarily for overall performance. Depending on the final overall design and the required spec, we may require more current than the op amp can provide.

The op amp has very little space in terms of footprint, measuring in at only 3.9mm in width. These measurements make it ideal for keeping the overall size of the design relatively smaller. The op amp option also costs around $0.49 according to DigiKey, making it a cheap and relatively expendable component to have on board. While the high voltage demands and low current output may be detractors to consider, the option does still benefit with being low power and may ultimately benefit us. The following features of the op amp are given below and taken from said op amp's datasheet.

- Short-Circuit Protection
- Offset-Voltage Null Capability
- Large Common-Mode and Differential Voltage Ranges

- No Frequency Compensation Required
- No Latch-Up

4.9.2 **OP2177ARZ**

Another option to explore in terms of operational amplifiers is the OP2177ARZ from Analog Devices. Reviewing over the specs as well as the datasheet for the component, this option seems to yield more efficiency and flexibility compared to its counterpart. For example, within each datasheet is given types of configurations for how to set up the op amp properly for a given application. The datasheet for this option has more variety and applications, along with in depth instructions on the design of each op amp configuration, compared to the previous option. This will make finalizing the overall design of the board more feasible if this option is implemented.

There are also areas in terms of specs where this device is much more efficient than the previous one. In terms of current and voltage supply, the op amp can take up to 400uA and around 5 to 2.5 V (single/dual power supply), respectively, which consume less power overall compared to its competitor and making it more efficient in terms of energy harvesting and energy saving. Furthermore, in terms of saving power and energy, the output for this amplifier is 10mA compared to the 25mA. This factor may come to either help us or hinder us depending on how much current we need.

There are, however, some differences that could hinder this as an option. While not a major difference, there is a 0.2 greater slew rate for this option, meaning a slightly greater, but not significant, chance of voltage loss. Another issue that arises is the price, which runs around $3.92, meaning this option is around 8 times more expensive and less expendable as an option for the design. However, despite the increased price and possible issues with a greater slew rate, the option seems to have more energy efficient means about it that would benefit us in terms of saving energy.

A list of features for this given op amp are shown below and taken from the component’s datasheet.

- Low offset voltage: 60 μV maximum
- Very low offset voltage drift: 0.7 μV/°C maximum
- Low input bias current: 2 nA maximum
- Low noise: 8 nV/√Hz typical
- CMRR, PSRR, and AVO > 120 dB minimum
- Low supply current: 400 μA per amplifier
- Dual supply operation: ±2.5 V to ±15 V
- Unity-gain stable

- No phase reversal
- Inputs internally protected beyond supply voltage

4.9.3 **BA15218F-E2**

Another option in terms of op-amps that could be considered for our design in case we need a filter is the BA15218F-E2. The component mentioned is manufactured by Rohm Semiconductor and is advertised as an IC Op-Amp according to its descriptor. Like options for other components of different capabilities, the functionality of this component along with the tradeoffs it provides must be taken into consideration when selecting it for our design. The following can be noted for this option.

The main takeaway from this option is that it has a greater bandwidth than the other options, measuring in around 10MHz, making it an ideal option in terms of data transfer. It also had a price of $0.83, which is slightly more expensive than the first option, but not near the $3 mark of the second option, making it a cost-effective option in the long run. Finally, the input biases for the device are much larger, which could be beneficial if utilized properly.

Despite these advantages, there are some design choices and other tradeoffs to consider. For example, the slew rate for this option is 3V/us, which is much greater than the other options and may prove disadvantageous in our overall design if included. The op amp also requires around 4 amps to operate on a single power supply, which is less than the previous option, but further research on our power supply will be needed in order to optimize for this.

Despite these tradeoffs, this opamp may prove beneficial in our overall design. The list of features for this device are mentioned below and taken from the datasheet:

- High Voltage Gain
- Low Input Referred Noise Voltage
- Low Total Harmonic Distortion
- Wide Operating Supply Voltage
- Operating Supply Voltage (split supply): ±2.0V to ±16.0V
- Slew Rate: 3V/µs(Typ)
- Input Referred Noise Voltage: 1.0µVrms (Typ)
- Total Harmonic Distortion: 0.0015% (Typ)
- Temperature Range: -40°C to +85°C

4.9.4 **Op-Amp Summary**

Name	Manufacturer	Min Voltage Input	Current Draw	Slew Voltage	Price
BA15218F-E2 Op-Amp	Rohm Semiconductor	4V-32V	4A	3V/us	$0.83
OP2177ARZ Op Amp	Analog Devices	5V single, 2.5V double	400uA	0.7V/us	$3.92
UA741CDR OP Amp	Texas Instruments	7V	1.7mA	0.5V/us	$0.49

Table 7: *Op-Amp Comparison Table*

Given the options available to us in case we need to implement an op-amp into our design, the Rohm option seems to be the most efficient option available to us. While the slew voltage may prove a challenge for us, the supply required for operation is ideal for our power saving. The other two options have greater specs in terms of slew voltage but are ultimately held back by required voltage and pricing. While the more expensive of the options, the analog option would be a good second option due to its minimal requirements in terms of voltage and its low current draw. The TI option would be a last resort option due to its high voltage requirements, which may prove difficult to attain with our energy harvester.

4.10 Frequency Tuning Actuator

In our research for understanding and creating a proper energy harvesting system, the subject of one specific block in the design came up. This said block in the first phase of the overall design, mentioned by Wahied and Gihan in their research for Piezoelectric Energy Harvesting Systems, is the use of a frequency tuning actuator.

According to the respective authors, it is an optional block that aims to match the resonance frequency to the input vibrations to maximize mechanical to electrical conversion. While, again, they mention that this design consideration is optional, the ability to implement a process like this to maximize energy harvested would be integral to maximizing the efficiency of our design, so a clear understanding of how to implement it is needed.

The design would consist of using an actuator’s vibrations and tuning it with the overall response vibrations of the transducers themselves. However, with further research, it seems the reason it has proven, according to Wahied and Gihan, to be optional is due to the low maximization it presents. An experiment conducted at HAL archives and their respective researchers, which can be found in the article

“Frequency tuning of piezoelectric energy harvesters thanks to a short-circuit synchronous electric charge extraction,” concluded that a frequency tuning actuator added to a design allowed for maximized harvesting, but only a few microvolts worth.

However, the article does go into some in depth analysis of how to utilize a proper frequency tuning actuator, with test results and circuit designs to reference. Therefore, this block in the energy harvesting design should only be utilized if we wish to slightly maximize our results, but again is proven only optional due to its said slight maximization.

4.11 Transceiver

The purpose of this section is to discuss possible transceiver options, along with the features of each component. When considering the implementation of a transceiver in our project design there are two separate cases that are obviously related. The main factor with considering the implementation of a transceiver is that it can function as a transmitter or a receiver. This is critical to our design to transmit the data we will be recording via the accelerometers. This implementation inherently leads us to have two transceivers with one primarily functioning as a transmitter and the other as a receiver. These separate cases will allow us flexibility in implementation and maybe for additional features such as software maintenance being completed through the transmitter to receiver link in reverse.

We looked to utilize a low power transmitter, since the piezoelectric transducers can only generate so much power. The ideal operating range that we have selected for all components of the design is between 1.6 to 3.6V. Leading to the transceiver having to meet these criteria. The transceiver must be able to operate using minimal power similarly to the other electronic components utilized in the design.

4.11.1 **nRF24L01+**

The nRF24L01+ is a single chip transceiver operating at 2.4GHz with an embedded engine protocol called Enhanced ShockBurst^{TM} that is meant for low power wireless applications. The operating frequency of the transceiver is 2.4 – 2.525GHz in the worldwide ISM. ISM stands for Industrial, Scientific, Medical, and refers to the frequency bands that are reserved to these selected industries. Additonally, the nRF24L01+ can be configured and operated through a SPI, which is a Serial Peripheral Interface. The registers can be accessed in all modes, meaning prior to transmitting the transceiver can be in low power mode and can begin to receive the data that has to be transmitted.

The nRF24L01+ has configurable frequency channels and air data rate. Air data rate is the rate which data is transmitted. For this transceiver, the air data rate can be configured between 250 kbps, 1 Mbps and 2 Mbps. The combination of having high air data rates and the ability to function at low power levels makes this transceiver ideal for our design. The operating voltage that the nRF24L01+ operates at is ideal since we are limited in the power we can generate and distribute via the piezoelectric transducers.

When comparing to the other transceivers discussed in this section, the nRF24L01+ has the ideal features we are looking to implement in our design. The low operating voltage and small power consumption are great for our design. There is some drawback to this option like the overall cost to purchase the component from SparkFun is $20.95. This cost makes this component the most expensive out of all the options. Even though, the nRF24L01+ is by far the components with the most capabilities.

Below is a list of the key features that the nRF24L01+ can provide to our design

- 250kbps, 1Mbps, and 2Mbps on air data rates
- Ultra low power operation
- 26uA in standby mode
- 1.9 to 3.6V supply range
- 11.3mA in transmitter mode
- 13.5mA in receiver mode at 2Mbps air data rate
- 900nA in power down mode

4.11.2 **RFM69HCW**

Another transceiver option is the RFM69HCW, that provides beneficial to our design that include the specialization for low power consumption with high power transmitting capabilities. Just like the nRF24L01+, this transceiver offers the user the ability to configure frequency channels they choose to operate on. The RFM69HCW is transceiver capable of operating over a wide frequency range of 315MHz to 915MHz ISM frequency bands. This transceiver who is manufactured by HopeRF Electronics and interfaced on a breakout board by SparkFun, enable us ease of implementation and integrating into the overall design.

The RFM69HCW is ideal for our design, since it operates at a low voltage level and draws a relatively small amount of current. Additionally, this transceiver offers applications over a wide range of frequencies, which include 315MHz, 433MHz, 868MHz, and 915MHz ISM frequency bands. This is similar to the nRF24L01+ which operates on the ISM frequencies, but at higher frequencies. Like the nRF24L01+, the RFM69HCW operates at a similar supply voltage with the range of 1.8 to 3.6V. This supply voltage range is ideal for our design and fits within the low power criteria for our design.

In addition to nRF24L01+ which can be purchased on SparkFun, the RFM69HCis also available to be purchase for $11.95. When comparing to the other transceivers, this transceiver falls in the middle for overall cost, but has similar features and characteristics to the nRF24L01+ transceiver discussed prior.

Below is a list of key features that the RFM69HCW can provide to our design
- 1.8 to 3.6V supply voltage
- 16mA in receiver mode
- Low power consumption
- Bit rates up to 300kbps
- Several different modulations
- +20dBm – 100mW power output capability

4.11.3 **LS-S100**

Another transceiver option is the LS-S100, which is manufactured by Lensen Technology. This transceiver usually applications include small microcontroller wireless communication designs and other port communication systems. This transceiver provides our design with the necessary transmitting functionality that the previous transceivers provide.

When comparing this transceiver with RFM69HCW, the transmit current is 100mA compared to 130mA, but the overall transmitting power of the RFM69HCW is higher with 100mW. The receiver current is 30mA compared to 16mA utilized by the RFM69HCW which has a low receiver current, but a higher transmitter current. In regards to the capabilities and the usability of the transceiver in reference to our design is that it could fulfill the design requirements. Not to mention the cost of LS-S1000 is at $16.00 and can be purchased on Tindie, which is an electronic supplier. The relatively moderate cost does help in assisting to keep cost down.

There are some drawbacks with this transceiver that include a high supply voltage of 5V. When comparing to other components that are utilized to fulfill our design, this supply voltage level exceeds the 3.3V we are looking for to utilize. The low available power that is generated by the transducers may not supply enough power in order for the LS-S100 transceiver to operate properly. To avoid this scenario, we are looking for components with small supply voltage, but this component is on the high end of the spectrum.

Below is a list of the key features that the LS-S100 can provide to our design

- Power output of 100mW
- Supply voltage of 5V
- 10uA sleep mode current
- 30mA for Receiver mode
- 100mA for Transmitter mode
- 433MHz frequency band

4.11.4 **RTF-DATA-SAW**

Another transceiver option is the RTF-DATA-SAW, which is manufacture by ABACOM Technologies. This transceiver is best suited for half-duplexed radio transmission with relatively fast receiving to transmitting switching. These transceivers capabilities meet some of the requirements we must meet, but the overall supply voltage of 5V really hinders the ability to implement this transceiver for our design. When considering other options, the cost of this transceiver at $20.25 is on the high end and with the high supply voltage needed to operate this transceiver might not only affect performance of this transceiver but the whole design as a whole, since the design operates solely on the power generated by the piezoelectric transducers.

Additionally, comparing the frequencies for the transceivers, all of the transceivers operate within a similar range except the nRF24L01+. This transceiver has an operating range of about two times that of the other transceivers. When considering the bandwidth, we can assume that a higher bandwidth will result in a higher maximum bit rate by Shannon Theorem. That's an important factor to consider since the amount of data that has to be transferred may be very large. And with a higher bit rate will allow the transmitter to transfer data at a faster rate.

The transceiver power consumption of is 3mA is low very low when considering some of the prior transceivers have a current of 130mA when transmitting. This transceiver could be implemented and fulfill our data transmission requirement, but with the high supply voltage hinders is potential implementation.

Below is a list of key features that the RTF-DATA-SAW can provide to our design

- Supply voltage of 5V
- Power consumption between 2.5 to 4.5mA
- Power output of 8mW
- 433.92MHz frequency band

4.11.5 **433MHz RF Link Kit**

Another transceiver option is the 433MHz RF Link kit, which is manufactures and distributed by Seeed. This transceiver is actually a transceiver, but actually a kit that provides both a transmitter and receiver to complete a data transfer network. This kit could provide us a solution of having a complete wireless communication network for almost a quarter of the cost when compared to purchasing two transceivers. The inherent drawback to this kit is that you would lose the flexibility of being able to send info in both directions not just from the microcontroller.

Comparing this kit to the other transceivers, the frequency is in a similar range to the others except to the nRF24L01+, which operates at a much higher frequency. The biggest advantage of this kit is the price, but we wanted to ensure that the components would actually perform as intended when considering the supply voltage. The operating voltage of the kit is around 5V; however, the voltage is very different for the transmitter and receiver. This same characteristic can be found among the other transceivers where if there is a high output power then there is a higher bit rate. Overall, the higher the bandwidth the higher the bit rate. Below is a list of key features that the 433MHz RF Link Kit can provide to our design

- 433MHz bandwidth frequency
- ASK modulation
- 3 to 12V operating range

4.11.6 HC-05

Another transceiver option is the HC-05, which is manufactured and distributed by HiLetgo. This Bluetooth module is a transceiver, that functions as both a receiver and a transmitter. This transceiver was an attractive option for us when it came to implementing it with the ATMEGA328P. The large amount of support in terms of software development led to the selection of this module. The ability to send any amount of data we needed within a small amount of time, helped to meet our engineering requirement for data transmission. Unfortunately, due to the operating voltage of the transceiver and the limited amount of power we could generate, we implemented an external battery to power the module. We choose this option so that the user could turn the transceiver on via an external switch.

Below is a list of key features that the HC-5 can provide to our design

- 2.4GHz frequency band
- UART Communication
- 3.6 to 6V operating range

Name	Manufacturer	Operating Voltage	Current consumption (Transmitting)	Frequency	Price
nRF24L01+	Nordic Semiconductors	1.9 to 3.6V	8.0 to 8.9mA	2.4 to 2.525GHz	$20.95
HC-05	HiLetgo	3.6 to 6V	30mA	2.4GHz	$7.99
RFM69HCW	HopeRF Electronic	1.8 to 3.6V	16 to 130mA	290 to 1020MHz	$11.95
LS-S100	Lensen	5V	30 to 100mA	433MHz	$16.00
RTF-DATA-SAW	ABACOM Techologies	5V	2.5 to 4.5mA	433.92 MHz	$20.25
433MHz RF Link Kit	Seeed	3 to 12V	low	433MHz	$4.90

Table 8: *Transceiver Comparison Table*

4.11.7 **Summary on Transceiver**

When considering all the above transceivers, the transceiver that best suits our design needs was the HC-05 The transceivers operating voltage is less than ideal for our low power application, but since we implemented an external battery as a power supply, we were not concerned with powering the transceiver. Additionally, the bandwidth frequency is the highest among all the mentioned transceivers. Bandwidth is an important aspect of the transceiver due to amount of data we may have to transmit. With a higher bandwidth results in a higher data bit rate. This is very important so that we are transmitting as much data as fast as we can. The other transceivers have a significantly lower bandwidth which would potentially bottleneck the amount of data we are able to transmit is a certain amount of time. This consideration also is related to the amount of power we are generating, and the duration of time is taken to completely transfer all the data after a given run. The price also played a role in selecting HC-05, since its relatively lower cost when compared to the other options.

4.12 LCD

An LCD will benefit the end user by displaying the information that is clear and easy to read. For our project, an LCD would be a component that may be implemented since our goal of the energy harvesting system is to have the MCU and its components to utilize less power. An LCD would use up more RAM and energy compared to the other components found on the board. Below are options that may be used within the energy harvesting project to provide convenience for the end user. The main propose of using this unit would be to show the amount of power produced by the piezoelectric sensor as well as the amount of force being applied to the unit.

4.12.1 **Memory LCD**

This display contains the unique feature of retaining the pixel placement while using less power than a standard LCD or an e-paper (electronic paper) display. These displays use up to 15 μW for a static image and 30 μW for a dynamic update of 1 Hz for a 1.35-inch display. This display is very beneficial for our project since it consumes less power than other units, which is our main goal in creating an energy harvesting platform. Unfortunately using this display would not be ideal with our current MCU set up since the display is write only and takes up the entire 96x96 bit (1,152 bytes) which is about half the RAM of the total 2 KB. 96x96 is the smallest option available for this display and these units are not produced in large quantities compared to other displays.

4.12.2 Graphic LCD

The main advantage a graphic LCD has over the character LCD is the ability to display more than text. This feature provides more benefits to the user by displaying visual aids which will make the information easier to understand. These displays tend to be much larger than their counterpart as more space is needed to accurately display the images. The main drawback of using this unit comes down to size, price, and power consumption. Using this for our project will take up a lot more valuable space used for other components and will cost more as well as take up more power than a character LCD. Even though this option is attractive to the consumer, our project is more focused on lower power consumption and cost, so this display does not fit our project’s narrative.

4.12.3 Character LCD

Character LCDs are great for display quick information through text and can be backlighted to use in environments with low lights. One of the smallest formfactor that can be usable in our system is a 16x4 (16 characters by 4 lines) which contains a viewing area of 62 x 26 mm and each character has a size of 2.95 x 4.75 mm. Sizes range from 8x1 to 40x4 to display different characters. If a display is chosen for this project, this is our main choice for the cost and functionality with low power MCUs.

4.12.3.1 Interfacing

Using a character LCD has two modes that can be used to interface with the microcontroller by utilizing a 4-bit or 8-bit mode. All of the character LCDs contain 4-bit and 8-bit parallel interfacing modes. In 4-bit mode, only four data lines are used (D4 to D7). The 8-bit data that is being passed through will divide in half and will be sent using two parts. Using this mode will be slower than 8-bit mode as the data is sent in two parts instead all at once.

With 8 data lines being used, 8-bit mode provides a fast communication between the LCD unit and the microcontroller. Even with this fast communication, the downside is that more pins are used for the LCD unit instead for other functions. 4-bit mode is more common as the LCD units are slow in displaying the characters. The tradeoff of pins and speed will be considered in our project as displaying the information faster is a benefit to the end user.

4.12.3.2 Backlight

The main purpose of implementing the character LCD is for readability on the information gained from the sensors. Displays that contain a backlight are known as a transmissive LCD. Implementing a backlight will help with legibility in certain lighting conditions especially environments with low to no light source. The main drawback presented with this implementation is power consumption, as it is dependent on the size of the transmissive panel and the number of backlights being turned on.

Some colors that these panels use to improve readability are yellow-green, white, or gray. One type of character LCD that does not implement blacklights are reflective display modules. Reflective displays are valuable in bright environments or outdoor areas with a lot of sunlight. This type of display is advantageous for our project, as reflective displays consume less power than displays that are backlit. With a transflective LCD, the display combines technologies used with transmissive and reflective LCDs. Transflective displays are suitable for all lighting environments and are more versatile than its counterparts.

4.12.3.3 LCD Character Size

In choosing the right LCDs to compare, one factor that must be considered is the size and number of characters that can be displayed to the user. One group that can be eliminated are displays with only one row as the project will display more than one data set. Another group that can be limited are ones that only display 8 characters since the data will be abbreviated and hard to read. A 12x2 display may be considered but not ideal for outputting all the information. A 40-character display will be too large for our project and will consume more power. The ideal size will be 16- or 20-character display with 2 or 4 rows to showcase all the data collected by the piezoelectric sensors.

4.12.3.4 Pinout

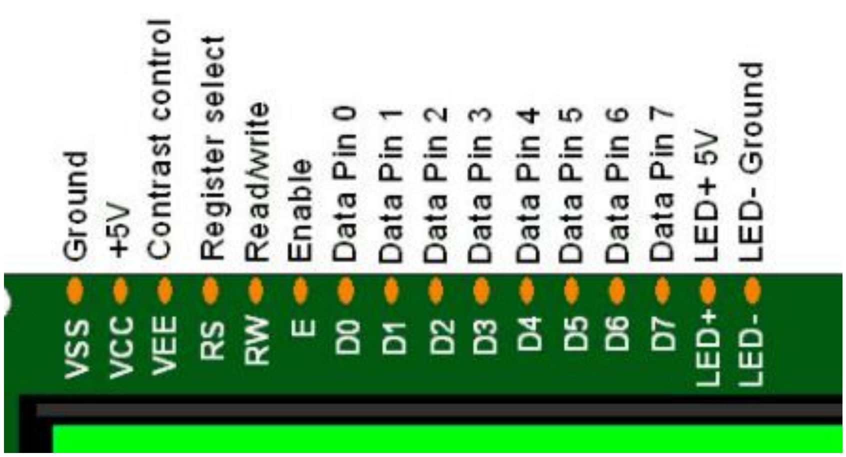


***Figure 7**: LCD Pinout*

As the image above provided by Electronic Wings [22], these character LCDs contain 16 pins in which there are 8 data pins (D0 – D7), 3 control pins (RS, RW, and EN) and 5 pins for the supply and backlight. The first pin VSS is connected to ground while the second pin (VCC) is connected to the power supply of 5 V. VEE is for controlling the contrast and brightness of the display. RS is the register select and lets the microcontroller send data and commands to the LCD.

When RS is set to low, then commands are sent over such as clearing the display. When RS is set to high, then data is sent such as characters being displayed. RW is the Read / Write pin and is usually set to write in order for the information to be placed on the display. E or EN is the enable pin that enables the LCD to process data.

D0 through D7 as mention earlier are the data pins and are used to transmit data to the LCD. As stated in the Interfacing section, all 8 of the pins can be used for a faster output or 4 can be used to save the other 4 pins for other uses. LED+ and LED- (sometimes referred to as A-K for Anode and Cathode) are pins to control the backlight of the LCD. LED+ is connected to the 5 V source while LED- is connected to ground.

4.12.3.5 16x4 Character Transflective Displays Comparison

Note that all the displays contain a character count of 16x4, have 4-bit/8-bit parallel interfacing options, and are transflective displays. The price is for a quantity of one LCD unit.

Manufacturer	Viewing Area	Weight	Color	Cost
DisplayTech	Width: 60 mm Height: 25 mm	29g	Yellow	$13.50
Crystalfontz America	Width: 58.8 mm Height: 31.4 mm	34g	Yellow-Green	$12.93
Focus LCDs	Width: 61.8 mm Height: 25.2	59g	Yellow-Green	$16.22

Table 9: *16x4 Transflective LCD Comparison*

In this comparison, these displays have a common trend as the weight of the unit increases the cost of the component decreases. Our goal is to decrease the weight of the platform as well as lower the cost of the self-funded project. With this tradeoff, the LCD panel by Crystalfontz America provides the most benefits being under $13 dollars while many other units in its size are priced at above it. In comparison with the other two types of displays (reflective and transmissive), most of the measurements are the same except for weight and cost.

The transflective and transmissive displays weigh the same while the reflective display weighs about 10g less than its counterparts because of the absence of a backlit unit. With the absence of this unit, the cost of the reflective display is less than the other models being about a couple dollars cheaper. If our project remained outdoors, the reflective display would be the best unit of choice as the display is readable in areas with a lot of light and has the lowest cost among the three types of displays.

4.12.3.6 20x4 Character Transflective Displays Comparison

Another possible choice for a display would be 20 characters, giving four more characters to output more information to the end user. The 20x4 displays contain more interfacing options than the 16x4 which only contained 4-bit/8-bit parallel interface. The 20x4 has USB, Logic Level Serial, Logic Level Serial Inverted, SPI, I2C, RS232, and 4-bit/8-bit parallel interface. USB, Logic Level Serial, Logic Level Serial Inverted, and RS232 interfaces can be eliminated from our selection since all these displays are above the $50 price point. The only affordable interfaces are SPI, I2C, and 4-bit/8-bit parallel interface which all cost under $20. All of the displays contain a 20x4 character count and are transflective.

Manufacturer	Interface	Viewing Area	Weight	Color	Cost
DisplayTech	4-bit/8-bit parallel	Width: 60 mm Height: 25 mm	50g	Yellow -Green	$15.46
Crystalfontz America	4-bit/8-bit parallel	Width: 60 mm Height: 22 mm	52g	Yellow -Green	$15.90
Newhaven Displays	4-bit/8-bit parallel	Width: 60 mm Height: 28 mm	68g	Yellow -Green	$18.88
RS Components	SPI	Width: 75 mm Height: 25 mm	72 g	White	$17.86
Crystalfontz America	I2C	Width: 77 mm Height: 25.2 mm	73.3g	White	$17.86

Table 10: *20x4 Transflective LCD Comparison*

With the increased character count by four, the prices jump by a couple of dollars for 20x4 displays. The weight and viewing area all increase significantly with most of the panels containing 77 mm by 25.2 mm. The cheapest display cost $15.46 by DisplayTech and contains a small view area of 60 mm by 25 mm.

4.12.3.7 Overview

With the number of options for 16x4 and 20x4 character LCDs, the favorable choice for our project would be Crystalfontz America 16x4 display. The 20x4 display does not merit the extra two to three dollars for a total of an extra 16 characters in our use case. A 20x4 display contains more weight than the 16x4 and the cheapest displays of the 20x4 have the same pinout and interface. There are more inconveniencies when using a 20x4 display as it provides most of the same benefits that a 16x4 display contains. The 16x4 Crystalfontz America display became our final choice as it contains a reasonable priced display for $12.93 while only being 34g and having a 58.8 mm by 31.4 mm viewing display.

Upon further investigation and testing, we would not be able to power the LCD with this setup as the power supply is being used up by the two major components (accelerometer and microcontroller). Our group’s original plan was to develop a second unit that receives the data through a second MCU with an LCD and a receiver. The LCD would display the X, Y, Z axis in each row of the unit in real time as the receiver delivered the information. Instead of pursuing this route since these components would increase our budget, our group instead developed a mobile application to view the accelerometer data. This approach is more versatile, and the application can display more information to the end user. If allocated more time and with an increased budget, we would have developed a unit that would be able to display the accelerometer without the usage of a device such as a smartphone.

5 Design

In this section we will discuss the hardware and software designs that will be used to visualize our design.

5.1 Implementation

This design is meant for implementation on a rollercoaster with no means of powering onboard devices. With that the transducers allows us the flexibility to use these devices to extend the functionality of the coaster. Some of these functionalities include using sensors for analytics to properly maintain and ensure the safety of the coaster. The “unit” should be hard mounted for maximum mechanical vibrations. This ensures that the piezoelectric transducers are experiencing the largest amount of vibrations to convert into electrical energy. While the amount of energy is minimal, the electric energy generated is sufficient in powering all the components needed for this design.

During a single run of the coaster, the piezoelectric transducers are converting mechanical vibrations into electrical energy. Meanwhile, the onboard microcontroller (CPU) is using that energy to distribute power to the sensors that are collecting the analytical data of each run. An Accelerometer will be utilized to record the acceleration, velocity, and position of the coaster at any time of a run. The data collected is immediately stored in memory for later retrieval. The “unit” will not always be running on each and every run, rather every couple of runs to allow if need be the power storage to be charged. After a successful run, the CPU is still running and enables the transmitter to send the data to an offboard receiver which then displays that data on an LCD screen for visual representation.

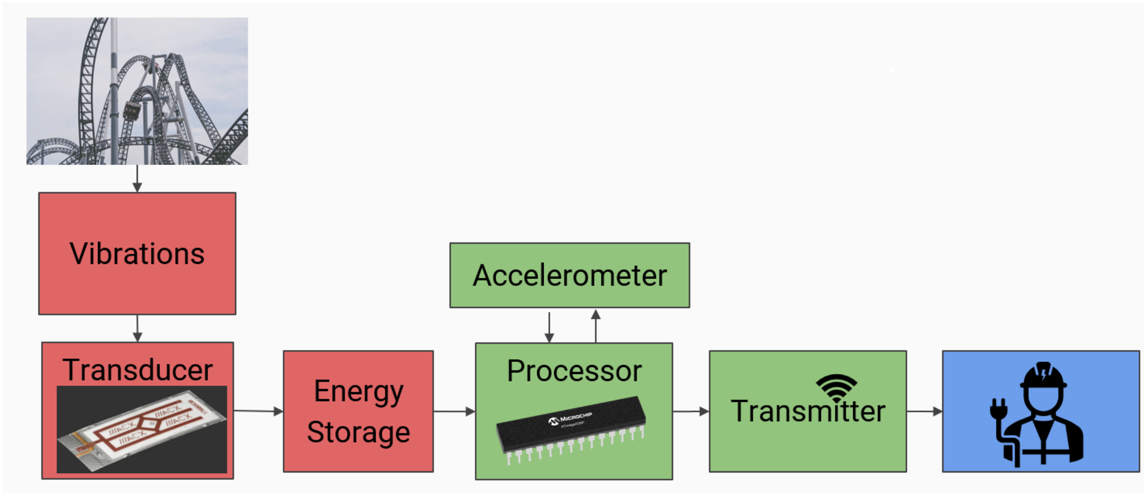


Figure 8: *Overall Design*

5.2 Motivation

The main purpose for this design is to power onboard devices without any source of onboard power. The focus was realized that onboard sources of power tend to be very expensive. This design provides a relatively cost-effective solution utilizing piezoelectric transducers. These transducers produce electrical energy from harnessing mechanical vibrations while aboard a roller coaster cart. The low cost and ease of implementation lead to be a key factor in deciding to choose this design as our project. On the coaster with people the availability of space is very limited, but the inherent size of the transducers is very small. This enables the "unit" to fit in most of the possible locations onboard a coaster.

The overall combined size which includes all of the components was a very attractive design to choose as stated above. Since these sensors are mostly durable, they were the best suited option for this design to be implemented. Moreover, the interchangeability of different sensors used will allow for alternative focuses of data to be collected. This is very important to the overall design, since inevitably this project could be pitched to companies. The ability to have versatility and focus on any analytical data potentially of interest trends well with potential consumers.

5.3 Hardware Design

The "units" hardware design will be both a simple but efficient design that utilizes the many attributes of component selected for the design. (talk about the components selected and how each specifically interacts with one another) As mentioned previously, piezoelectric transducers will either be connected in series or parallel in some kind of array that harnesses the mechanical vibrations. This piezoelectric array will be connected to (may require some sort of amplifier circuit) the electrical energy storage to charge the onboard source of power. In turn this source of energy supplies the required power to operate the remaining components located on the Printed Circuit Board. The CPU will be located on the PCB, along with the sensors that are connected to it via one of the conductive tracks found on the PCB.

The sensors are allocated power via the CPU which sends the data collected back to the CPU for memory allocation. (Probably will use some sort of external memory device that will save data even after the power is turned off, like an SD card for example) The CPU chosen will probably be a single core since multithreading is not necessary to fulfill this design. Simply simulating multitasking should be adequate for the purpose of this design. Supporting this, while on a run the “unit” will only record and store the data in memory. Once a run is completed, the data is read from memory sent to the receiver via the transmitter (most likely via Bluetooth connection since there is no need for a central signal location and inherently cheaper than a WIFI module) and displayed on the LCD for the user to precisely monitor a specific roller coaster.

Below is a list of components that will be discussed in this section and why they were selected to visualize this design:

- Piezoelectric Transducers
- Energy Storage
- PCB
- MCU
- External memory
- Transmitter/Receiver
- LCD Display
- Accelerometer

5.3.1 **Piezoelectric Transducers**

The piezoelectric transducers are optimal for the objectives of this project. Since there are no onboard sources of power for the onboard devices, they will allow for operating all components of the “unit” during a single run. The transducers will be arranged where several are utilized and will more than likely be orientated in a parallel configuration which will produce a higher power. This may be necessary in powering all the components at a single time. Since the unit is utilized onboard a roller coaster and with the inherent mechanical vibrations which is the sole contributor for piezoelectric transducers being selected.

5.3.2 **Energy Storage**

An energy storage device (haven't decided this yet) will be used to storage and provide power to the onboard components. This "battery" will be charged via the piezoelectric transducers as stated above. The charging time will last the duration of a single roller coaster run, providing enough power during and in-between runs. While in-between runs, the "battery" will provide the microcontroller power to send the stored data to the transmitter to transfer the data. The stored power must last the entire duration of the microcontrollers operating time. This time may vary based upon which sensors are being used and how many, due to the amount data collected could vary.

5.3.3 **PCB**

A printed circuit board (PCB) is used to mechanically support and electrically connect electronic components using single traces, tracks, and or conductive pathways etched from one or more layers of copper. The copper sheets are laminated onto or in between a non-conductive substrate layer. Usually the non-conductive layer is composed of fiberglass designated by FR4, where fiberglass is stacked onto one another and fixed with resin to make it into a single unit. PCB are basically a multilayered cake with copper and fiberglass layers that make it up.

In the case for our design, we will create a custom PCB that will fulfill our design. The PCB will be equipped with all of our electronic components. This includes the MCU, piezoelectric transducers, capacitors, resistors etc. The main reason for a custom-made PCB is to decrease the overall cost. If we were to acquire an already built unit, some of the already built in features would not be used which would be wasting space and money. On the other hand, all components connected via the PCB will have a specific use to fulfill our design.

More than likely will use a printed wiring board (PWB), which is a board that only has copper tracks and features and no built-in electronic components such as resistors or capacitors. The reason being is that we are starting from scratch to ensure that we keep cost down and eliminate unnecessary components on the PCB to keep the overall size of the unit down, since we have a limited space complexity.

5.3.4 **MCU**

Microcontroller is an intelligent integrated circuit that consists of a processor unit, memory modules, communication interfaces and peripherals. Generally, an MCU is used across a large range of products and devices such as automobiles, medical equipment, remote controls, robot, drones etc.

The functionality of an MCU goes beyond just performing operations, its ability to interface with communication and peripherals devices are the main functionalities we were looking towards to harness. The MCU in our design will control the accelerometers along with all the other components we include on the PCB. It is the main control unit of design and will realize all of the functionalities we look to implement. The MCU will turn the unit from low power mode while not on a run and will turn it on prior to the coasters run.

Additionally, the MCU will act as the power distribution block where it will distribute power when a component is required to be running. For example, while on a run the accelerometers will require power to record the run data. On the other hand, after completion of a run the MCU will turn off the accelerometers and redistribute power to the transmitter. In doing so to allow the data to be transferred to the end user.

In the prototyping phase, once we have decided on the microcontroller, we will like to utilize we will include the features as to why the MCU benefits our design. Some aspects were considering for a microcontroller to have are a low power mode, sleep mode, fast clock speed, and enough RAM to be able to simulate multitasking.

5.3.5 **External Memory**

When considering the type of memory to select for this design, the memory must be both read and write type memory. This is due to data that will be collected then written to memory and then read from memory to be transmitted to the receiver to be displayed for data analysis. We must ensure that there is not a possible chance for the loss of data form a sudden shut off of the unit. To ensure this some type of external memory will be used possibly in conjunction with RAM since all stored memory is lost on RAM once a shutdown occurs. An SD card is being consider as a potential option for our design to ensure that the data is backed up in the off chance of data loss. Random access memory (RAM) is most likely the best option for the design since, there will be several memory accesses on a single run. The memory must not only be fast, but consistent and having a constant access time with RAM memory allows us to know the approximate amount of time it will take to store all the data within a given run.

5.3.6 **Transmitter/Receiver**

The wireless module sends and receives data signals via two antennas. Data is collected via the sensors on a particular run, stored, then sent to the receiver for data acquisition and analysis. While prototyping, it will be decided whether to utilize a Bluetooth or Wi-Fi module based upon the design’s specifications. For example, the supply of power may be limited so the module that requires a smaller amount of power will be more ideal for practicality of the design. Since cost is an important factor when deciding which components satisfies the design, the more cost-effective module will be chosen. Additionally, space limitation is apparent when trying to have the design located on a roller coaster car, so the smaller module is inherently beneficial to the overall design. This component is integral to the design since, all of the data recorded must be transmitted after a run. The data will be received and stored for the user to determine any changes that must be made. This ensures the safety and integrity of the roller coaster after each and every run.

LCD Display

The LCD display will be implemented for the user's ability to accurately evaluate and assess the data. Simply to display the collected data after a particular run. This gives the operator the ability to properly maintain and ensure the safety of the coaster, while viewing the data. The data is display after the receiver module receives the data from the transmitter. Additionally, the data will be stored off the design unit to ensure a data record exists for proper data analysis.

The LCD screen will be intended to help the end user to view all the transmitted data that the accelerometers collected on a run. The main reason of considering a LCD display is to assist the user and help facilitate the analysis of the data.

The inclusion of this feature has not been decided, but if all factors allow it, we will include an LCD. If not, then we will neglect to integrate an LCD display.

5.3.7 **Accelerometer**

One of the final challenges given in the design of this device was determining a parameter to measure. Given their low current draw and their ability to use physics to their advantage, accelerometers were determined to be beneficial to the design. Accelerometers in the design could be used to determine the speed and vibration of the device and determine the safety means for a person in contact with this device. Considering the device ideally would be used on a rollercoaster, it is imperative that safety comes first with customers. Determining if the vibrations and speed are safe and running properly through accelerometers could potentially save a life.

5.4 Software Design

In this section we will discuss our Software design along with any potential problem and the solution we encounter while building our software.

5.4.1 **Multi-threading and Multitasking**

First let's consider what multitasking and multi-threading are and define them explicitly. Both are used on a multitasking processor, which implies that they are multitasking. Each are completing multiple tasks at the same time, but what is being executed is one of the main differences. Multitasking executes processes while multi-threading executes threads.

For multitasking, several programs or processes are being switched to and executed in real time. Each process has its own address in memory or its own memory area which leads to a time delay when switching between processes to perform multitasking. Another component of this is Context switching, which is the process of storing the state of the process currently being executed. The purpose of this is to ensure that the process can later be return too and restored to its past state to resume execution of that process. While context switching is utilized in both cases, in multitasking the cost and resources needed are expensive.

For multi-threading, several threads are being switched to and executed concurrently in real time. Threads are the smallest unit of processing that can be scheduled by an operating system. Each thread shares the same address space of the process that is a part of. This saves run-time when context switching between threads since its inner-process communication which is faster. Multi-threading can be realized on either a single-core or multi-core CPUs. As mentioned before a single-core CPU can carry multi-threading where context switching occurs often enough to appear as threads are running concurrently. A multi-core CPU could be chosen for the design and if so, threads will actually run at the same time with each core running a particular thread.

Now let's define each case in terms of our design application. For example, a specific process could be data collection from the accelerometers. In this process, the sensors are instructed to start to record data, so turned on. Additionally, this process will inherently include reading and writing to memory. We could visualize each of these tasks as a thread and say we have a single-core CPU. Now were visualizing multi-threading on a single-core where first the write thread is being execute to write all the data from the sensors to memory. Then a context switch will occur within the process to the read thread once a single run is completed. On completion of a run the read thread is executed and all the data is read from memory and sent to the transmitter. This would-be additional thread to execute and turn on the transmitter module.

The approach that is a simpler option would be simulate multitasking using an internal clock of the CPU. Rather than having threads and process to deal with, the processor will deal with a single process at a time. As stated above, context switching will be utilized to switch to another process with the saved state of that process.

5.4.2 **Read-Write Collisions**

First let's consider what Read/Write commands are and explicitly define them separately, then discuss the potential problem these commands may cause us.

We would first create a read function within the microcontroller software. This function will have the capabilities to read all the recorded data from memory and write to the transmitter to send the data after a recorded run. This function should be indicated be a visible LED on the PCB to let the operator know the microcontroller is still running and executing after a run. This function solely reads the data from the memory file and writes to the transmitter.

Additionally, we would have a write function that reads the recorded data from the accelerometer on a run and writes the data to the memory file. Where later the read function reads and transmits the data. The Write function can only augment memory, not read from memory.

Now let's consider the problem of Read/Write collisions. Suppose WRITE (Our Write Function) handles the assignment of reading from the accelerometer and writing to memory. Then the READ (Our Read Function) handles the task of reading from the memory file and writing to the transmitter for data transmission. Assuming the use of a single core CPU, we can't read and write from the memory file at the same time. If we choose to do so, mutexes would need to be implemented as both the read and write functions. As stated above, if the memory file is read and written to, this would create a collision. If we choose the approach of writing to memory then closing the file and reading from memory then closing the file, we would run into the issue of a large amount of opening and closing of the memory file.

If we use a single core CPU the collision problem arises, but our design is a unique scenario where we would implement a design that only writes to memory continuously once and reads from memory the same amount of time. Simply reading and writing should never occur at the same time, since writing to memory occurs on a run and reading from memory occurs after a run. This is to avoid the problem of transmitting data over a large distance. Since the receiver will most likely be located close to the landing platform.

5.4.3 **Sensor Recording Time**

We have to consider the possible scenarios of when we should have the accelerometer record. In the design that we are implementing, there two possible recording approaches. First, there is the approach of allowing the accelerometer to record for the entire duration of a run and the approach of only recording data at specific points of interest during a run. The points of interest will more than likely be specified by the operator so they can more accurately monitor certain aspects of the coaster.

Either scenario there will be adequate data to be used for analysis and maintenance. In the first approach, there will be much more data recorded than the second. This being since the time of recording is larger in the first approach. While implementing the second approach, there would be time intervals that will tell the accelerometer to record and not to record.

In reference to our design, we will implement the second approach since the time of recording should be small enough where the size of data recorded is a manageable size to analyze.

5.4.4 **Accelerometer Initialization**

The accelerometer initialization process will assign the accelerometer to the correct pin assignment on the Arduino microcontroller board. The pins have to be set prior to attempting to utilize the accelerometer for recording data. The pins are assigned individually and are given separate variables for programming utilization. For instance, the power and ground pins must be assigned to enable the algorithm to have the capabilities to start and stop recording data by simply turning off the power to the power pin of the accelerometer component.

Once the pins have been assigned, the process will enable the accelerometers to begin recording. As of now, the process has not defined the duration of permitted recording time. Although, the time for recording will reflect the amount of time a particular coaster ride lasts for. So, the design will have the capability to adapt to the coaster it has been fitted too. For the purpose of designing the initialization of the accelerometer we ignore the duration for permitted recording time and focus on when to start and stop recording.

As stated previously, the process will set the pins of the accelerometer, but also will control when the to start and stop recording data, and how to store the data as well. One option to implement to start recording is to have a technician manually start the unit to being recording. There are several drawbacks with this approach, the first of which is that now there is a lack of automation. This leads to an increased amount of money and resources that must be allocated to keep the system up and running continuously after each and every run. Another option for implementation is to have the process complete this task.

The approach for this would involve the accelerometer having a live sensor value to pick up when the coaster begins to accelerate. One approach is to have the process monitor for a change in acceleration to begin the recording segment. An example for implementation could involve a while loop, to where the accelerometer will not record until a certain acceleration value is met. This scenario will ensure that the only data being recorded is on a coaster run. Additionally, this approach ensures the quality of the data, since the user will want to focus on actual data from a ride and not data while not in motion. Below is a representation of how the initialization process should function.

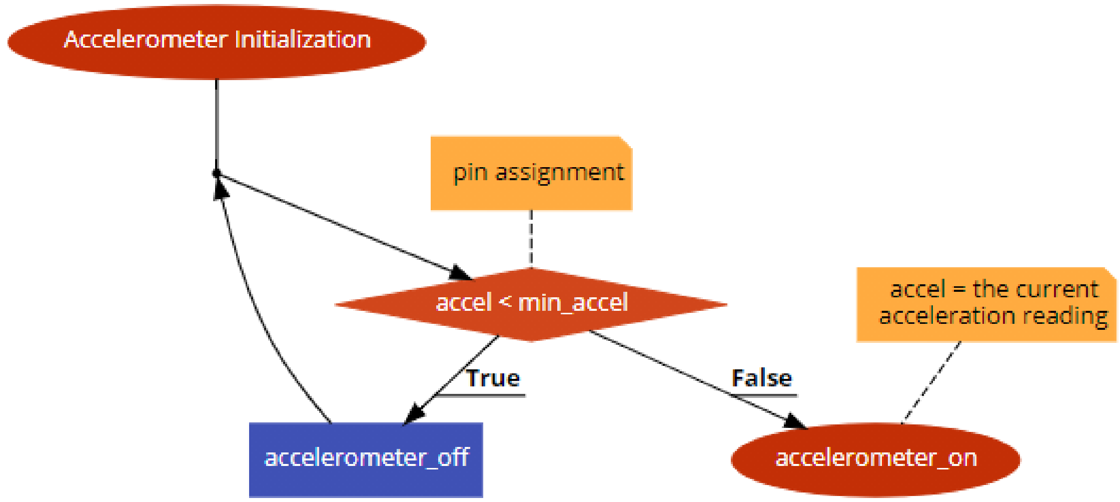


***Figure 9**: Accelerometer Initialization algorithm flow*

5.4.5 **Velocity Conversion**

The velocity conversion function will take the acceleration found by the accelerometer and convert that into the velocity of the coaster. The functions only input parameter will be an acceleration value. This function will be called in a loop to ensure that every acceleration value is converted and then stored with its accompanying velocity value. The function will take the integral of acceleration over a specific time and the resulting value is the change in velocity.

5.4.6 **Position Conversion**

The position conversion function will take the acceleration found by the accelerometer and convert that into the position of the coaster. The functions only input parameter will be an acceleration value. This function will be called in a loop to ensure that every acceleration value is converted and then stored with its accompanying position and velocity value. The function will take the integral of acceleration over a specific time twice and the resulting value is the change in velocity. We could use the velocity value we found previously, but the method choose avoids any rounding of the required value until after the conversion.

5.4.7 **Logging Data**

In this section, we will discuss the recording of data, consider the complexity of recording too much data, and how we will handle this data.

So, our design comes with a large amount of data recording. The whole premise behind the design is to record and acquire data. On a single run, during the duration of the run, there will be a large amount of data recorded and then must be stored. When considering the amount of data being recording, we must consider the duration of a single run. On average a modern roller coaster lasts several minutes. Suppose in that allotted three minutes, how often does the acceleration forces change. We can assume the acceleration forces are constantly changing resulting in the accelerometer read and measuring those changes.

We must be able to with the software design quickly take the recorded data and write to memory to store it for later transmission. As of now we do not know the amount of potential data that we are needing to store, but there is room for change by just implementing more external storage. Additionally, there's a scenario where we are recording and writing to memory often. This may result in the MCU being overwhelmed. In order to avoid this scenario, we may look to take the average of the acceleration forces in the duration of a single run or even smaller times within a given time to avoid over recording. With doing so the average would still give a good indication of what and how a given coaster is performing at any given moment of a run.

Since, with our design the are to disguised periods of operation, a recording period which occurs while the coaster is operating and a transmitting period which occurs after a run where the MCU is reading from memory to transmit the data. These very distinct operation periods allow us the flexibility to ignore the complexity of writing and reading form memory at the same time and simply just doing one after the other.

Once the accelerometer begins to measure the acceleration forces, the MCU will write the changes in forces to memory. This process will be completed by the software.

5.5 Simulation Software

In this section we will discuss the potential simulation software's that we could use to design and implement circuit designs.

5.5.1 **Multisim**

Multisim is an electronic schematic and simulation program that integrates SPICE (Simulation Program with Integrated Circuit Emphasis) Simulation with an interactive schematic environment that helps the user to visualize and analyze electronic circuit behavior. In addition to SPICE simulation, Multisim allows the user to quickly iterate through PCB designs and improve their prototypes performance. The use of Multisim software reduces the number of PCB prototype iterations that will be needed to complete the design, along with the overall cost being reduced from the small of prototype iterations.

Some of the key features of Multisim include reducing design time with fast schematic capture through quickly building, analyzing and iterating on circuit designs with 30 manufacturer verified benchtop instruments. As stated above, another key feature includes reducing prototype iterations with 20 easy to configure analyses that identify the limits and inefficiencies of the design. Another feature is the ability to rapidly move from design and circuit simulation to PCB prototyping and back to edit and verify all design implementations using Ultiboard. Multisim is such an expansive software that the features included are almost limitless.

Unlike LTspice, Multisim is not limited to analog circuits, rather Multisim can design and simulate analog, digital, and power electronics. LTspice is generally limited to components the LT manufactures, while Multisim includes most electronic components.

5.5.2 **LTspice**

LTspice is a SPICE simulation software that allows the user to capture circuit schematics and analyze waveforms with enhancements and models for easy simulation of analog circuits. LTspice is a computer software program that was produced by semiconductor manufacturer Analog Devices. LTspice is the most widely used and distributed SPICE software in the professional industry.

Some of the advantages of using LTspice include fast simulation especially for switching mode power supplies. Another advantage is that there is a stable SPICE circuit simulator, along with an extensive library of schematic and symbols editor. The easy to use waveform viewer allows the user a simple way of analyzing the data. Additionally, another feature includes the library of passive devices that has a plethora of designs and with LTspice the simplicity of usability allows the user to start simulating very quickly.

The free to download feature is extremely useful in a budget limiting setting. LTspice saves the designer money by eliminating the need for buying and testing components. The key analysis in circuit design like DC, AC and frequency response etc. are all much simpler to analyze. The feature where you are viewing the waveform allows you to still interact with the circuit and input probes in the circuit to focus on a specific aspect of the circuit.

5.5.3 **PSpice**

PSpice is a SPICE circuit simulation software that allows the user to simulate and verify values for analog and mixed signaled circuits. PSpice stands for Personal

Simulation Program with Integrated Circuit Emphasis. PSpice helps user to find and fix circuit design issues while simulating the circuit to prevent any design issues before they go into manufacturing. With the innate power that PSpice provides, the designer is able to be confident in the design without any precautions to issues with the design.

PSpice ensures the reliability of the users' circuit since the user can simulate every possible combination of components within the circuit. This helps the user identify the characteristics of the circuit to determine whether that matches the needs the user need for their circuit design. Additionally, you can simulate these same circuit design changing operating temperatures to determine the characteristics of the circuit at varying temperatures. The power of a circuit simulation software is the ability to have unlimited prototypes and versions of a circuit design. This also highlights the point that there is no need to buy any components for testing and only purchase the components the visualize the last rendition of the circuit design. Furthermore, the overall cost of the components is dragged down and results a lower cost to build the circuit design. The lack of design issues that PSpice helps facilitate, leads to increased manufacturing yields, fewer prototypes, and finally a reduced cost to produce the design. The ability to test for any scenario is the greatest benefit when using circuit simulation software.

Simulation Software's	**Multisim**	**LTspice**	**PSpice**
Application	Analog and Mixed signaled Circuits	Analog Circuits	Analog and Mixed signaled Circuits
PCB Design	Ultiboard is a PCB layout software integrated within Multisim	Only capable of SPICE simulations and designs	Only capable of SPICE simulations and designs
Testing Design Tools	30 manufactured verified benchtop instruments	several design tools for full scale simulation	Design and analysis tools for schematic and simulations
Applicable Components	Most electronic components	Focuses on manufactured LT components	General components integrated in libraries
Accessibility	$662.00/year for the Education Editions and a free trial for students	Free to use and download	Free trial with active students and must request a quote for accessibility

Table 11: *Simulation Software Comparison*

5.5.4 **Summary on Simulation Software**

With all the varying circuit design simulation software's, the differences between each is somewhat negligible, and each software helps the designer to design and test their circuit. Each of the above stated SPICE software focuses on different types of circuits. Multisim is an exception and covers all of the potential circuit design. While LTspice focuses on analog circuits and PSpice on analog and mixed signaled circuits.

These circuit simulation software's provide us with a wide range of applications. From the comparison chart above, the similarities and differences are easy to see. The key takeaway from the chart is the accessibility of each simulation software, LTspice is the only exclusive free to use software, while both Multisim and PSpice provide a free trial to students. Along with the application of each software. While designing, we will be visualizing both an analog circuit for energy harvesting power supply and a mixed signaled circuit for our sensory unit. This will inherently cause us to choose a software that can design both types of circuits or use two different software's to completely visualize the design.

While each SPICE simulation software that has been mentioned above is quite capable to fulfill our need in designing and testing our circuit design. We will choose the software that best suits our needs. Once our needs are identified, the software that fulfills those need will be selected. As of now we have not done so.

5.6 Integrated Development Environment (IDE) Software

In this section we will discuss the potential IDE software's that we could utilize based upon which Microcontroller unit we select to fulfill our design.

5.6.1 **Arduino**

Arduino IDE is a cross-platform application that is used to write, edit, build executables, and debugging of code. This combination of activities helps with increasing our productivity from the ease of use and the cross-platform is a plus.
Some of the advantages of the Arduino IDE include a varying board module option. This in essence is that the IDE gives us the ability to choose any of the available microcontroller units that are supported by Arduino. This is further supported by third-party hardware suppliers that ensures that the IDE is not limited to proprietary boards that Arduino manufacture.

Another major feature that is incorporated within the Arduino IDE is the hundreds of integrated libraries. These libraries help us with integrating different hardware components. For instance, SD, which is the libraries for reading and writing to SD cards. As discussed in the Hardware section, SD cards are being considered as a storage device for its usability and functionality. Another key library is CurieTimerOne, which gives us access to Timer functions, where we could implement if we need to have a function execute in a certain amount of time. If not the function being execute will be stopped and basically time out.

Additionally, the Serial Monitor feature within the IDE acts as its own window. This separate terminal which helps the user to identify and debug the written code within the module. Once a program is compiled, the output screen will clearly display the errors that have to be addressed in order to reupload the hex file to the MCU.

The ability to use AVRDude is an integral feature that can be utilized to program the Arduino boards flash memory. The program is used for downloading and uploading the on-chip memories of AVR compatible microcontrollers. AVRDude can be used effectively on the command line to read and write to all types of memory located on the Arduino microcontroller. The IDE converts the executable code into a text file in hexadecimal than that is uploaded to flash the Arduino board to execute our code.

These MCUs are commonly found within Arduino preassembled boards and are based on an advanced RISC architecture. The RISC architecture has many benefits that could be provided by it, as such these include that RISC is designed to execute computing tasks in the shortest amount of time. This an essential aspect, since we are not only limited to time to send the recorded data to the end user post run, but also are limited in power so the smaller amount of run time is ideal for our application. This is so since the amount of time in between runs is small. This feature of the low power board benefits our design due to the small amount of time to compute the necessary amount of instructions needed to transmit the sensor recorded data from the prior run. The IDE allows us the ability to manage where and how the memory handles the read and write instructions.

5.6.2 **TI Code Composer Studio**

TI Code Composer Studio is an integrated development environment that supports TI's microcontroller and embedded processors. The software includes a C/C++ compiler, source code editor, and debugger and many other features.

Some of these features include a simple mode which is a trimmed down version of the IDE that limits the number of functionalities by just displaying the essential ones. Once a user is familiarized with the interface, they can switch back to the standard mode to display the more advanced functionalities.

Another feature of Code Composer is that the IDE has built in functions for MSP boards. These boards are being considered and have low power consumption which is ideal for our design application. Furthermore, this IDE has compliers optimized for MSP430 board to increase the performance of the software prior to being flash to the board itself.

A very unique feature within Code Composer is that the IDE has a low power advisor called ULP. The essence of the advisor is to optimize our code, so that it saves every little bit of power. In our design that could be essential since we are potentially limited in the amount of power we can generate. There are built in hardware debugging functions that allow the user the ability to monitor certain situation that could arise. For instance, in our application we will have a large amount of executed instructions that are asking to store data in the memory, which could lead to a stack overfill situation. The IDE includes a easy solution which is a break statement, which causes the program to break from its current executed instruction.

TI Code Composer Studio has a vast amount of resources that the user can utilize. A large selection of devices that the IDE supports enables the us the flexibility in choosing the appropriate MCU for our design.

5.6.3 **MPLAB**

MPLAB IDE is an integrated development environment that supports Microchip's microcontrollers, microprocessors, and digital signal controllers through enabling the user to configure, design, debug, and verify embedded designs.

Some of these features include a real-time Data visualizer that enables the user to be able to see the recorded data being recorded to accurately determine if the microcontroller is operating as intended. An additional feature that is beneficial to the development process is the ability to view I/O pins with the intention of verifying and manipulating the pins to correct any errors in assigning of pins.

Another feature of MPLAB is that there is the capability to easily define register and certain bits. This is very important when coding the microcontroller so that this ensures that the registers are not used multiple times. Furthermore, the main function for this feature is to make the production of programming more efficient and precise.

A very key feature within MPLAB, is the MPLAB Harmony. Which is a fully integrated embedded software development application that reduces development and production time through the use of a completely integrated library whose modules are interchangeable. For instance, there are several modules for peripherals that easy the implementation process for already written modules as mentioned before. The idea is to have the product reach the production phase as completely as possible. In the case of our design, the capability to implement Bluetooth module, accelerometer and USB rather seamlessly is quite an attractive option when selecting which MCU to utilize.

MPLAB IDE offers the user a selection on which debugger best fits their project. There are several different options for a varying of applications. For instance, MPLAB ICD 4 is the most robust debugger, but does not support AVR microcontrollers. This helps the user to have a debugger tailored to enhance the development and implementation of the programming software.

MPLAB IDE has an extensive library of supported peripherals that the user can utilize. A large application basis that covers multiple product manufactures that include Microchip and AVR. This gives us the freedom in selecting our microcontroller programming software.

IDE Software's	**Arduino**	**TI Code Composer Studio**	**MPLAB**
Application	AVR microcontrollers	TI microcontrollers	Microchip and AVR microcontrollers
Low Power Optimizer	RISC style architecture help with low power management	ULP is a low power advisor	Low voltage programming is a built-in option
Debugger	Unique Serial monitor clearly displays errors within code after execution	Specialized debugger for hardware components	Three separate debuggers for different applications
Peripherals	Provides hundreds of integrated libraries for hardware	Rather large library of varying MCU's and hardware components	MPLAB Harmony for easy to use integration libraries
Accessibility	Free to use and download	Free to use and download	Free to use and download

Table 12: *IDE Software Comparison*

5.6.4 **Summary on IDE Software**

With all the varying IDE design software's, the differences between each is somewhat negligible, and each software helps the designer to design and edit their source code. The main difference between the IDE's discussed above is that each software is optimized for a specific series of microcontroller unit. For Arduino, its Arduino boards, for TI Code Composer Studio its TI manufactured microcontrollers, and for MPLAB its Microchip and AVR microcontrollers.

Each has its more important features which are stated above, but for each the ease of use is ideal for any application. Additionally, from the comparison chart above, the similarities and differences are almost negligible where each IDE has an option for any potential problem. Our main inherent problem that we are looking to solve, is the lack of potential power.

While each IDE design software that has been mentioned above is quite capable to fulfill our need in designing and testing our circuit design. We must first identify the microcontroller that will fulfill all of our needs. We've selected ATMEGA328P, which is used in Arduino Uno products. When selecting the microcontroller that is best suited for our design, the main topic of conversation was the need to consume the smallest amount of power. From the researched microcontrollers found within the Research section, ATMEGA328P was found to consume the smallest amount of power. This is extremely important since the amount of available power is unknown as this point in time. Taking this in to account we are preparing for the worst-case scenario of a small power supply.

5.7 Printed Circuit Board (PCB) Design Software

In this section we will discuss the potential PCB design software's that we could utilize based upon which software best suits our needs to fulfill our design.

5.7.1 **Eagle**

Eagle is an electronic design automation software that allows printed circuit board designers to connect schematic diagrams, component placement, PCB routing, and a vast library of electronic components with their accompanying schematics. This allows the user to easy implement new components seamlessly and easy by simply looking up the part by application or part number.

The main attraction to using Eagle is the PCB layout software that has schematic editing tools and a vast array of features. The features include a schematic editor, which includes a SPICE simulator, Modular design blocks, and electronic rule checking. The SPICE simulator as stated above, tests and verifies circuit performance. Modular design blocks enable the user the ability to reuse design blocks that are paired with synchronized schematic and PCB circuitry. And the electronic rule checking function finds any errors and misplaced wires within the schematic that are in need of correcting.

The next feature that Eagle includes is the PCB layout editor. The editor has real time changes that sync automatically between the schematic and the PCB layout to enable for fast design process. While editing the PCB layout, there are multiple alignment tools that will help in arranging the order of different components apart the schematic. A unique tool found within the editor is that you can route multiple traces by pushing and shoving them. This includes the scenario where there is an electronic component that multiple traces must go around without touching one another.

An additional feature that Eagle offers is automatic obstacle avoidance routing that when a user is drawing a trace it will automatically go around any object obstructing the trace from reaching its destination. Convenient tools like cornering are super useful to have an efficient time routing and editing the traces within the PCB design. As stated above, design rule checking is an extremely powerful tool that not only enables the user to completely customize the rules and constraints of the PCB, but also help in avoiding any errors that could arise when not doing so.

3D PCB models is an extremely important feature of Eagle that we are considering. The 3D models show the user the exact dimensions and specs of the PCB after completion of the PCB layout design. On top of that all included electronic components have their own unique footprint, symbol, 3D model, and parametric. The values associated with a specific component help the user in determining whether the component will work for the design.

5.7.2 **KiCad EDA**

KiCad is a free software designed for electronic design automation (EDA). This program facilitates the design of schematics for capture, a PCB layout designer that is directly translated from the schematic, and a 3D viewer which helps the user visualize the PCB layout with a 3D rendition of the design.

The schematic capture feature is highly efficient and allows the user to focus on the design, while the interface helps to increase productivity in the design process. All of the editing tools that exist are available within KiCad. These tools allow the user to edit in a number of facets, for instance, you can drag any components while the traces are still connected to the components. In doing so the traces remain connected and are move to mirror the change in location of the electronic component. Another neat feature is the ability to have a very large design without any restrictions. Enabling the user to completely visualize their design. In the case of our design we will have relatively large design so the ability of not needing to have multiple subsheets is important. The option of having multiple subsheets can be used to decrease the overall design size of the schematic.

The electrical rules check, similar to Eagle, allows the user to automatically verify the schematic connections. In addition to checking the pins for any conflicts, unconnected pins, and any missing component drivers apart of the schematic. The electronic rules checker allows the user to specify any errors that user wants to output when having two pins connected. For instance, let’s have any bidirectional pin produce an error if is connected to the output. In this case if the user connects any bidirectional pin to the output pin the checker will produce an error automatically. This functionality is extremely useful when the user is aware of certain errors they are trying to prevent.

The bill of materials features allows the user to export the BOM as a file that includes all the values of each component that is included in the PCB design. The manufacturer, the value, and specs of every component are some of the substance of the BOM. Finally, the integrated libraries similar to Eagle, are always being changed and updated, so the libraries are always improving and adding new components to be selected from.

The PCB layout functionalities in essence are the same to Eagle. A key feature is the push and shove router which allows the user to push any group of traces to divert around an obstruction within the PCB design. Even if the traces are obstructed by another electronic component, the traces will be rerouted. Through the editing of traces to decrease the overall length of a trace, enables the design to have a faster response and processing time due to the small trace lengths.

5.7.3 **DesignSpark PCB**

DesignSpark PCB is a free electronic design automation software used for printed circuit board and schematic designs. Within a particular design project, the project can have an unlimited number of schematic sheets. This helps the user in organizing the schematic, while also allowing for the size of each sheet to remain relatively small for easy and concise schematic design.

Like the previous PCB design software's, DesignSpark PCB includes a schematic capture feature. The feature allows for the user to draw and design a circuit that includes imported components that are needed to fulfill the design. The components can be rearranged and the connected are made to other pins of components. Like Eagle and KiCad, DesignSpark allows the user to split up the schematic design into individual sheets. Similarly, there is no schematic size limitation or limit on the amount of individual sheet, practically allowing the user to design a limitless PCB design.

Similarly, to the schematic capture feature, DesignSpark PCB allows for an unlimited number of nodes and pads. This flexibility really allows the user to focus on the design of the PCB layout. There are certain drawbacks which include that the PCB layout may result in an inefficient design due to its sheer size. If a PCB layout design is optimized and concise, the overall efficiency of the design will go up as well.

Another feature that is shared among the PCB design software's include an autorouter feature. This routes the traces automatically between components on the PCB layout. This will decrease the overall design time of the PCB layout design, but may lead to some error of wires crossing or overlapping. Though this is an inherent issue, it is easily fixed by rerouting the overlapping traces and the job is done.

DesignSpark PCB is a great option for any user looking to design a PCB layout. With the software being free is added bonus and it easy to use interface. The lack of familiarity with this software will more than likely cause us not to select it for use in facilitating the PCB design process.

PCB Design Software's	**Eagle**	**KiCad EDA**	**DesignSpark PCB**
Application	EDA software for PCB's	EDA software for PCB's	EDA software for PCB's
Schematic Capture	Includes a SPICE simulator to verify circuit performance	Allows for components to be dragged while still connected	Includes imported components to draw and design circuit
PCB Layout editor	Has real time changes, along with a push and shove router	Similar to Eagle, there is a push and shove feature	Highly capable editor with unlimited nodes and pads
Libraries	One such is a 3D modeling of the PCB's	Built in electrical rules checker defined by the user	Has the ability to import components on top of existing libraries
Accessibility	$100.00/year for Eagle Standard and a free version	Free to use and download	Free to use and download

Table 13: *PCB Design Software Comparison*

5.7.4 **Summary on PCB Design Software**

With all the varying PCB design software's, the differences between each is somewhat negligible, and each software helps the designer to design and visualize their PCB design. The similarities between the software's are obvious since all PCB design software's are electronic design automation (EDA) software's. These types of software's are to help design schematics, PCB's, and to be to have a 3D viewing tool for every design.

Shown above in the PCB Design Software Comparison table are the similarities and the few differences between the software's. In that case what it comes down to is accessibility. We are considering all the discussed EDA's, but cost will ultimately be a factor in selecting a PCB design software to utilize. That being said KiCad is a free to use platform, while Eagle requires a subscription to access. Like KiCad, DesignSpark PCB is a free to use software that enables users to capture schematics, edit PCB designs, and view the design in a 3D viewer.

When deciding which PCB design software to use, accessibility and familiarity are the biggest factor is deciding which software to use. Each software will enable us to fulfill our design with designing and testing our PCB layout. The more plausible software that we would select will be Eagle, since we all have past experience.

5.8 Build, Prototype, Test, and Evaluation

The prototyping of this project was implemented in three phases, each with their own unique problems and complications. The first phase was focused on the power supply of the system. Experiments were be constructed to ensure a maximal conversion of energy from the mechanical vibrations to chemical energy (energy stored within a battery/capacitor).

A few of the key focuses of this phase were size, efficiency, and optimal resonant frequencies. All these topics were explored while maintaining the governing budget constraints. The second phase developed the system that maintains peripheral sensors and data acquisition. This phase includes the components such as the processing unit(s), peripheral sensors, printed circuit boards, user interface components, and data transmitters.

While both Phase I and Phase II were executed simultaneously, it is important to note that Phase II is heavily limited by the amount of power that Phase I can provide. Solutions to this predicament are also discussed in later sections. Phase III focused on combining the systems developed during Phase I and II. During Phase I, the power supply was designed to meet to the requirements of the unit developed in Phase II, and in Phase II the unit was designed to use as little power as possible as to easily be operated by the power supply developed in Phase I. These parallel dependencies required large amount of communication between both parties responsible for the first two phases.

5.8.1 **Prototyping: Phase I, Energy Harvesting Power Supply**

This phase focuses on the harvesting of the energy from the mechanical vibrations, rectifying the voltages produced from the transducers, and storing the energy. According to Wahied and Nagib, there are nine key blocks to consider in the design process of a piezoelectric energy harvesting system. All of the following are based on the design requirements set by Wahied and Nagib [10]:

5.8.1.1 Piezoelectric Energy Harvesting System Standard Functional Blocks [10]

1. **Vibration Source**

The best environment for implementing a piezoelectric energy harvesting system is one that provides varying amplitudes and frequencies of energy in the form of vibrations. This block is fulfilled by the environment selected; on board a roller coaster.

2. **Energy Harvesting Transducer**

This transducer will convert the energy provided by the vibration source into a useful electric form. This block is fulfilled by the piezoelectric transducer component.

3. **Accelerometer**

This block is optional yet provides a measurement of the vibration source. This measurement can be used to calculate the resonant frequency and damping. Note that accelerometers are already in the overall design of the project and can likely be used for more than one function.

4. **Frequency Tuning Actuator**

Another optional block, this may be used to tune the generator. This tuning can match the resonant frequency of the harvesting transducer with the vibration source, maximizing energy captured by the harvester.

5. **Power Processing Interface**

This block refers to a circuit that enables optimal energy extraction from the transducers.

6. **Electrical Energy Storage**

This block is a requirement. Wahied and Nagib [10] describe this energy storage device as a device with the ability “to cope with intermittency of generation and consumption.” This storage device can easily be a super-capacitor or a rechargeable battery.

7. **Voltage Regulation**

This block is a requirement. The electrical energy storing component will have a varying voltage due to fluctuations in power generation and power usage. The voltage will also need to be regulated to effectively power the devices of this project.

8. Computational Load

This block represents Phase II; the processing unit. This unit is simply powered by the energy harvesting system. It does have the option to throttle the performance demand by communicating with the harvester control.

9. Harvester Control

The harvester control block consists of circuitry that calculates the necessary damping and resonant frequency, sending that information to the power processing interface and the frequency tuning actuator to actively fine tune the generation of power.

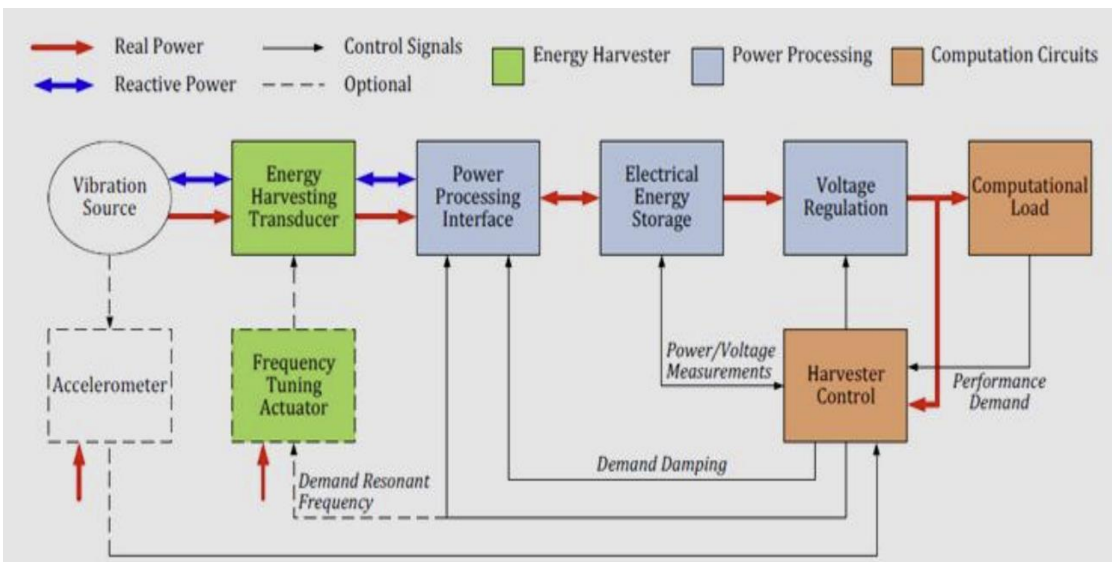


Figure 10: *Block Diagram [10]*

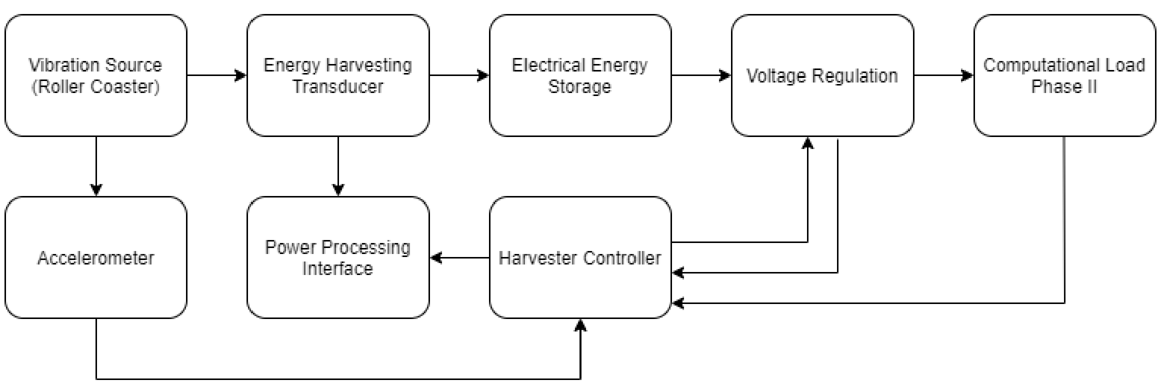


Figure 11: *Simplified Block Diagram, Developed in reference to [10]*

All the design blocks discussed by Wahied and Nagib [10] were explored. While some of the blocks are not requirements, they are valuable as they will allow the system to be more efficient overall. The limiting factors on exploring these useful blocks are budgetary and size-related constraints.

5.8.1.2 Transducer Design

Roller coasters tend to have a large array of vibrations and jerky-motions. This results in an abundance of different frequencies, likely allowing the designers to select multiple desirable resonant frequencies for the transducers purchased. Multiple resonant frequencies can be explored with different sized crystals, different kinds of crystals, and are highly component-based.

While piezoelectric transducers can create large differences in voltage when placed in series, a design where numerous transducers (each possibly having different resonant frequencies) are placed in parallel can be implemented. This design allows for more power generation across fewer terminals. Additionally, the voltage variance across the terminals of the Energy Harvesting Transducer block would be much greater when the transducers are placed in series. This is not a desirable case and promotes an even greater need for a voltage regulator.

5.8.1.3 Coaster Simulation

In order to select transducer components with appropriate resonant frequencies, a vehicle or simulation of a vehicle is required to provide vibrations for study. While receiving data from roller coasters directly would be ideal, there are numerous other opportunities for vibrating environments. Air conditioning units, off road vehicles, kitchen blenders, drying machines, water borne vehicles, and many other easily accessible environments are options during the prototyping phases. All of these environments can aid in testing the energy capturing properties of Phase I. Additionally, the completed project can further provide itself more information about how its own design could be improved. Accelerometers are part of the design for data collection regarding the coaster, but that same data can provide information of the vibrations of the coaster for the purpose of selecting more appropriate transducer resonant frequencies.

5.8.1.4 Morphological Analysis

According to Gharieb and Nagib [10],

> “Morphological analysis is an effective creative thinking technique in the design process. Its procedure involves analyzing the problem to identify the primary parameters which are involved and then to consider alternative solutions to achieve the required results.”

Gharieb and Nagib further describe the primary parameters involved when designing an such an energy harvesting system. These primary parameters considered within their research are:

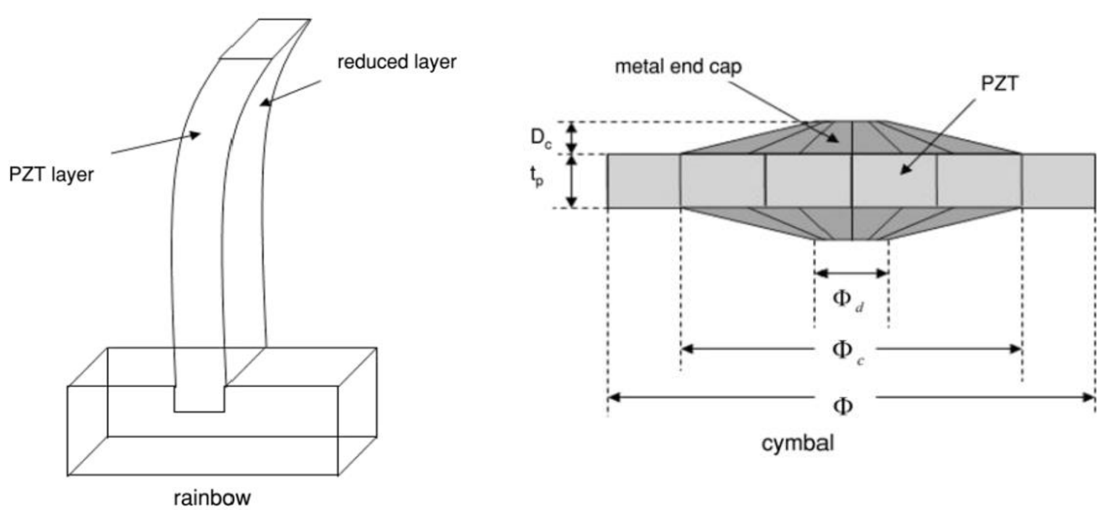
1. **Material selection**

The selection of material heavily impacts the performance of the energy harvesting design. Different piezoelectric crystals, models, and brands should be considered during the overall design. While capturing the energy from the vibrations can be fine-tuned with concepts such as rectification, the leading constraint is the conversion of vibration energy into the electric potential within the piezoelectric transducer. This argument is further categorized into the fundamentals of power harvesting with piezoelectric crystals. Sodano separates the two important fundamentals as the following domains; “the first is the direct piezoelectric effect that describes the material’s ability to transform mechanical strain into electrical charge, the second form is the converse effect, which is the ability to convert an applied electrical potential into mechanical strain energy.” [84]

For this project, the direct piezoelectric effect is under consideration, as it is responsible for the sensory and energy harvesting characteristics of piezoelectric transducers. Therefore, materials and components will be determined specifically by their ability to convert vibration into electric potential (direct piezoelectric effect), whereas the converse effect is unnecessary and will not be implemented within the energy harvesting portion of this design.

2. **Geometry and Structure**

Piezoelectric transducers come in many shapes and sizes. The most common piezoelectric structures are unimorphs, bimorphs, multilayered stacks, rainbows, s-morphs, moonies, and cymbals.



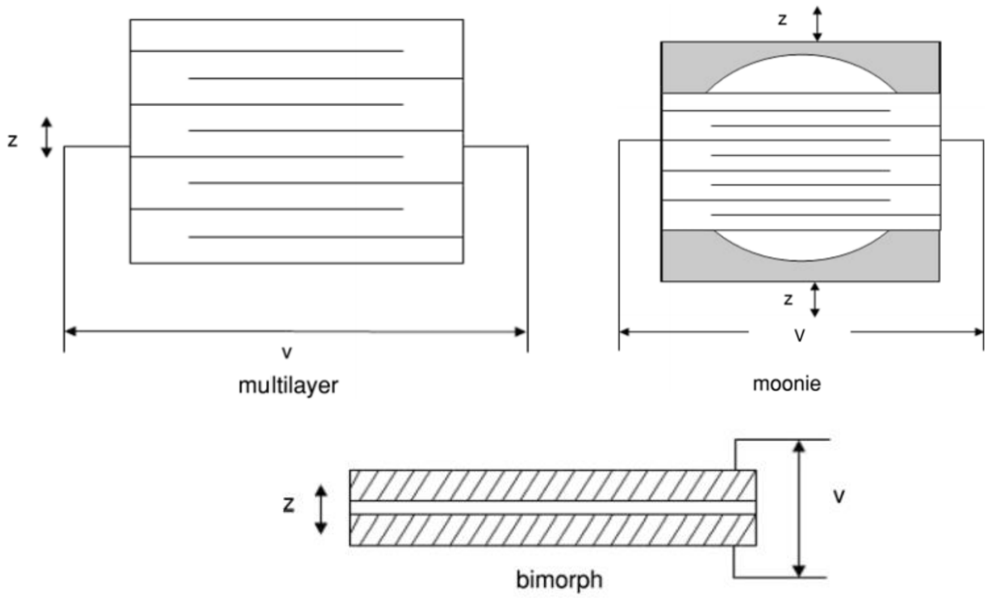


Figure* 12*: *Different Morphologies of Piezoelectric Transducer [85]*

While there are many options regarding overall shape and design of the piezoelectric transducer, each with respective advantages and disadvantages, the structure utilized in this design is a bimorph. Bimorphs are considered to be one of the easiest and cheapest to fabricate, resulting in a cheaper component to purchase. As the piezoelectric transducer can easily be the most expensive part of this project, selecting the bimorph further meets our budgetary constraints. Additionally, PZT (Lead Zirconate Titanate) bimorphs are considered to be more effective in random vibration environments. [10].

3. Loading Modes

There are two notable loading modes for the bimorph geometry, the 31-mode and the 33-mode. As shown in figure below, the modes refer to the direction that the voltages and stresses act. The first number in the mode description describes the axis of action for the difference in voltage. In both figure (a) and (b) the voltage is acting in the “3” axis, hence the first number in both modes are represented as 3. The second number in the mode description refers to axis of action for the force applied to the piezoelectric transducer. In figure (a) the arrows are expressing an applied force in the “1” axis. In figure (b) the arrows are expressing an applied force in the “3” axis. Hence, the mode for figure (a) is mode-31, and the mode for figure (b) is mode-33.

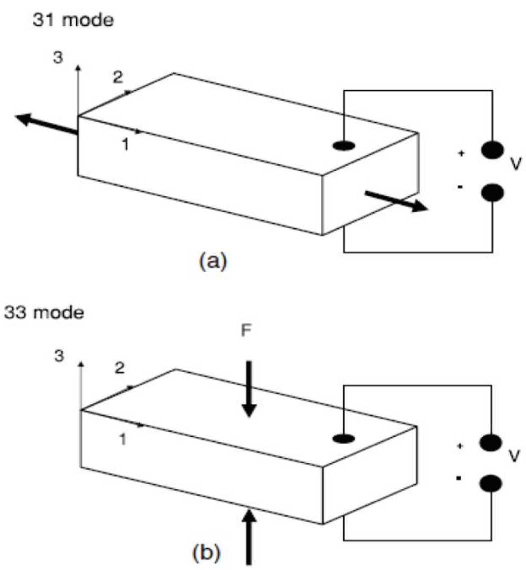


Figure 13: Loading Modes

The coupling factor of the 33-mode is generally higher than that of the 31-mode setup, therefore harvesting more energy. [10] However, when the device is very small and exposed to a very low vibration source, the 31-mode can be a better design choice. This is not the case for this application. Therefore, a 33-mode, where both the voltage and forces act along the same axis will be implemented for maximal energy harvesting.

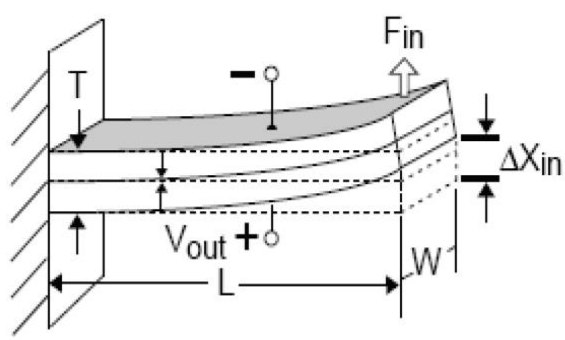


Figure 14: Cantilever 33-MODE Bimorph

4. Electrical connection, parallel and series

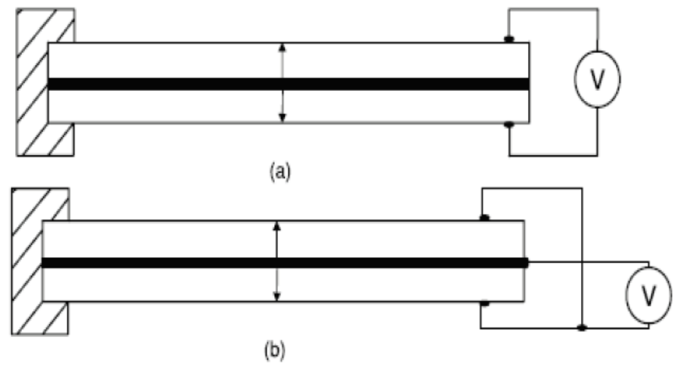


Figure 15: *Electrical Connection Options*

Different electrical connections can produce either more power, or more voltage, and these connections vary among available piezoelectric transducers.

5. Fixation of piezoelectric cantilever

There are two common fixations of the piezoelectric transducers for the purpose of energy harvesting as shown in the figure below. The simple beam fixation provides two points of connection, resulting in a safer and more robust design. However, the cantilever beam fixation can harvest more energy than the simple beam design. Additionally, in order to alter the resonant frequency of the cantilever beam, a small weight can be attached to the end of the beam. Matching the resonant frequency of the piezoelectric transducer and the frequency of vibration provided by the environment can dramatically increase the amount of energy absorbed by the system.

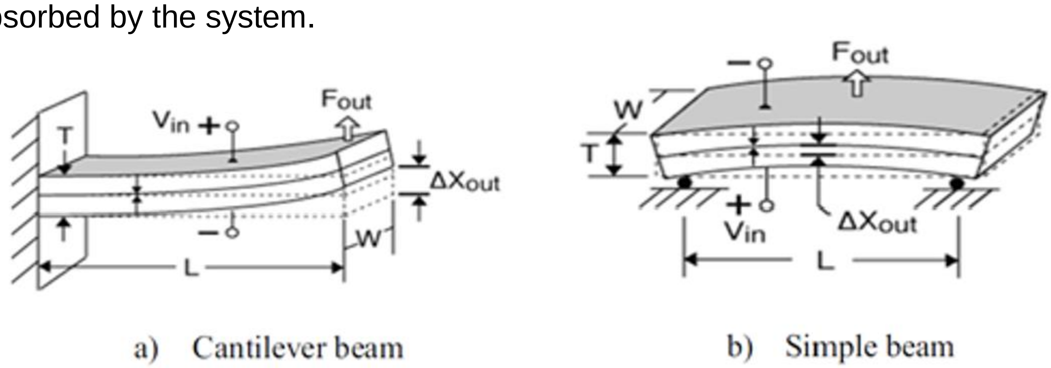


Figure 16: *Mounting Options*

6. AC-DC Converters

The voltage provided from the piezoelectric transducer will not be a constant source of voltage. The voltage will vary in both magnitude and polarity as an AC signal. Therefore, the voltage provided by this source needs to be rectified to be properly used by the remainder of the system's components. This can be done with many kinds of circuits. The first option is the implementation of a half wave bridge rectifier:

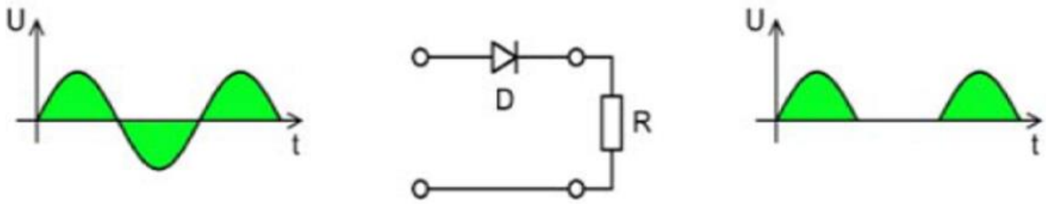


Figure 17: *Half Wave Bridge Rectifier*

While the half wave bridge rectifier provides a rectified signal, the efficiency of this system is very poor. The negative portion of the signal is not being converted to usable power, already resulting in a very poor efficiency. The next option considered is a full wave rectifier:

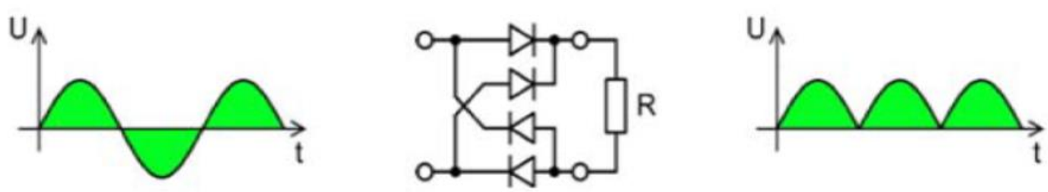


Figure 18: *Full Wave Bridge Rectifier*

Full wave rectifiers are far more efficient than half wave rectifiers as the entirety of the input signal is theoretically rectified. Therefore, a full wave bridge rectifier is desirable over the implementation of a half wave bridge rectifier. The next circuit under consideration is a voltage doubler:

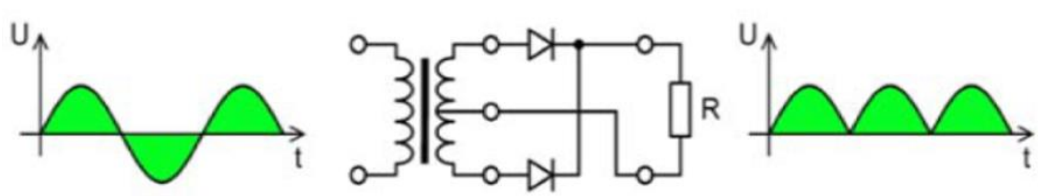


Figure 19: *Voltage Doubler*

The voltage doubler does as the name would suggest as it doubles the input voltage, having an output of $2V_i$. This design could be desirable should voltages of higher magnitudes be required for charging the energy storage system. A more advanced method of AC-DC conversion requires the use of MOSFETs, resulting in a high efficiency and low power loss. This circuit is known as a synchronous rectifier.

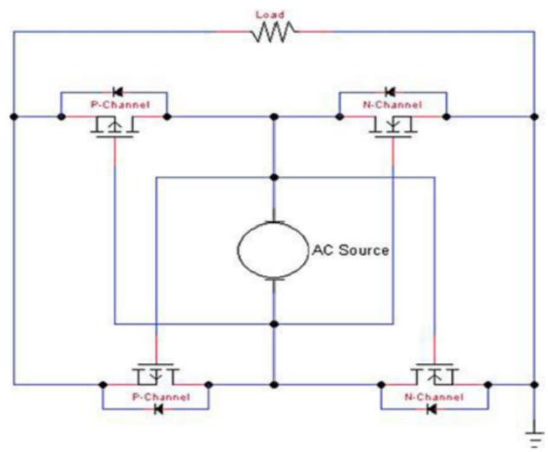


Figure 20: *Synchronous Rectifier*

The synchronous rectifier is considered the best form of rectification for this design due to its high level of efficiency. Additionally, the required MOSFETs are not anticipated to impact the budget of the design by any considerable amount.

7. DC-DC Converters

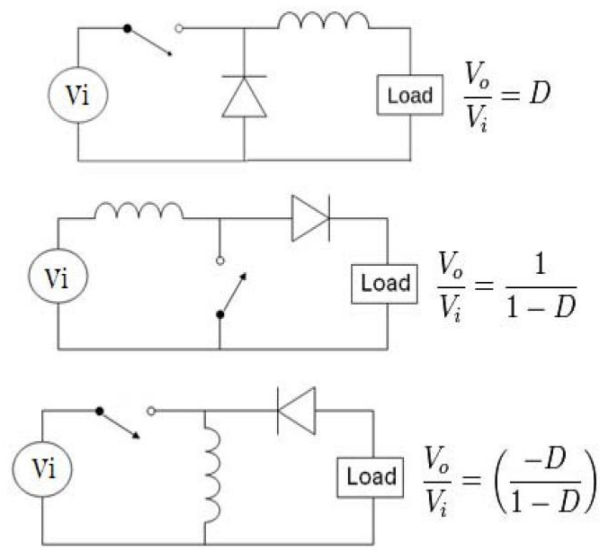


Figure 21: Buck, Boost, and Buck-boost DC-DC Converters

DC-DC converters must be used in order to regulate the voltage provided by the capacitors, of which are charged by the transducers.

8. **Storage media**

Either capacitors, supercapacitors, or rechargeable batteries can store power for this system. Any media that can oscillate its voltage over a large magnitude without excess loss is applicable to this project.

5.8.1.5 Test Plan and Comparison of Transducers

During the research phase, it was quickly found that the common piezoelectric haptic sensors (frequently found for under $20 for a large pack) would be irrelevant to this project. Unless someone were to constantly tap the sensors during operation, there was no way the piezoelectric would be capable of providing enough power through sheer vibrations. It is important to note that when referring to piezoelectric transducers and piezoelectric sensors, the terms “sensor and transducer” are essentially synonyms when one considers the chemistry of the piezo.

Both systems rely on the piezoelectric’s ability to develop a charge while under a stress. However, in industry it is common to refer to piezoelectric systems as a “sensor” if they provide enough voltage for a processor to recognize changes, and as a “transducer” if they are capable of providing a meaningful amount of power when submitted to an appropriate amount of stress.

When selecting the proper transducer, it became apparent that the more power the transducer is capable of harvesting, the more expensive the transducer would be. This was naturally expected, but the jump from a simple piezo-touch-sensor (approximately $0.50) to a piezoelectric that is recognized as a transducer ($344.00), capable of generating 1.4mW of power, proposed a steep change in price. The transducer quickly turned out to be the most limiting component of the entire design. Should the transducer be of too poor of quality (cheaper), it would not provide enough power to the remainder of the system. Should the transducer be of high enough quality to provide large amounts of power at high frequencies, it will easily become the only component this project can afford.

After extensive research and comparison, it was found that Mouser purchases transducers in bulk from a well-recognized company in piezoelectric transducer manufacturing; MIDE. This significantly reduced to price for this project, bringing relevant transducers down from $82.00 (MIDE’s direct sale pricing), to a more manageable price of $43.63 (Mouser’s pricing) per component. MIDE provided the most information about their transducers allowing us to make more educated decisions as to which transducers they offered would be relevant to the project. Additionally, MIDE developed these piezoelectric with energy harvesting in mind.

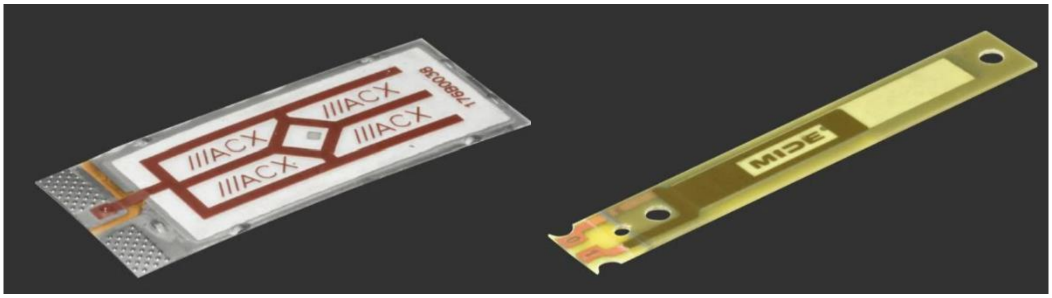


Figure 22: *MIDE S118-J1SS-1808YB (Left) and S129-H5FR-1803YB (Right) Piezoelectric Bending Transducer [83]*

Piezoelectric bending transducers require a controlled vibrating environment to be tested. This environment consists of an amplifier, a large speaker, and tone generator, and an oscilloscope. The piezoelectric shall be mounted to the speaker in a perpendicular cantilever fashion, with its terminals connected to an oscilloscope for recording data.

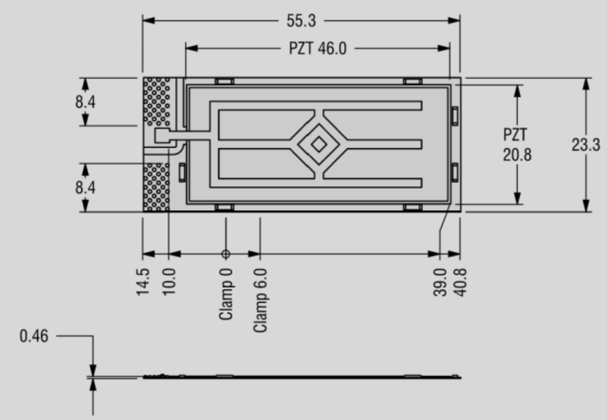
To control the frequencies, a tone generator was be turned on, amplified, and played through the large speaker. This speaker then oscillated at the frequency governed by the tone generator, providing the vibration to the transducer. In order to test the capabilities of the transducer, the frequency was altered until the AC wave reached a maximum. This is considered the resonant frequency of the energy harvester, where the most power can be harvested. One may increase the volume of the speaker to increase the oscillation as well, therefore increasing the output voltage of the transducer.

Theoretically, the transducer has a different resonant frequency when placing a voltmeter across its terminals, versus placing an electric load across the terminals. Placing a load on the transducer should lower the resonant frequency of the transducer. The higher the load, the more the resonant frequency is reduced. This is very similar to how one would run an electric motor by hand, generating a voltage across the terminals. Then when a load is placed across the motor, it gets much harder to turn by hand, but now the voltage can be used.

To test a transducer this way, very small weights can be added to the end of the cantilever to attempt to reduce the resonant frequency in search for a greater magnitude of voltage at lower vibrational frequencies.

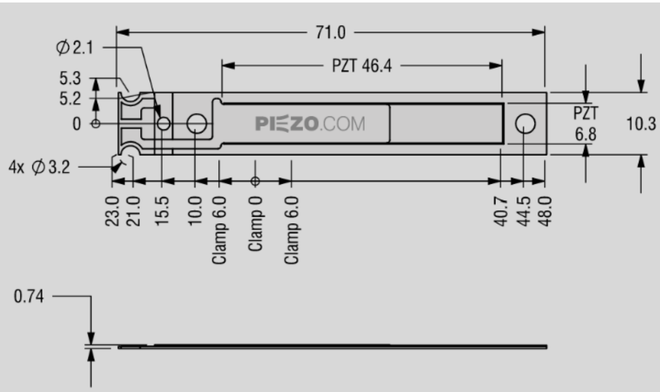
Table 14: *Comparison of Transducers [83]*

Part #	S118-J1SS-1808YB	S129-H5FR-1803YB
Length (mm.)	55.4	55.4
Width (mm.)	23.4	23.4
Thickness (mm.)	0.46	0.74
Temperature Range	-60° C to 120° C	-60° C to 120° C
Mass (grams)	2.8	1.4
Capacitance (nF)	100	22
Rated Drive Voltage (+/-V) off of Resonance	120	200
Free Deflect (+/-mm)	0.80	0.23
Blocked Force (N)	0.20	0.06
Spring const (N/mm)	0.25	0.261
Resonant Freq (Hz)	130	175
Max Drive Volts @ Resonance (V)	10.0	10.0
EH Resonant Freq (Hz)	130	49
Open Circuit Output (+/-Volts/G)	6	4
Resistor Load (Ohm)	15700	18000
Output Voltage (V)	17.3	28.2
G rating (+/- G's)	8	8
Price Per Unit	$31.92	$43.63



Layer Material	Thickness mils / mm
Polyester	2.0 / 0.05
Copper	1.4 / 0.03
PZT 5J	6.0 / 0.15
Stainless Steel 304	6.0 / 0.15
Polyimide	1.0 / 0.03

Figure 23: *S118-J1SS-1808YB Dimensions [83]*



Layer Material	Thickness mils / mm
FR4	3.0 / 0.08
Copper	1.4 / 0.03
PZT 5H	10.0 / 0.25
Copper	1.4 / 0.03
FR4	14.0 / 0.36

Figure 24: *S129-H5FR-1803YB Dimensions [83]*

5.8.2 **Phase I Results**

Designing the energy harvesting part of the project required extensive research and understanding of the components involved. Vibrations were not the only source of energy considered. Other “free” energy sources also considered were solar, wind, and heat. After reviewing our options, vibrations proved to be the most easily accessible on rollercoasters. The chosen transducer to harness the power from the vibrations is the piezoelectric transducer. Piezoelectric transducers take advantage of the piezoelectric properties of certain materials. The term piezoelectric expresses a material’s ability to develop a voltage across its body when introduced to mechanical stresses.

The vibrations of the roller coaster cause vibrations in a cantilever embedded with piezoelectric materials, providing an AC signal. This AC signal was then rectified using a low-loss full-wave bridge rectifier. Once the energy was properly rectified to a DC voltage, it was stored on a supercapacitor. After this voltage reaches a high enough threshold, a buck converter transfers portions of the stored charge from the supercapacitor to the overall output of Phase I. This output voltage was selected to be 3.3 volts in order to provide enough voltage to power the relevant components of Phase II.

Perhaps the most challenging part of Phase I was designing a testing environment. For obvious reasons, a roller coaster was not available to use for testing. Therefore, a roller-coaster-simulating environment needed to be constructed to vibrate the transducers as desired. To accomplish this, the following system was designed with what resources were available:

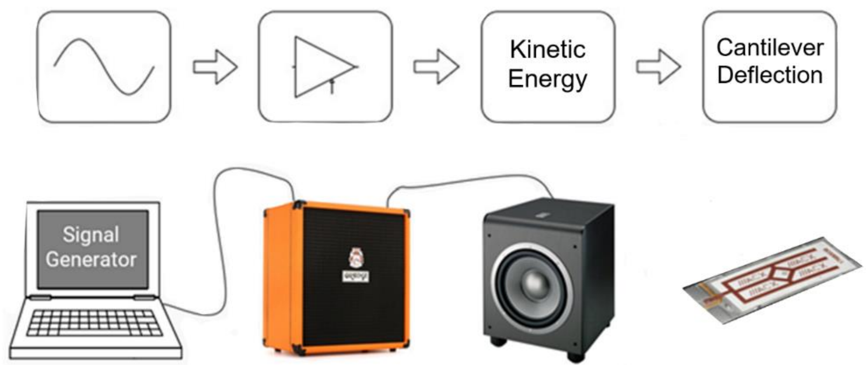


Figure 25: *A signal is generated (left), amplified through a bass guitar amplifier, the amplified signal is sent to a subwoofer, and the subwoofer vibrates the cantilever (right).*

Figure 2 expresses the testing environment developed to test the Phase 1 design in both ideal and non-ideal scenarios. First, a controlled AC signal at predetermined frequencies is generated on a computer application. Second, this signal is sent into an amplifier to increase the power of the signal. Third, the amplified signal reaches a subwoofer, a speaker capable of converting the signal to an oscillating mechanical movement. Subwoofers are designed to handle low frequencies in the audible range (20 to 20,000 Hz), so our harmonics were predominantly chosen within the audible range to ensure the subwoofer's performance. While the testing environment turned out to be a huge success, the first prototype of Phase I was not very successful in capturing energy from the vibrations.

Prototype I was a simple test of a single piezoelectric transducer connected to an energy harvesting unit. While the piezoelectric could capture large amounts of energy (verified by oscilloscope), the harvester was not efficient, and required redesign. Prototype I was only able to reach 4.21V within 75 minutes.

Prototype II featured a far more efficiency, provided by the BOB-09946 energy harvesting unit. This design, combined with closely monitored mechanical coupling, was able to reach 9.76V in 100 minutes.

The final design introduced the same electric efficiency, but with the addition of a far more robust mechanical mounting system. The piezoelectric cantilever was firmly clamped and bolted to the subwoofer, simulating strong mechanical coupling with the roller coaster. This drastically improved the results of the energy harvesting system, generating 9.91V in under 10 minutes.

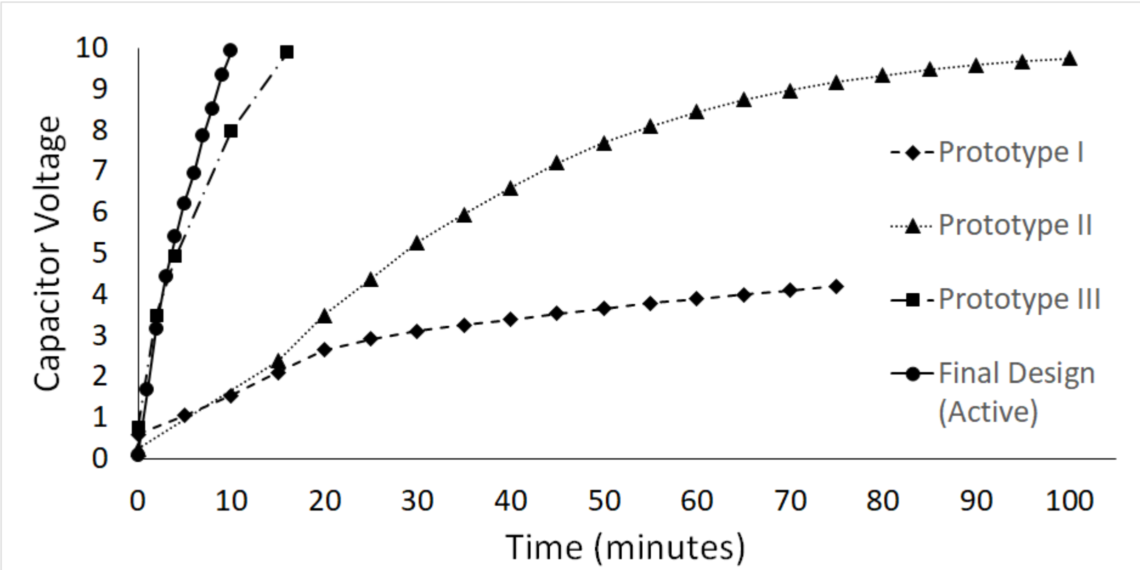


Figure 26: *Voltage of supercapacitor over time during testing of Phase I. All voltages read while providing the resonant frequency of the system, resulting in the best-case-scenario charge times for each design.*

5.8.3 **Prototyping: Phase II, Sensory Unit**

This phase focused on the design and implementation of the processor with accompanying sensors to realize our design of the sensory unit. The main purpose of this phase is to ignore the Energy Harvesting Power Supply and primarily focus on the Sensory unit.

5.8.3.1 Sensory Unit Components

The Sensory Unit's purpose is to record data via the accelerometers. The data is collected then transmitted for data analysis via a transmitter that is a part of the Sensory Unit. The data will be received by a receiver then display on an LCD for easy to read data analytics. Below will be the necessary components needed to fully realize the Sensory Unit.

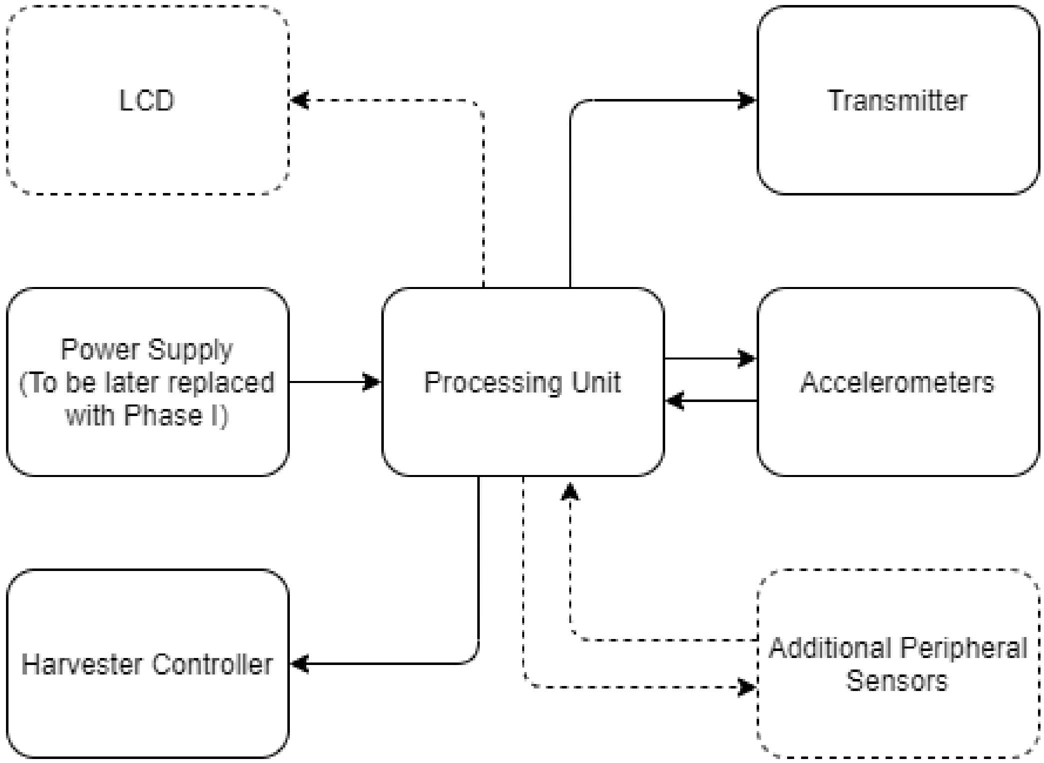


***Figure 27**: Phase II Block Diagram*

5.8.3.2 Processing Unit

The Processing Unit encompasses the Arduino microcontroller that we've selected for our design. The MCU will control the entire functionality of the Sensory Unit. These functionalities include turning the unit form low power mode to full power mode, start recording to stop recording, from reading to writing from memory, and the transmission of data.

5.8.3.3 Operating Modes

The Sensory Unit will have two functional modes of operation. The first mode being a Low power mode. The unit will only enter this mode if ever the case the unit is lacking the necessary power to operate on a run. This mode will have the function to store the generated power on a run. While is this operation mode, the Sensory Units only functionality will be to store generated power. The other functionality of the Unit will be turned off essentially.

This mode is only necessary if there is a lack of available power. As of now we will design for this case, but it could turn out that the Energy Harvesting Power Supply is efficient enough to generate the necessary power. Therefore, a low power mode may be surplus to requirements for our design. Additionally, when considering Phase II, there is not a need to include a low power mode since there is constant supply of power which will be replaced with Phase I the Energy Harvesting Power Supply.

The second operation mode will be a full power mode. Essentially, all of the functionalities will be restored and utilized during a run of the coaster. When operating in this mode, the Sensory Unit will have full functionality to record using the accelerometers, along with transmission of the collected data after a completed run. This mode is considered the normal operations mode and will be used consistently while testing Phase II.

Below simply demonstrates the flow that changes the Sensor Unit into the low power mode.

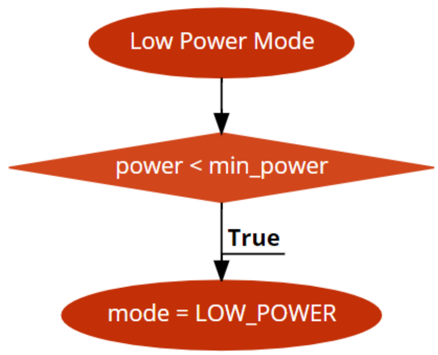


Figure 28*: Operating Modes algorithm flow*

5.8.3.4 Sensors

The Sensory Unit will have onboard sensors to record data during a run of the coaster. The sensors will provide the user data on the performance of the coaster. The sensors that we are utilizing to fulfill our design will be accelerometers. These sensory components can provide us with sufficient data when recording on a run. Not only for their versatility, but also the ability to find additional data values using the acceleration value alone. The prototyping will allow for additional sensors to be utilized and as of now the only sensors that we will be using are accelerometers which could change depending on time and ease of implementation. In this phase are main goal is to implement the sensors and facilitate the major component of our design that includes measuring and collecting data. This phase of the design will later be integrated in Phase III, where each phase functioned as intended independently and now must perform in conjunction with one another.

5.8.3.5 Accelerometers

Accelerometers are extremely useful component when it comes to changes in acceleration on an object or in the case of our design, a coaster car. The accelerometers give us the ability to not only measure the coasters change in acceleration, but also the velocity of the coaster or the speed and the position of the cart where these changes occur. These measurements provide an insight in the performance of the roller coaster at any moment of the run.

The NXP Semiconductors Tripe Axis Accelerometer was selected for its triple axis capability and its affordability. Additionally, the size of the accelerometer is ideal for the design to keep the overall size small for usability. The desired mounting location has not been decided or considered since the Sensory Units functionality is the top priority. While the accelerometer will be hard mount to the Arduino UNO R3 developer board. This prototype is meant to be a raw rendition of our final design to verify the functionality of the overall design.

When considering implementation, we will include at least one accelerometer, but there may be an inherent benefit to utilizing more than one. Let’s consider the case where one of the accelerometers fails, how are we going to record the data of a run. One solution is to implement more than one accelerometer. Of course, with this solution there are inherent drawbacks like now we have twice as much recorded data to store and transmit. Resulting in the need to implement a larger memory and potentially to provide more power to the Sensory Unit after a recorded run to transmit the data.

In any case having an additional accelerometer is beneficial to our design to verify the data being recorded is the same from both sensors. There could arise the situation where one of the sensors is miss reading or malfunctioning and it would be caught by the fact from having two accelerometers. When implementing the accelerometers, they will be hard-mounted to the Sensory Unit which will include more than one.

The accelerometers will not always be recording data, as stated previously the accelerometers will only be active while the coaster cart is on a run. We have not decided how to implement them in code, but without a doubt the sensors will either start measuring acceleration once there is a change from not moving or being measuring once a timer triggers the sensors. Usually, a roller coaster will not be on a run in a short amount of time. The issue with this approach is there may not be a consistent amount of time that the coaster cart is not moving. So, for ease of implementation the sensors will being measuring acceleration once the cart begins to move.

Once the prototype has been assembled (pending tomorrow). We will test the accelerometers in a variety of scenarios, but for simplicity as discussed in the Phase I testing, we will have a controlled test on the same vibrating apparatus that the piezoelectric transducers were tested on. Since, the piezoelectric transducers verified that they were capable of generating reliable power from the vibrations. We are able to assume that the accelerometer will have sufficient changes in the acceleration forces for the accelerometer to measure and record. With the triple axis capability that the accelerometer provides, will give us the flexibility to test the changes in forces in any of the three axis's.

As mentioned previously, the prototype will ignore the power supply component in Phase I. This is important when we consider that the power provided will be a consistent supply of reliable power. This ensures that when we test the Sensory Unit, we will have ideal conditions. Now we are still considering the possibility introduced in Phase III that the amount of power supply is adequate for what was provided by the power supply. In order to take this into account we will test with similar available power that will be generated by the power supply that is prototyped in Phase I.

5.8.3.6 Data format

The data that will be recorded by the accelerometers is essential to the Sensory Unit. The purpose of this phase is to finalize our Sensory Unit design and confirm that the design will perform. The performance is solely based upon the data that is collected. Therefore, the recorded data must be accurate with the use of more than one accelerometer to ensure this. As stated previously, the data will be recorded and then stored in the Sensory Units memory until after the current run. Below are the measurements that we focus on currently and can added to if there is a need to within a data structure.

The importance of these data parameters is that they give a large snapshot into the recorded run of the coaster. We will know where exactly on the run, the change in acceleration occurred and how fast the coaster cart was going at that specific time. The ability to where is essential in determine the performance of the Sensory Unit.

5.8.3.7 Transmission of data

The Sensory Unit will tell the accelerometers to begin recording and the data recorded on a run will be written to memory. As stated above, the measurements we are concerned with are acceleration, velocity, and position. These measurements will be stored in memory with a unique tag to distinguish between certain points within a recorded run. Once the coaster finishes a run, the Sensory Unity will stop the accelerometers from recording and the data will be transmitted.

The transmission of the data begins with the data being read from memory by the processor and sent to the transmitter to be transmitted to an offboard receiver. The transmitter will either be a Wi-Fi or Bluetooth module. Both will be utilized to test with in order to determine the most effective component.

Below demonstrates the data flow within the Sensory Unit while recording, storing, and transmitting data.

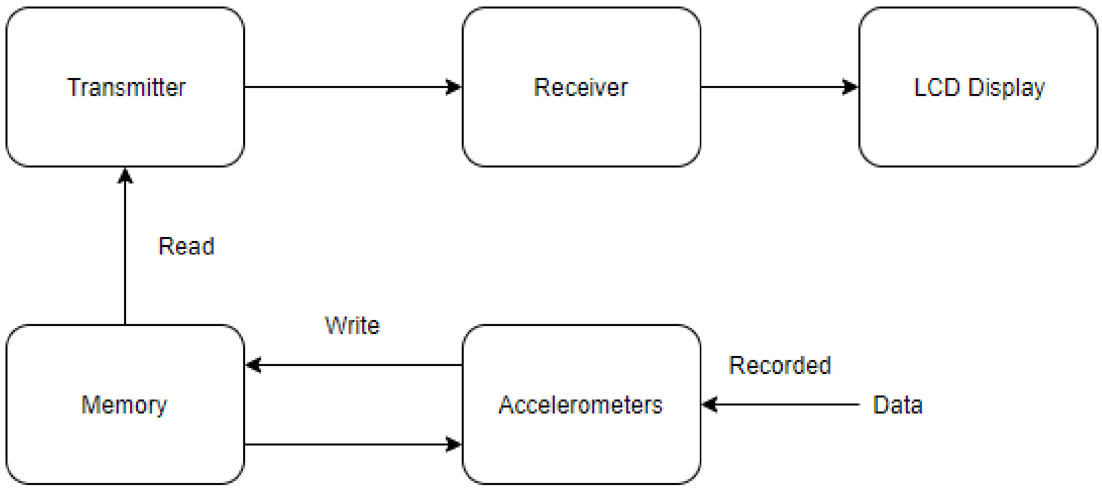


***Figure 29**: Transmission of Data Block Diagram*

5.8.3.8 User Interface

Designing the mobile application part of the project required Phase II to be completed. Phase II implementation was a major factor in designing the features of the Mobile Application. Part selection on which sensor was to be implemented affected the apps design. After finalizing Phase II with implementing an accelerometer, allowed for the structure of the app to begin to take shape.

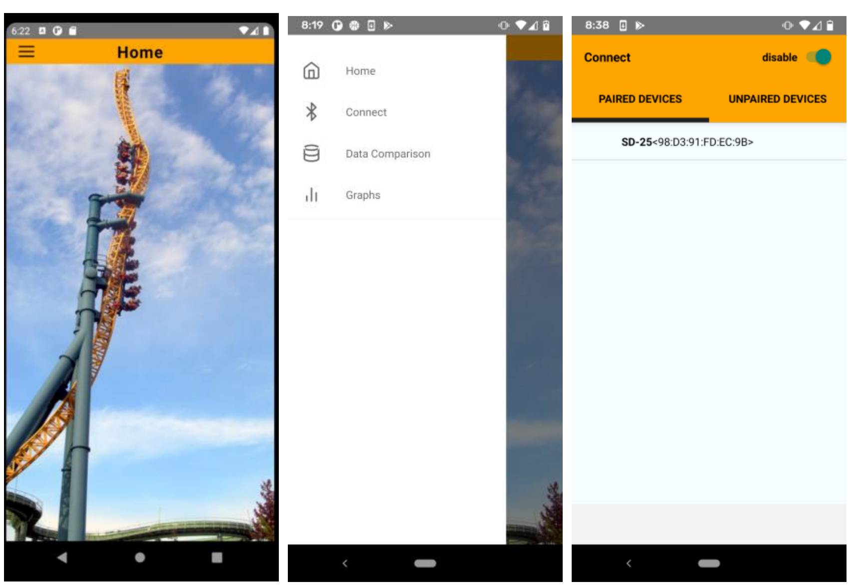


***Figure 30**: User Interface*

Testing with the accelerometer gave the format of the recorded data the Mobile App would have to handle. The accelerometer records and displays data in three dimensions. This format was taken and translated to the app in reference to database storage. The data of all recorded runs are stored using MongoDB. The app allows the user to view all recorded runs by selecting any date from a popup calendar. The data of the selected date is displayed on the Data Comparison screen which can be accessed using the side menu.

Additionally, the data is displayed immediately after a date is selected in a graph to easily analyze the changes of the accelerometer data. The graphs clearly display the x, y, and z components of the acceleration versus time. This helps the user in analyzing the data to pinpoint exact times the accelerometer was recorded. Another additional feature allows the user to select two different dates to compare data in order to evaluate the performance of a particular ride. The performance can be determined using these graphs to visually see the changes in recorded data.

The connection process on the connect screen of the app is straight forward and utilizes native android. There is a switch found on the connect screen that turns Bluetooth on and off and is reflected on the phone as well. Once Bluetooth is on, there is a button to enable scanning for nearby Bluetooth devices. Once a device is paired with the app, it is then stored in a paired devices array. This array allows for the app to connect quicker and more easily to remembered devices. This is vital for our design since we are limited on power and recording time. As mentioned in Phase II, data collection occurs for a duration of around 2 minutes 30 seconds with a transmission time around 30 seconds. This led to the prioritization of connecting Bluetooth and transmitting the data as quickly as possible. The connection time was reduced using the paired devices array as mentioned before.

One of the most challenging components for the Mobile Application was implementing a Bluetooth serial library that worked correctly, since Bluetooth serial is only used on Androids and is an older application of Bluetooth. There were considerable setbacks in implementing a library, but a library was implemented, and the Application functions as intended to be used as a visual aid in data analysis.

***Figure 31**: UI for Data Display. Above showcases the Data Screen, where a user can select two dates to compare the accelerometer data of those two dates. The remaining screens demonstrate the individual acceleration Tab Screens, where the data for each date correspond to a singular graph on each screen.*

5.8.4 **Prototyping: Phase III, Combining Stage**

Phase III combines both phase I and phase II in order to finalize the design. For this phase to be performed smoothly, the power provided to the processing unit and its peripherals in phase II must closely match the power provided by the power supply developed in phase I.
Once both phases are successfully combined, phase III focuses on stressing the abilities of the overall prototype. Answering the following questions

- How long can the prototype operate on one full charge?
    - Onboard active vehicles?
    - Without generating power (motionless)?
- How long does the device take to fully charge?
- Is additional thermal cooling necessary?
- What is the optimal runtime in order to ensure the device maintains a desirable charge?

This phase may also expose that the power supply developed in phase I is not sufficient to power the overall device, therefore requiring further research in phase I. Possible solutions include additional transducers and more accurate tuning systems. Should this phase expose that the power generated is more than sufficient, additional features may be explored.

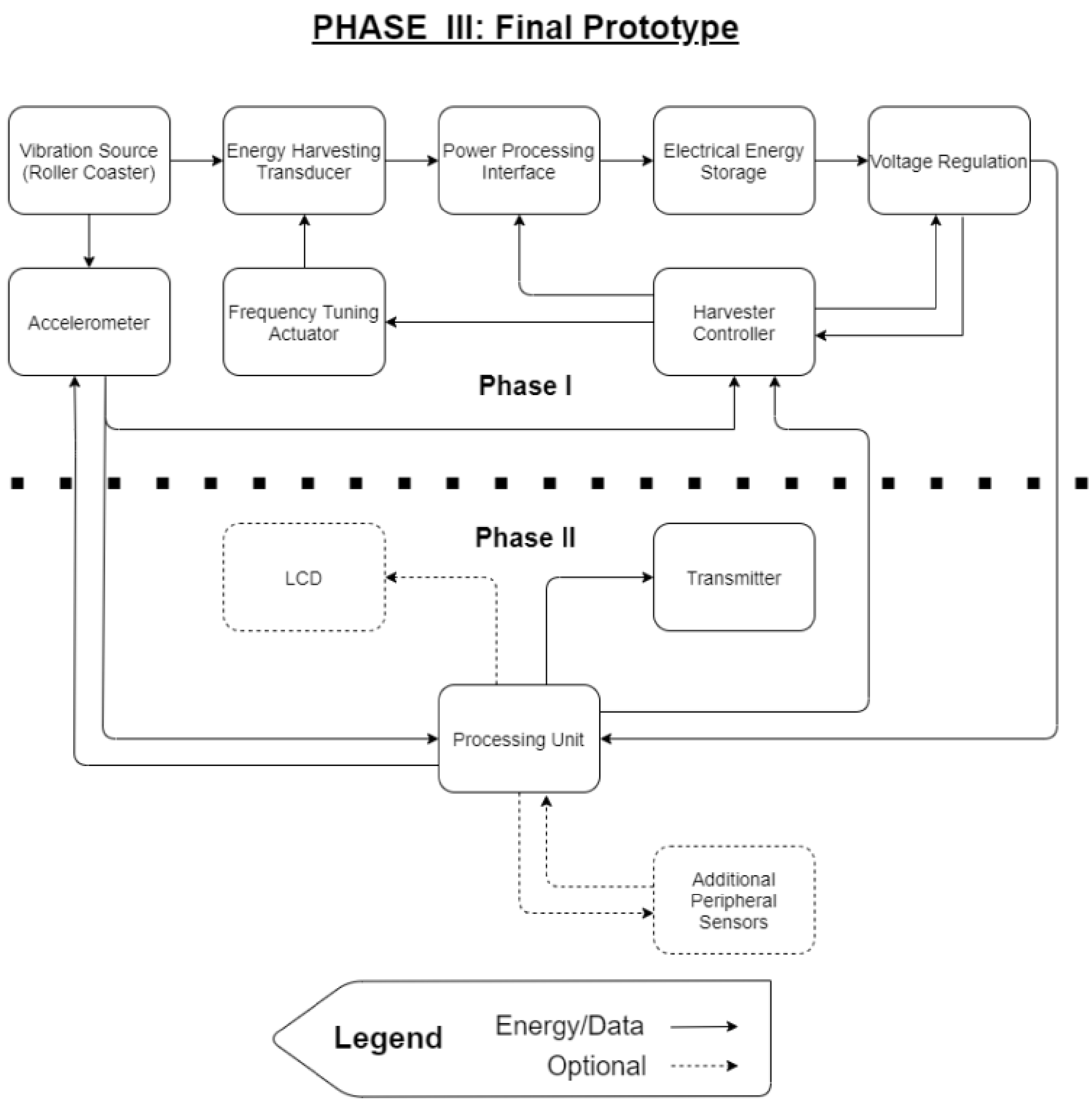


Figure 32: Phase III Block Diagram

5.8.5 Flexibility of Project: Additional Features and Low Power Modes

The piezoelectric transducers are anticipated to be the design feature that provides the most limitations on the project. If the transducers can provide a large amount of power, it will be very simple to introduce more demanding sensors, more user-friendly features (such as an LCD), and longer operation times. Should the transducers not provide enough to power these features, the system will still be capable of capturing data utilizing accelerometers.

Considering an even worse scenario, if the piezoelectric transducers provide less power than the requirements to continuously monitor the rollercoaster, low power modes can be introduced to allow the transducers to charge the system to operating requirements. Under these requirements, this sensory unit would be powered intermittently to extract data during pre-determined increments of time. This implementation would likely have the system in low power mode during x-laps of the coaster around the track, and then return to collecting data for the duration of one complete lap around the coaster track. Naturally, this same concept of intermittently powering the system can also be used when implementing more demanding components and can even permit the use of even more demanding components.

5.9 Final PCB Design

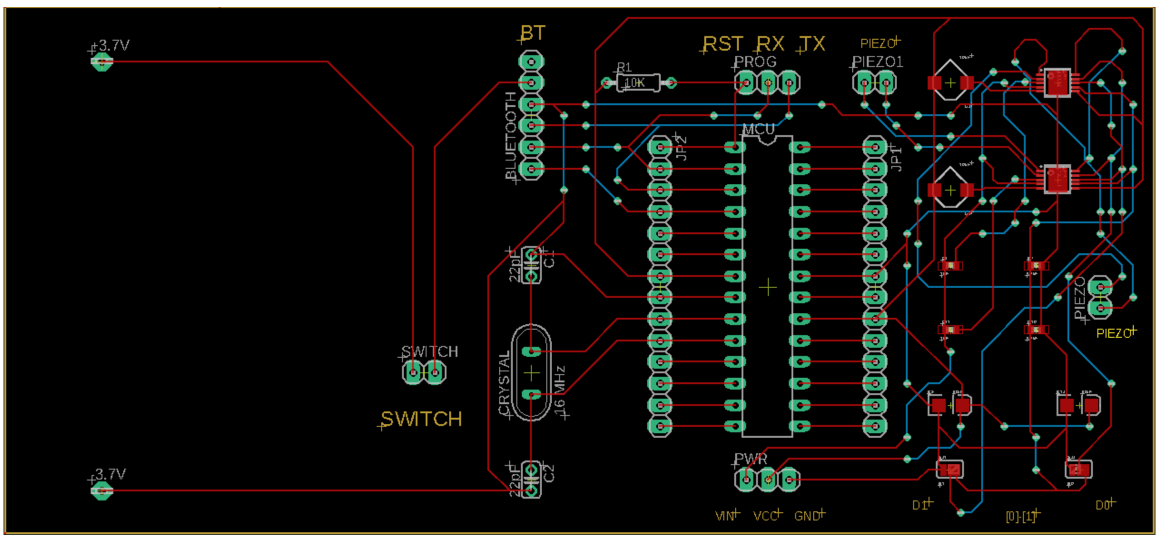


Figure 33: *Final PCB Design*

With this design, the major components identified within the layout are the MCU, the accelerometer sensor, transmitter, energy harvesting unit, supercapacitor, and the piezoelectric bending transducer.

In the center houses the MCU and on the left the Bluetooth module to transmit the data. On the right side of the PCB, the energy harvesting unit is in place to gather power for the system. The energy harvesting unit is connected to the piezoelectric transducers along with the supercapacitor to store energy. The piezo material contains the two leads (4 total, 2 for each piezo) which serves as the input connection for the material. The purpose of the supercapacitor unit is to store energy and to dissipate energy a lot slower than regular capacitors that take up the same footprint. Our goal with this design is to include all the necessary components to harvest the energy provided through vibrations and being able to transmit the data produced and obtain within the system. This goal is achieved with the usage of the surface mounted components on the PCB.

6 Testing

6.1 Microcontroller Testing

In order to test the ATMEGA328P, a developmental board (Arduino Uno Rev 3) was purchased to test out the component. Using the Arduino IDE, the platform contained a lot of example code and libraries in order to showcase the potential of the MCU. When the IDE first opens up, a sketch template with two functions to setup and loop the code which houses the main component of the source code. By going under the file section, example code and custom libraries containing extended examples are present. As explained in our testing of the accelerometer, these libraries can extend the usage of the original libraries provided. As inputting code into the MCU, this can test if the unit can successfully interface with the computer. As performing various tests with different size coding projects ranging from 10 percent to 50 percent usage of RAM, each project was successfully run and the MCU displayed the correct output. Having a functioning MCU can craft a successful project as it controls and interfaces with the various components found within the project.

6.2 Accelerometer Testing

The accelerometer chosen for our initial test was the MMA8452Q Accelerometer Breakout Board which contains six pins: 3.3V, SDA, SCL, I2, I1, and Ground. As mention before in the I^2C standard, SDA and SCL are used to interface with the MCU. An advantage using this part is that under normal operations, between 7 to 165 µA are produced.

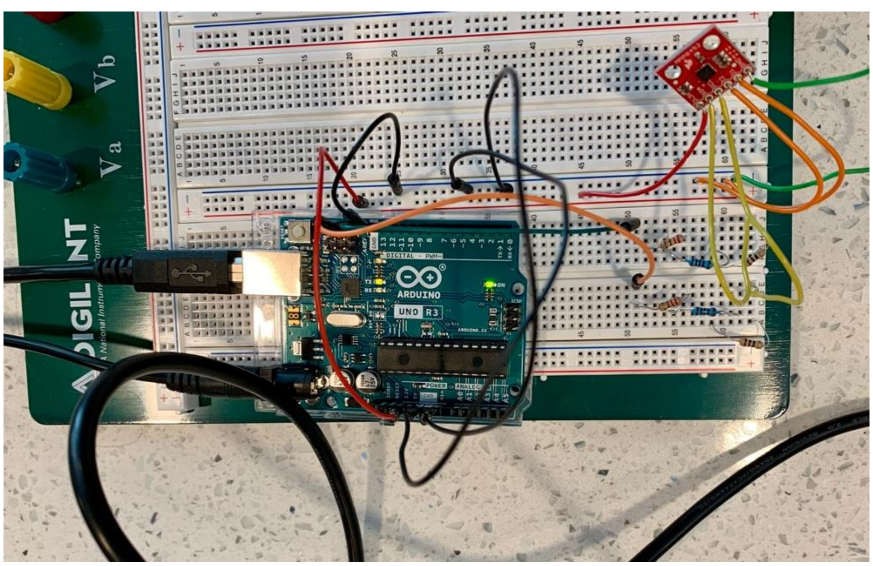


Figure 34: *Breadboard Layout*

As showcased in this image above, the microcontroller is connected to the computer with a USB Type A to Type B cable to upload code from the Arduino IDE. The part on the top right-hand side is the accelerometer which contains wires that are soldered in order to test the functionality of the part by moving it within the X, Y, and Z planes. The three pins of Ground, I1, and I2 are connected to the three ground pins located in the developmental board. I1 and I2 which stands for programmable interrupt 1 and 2 are connected to ground as there is no output for this test to indicate data ready. The 3.3 V pin on the Arduino is connected to the 3.3 V on the accelerometer and the SCL and SDA lines are connected to each respected pin as well. Moving the accelerometer in different directions outputted different orientations within the X, Y, and Z plane. This output can be viewed by the Serial Monitor under the Tools tab as the I^2C protocol is used for interfacing. As the output shown:

Time Stamp (ms)	X	Y	Z
14:10:52.672	417	-463	619
14:10:52.705	252	-553	751
14:10:52.739	394	-608	665
14:10:52.772	535	-681	725

Table 15: *Accelerometer Output*

At each timestamp, which is measured in milliseconds, the accelerometer can detect changes within the X, Y, and Z orientation. Performing this showcases that the accelerometer works as intended and can interface with the MCU. The accelerometer is a crucial part of the project and provides the main source of information to the end user.

6.3 Piezoelectric Transducer Testing

Multiple experiments were conducted to test the piezoelectric transducers. As per previously discussed research, the resonant frequency should change when weight is added to the end of a cantilever. This behavior is planned to be used to tune the transducers before or during operation. The following experiments were made to test this theory:

6.3.1 Transducers: Experiment 1, Voltage and Resonance

To test the piezoelectric transducers, and find their resonant frequencies, a system with no other components from the project was implemented. After isolating the component, the transducer was connected to an oscilloscope monitoring the AC voltage generated by it.

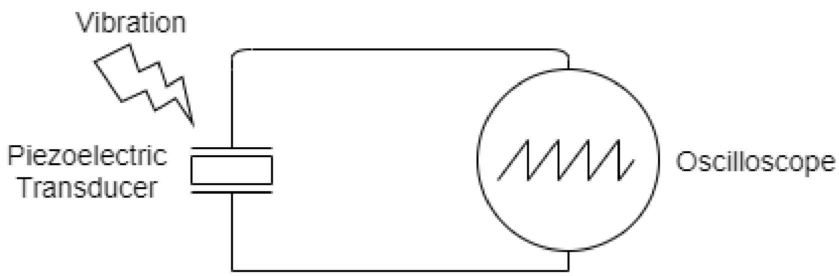


Figure 35: Piezoelectric Transducer Voltage-Test Setup

In order to generate the vibration, a controlled vibrating environment was developed. This environment consisted of an amplifier, a large speaker, tone generator, and an oscilloscope. The piezoelectric was mounted to the speaker in a perpendicular cantilever fashion, with its terminals connected to the oscilloscope.

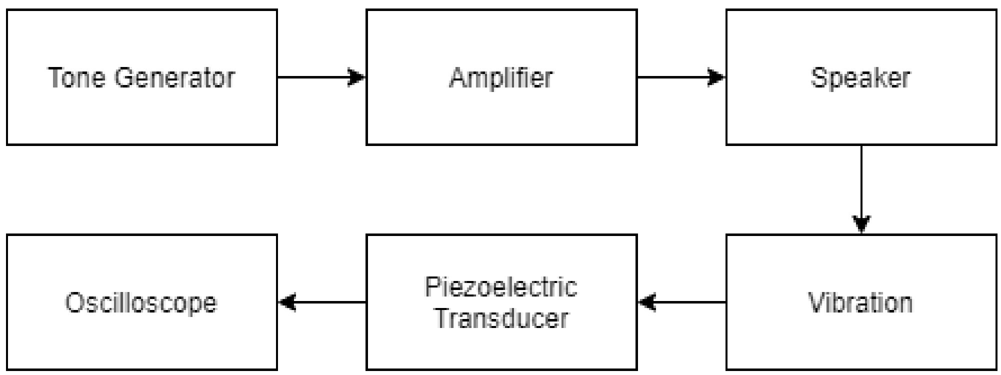


Figure 36: Vibrating Environment Flow Chart

A desktop computer generated the tone and transferred it to an amplifier. The amplifier used was an Orange Crush Bass 50 1x12" 50-watt Bass Combo Amp made by Orange Amplification. This amplifier was then hooked up to a subwoofer, a speaker capable of emitting very low frequencies. While the amplifier was a Combo Amp, and had its own subwoofer, an auxiliary subwoofer was utilized to preserve the quality of the amplifier. This was due to the requirement of attaching the piezoelectric to the subwoofer's dust cap.

Once the tone generator fed a tone into the amplifier, the amplifier amplified the signal, and fed it into the subwoofer, created vibrations at the frequency provided by the tone generator. This vibration was applied directly to the piezoelectric transducer as the transducer was mounted to the dust cap in a cantilever fashion.

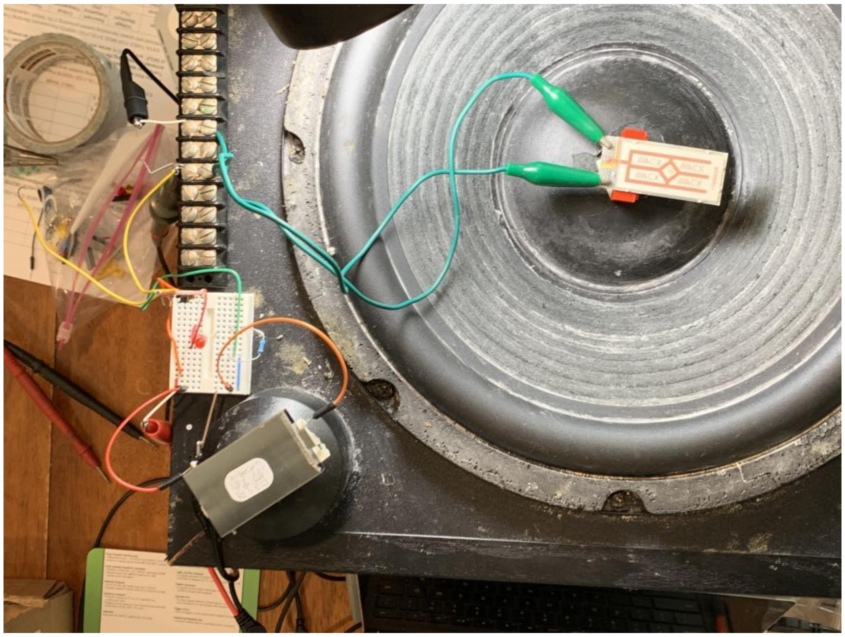


Figure 37: *Piezoelectric Transducer Voltage-Test Setup*

The figure above shows the piezoelectric transducer mounted to the dust cover of subwoofer (top left). A super capacitor and a bread board with additional components can be seen. These additional components were used in further experiments.

6.3.2 **Experiment 1: Transducers, Production of Voltage and Variance of Resonant Frequency**

For the first experiment, the parameters recorded are as follows:

1. **Voltage Maximum**

This parameter is defined as the voltage difference from the maximum and minimum voltages provided by the transducer. This parameter is expressed in voltage.

2. **Resonant Frequency**

The resonant frequency is the frequency at which the transducer is providing the voltage maximum. This parameter is expressed in hertz.

3. **Weight Added**

This is the amount of weight fixed to the end of the cantilever. This weight is expressed in grams. The intention of this weight was to change the resonant frequency of the system.

For the first experiment, the S118-J1SS-1808YB transducer was tested under the following procedure:

1. Fix the transducer to the dust cap of the speaker in a cantilever fashion.
2. Orient the leads such that they make little impact on the vibrations.
3. Connect the leads to an oscilloscope to monitor the AC voltage provided.
4. Turn on the tone generator.
5. Set amplifier to 75% volume, 50% gain. Levels above this will can produce voltages above rated values.
6. Vary frequency of tone until maximum voltage peak to peak is found.
7. Record frequency and voltage acquired.

Case	Voltage Maximum (V_{pp})	Resonant Frequency (Hz)	Weight Added (g)
1	32	119	0
2	13	118	0.352
3	12	118	0.528
4	10	118	0.704
5	9	118	0.88
6	8.5	118	1.056
7	8.2	118	1.232
8	8	118	1.408
9	7.8	118	1.584
10	7.7	118	1.76
11	7.6	118	1.936
12	6	118	11

Table 16: *Experiment 1 Results, S118-J1SS-1808YB*

The resonant frequency of this piezoelectric is rated to be 130 Hz, not far off from the experimental findings. However, contrary to the expectation, the results of this experiment proved that (for under these circumstances) resonant frequency did not change for the piezoelectric when weight was added. Small amounts of weight were added in order to vary the resonant frequency. To our surprise, it was not the resonant frequency that changed, but the voltage the resonant frequency could produce.

In order to check if we were applying the necessary weight, Case 12 applied a weight of 11 grams, the amount of weight deemed safe to apply the piezoelectric without harming it. The resonant frequency remained the same. A similar experiment was held for the S129-H5FR-1803YB, obtaining the same end result; the resonant frequency is not able to be altered via the addition of weights on the cantilever.

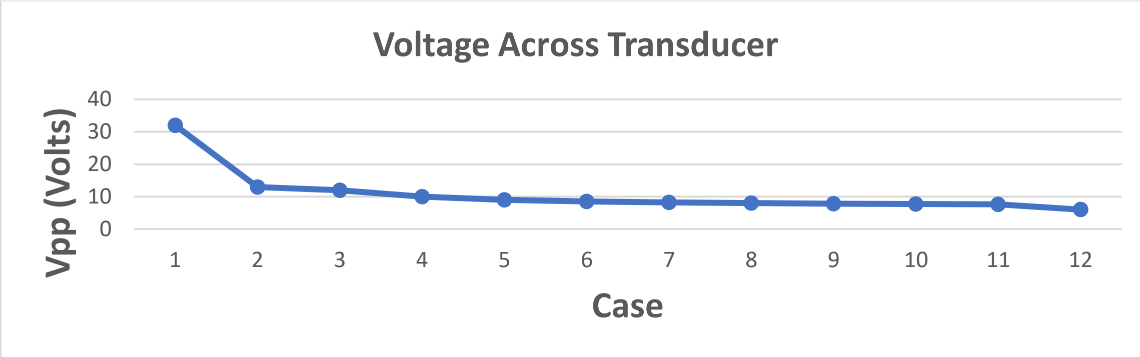


Figure 38: S118-J1SS-1808YB Voltages Over Weighted Cases

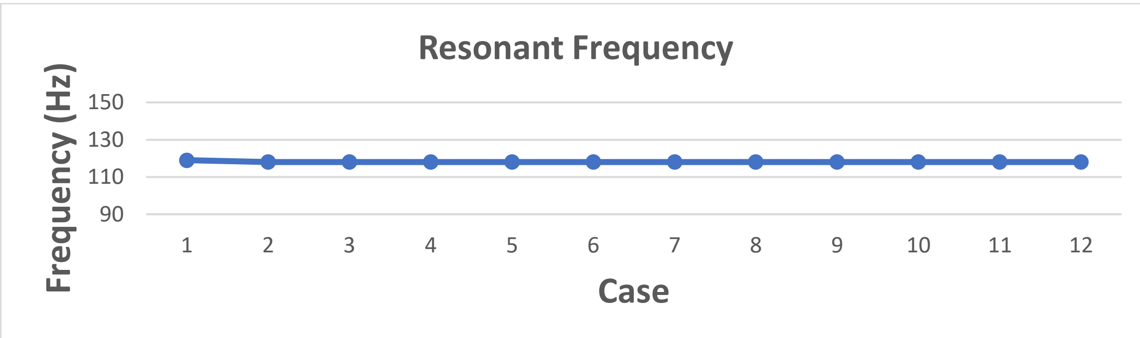


Figure 39: S118-J1SS-1808YB Resonant Frequencies Over Weighted Cases

While the research suggested that adding weight to the end of a piezoelectric transducer will reduce the resonant frequency of the piezoelectric, allowing for tuning of resonant frequency, the data acquired does not agree with that statement. This is speculated to be due to the inaccuracies of the experiments conducted, or the scale of the experiment itself. The inaccuracies of the resonant frequency changing could be that the scale of the system doesn't allow for such changes. The piezoelectric transducers cannot hold large amounts of weight, and therefore are not heavily impacted by the weight added at the end of the cantilever.

The inaccuracies of resonant frequency could also be that we are generating the maximum voltage at the resonant frequency of the entire system as opposed to the resonant frequency of the actual transducer. This makes sense, as the resonant frequency of both transducers are rated differently, whereas the experimental resonant frequency proved to be the same for both transducers. Another explanation is that the resonant frequency depends far more on the structure of the component itself and the external forces (added weight) merely dampen the response. This explanation makes sense as the voltage dropped at an exponential rate when the weights were added. The conclusion of experiment one is that the resonant frequency of the transducer cannot be altered under these circumstances, but that the transducers can offer lots of voltage.

6.3.3 **Experiment 2: Transducers, Magnitude of Power Supplied**

After establishing that the piezoelectric transducers provided a substantial voltage when subjected to appropriate frequencies, the power output of the system was then tested. A component was selected that contained a full bridge rectifier and a buck converter. The component selected was the Sparkfun BOB-09946. This device was originally meant to jump-start the prototyping process, but instead became a cheap solution effectively and efficiently capturing and utilizing the energy provided by the transducer.

It was selected for its highly specialized purpose and affordability, as it was designed to accept AC power generated by very low power energy harvesters. Once this device rectifies the input voltage, it then stores the voltage in an external array of capacitors provided by the designers. Once the capacitors reach the appropriate charge, the buck converter provides a steady regulated voltage as its output. In order to test if the piezoelectric transducer could provide enough power for the microprocessor selected, the following system was implemented:

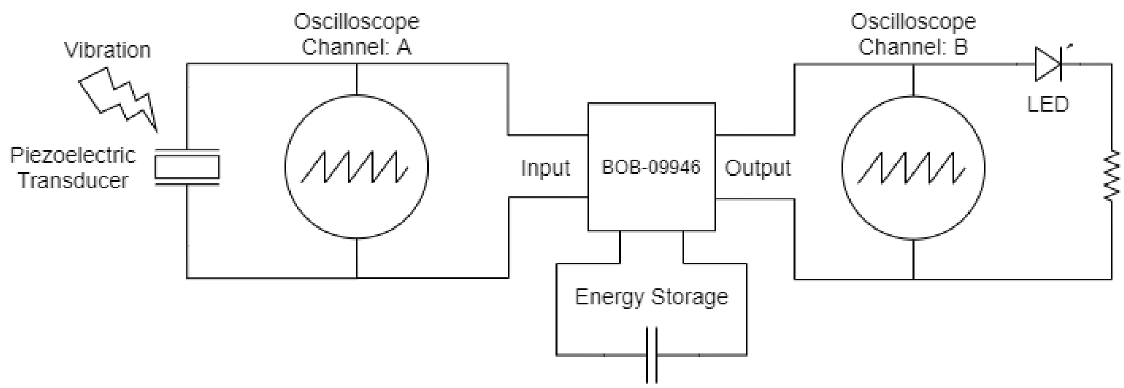


Figure 40: Piezoelectric Transducer Power-Test Setup

The BOB-09946 power management system has multiple settings that can be altered on the board to change the output voltage. For these initial experiments, the output voltage was defined to be 3.3V by soldering junction D1 to high and D0 to low as shown in the figure below.

D1	D0	V_{OUT}	V_{OUT} QUIESCENT CURRENT (I_{VOUT})
0	0	1.8V	44nA
0	1	2.5V	62nA
1	0	3.3V	81nA
1	1	3.6V	89nA

Table 17: *Output Voltage Capabilities*

Utilizing a voltage of 3.3V, the output was wired to a LED in series with a resistor. This was implemented to provide optic feedback to the designer when the BOB-09946 was providing the steady stream of 3.3V. After adding a load to the terminals of the piezoelectric transducer, the resonant frequency of the transducer reduced by approximately 20Hz. As shown in figure 36, oscilloscopes were monitoring the input from the piezoelectric to ensure operation at resonant frequency and monitoring the DC output voltage from the BOB-09946. Under ideal conditions, the experiment was able to provide approximately 1.4mW of power to the resistor while still charging its capacitors. This amount of power was deemed enough to run the processing unit and its axillaries, but more tests will need to be completed to assess the number of peripherals that can be installed on the overall design. Note that this behavior was under ideal conditions, and further testing will be required to prove its application to vibrations generated by rollercoasters.

This result proves that this design concept will work under the extreme condition of endless vibrations at resonant frequency. While proving the overall concept of the design, more information about the vibrations present on an actual roller coaster will be required to prove there is enough energy to capture to power the sensors for a set amount of time. This experiment also provided further confirmation that the microcontroller will need to enter a low-power state in order for the system to obtain enough charge to operate the sensors intermittently. The system was also only operated with two 470uF capacitors in parallel, providing 940uF of capacitance. The system will be capable of charging for longer periods of time and more importantly running for longer periods of time once a proper supercapacitor or rechargeable battery (which requires additional circuitry) is installed.

Overall, these first set of experiments utilizing the MIDE S118-J1SS-1808YB Piezoelectric Bending Transducer and the Sparkfun BOB-09946 harvesting system proved very successful. Additionally, not all functional blocks described in the prototyping section were included in this design. Meaning that blocks that added efficiency were excluded for simplicity of the initial experiments, leaving more room for improvement.

6.3.4 **Experiment 3: Transducers, Comparison of Power Supplied**

For the final experiment, the two transducers selected are directly compared to one another in a series of tests. For the first test, the same setup in experiment 2 was utilized, including the 970uF of capacitance. The comparison in question is which piezoelectric transducer can provide the best runtime versus downtime. In order to test this, both transducers were subject to the same excitation, and judged by how long they can maintain providing 1.4mW of power continuously.

For the third experiment, the parameters are recorded are as follows:

1. **Capacitance**

This parameter is defined as the amount of capacitance, in Farads, the energy storage system has.

2. **Runtime**

How long the system could provide 1.4mW of power as governed by the power harvesting unit. Expressed in seconds.

3. **Downtime**

How long the system required charging between providing 1.4mW of power as governed by the power harvesting unit. Expressed in seconds.

4. **Amp Mag. (Amplification Magnitude)**

The amplification magnitude at which the system was fed to provide the bare minimum amount of energy to the system to maintain an operating charge on the capacitors. Measured as a relevant amplitude, and to be more accurately tested.

5. **Critical Mag. (Critical Amplification Magnitude)**

The amplification magnitude at which the system was fed to provide maximal energy to the system. At this amplitude, the capacitors neither gain nor lose charge. Measured as a relevant amplitude, and to be more accurately tested.

For the case utilizing 970uF capacitance as the energy storage, these were the results:

Transducer Model	Capacitance (F)	Runtime (s)	Downtime (s)	Amp Mag.	Critical Mag.
S118	940uF	Indefinite	-	70%	50%
S129	940uF	5.5	62	70%	-

Table 18: *Experiment 3 Results*

Despite the S129 model being more expensive, and looking better on paper, the S118 model performed far better. As the data collected shows, the S118 was not only able to achieve steady state for the system (at 50% amplitude), it was also able to maintain feeding a steady 1.4mW indefinitely at the magnitude of 70%. Theoretically, with this transducer all necessary components can be powered. The S118 model is assumed superior due to its more flexible construction.

6.3.5 **Experiment 4: Transducers, Capacitor Leakage and use of Supercapacitors**

After successfully selecting the S118 piezoelectric transducer model, a supercapacitor replaced the normal capacitors of the system. This altered the capacitance from 940uF to 120mF. After charging the supercapacitor to a comfortable operating capacity, the tone generator was shut off, and the supercapacitor was allowed to leak. No load was applied during this part of the experiment.

For the fourth experiment, the parameters are recorded are as follows:

While one would expect the selected supercapacitor to outperform a small array of capacitors, the results were impressive:

Capacitance (F)	Discharge Rate (V/s)
970u	0.000125
120m	0.000043

Table 19: *Experiment 4 Results*

With this data, considering that the capacitor is charged to 10 volts, and allowed to dissipate to 3.3 volts, it would take the 970uF capacitance 53,600 seconds, or approximately 15 hours to lose voltage. However, the supercapacitor would take 155,814 seconds, or approximately two days to discharge.

Another important note is that the S129 transducer took so long to charge the capacitor to an appropriate level of charge, that no data could be collected regarding the S129 model with the supercapacitor.

6.3.6 **Overall Results of Experiments**

6.3.6.1 Vibration Requirements

Due to the budgetary restraints of this project, a small number of fair-quality transducers were implemented and tested. These transducers were able to create the required amounts of voltage and power; enough to power the microprocessor. However, the magnitude of the vibration required for this behavior was considered substantial. Our team is reaching out to current rollercoaster engineers for exact vibration measurements regarding active rollercoasters. These measurements, if acquired, will be used to provide the piezo with the appropriate amount of vibration to test viability. Should the vibrations we provide during experiments exceed the vibrations of a real roller coaster, a possible result is that this project will be unrealizable without the use of higher quality piezoelectric transducers.

6.3.6.2 Mechanical Coupling Requirements

Perhaps the most important factor discovered is the nature of the mechanical coupling to the piezoelectric transducer. While fair methods of mechanical coupling were used, anything present causing dampening of the vibrations greatly reduced the ability of the transducers to produce voltage. Stronger and stronger methods were used to mechanically couple the transducer to the vibration generator, resulting in reaching the maximum voltage ratings of the transducers when given the proper excitation.

The mechanical connection must also be very strong on the terminals connecting to the circuit. With one of the transducers, #2, the connection at the terminals were solderable, and proved to be an excellent way to connect to the terminals. However, it was found that this transducer provided much less power due to its strong shape. The other transducer, #1, proved to be much better at developing voltages under the same vibrations, but the #2 transducer proved to be more robust, as one of the S118 model transducer's structure was compromised due to poor mechanical coupling.

In the final design, mechanical dampening must be reduced to a very low minimum and the mechanical coupling must be robust in order to generate enough power from the transducers and protect the piezoelectric transducer.

6.3.6.3 Selected Components

Part	Model
Transducer	MIDE S118-J1SS-1808YB
Capacitor	BZ12GA124ZLBA2 16 V Supercapacitor
Power Harvesting Unit	Sparkfun BOB-09946

Table 20: *Selected Components*

6.4 Testing Method

In the course of the design process, it was integral that we had a proper way of testing our device when it was fully fabricated. Due to the possible inability to place this device on an actual rollercoaster, we needed to mimic the environment as much as possible. The following testing methods were used to demonstrate our device.

6.4.1 Static Testing

In a static testing environment, our device's transducers are mounted to a sound producing amplifier that is being sent a given frequency signal through a nearby laptop. The given vibrations would then generate the voltage for our device and ultimately power our accelerometer. Furthermore, the device along with the amplifier remain in a stationary position while the accelerometer still collects data to send to the end user. The purpose of this test is to mimic the vibrations of a rollercoaster at ideal frequency and to be sure the device can power on the vibrations.

6.4.2 Dynamic Testing

In a dynamic testing environment, the same type of set up is applied, only in a moving environment this time. To complete this test, we utilized one of our vehicles and placed our testing equipment inside. Once the device was charged, we would drive for approximately 2 minutes and 30 seconds or more, as our specifications recommend, and then send the data to the end user via Bluetooth. This test is to demonstrate the accuracy of the Bluetooth data being sent as the accelerometer collects data for the end user in an ever-changing position.

6.4.3 Non-Ideal Testing

Finally, we have our non-ideal test. In the two previous tests, we vibrated the transducers at an optimal frequency to maximize the produced voltage. However, it is important to note that these ideal frequencies are difficult to mimic in real world situations. Therefore, we installed our device onto a lawnmower, a vehicle that produces vibrations but is also in a state of motion. This test is important in understanding the physics of the transducers and how we will not always get an ideal frequency and voltage generation. Furthermore, this case helps to understand what improvements can be made in the overall design to increase voltage generation or even piezoelectric resonant frequency.

7 Administrative Contents

This section highlights the managing aspect of the project.
This section includes:

- Budgeting which identifies our financing options
- Project Milestones to list out important dates
- Task Delegation to assign various functions to the members of the team.

7.1 Overall Budget

Item	Amount	Cost	Total Cost
Piezoelectric Transducers	3	$32	$96
Microcontroller	1	$23	$23
Accelerometer	2	$25	$50
Transceiver	1	$10	$10
BOB Unit	2	$30	$60
Supercapacitor	1	$38	$38
Crystal Oscillator	1	$10	$10
Bluetooth Dev Board	1	$30	$30
Printed Circuit Board (no comp.)	2	varies	$14
Printed Circuit Board (comp.)	1	$70	$70
Enclosure	1	$11	$11
Misc Components*	~	varies	$140
Shipping Costs	~	varies	$162
Approximate Total Cost	~	~	**$714 (Max: $750, $36 under)**

**Misc Components includes any items that were used for the fabrication of the board, such as wires, headers, tools, etc that weren't integral to the purpose of the design.*

Table 21: *Overall Budget*

7.2 Project Milestones

This table list the deadlines, tasks, and milestones that are for this project and spans across the two semesters of Senior Design 1 and 2.

#	Task	Start Date	Due Date	Status	Responsibility
Senior Design I					
1	Idea Creation	8/25/2020	9/2/2020	Complete	All Members
2	Idea Selection and Roles Assignment	9/1/2020	9/8/2020	Complete	All Members
Project Report					
3	Initial Document: Divide and Conquer 1.0	9/8/2020	9/18/2020	Complete	All Members
4	Initial Document Updated: Divide and Conquer 2.0	9/22/2020	10/2/2020	Complete	All Members
5	Table of Contents	9/22/2020	10/9/2020	Complete	All Members
6	Parts List	9/22/2020	10/23/2020	Complete	All Members
7	First Draft	9/22/2020	11/12/2020	Complete	All Members
8	Final Draft	9/22/2020	12/8/2020	Complete	All Members
Senior Design II					
9	Build Prototype	9/22/2020	2/01/2021	Complete	All Members
10	Testing / Redesign	2/01/2020	4/10/2020	Complete	All Members
11	Finalize Prototype	3/15/2021	4/10/2020	Complete	All Members
12	Peer Presentation	3/01/2020	4/01/2020	Complete	All Members
13	Final Report	1/01/2021	4/25/2021	Complete	All Members
14	Final Presentation	4/10/2021	4/21/2021	Complete	All Members
15	Final Document	4/14/2021	4/27/2021	In Progress	All Members

Table 22: *Project Milestones*

7.3 Task Delegation

Richard Klenotich II: Aiding in design and testing of electrical based concepts of board, managing budgetary needs and constraints. Energy Storage for entire system.

Juan Rodriguez: Programming and developing software for the microcontroller such as interfacing and displaying data to the LCD. PCB design.

Kristopher Walters: Design, prototype, and implement energy harvesting power source. Funding acquisition. Experiments and Procedures. Testing environment.

Nicholas Villalobos: Developing code for the microcontroller. Transceiver operations and code. User interface applications.

Individuals worked together to achieve common goals. Therefore, these designations refer to leadership roles and responsibilities with respect to deadlines.

7.4 Stretch Goals

These stretch goals are improvement and additional modifications that can improve our project. These are not the main objectives of our project, but if allotted more time, can be pursued to complete these additional goals.

7.4.1 Desktop Application

Our platform will display the data collected using the mobile application on Android that is developed using React Native. Another way that the information can be displayed digitally is using a desktop application. The main advantage of using this user interface is having more real estate so the end user can clear see the information presented on the graphs. The desktop application will connect with a Bluetooth module implemented on the PCB and will receive the accelerometer data that was collected during the duration of the ride.

7.4.2 Wireless Charging

With the increase usage of wireless charging and the standard of Qi charging, the convivence of taking the platform and placing it down on a charging mat will benefit the end user. Instead of using the traditional USB type A to charge through a cable, using a Qi wireless charging module will provide the end user with one less cable to worry about.

7.5 Facilities and Equipment

To maximize our efforts in completing this project and having a successful design process, a thorough overview of available resources at hand must be completed. Thankfully, UCF has provided various resources for student in terms of facilities and equipment. Through these, the product will be able to be efficiently designed.

7.5.1 **Facilities**

Facilities could range from any sort of location in terms of a meeting area or even a lab for testing different forms of equipment. Given most of the time will be spent on campus or near UCF, the use of the facilities around campus are imperative to efficiently prototyping and creating the design. The following facilities available have been highlighted below for our use during the commencement of this project. As mentioned before in the constraints, it is important to note that due to COVID-19, it may not always be possible to have access to these areas as in previous semesters without prior approval. This will increase the challenge of prototyping and completing the design, but it may open new opportunities for how the project may be completed.

7.5.1.1 Idea Lab

The Idea lab is a space located in between Engineering buildings I and II in the commons area, right next to the stairs. It is designed for students to come and brainstorm various ideas within their project in a comfortable and closed off setting. The lab is open Monday through Friday and is free admission. In this setting, our group would be able to brainstorm better ideas on how to further develop our board through discussion, schematics, and prototyping. It would also allow for more productive face-to-face discussion as well given the limitations of zoom. However, lab use will more likely than not be restricted due to COVID regulations and any questions or concerns would have to be presented to Dr Richie, our Senior Design professor and mentor, or Dr Hoekstra, director of the idea lab.

7.5.1.2 Texas Instruments Innovation Lab

The Texas Instruments Innovation Lab is a facility located in Engineering II available to students from 10am-10pm Monday through Friday. Special requests for Saturday or Sunday usage must be scheduled in advance through the lab director. The lab is equipped with an array of testing equipment one would find in a professional setting, including testbenches for soldering and testing hardware, equipment such as oscilloscopes, power supplies, and digital multimeters for parameter testing and functionality, and microprocessors available for testing and debugging. Given most of the prototyping stage will be hands on work with the board, the TI lab is an ideal location to do the heavy lifting of this phase. Again, as mentioned in constraints, access to this lab may be limited for the most part and any questions or concerns our group will have must be directed to Dr Richie or the lab director Don Harper and their assistants.

7.5.1.3 Zoom

While not a physical faculty, zoom provides a much-needed advantage in the current health crisis. As discussed before, COVID-19 has crippled many common ways of communication for senior design, such as sit down, face to face meetings.

However, thanks to Zoom being available for personal use outside of the classroom, this makes the act of meeting up for discussion and planning safe and more feasible. It also allows for us to present our work and findings in a special presentation mode, which can aid in everyone's understanding of the research and progress of the design. The only limit to Zoom would be its occasional 40-minute limit, which can thankfully be bypassed with the use of a student account from UCF. Internet limitations could also hinder meetings as well

7.5.2 **Equipment**

With a set of possibly available faculties for us to use, the fact of the matter which remains is the available equipment for us to not only build our board but test it as well. The following areas have been highlighted as possible equipment to use for the project:

7.5.2.1 UCF Provided Testing Equipment

Given the limitations presented with having access to certain facilities at times, the professors for Senior Design have graciously provided equipment for our team to use. Access to this set of devices will greatly aid in our development of the design outside of the facilities and in our own personal areas. The following list of equipment is available to us:

- Analog Discovery 2 Oscilloscope
- BNC Adapter
- Impedance Analyzer
- Breadboard breakout for AD2
- Breadboard complete with clips, wires, and probes

7.5.2.2 TI Lab Equipment

As mentioned before, the TI Lab contains useful equipment that can be found in a professional engineering setting. Should the lab be used to complete the project, the following equipment is available for use as described on the main page of the lab's website:

- Electronic Lab Bench (4): Equipped with an oscilloscope, function generator, power supply and a digital multi meter.
- General workspace (3 large wooden tables)
- Fully-stocked cabinet of TI microprocessor boards
- Soldering stations with soldering irons (3)
- Microscope for surface-mount soldering
- Basic tools

7.6 Consultants, Subcontractors, and Suppliers

When it comes to the design of a project, a small team rarely is able to complete a large task as this on their own. To combat overwhelming ourselves with one hundred percent of the burden of this design, our team must not only use resources available to us, but also branch out to other areas in order to complete the overall goal. Areas that are reachable in terms of assistance include consultants, subcontractors, and suppliers. Through thorough use of these factors, the overall design will be more feasible to not only create but understand the methods behind its construction.

7.6.1 Consultants

Consultants refer to a group of people our team can reach out to for advice on anything from updating on the progress of our report and overall project to even people who can inform us on different concepts and ideas to further help us conceptualize and realize our design. Reaching out to the right people can keep our design on the right track and free of errors as well. The following types of consultants are listed below.

7.6.1.1 Senior Design Mentors

As part of Senior Design I and II, each team is provided a team of professors to guide them in the right direction for their project. This can range from informing the teams about different deadlines coming up to teaching the team about how reports are created in the professional industry to even critiquing the design and research involved in it. Given their strict deadlines and their constant contact with the teams for the semester, their guidance is more than required in order to be steered in the right direction. Their guidance can allow for deadlines to be met, improvements to the research and where to look, and even further advances in the design process.

7.6.1.2 Other UCF Professors

Given the experience of the professors assigned for Senior Design, they are not the only professor available for advice towards completing the overall objective. UCF contains a vast amount of professors with ranging experience and training to lead us in the right direction. For example, since our design relies heavily on piezoelectric transducers, preferably a professor who has had experience in researching or even using said transducers. Another example would be to refer to a professor who has experience in transmitting data wirelessly, whether through a Bluetooth or through other means, since our design also involves transmitting data wirelessly. Venturing outside our given mentors for Senior Design to other professors in our department will most definitely aid in our success for designing our idea.

7.6.1.3 Outside Professionals

While UCF does have a wide variety of professors to refer to in terms of advice, this is not where the limit for possible consultants stops. There are a great number of people in the professional industry with experience in project design to refer to when seeking professional advice for our device. For example, Kristopher Walters in our group has worked with Disney's Hollywood Studios Sustaining Team for an internship and has worked with individuals that can give professional advice based on mounting the device to a rollercoaster and even design-based questions. Another example is Richard Klenotich, who is currently employed at Leonardo DRS and works with different levels of professional engineers who have had experience in designing electrical based designs for electro-optics devices. Using outside consultants wisely can not only expand our overall web of consultants, but furthermore expand our efficiency in designing our project.

7.6.2 **Subcontractors**

In order to efficiently build our board once the design is finalized, we will need to refer to professionals to aid in our endeavors in terms of building it. The professionals are referred to as subcontractors.

7.6.2.1 PCB Manufacturers

While our group might be able to create a board using a prototype PCB breadboard, the actual final board itself will need to be designed in a professional manner since a thrown together breadboard would not be accepted outside of testing. Thankfully there is a selection of PCB manufacturers available for us to select from. Two selections we have concluded we will refer to are PCBWAY and JLCPCB, who have been used in the past from previous Senior Design students. Through their contribution to our project, we will be able to design a professional board that will be presentable, easily modifiable, and competently made.

7.6.2.2 Quality Manufacturing Services (Component Layer)

Our group can order the PCB from other facilities that are available, but another issue that is at hand is the possibility of messing up any of the components being placed on the board. While bigger components such as possible inductors won't be too much of an issue to solder on, more finer components such as op amps, or even the use of 0402 size components, being soldered on personally could lead to some unforeseen consequences. Quality Manufacturing Services in Lake Mary provides exactly that kind of service, allowing professionals to take our PCB and components and lay them on professionally without the possibility of personal error. This may contribute to an increased overall cost for our design, but the cost would outweigh the possible cons that come with soldering components on by ourselves.

7.6.3 **Suppliers**

In the process of creating our design, we will also need access to groups which can provide us with individual items for either subcontractors or ourselves to assemble onto the board. The provider of these components and such are suppliers. Through the use of these suppliers, we will be able to procure items to not only create our board, but also even test our board. The following suppliers are highlighted below.

7.6.3.1 UCF

Already highlighted previously, UCF can also be considered an initial supplier for our design in terms of test equipment and access to different tools for construction. Senior Design supplies the group with a set of different test equipment, which has been highlighted in the equipment section, and has the TI Lab which has access to certain materials for construction, such as soldering irons, microcontrollers, and test equipment. While not necessarily integrated into the design, these items are crucial to the overall completion of our goal since we will need testing equipment and access to different forms of construction we would not easily access on our own.

7.6.3.2 Mouser

Mouser is a popular component distributor that sells the products of different vendors for design related builds. They contain anything from small surface mount resistors to heavy duty connectors for military related designs in their database. Along with their extensive database, Mouser often provides an extensive list of the functionality of each component along with a datasheet to fill in any gaps of knowledge. Should we choose a main source to buy any components from, Mouser would be the ideal choice given their reliability in delivering materials. One may suggest the use of Digikey, another popular distributor, but given their issues with final costs, it can be difficult to rely on them for accuracy of pricing.

7.6.3.3 Murata

Murata is one of many electronic component distributors available at our disposal. One way they are superior to other options is that they specialize in piezoelectric components. To complement their emphasis on this component, they also provide them at reasonable and cheap prices with a fast rate of delivery according to reviews. Considering our design is heavily reliant on piezoelectric usage, this distributor is a perfect choice for our prototyping and eventual creation of our board.

7.6.3.4 American Piezo (APC)

APC uses CNC technology to manufacture different shapes and sizes of the piezoelectric ceramic material. Some of the common shapes include discs, rings, and plates. The outer dimension provided for the disc is 0.250” to 2.0” and contain a thickness ranging from 0.008” to 0.4” depending on the material.

8 Conclusion

After extensive research and prototyping, our team was able to successfully design a sensory device that extracts its own power from the vibrations of the vehicle it is installed on. While our design was very successful, it required many ideal conditions. These ideal conditions included the constant presence of the piezoelectric transducer’s resonance frequency, and installation on a vehicle with large amounts of vibrations. These requirements can be avoided by installing a more diverse array of piezoelectric transducers or by installing transducers capable of changing their resonant frequency in response to stimulus. Both solutions were unfortunately far beyond the financial capabilities of this project. These solutions would also provide the entire system with more power, allowing for more data collection, additional peripheral sensors, or even sensors that require a substantial amount of power. These solutions will not be cheap, as the overall energy harvesting design used in this project accounted for approximately 72% of the entire budget. Despite the financial constraints on the energy harvesting process, it was still considered a huge success.

On the software aspect of the project, the microcontroller was successfully able to manage the power given to the system. When the Atmega328p was placed in low power mode for 8 second intervals, the system was harvesting more energy than the entire system consumed. The power was properly distributed to the peripherals to turn on and collect data from the accelerometer. The only downside to this approach was the data points were collected every 8 seconds since the microcontroller could not accept any outgoing signals from the peripherals during low power mode. Even with this tradeoff, the system was able to function and provide useful data to the end user in the form of the mobile application. Developing the Android app was challenging, but despite the setbacks the application properly displayed and recorded the data in three dimensions to the end user. After all these successes, our fully functional system provides data to the end user through the energy harvested from the piezoelectric transducers.

9 Appendix
9.1 Work Cited

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9.2 Copyright Permission Request

9.2.1 **Power Converters Design and Analysis**

Pooya Davari
RE: Copyright Permission
To: Juan Rodriguez, Cc: n.ghasemi@uq.edu.au, f.zare@uq.edu.au

12:15 PM
Details

Dear Juan,

You are welcome to use it, please remember that you need to cite the paper that you are taking the figure from it.

Venlig hilsen / Best regards

Pooya Davari
Associate Professor
PhD, SMIEEE
IEC Member (JWG6&WG8)
Editor-in-Chief, Circuit World

Department of Energy Technology

Personal Profile

Projects: REPEPS, LOW-HARM, eSMR-MeOH, BioCat, HiRED, MHDPES, NHTD

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Employee No. 132681 I EAN: 5798 000 42 08 16 I VAT No.: 29 10 23 84

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See More from Juan Rodriguez

Found in Sent - UCF Mailbox

Juan Rodriguez
Copyright Permission
To: pda@et.aau.dk, n.ghasemi@uq.edu.au, f.zare@uq.edu.au

12:09 PM

Hello,

I am a student at the University of Central Florida. I am currently doing research for my Senior Design Capstone Project in regards to Piezoelectric Sensors. I would like to obtain permission to use an image for my research paper in regards to resonance frequencies in piezoelectric. Please let me know if I have permission to use Figure 1: Resonance and anti-resonance frequencies in piezoelectric impedance frequency response within the paper "Power Converters Design and Analysis for High Power Piezoelectric Ultrasonic Transducers"

Thank you,

Juan Rodriguez

9.2.2 **Electronic Wings**

ElectronicWings 1:57 PM
Re: Copyright Permission
To: Juan Rodriguez

Yes, of course you can.
As open source policy, please mention credit & URL link.

Regards,
ElectronicWings

See More from Juan Rodriguez

Found in Sent - UCF Mailbox

Juan Rodriguez 11:36 AM
Copyright Permission
To: contact@electronicwings.com

Hello,

I am a student at the University of Central Florida. I am currently doing research for my Senior Design Capstone Project in regards to LCDs connection to a microcontroller unit. I would like to obtain permission to use the image found within the article "LCD16x2 Interfacing in 8-bit with 8051". Please let me know if I have permission to use the image pertaining the pin layout for the LCD display.

https://www.electronicwings.com/images/user_images/images/8051_20160803/8051_LCD_16x2_8bit/LCD16x2%20Pins.png

Regards,

Juan Rodriguez

9.2.3 **Transducers; Dimensions, Layer Specifications**

EMAIL US

First Name* Kristopher

Last Name* Walters

Email* walters.kristopher@knights.

Phone number

What Is Your Enquiry About? Technical Question

Do You Mind Sharing How You Feel? Happy

Message

I am an undergraduate at the University of Central Florida. My senior design team and I are requesting permission to use images from your website for our project. The images we would like to use are of the dimensions, layer specification, image of the transducer regarding these two products:

S118-J1SS-1808YB (https://piezo.com/products/piezoelectric-bending-transducer-s118-j1ss-1808yb)

S129-H5FR-1803YB (https://piezo.com/products/piezoelectric-bending-transducer-s129-h5fr-1803yb)

We are successfully using these products to harvest energy. May we use the images in our paper?

Send Message

Piezo.com is a Division of Mide Technology

enDAQ is a Product Line of Mide Technology

EO

Emily O'Donoghue <help@piezo.com>
Mon 12/7/2020 3:34 PM
To: Kristopher Walters

Hi Kristopher,

You are more than welcome to use our photos! We just ask that you reference us in your project :)

Best,
Emily

How would you rate my support?

PIEZO.COM | **Your Customer Success Team**
help@piezo.com

PIEZO.COM is a Division of Mide Technology

9.2.4 **Measuring the wheel-rail forces of a roller coaster (Pending)**

Juan Rodriguez Sent - UCF 11:27 AM
Copyright Permission
To: andreas.simonis@ifs.rwth-aachen.de

Hello,

I am a student at the University of Central Florida. I am currently doing research for my Senior Design Capstone Project in regards to Piezoelectric Sensors. I would like to obtain permission to use an image for my research paper for my section on existing projects. Please let me know if I have permission to use Figure 2: Non-rotating dynamometer for a car tire according to Ev- ers et al. (2002) and Bonfig (1995) found within the paper: "Measuring the wheel-rail forces of a roller coaster".

Regards,

Juan Rodriguez

9.2.5 **Speed Bump with Piezoelectric Cantilever System (Pending)**

Juan Rodriguez Sent - UCF 11:24 AM
Copyright Permission
To: esti@instrument.itb.ac.id

Hello,

I am a student at the University of Central Florida. I am currently doing research for my Senior Design Capstone Project in regards to Piezoelectric Sensors. I would like to obtain permission to use these two pictures for my research paper for my section on existing projects. Please let me know if I have permission to use Figure 1: Speed bump mechanical module and Figure 2: Piezoelectric cantilever module found within the paper titled: "Speed Bump with Piezoelectric Cantilever System as Electrical Energy Harvester".

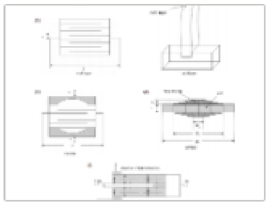
Regards,

Juan Rodriguez

9.2.6 **Piezoelectric Morphologies (Pending)**

KW

Kristopher Walters
Mon 12/7/2020 3:10 PM
To: cookchen@soe.rutgers.edu



Hello,

I am an undergraduate at the University of Central Florida. My senior design team and I would like to include images from your publication (**Powering MEMS portable devices — a review of non-regenerative and regenerative power supply systems with special emphasis on piezoelectric energy harvesting systems**) in our senior design paper. We are planning to use them to discuss our decision in transducer selection.

See related images attached.

Thank you,

Kristopher Walters

Reply | Forward

9.2.7 **Piezoelectric Design Images (Pending)**

From: Kristopher Walters
Sent: Wednesday, November 11, 2020 12:13 PM
To: Wahied@ksu.edu.sa <Wahied@ksu.edu.sa>; Gihan@ksu.edu.sa <Gihan@ksu.edu.sa>
Subject: Senior Design Permission Request

Hello Dr. Wahied and Dr. Gihan,

My undergraduate senior design team is working on a project regarding piezoelectric transducers. We plan to use an energy harvesting system to power sensors on board rollercoasters. We came across your research, **Design Considerations for Piezoelectric Energy Harvesting Systems (2014)**, and it has been an excellent source to expand our understanding.

May we have permission to utilize images from this paper (and properly cite them) in our senior design paper?

Thank you,

Kristopher Walters
Major: Electrical Engineering
University of Central Florida