Powering Roller Coaster Sensors Via Piezoelectric Transducer

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***Abstract* — Sensory devices require power to collect data. Roller coasters without onboard power are typically unable to host these sensors. The following design proposes to harvest energy to provide power onboard roller coasters using piezoelectric transducers. By harvesting the energy from mechanical vibrations, the transducers may power a peripheral device such as an accelerometer. A processor will then collect the data from the sensor while also governing power consumption. This data will be made available to the user through transmission.**

***Index Terms* — Piezoelectric Transducers, Energy Harvesting, Supercapacitors, Bluetooth.**

I. Introduction

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.

II. Project Objective

The objective for this design is to operate sensory devices with power harvested from vibrations onboard roller coasters. Additionally, the data that the sensor collects needs to be read, stored, and available for extraction.

The design proposed provides a solution utilizing piezoelectric transducers to harvest the energy from the vibrations present on the roller coaster. The sensor considered is an accelerometer due to their typical low power consumption. A microprocessor is to be implemented to govern data acquisition and control power consumption. A Bluetooth module will be used to easily transmit the data from the device to a mobile application. This mobile application then stores the data collected into a database, where all the data is time stamped for further analysis. All data is to be presented in a user-friendly manner, displaying the accelerations in three distinct axes.

III. Design Requirements and Specifications

Given the scope of this project, it is important that proper specifications were established early on so that the project could be developed with an unobstructed vision as well as reintroduce the functionality of the project when needing reference. Should failure to follow these specs occur, then the system needs to be evaluated fully and completely with an established solution before proceeding.

To start with, the device overall, including its peripherals, should use no less than 5 Watts of power overall. Because the point of the device is to conserve energy that is being harvested by the piezoelectric transducers and its corresponding BOB units, it is important that our on-board devices consume as little power as possible in order to both maximize the energy being stored as well as minimize the overall energy being used. The maximization and minimization will also be critical to the overall runtime, which will be discussed further on.

Secondly, the Bluetooth transceiver that is being used for this device must be able to send any and all data it collects to the end user in less than a single minute. In order for our device to be truly efficient and worth our customers time, we need to be able to show that the device transmits data in a quick, efficient manner, hence the strict timetable established for this device.

Furthermore, relating to time windows, the system needs to be able to run for more than two minutes on a single charge. Given an average time for a rollercoaster to complete its run is around two minutes and it is crucial to collect any data during that period of operation, our harvesters and given power storage must be able to not only harvest enough voltage to power the board but be able to run it for a given amount of time in order to maximize any data collection for the end user.

As for the physicality of the system itself, we established it should not weigh more than 5kg or 11lbs. The device needs to be able to be installed on a rollercoaster without being too invasive or being a possible liability to the functionality of the rollercoaster, so keeping it as lightweight as possible will reduce any possibility of it causing any invasive or even portability issue.

Finally, the established budget of the project is $700 and should not extend beyond that. This is to ensure that while a self-powering sensor, it can also be cost efficient to the user and not spending much money. However, given that there are possible mishaps that may occur in development, it could be possible to extend beyond $700, but this would defeat the purpose of making it cost efficient.

These are established guidelines to ensure a safe and functional device. While they do not necessarily have to be as strict as established, coming as close to these parameters as possible can ensure that the device would be economical, ergonomic, and pave the way for further self-powering devices.

IV. Design Constraints and Standards

These constraints placed on our project are implemented to create the platform that adheres to these limitations. With these limitations in place, our project is able to set boundaries that will help our project with a focused narrative. With this project, our major requirement is in the form of safety for our team members and other members using the equipment. The safety measures implemented protect our team members from an electrical shock or faultily power systems while working on stationary vehicles.

Our product must be reliable as the system will be onboard various environments including hot or cold weather as well as rain. Along with dealing with environmental constraints, our major limitation was placed on budgetary as well as time constrains. This project was fully self-funded as our team members purchased parts using our own monetary means without the aid of a sponsor. Without a sponsorship or any other additional cash flow, our budget was limited so the project did not exceed our own revenue source. With the limited amount of time our project contained as well as shipping times for certain items being prolong due to the pandemic, our team worked quickly and efficiently to manage our time allotted for the project. By implementing a schedule, our team divided the workload amongst the members to accomplish our weekly goals.

V. Overview of System

A. Piezoelectric Transducers

The piezoelectric transducers were selected to meet 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 device 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.

B. Microcontroller: ATMEGA328p

For this project the Atmega328p was the ideal choice as the microcontroller. Similar to the Atmega328, the one chosen is a variation of the original as the P suffix stands for picoPower. Even though it is a little bit more expensive that the base model, this model provides the benefit of using less power which is ideal for our scenario.

These MCUs are commonly found within Arduino boards and are based on an advanced RISC architecture. Containing larger flash memory (32 KB) and more RAM (2 KB) than the other options is a great benefit as our data needs to be stored and execution of instructions need to occur quickly. In regard to power, this MCU contains six sleep modes with the most consuming mode taking only 15 mA (SLEEP_MODE_IDLE), while the lowest mode only utilizes 0.36 mA (SLEEP_MODE_PWR_DOWN) [1]. These modes along with the various support and documentations makes the Atmega328p the perfect choice for our project.

C. Supercapacitor

In the discussion of harvesting energy, we were presented with the obstacle of how we were going to store our energy that we harvested from the transducers and BOB units. Originally, we had considered a lithium-ion solution to this, but given their volatile nature, especially in a situation where they may be required to supply more voltage than they can handle and even have deterioration over time due to multiple recharges, we opted for another solution.

This is where our supercapacitor comes in. Given its ability to discharge energy more efficiently and have a commonly longer lifecycle than a battery, the supercapacitor is an optimal albeit more expensive choice for the application of an energy harvester. At a rating of around 16V, the capacitor ideally can hold more than enough voltage to supply the board its necessary power for the duration of a single rollercoaster run. Its 160mOhm ESR also allows it to be more efficient when not in use, as any discharge or voltage leakage is minimized due to this rating. This is reflected in prototyping Phase I when the capacitor was charged to around 9V and only had a voltage leak of 1mV per every 4 seconds when the transducers were not charging it.

Another positive of this component in our design is the exponential decrease in energy it takes from the BOB units over time. When testing initially with Phase I, the rate of voltage being stored in the supercapacitor decreased over time, especially when reaching around 9V. While this may at surface glance seem like a negative aspect of the supercapacitor since it is not reaching the 16V it can get to, in reality what this means that should there have been a mishap and the capacitor was charged for longer than it should have in ideal conditions, this would not overload the absolute maximum rating, especially if the capacitor is reaching a voltage threshold.

D. Accelerometer: ADXL377

This 3-axis accelerometer sensor operates around 1.8V - 3.3V and contains a rated current draw of around 300 μA. A low power consumption and operating at 3.3 instead of 5 volts made this sensor a great component to install on the system. A unique feature this accelerometer contains is the ability to measure a large span of acceleration data with a range of ±200g. With the extended functionality of measurement, the sensor can accurately capture more data points regardless of sudden motion like sharp turns.

E. Bluetooth Module: HC-05

HC-05 is a Bluetooth module that works using UART protocol through the use of the TX and RX pins. With this serial communication, the component easily interfaces with mobile phones and computers. This module supports multiple baud rates while containing a range of less than 100 meters. Containing a large range benefits the system to communicate easily with the mobile application over large distances. With quick transmission of data between the microcontroller and mobile application, the end user benefits from this transaction as all the data points appear on the application within a minute. Along with rated for low power operation, this module is fully functional within our system.

VI. Design Plan Overview

To accomplish the goals of this project, the work was divided into three distinct design phases. The three phases implemented were to distinguish clear goals in order make the final design as efficient as possible.

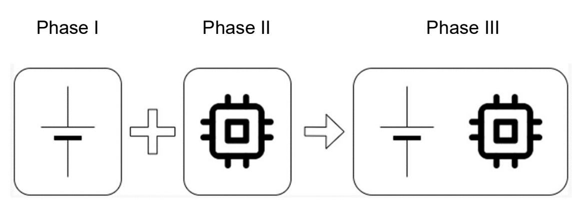


Fig. 1. Demonstrating the relationship between the phases of this project: Phase 1 (left) harvests and stores energy, Phase II uses energy to gather data, and Phase III combines the two to make one functioning data-storing sensor.

A. Phase I: Energy Harvesting

Phase I of the project focused on the energy harvesting system. The goal of this system was to supply the maximal amount power (and store it) as possible using minimal financial resources. This phase included developing a testing environment, testing piezoelectric transducer efficiencies, implementing energy harvesters, and storing the power harvested into a supercapacitor. The overall system was designed after studying the design proposed by Ali and Nagib [2].

B. Phase II: Data Acquisition

Phase II designed the data acquisition portion of this project. The goal of this system was to obtain the maximum amount of data while consuming minimal power. Decision making in this phase included assessing usable sensors, selection of a low power microprocessor, transmittance of data, and user-level data viewing.

C. Phase III: Combining Designs

Phase III introduced the final design of Phase I as the system used to power Phase II. This phase combined the overall efforts of the computer and electrical engineers into one device. Phase III was also reserved as the time to solve all unresolved conflicts between the previous phases.

VII. Phase I Design and 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:

Fig. 2. 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 third and 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 16 minutes.

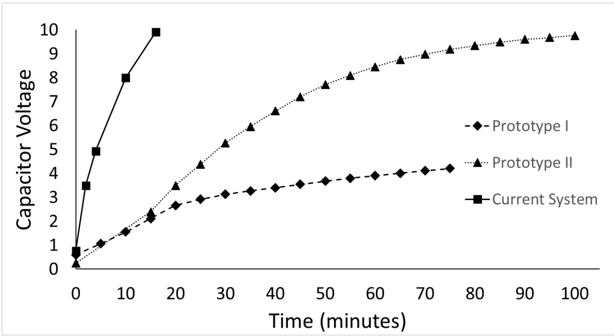


Fig. 3. Voltage of supercapacitor over time during testing of Phase I. All voltages read while providing the resonant frequency of the system, resulting in the best-case-scenario charge times for each design.

VII. PHASE II DESIGN AND RESULTS

As stated before, the main purpose of Phase II is to acquire data from the accelerometer and transmit it through the use of Bluetooth. The main challenge within this phase was implementing the design to consume less power. With the initial test running, the microcontroller was not placed in a low power state and would use all the power provided from the transducers. In this condition, the microcontroller would run for about two minutes with no peripherals connected. This scenario was not ideal as the MCU would distribute power to the other components. To overcome this obstacle, the MCU was place in a low power mode for a certain amount of time in order for the transducers to generate enough power to be utilized.

Figure 4 illustrates the logic for the microcontroller. The main goal for the MCU is to harvest energy for the system while collecting data for the accelerometer. The system gains power from the piezoelectric transducers and once the threshold voltage is reached (around 5V), the energy harvesters decide to provide power to the microcontroller. When the microcontroller is powered, it enters the lowest form of sleep mode (SLEEP_MODE_PWR_DOWN which consumes about 0.36 mA [1]) for 8 seconds. After exiting out of sleep mode, the MCU checks if Bluetooth is connected to the system. If Bluetooth is not available, the system will get the current accelerometer data in the form of the X, Y, and Z axis then enter into sleep mode again. Once Bluetooth is available, the data is transmitted from the MCU to the mobile application. The mobile application displays the data that is easy to read for the end user.

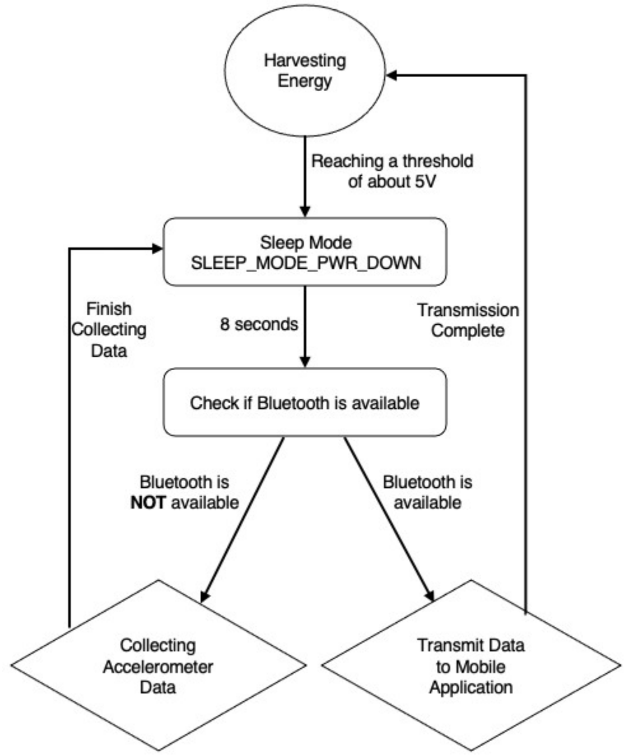


Fig. 4. Data Management Flowchart.

VIII. PHASE III DESIGN AND RESULTS

When testing finalized for the separate issues relating to phase I and II, phase III was ready to be implemented. This was accomplished by finalizing our PCB design and incorporating the separate hardware and software together on the board. Given a majority of our board had solder holes, this lead initially to some difficulty with integration but eventually it all was soldered on properly.

When finally testing the fully assembled system for the first time, we noticed an error in our prototype testing from previously. We had only powered the supercapacitor without the Atmega328p, Accelerometer, and Bluetooth previously and with the integrated system, we discovered that the capacitor would not charge up to the optimal 9V we had previously established. It would charge to around 5.03V before activating the Atmega328p and draining the capacitor to around 3.3V in 20 seconds. We had already ruled out the Bluetooth transceiver as an issue since we had installed a separate power source for it, so we debugged any other issues that might have been causing this, one of them being the possibility of our accelerometer drawing too much power since it had an extensive g range. Another possibility was an issue with the Atmega328p timer and not being properly coded to allow the capacitor and BOB units to reach an optimal charge before being used.

For this issue, the problem was identified with the microcontroller not distributing the power effectively. Once the threshold voltage is obtained, the microcontroller would provide all the power available to the accelerometer in an instant. To solve this issue, the Atmega328p was placed in the appropriate low power mode (SLEEP_MODE_PWR_DOWN) in order to consume less energy that was provided to the system. For the microcontroller to govern power to the peripherals, the pins were connected to the digital input (located on pin 14) in order to manual turn on and off the accelerometer when necessary. With this software solution, the system was able to consume less energy than the amount provided.

Fig. 5. Overall Enclosure for Device

For the enclosure of our device, we decided to go with the LeMotech Project Box. Given that our board will be exposed to various environmental hazards, our board requires an enclosure that will protect it from extraneous factors such as weather and various forces. LeMotech's enclosure provides the specs we need to where it can fit our board and piezoelectric mounting inside with ease while also protecting it from outside factors. Its rugged design also allows its internals to be protected from any force that may occur, given proper mounting for the units inside.

IX. Android Application

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.

Fig. 6. Mobile Application Data Display

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.

Fig. 7. Bluetooth Connection Screen

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.

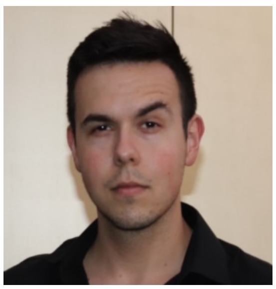
X. Conclusion

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.

THE ENGINEERS

Kristopher Walters is currently a student at the University of Central Florida and will graduate with a Bachelor of Science in Electrical Engineering. He recently finished an internship at Disney's Hollywood Studios where he worked on the numerous coasters and attractions. Currently seeking employment at both amusement parks and aerospace companies.



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