Bass Connections Program

Energy & the Environment: Design and Innovation

Construction and Analysis of a Low Frequency Energy Harvester of Ambient Human Motion

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Executive Summary

As technology is becoming an integral part of daily lives, the demand for convenient energy has grown exponentially over the last few years. The team addressed this demand by designing two backpack add-ons that harnesses energy generated from interactions with the environment: converting ambient kinetic energy to electricity to charge small devices. The team is prototyping two designs: an electromagnetic harvester that captures linear motion, and mechanical harvester that captures angular momentum. Simply put, the electromagnetic harvester consists of a powerful magnet that oscillates through a conductive, coil-wrapped tube, and the mechanical system consists of a pendulum that drives a gear system and motor. Both models are in their early stages and have undergone rigorous testing to determine which system will fare well in the long run. Out of the two energy harvesting methods considered, the team concluded that the electromagnetic system had the greatest potential (no pun intended). From the experimental testing, the magnet-spring system was able to store a maximum of 5.152×10^{-5} Joules within a 1000μF, 50V capacitor after one minute of activity. The average excitation frequency ranged from 1.83 Hz to 2.02 Hz, and the average excitation amplitude ranged from 3.35 in to 3.74 in. Based on these preliminary results, it would take the backpack roughly 16,836 days to charge the most recent model of the Apple Watch™. Although the current model is not suitable for generating enough electricity to charge electronic devices, the design holds significant promise for charging phones and other small devices in future design iterations.

Introduction

A severely underutilized source of energy that is generated in daily life is low frequency ambient mechanical energy. This mechanical energy can take many forms, for example, vibrations produced by wind and waves, or the movement of objects and people. Recently, there has been significant scientific interest in the potential to capture ambient mechanical energy, especially in the context of research literature (Tolou). Other than utilizing people, many forms of ambient mechanical energy harvesters have been created and are being implemented. The harvesting of wave power is a quickly developing and potentially revolutionary venture in the US sponsored by the Department of Energy (Dozier). Very recently, Wave Energy Scotland and Mocean Energy unveiled a prototype wave energy harvester with the projected ability to "power 50 million homes and cut 50 million metric tons of carbon dioxide [annually]" (Landl).

The aforementioned low frequency ambient mechanical energy also includes energy generated from natural human movements (e.g. walking home from school, moving between classes, biking to the store). Low frequency human energy harvesters first must overcome a number of obstacles before becoming viable and effective replacements for small, wasteful, short-lived, and environmentally harmful batteries. First, the harvester in question must be designed to respond to incredibly small movements, and in-depth optimization must be done to ensure energy is generated at all. Another point of difficulty is actually capturing and using this energy. The circuit the energy flows into must have a low enough resistance to utilize it, the energy must be converted from AC to DC, and a method of energy storage must be employed as energy is slowly harvested in small increments.

Other similar technologies (low frequency energy harvesters of human motion) exist either exclusively in research applications, or are being used for military backpacking applications (Himmelstein). The most publicly-accessible, effective backpack energy harvesters are heavy models with a body suspended on rails with a built-in energy generating system (Ball). A schematic of this design by Rome et al. can be seen in Figure 1 below.

Figure 1. Backpack-on-rails harvester designed by Rome et. al.

Our design eliminates this built-in element to make the overall product a more accessible and sustainable option, removing the need to buy an entirely new backpack and adjust to a different carrying experience (and thus, decreasing the cost and material input in the manufacturing process). The ideal model will simply be an add-on device designed to be carried either by hand or in a bag, rather than a full reconstruction of a bag itself.

Technical Design

Energy Type Selection

The design team considered four primary modes of harvesting energy: piezoelectric sensors, small solar panels, mechanical systems, and electromagnetic systems. Decisions were made using a Pugh scoring matrix, which can be found in Appendix A (Table A1). Initially, the team was optimistic about creating a piezoelectric construction, but creating a custom piezoelectric material would have been far out of the scope of this project, and purchasing effective materials would have been extremely costly (further, in many cases of actual piezoelectric application, the designs were criticized for the carbon footprint of the materials). Solar was also a promising choice in terms of energy generation, but for the purposes of the project, the team felt as though mechanical and electromagnetic harvesting methods would better exercise design abilities and innovation. From research, an electromagnetic system was the second most promising in terms of energy production and provided a lot of room for creativity. The team is currently considering a mechanical design system, which includes a pendulum and gear system, in which a thin weighted pendulum oscillates within an acrylic casing, as well as the electromagnetic system, which involves two small tubes, roughly the size of soda cans, placed on either side of the backpack. These tubes are wrapped in wire and a magnet oscillates between the wire loops, inducing a voltage.

Design Approach

Despite solar being the highest ranked in the team's decision matrix, the team decided to focus on an electromagnetic approach instead, as there is an existing market for solar harvesters in the backpacking field. The team also discussed how the electromagnetic approach has potential to be more elegant than a mechanical approach, with less net energy loss. Furthermore, the team decided to have the energy harvesting device be a separate component to attach to a backpack rather than built-in to the bag itself. This choice would save materials (and costs) from manufacturing or purchasing backpacks, and the user will have the flexibility of only using the device when desired.

Walking Data

Since both the electromagnetic and mechanical approach entail converting kinetic energy (from walking motion) to electricity, the first task was to analyse the motion from within the backpack and determine the ideal orientation for the system and parameters (dimensions, weights, magnetic field strengths, spring constants etc) for maximum output. A smart phone was used as an accelerometer and placed inside a backpack and worn by a team member who walked around campus. The data collected from this was analysed using Python (libraries such as NumPy, matplotlib and SciPy were implemented). Please refer to Appendix B Figures B1, B2, and B3 for the accelerations of the device inside the backpack along the x, y and z-directions. These figures represent the accelerations when a person walks at varied pace over varied terrain. The data indicates that there is some "side-to-side" and "up-and-down" motion that could be harvested by the device. The team noticed that the "up and down" motion in the z-direction was most significant, but wanted to also find a way to utilize the motion from the x and y directions. These observations inspired our choice to use the electromagnetic design to harvest energy from the z-direction, and the pendulum design to harvest energy from the x and y-directions.

Electromagnetic Design

For the electromagnetic approach, the team conceptualized a magnet moving between coils to induce voltage. Instead of converting kinetic energy directly to electromagnetic, a buffer in the form of springs was considered that would allow storage of kinetic energy into elastic and subsequently, transformed to motion of magnet. These parts could be housed in a cylindrical tube of inner diameter equal to the diameter of the magnet so as to ensure linear motion. The longer the tube, the greater the amplitude of the oscillations and therefore, greater electrical output (Liu). According to the prototype described by Liu et al, which involves a similar design, this would also reduce operating frequency of the device and bring its resonant frequency closer to that of human walking. For ends of the tube, a cap was designed with spaces for attaching a spring (see Appendix C). The coil would be wrapped around the outside of the tube, with as many turns as possible to generate maximum output voltage (Equation 1):

$$\varepsilon = -N\frac{d\Phi_B}{dt} \qquad \text{(Equation 1)}$$

Where N is the number of turns on the coil and $\frac{d\Phi B}{dt}$ is the rate of change of magnetic flux.

The resonant frequency is given by Equation 2:

$$\omega = 2\pi f_0 = \sqrt{\frac{k}{m}} \qquad \text{(Equation 2)}$$

Equation 2 implies that a smaller k and larger m will lead to a smaller resonant frequency (our goal, as human walking frequency is low). Thus, a spring with a smaller spring constant rating and heavier magnet should be used, which works well as the team found that heavier magnets (such as neodymium) tended to also have higher magnetic field, which is inversely proportional to induced voltage since the magnetic flux is given by Equation 3 below, where B is the magnetic field and A is the area perpendicular to the magnetic field.

$$\Phi_B = BA \qquad \text{(Equation 3)}$$

Pendulum Design

The basic idea behind the pendulum design was to use the tension of a swinging pendulum to rotate a pulley, harvesting mechanical energy, see Figure D3. The pendulum would be encased in a body attached to the inside of a backpack, sitting laterally against the carrier's back. The team sized the pendulum body against a textbook, an object that a student would already be carrying, to overcome potential friction in marketing towards young adults while also maintaining fairly reasonable dimensions. The alignment in the backpack was chosen for comfort—laying against the back as a laptop or book would within the backpack—while also maximizing the side to side sway of human motion while walking. A significant design constraint was weight. While other factors could be altered for comfort's sake, the weight demand of a mechanical design lay primarily in the large amount of metal parts. The gears, axle, and weighted pendulum (weighted to maximize generated energy), all contributed to a significant load. The design itself was also fairly inefficient: it requires a number of rotating axles that add to energy loss due to friction. The team attempted to mitigate this with a pendulum design involving only two axles and minimized friction by restricting the pendulum's degrees of freedom.

An alternative and final design consisted of a weighted pendulum, which would oscillate upon an axle that has a larger gear on the input axle. That input axle would then rotate a secondary axle which was connected to a smaller gear and a DC motor. The DC motor would generate power for the circuit. Since the pendulum created a significant amount of torque with a relatively low angular velocity, 3:1 gear ratio was used to increase the angular displacement of the DC motor's shaft, therefore increasing the potential amount of electricity that could be harvested by the pendulum (Figure D6). The oscillatory nature of the pendulum, however, temporarily posed a problem. As the pendulum would swing back and forth, the generated electricity would then oscillate as well, cutting the design efficiency in half, as the pendulum would only generate electricity as it swung in one direction. After much consideration, two possible solutions arose—the pendulum could either be connected to a mechanical rectifier or an electrical rectifier. A mechanical rectifier would ensure that the output shaft only rotated in a single direction, however, it would be subject to significant frictional losses as several more shafts would have to be used. An electrical rectifier (full wave rectifier) would convert the alternating current created by the DC motor into direct current, with a theoretical max efficiency of roughly 81.2% (Kumar) however the required base voltage for rectification was higher than the pendulum could create. The mechanically rectified pendulum design was ultimately chosen as the top pendulum prototype as it would be able to function on the necessary scale. Future iterations of the mechanical rectifier would be miniaturized in order to reduce prototype weight, or perhaps an electrical rectifier which could operate efficiently on a smaller scale could be used instead.

Circuit Design

The final part of the prototype is a circuit system that is able to store and transit the energy generated by the harvester. The current magnet and spring energy generating prototype generates AC electricity and low and fluctuating voltages. The team then determined through an extensive literature review that supercapacitors would be the ideal way to store the energy generated by the harvester.

Supercapacitors (or ultra-capacitors) can be viewed as an intermediate between conventional batteries and capacitors. Like capacitors, they can charge continuously even at low voltages, do not require a constant current, and have faster charge and discharge times. Their higher capacitance ratings means they can also store large amounts of energy. Also, super-capacitors are more durable than batteries and do not generate much heat. These properties make them compatible with the energy harvester and ensure that the device can harness all the generated energy. The major disadvantage though is that their output voltage level varies with their charge state, making it difficult to directly use them to charging devices. However, this issue can be solved by using a DC-DC converter that directly connects to a USB port.

The next part of the design process was to configure a way to connect the harvester to the supercapacitor. The team conducted another extensive literature review of past research on that specific topic. The team found that the most efficient way would be to use a specialized IC (integrated circuit) chip that was designed to manage power flows from low voltage sources. IC's have many integrated components that allow for the control of the charging, and performance of the circuit. The team determined the best options for energy harvester ICs that would be suitable for the circuit design, and designed circuit configurations based on the operation manual for the IC. However, upon delivery the ordered parts were too small to solder by hand, and would require a complex and lengthy process to create the circuit the team had designed based on the parts.

The solution the team found to this problem was to use a premade evaluation board for one of the chosen energy harvester ICs. The specific part is the Texas Instruments (TI) BQ25570EVM-206, which includes a pre-installed bq25570 (see Figure G1 and G2 for schematics). The board was designed to give maximum performance for a predetermined voltage input and output. Although this option offers less flexibility to tuning the IC to the specific energy harvester, it is still effective in charging the supercapacitor. This evaluation board also integrated other circuit components that provided low-voltage AC-DC conversion and voltage management. This AC-DC function in particular helped us curtail the voltage and current losses from adding external diode or rectifier components. The internal schematics of the evaluation board with the pre-installed IC chip is shown in Appendix G.

Manufacturing Process

The prototyping and manufacturing process centered around two different workflows: the mechanical system and the circuit system. This section will focus on physical part manufacturing and the assembly of the physical system.

Mechanical System

Under the umbrella of manufacturing for the mechanical system are two further subcategories. Initially, the final design that the team settled on to begin prototyping was a magnet-spring system utilizing changing magnetic flux to generate energy.

In the lowest fidelity iteration, the magnet spring system was realized using a cut PVC pipe of about 7”, a ¼” thick 2” diameter neodymium disc magnet (magnetized through the diameter), a wire, two springs (with spring constants 114 and 85.5), and two suction cups. The wire was wrapped around the PVC pipe’s center 36 times, and the neodymium magnet (see Figure D1) was suspended within the PVC pipe’s body using suction cups connected to each spring (the ends of which were attached to the ends of the pipe covering). Testing was done to judge the potential of the electromagnetic energy harvesting design using this initial prototype. After this assessment was made, a second iteration using the same PVC body was done with different magnet sizes and wire configurations. Thinner magnets and different springs were both tested, as well as a configuration where wires were wrapped at both ends of the pipe instead of around the center of the pipe body to prevent a net zero magnetic flux from this particular symmetry.

In a second iteration of the low fidelity design body, a longer PVC pipe (about 12”) was cut, and 3D printed magnet clamps replaced earlier suction cups. The springs used for the original iteration were far too short and stiff to effectively allow movement of the magnet. This presented a large problem. By permanently deforming the springs, the team was able to create a testable second iteration, however, this is not a final solution. To resolve and improve the system, this second and longer iteration will be tested with longer and lower k-valued springs and copper insulated wires instead of the previous aluminum wires. Eventually, in future iterations, the team would like to replace the PVC pipe with a lighter and more streamlined 3D printed PLA body.

While doing the initial back of the envelope calculations for the magnet-spring system, there was some doubt about the efficacy of the system, and a second design was suggested and added to the prototyping process. The second design the team went with was a pendulum system. The goal was to obtain initial numbers for both designs during prototyping before moving on to higher fidelity iterations with the most promising design.

The pendulum system is a more mechanical, gear-based system of energy generation with a body designed to be suspended against the back of the wearer, within the backpack. The initial casing for the pendulum system was laser cut from acrylic plates, and bolted together with about 1.5” in between the two plates. Between the plates, a thin steel pendulum rod was suspended on an axle, which allowed freedom of oscillatory movement by rotating ball bearings attached to the center axle. The compiled CAD drawings for a potential design and components can be found in Appendix D.

Figures D2-D6 represent the primary design for the pendulum system, where a pendulum oscillates within a plastic casing in order to spin a simple gear system and ultimately a DC motor. While this design is certainly lighter, it would require electric rectification in order to charge a battery. Since the pendulum design fails to meet the base input voltage for a full-wave rectifier, a mechanical rectifier was used instead. Ideally future researchers would be able to miniaturize the mechanical rectifier to fit within a smaller amount of space and then attach to the pendulum axle and DC motor.

The final iteration of the pendulum design included a mechanical rectifier as seen in Figures D7-D9, where Figures D8 and D9 will be used to explain the operation of the mechanical rectifier. Throughout both figures, the bottom left-most blue gear represents the input axle upon which the pendulum swings, while the central red gear represents the output axle connected to a DC motor. In Figure D8, when the input gear rotates clockwise, the sprag-bearing unidirectional gear which it shares an axle with is allowed to slip, making it inactive as denoted by the red X. The other sprag-bearing directional gear locks onto the shaft in order to transmit rotational motion to the next gear, ultimately resulting in the output gear spinning counterclockwise. The opposite can be seen in Figure D9, where the slipping of the rightmost sprag-bearing gear renders the right half of the gears inactive, while the left-most sprag-bearing gear locks onto the shaft in order to transmit rotational motion to the next gear, resulting in the counterclockwise rotation of the output gear.

Figure D10 represents the physical prototype for the pendulum casing, while Figure D11 represents the proof of concept prototype for a mechanical rectifier.

The gears used within Figure D11 were almost exclusively purchased from VEX robotics, with the sprag-bearing gears 3D printed as a fusion of a Roller Clutch file from Maker's Muse and a 60 tooth gear CAD file from VEX robotics.

Circuit System

The process of the design of the circuit was explained in the section above. The circuit design for the energy harvester prototypes was built to store the energy generated by the harvester while minimizing the energy or voltage losses due to circuit components. The performance of the energy harvester connected to the circuit is discussed in the next section.

The circuit schematic for the energy harvester prototype consists of a premade evaluation board for the energy harvester IC and a super-capacitor. A DC-DC converter could also be connected to the supercapacitor to allow for charging of external devices. The block diagram of the circuit connections is shown in Figure 2 below.

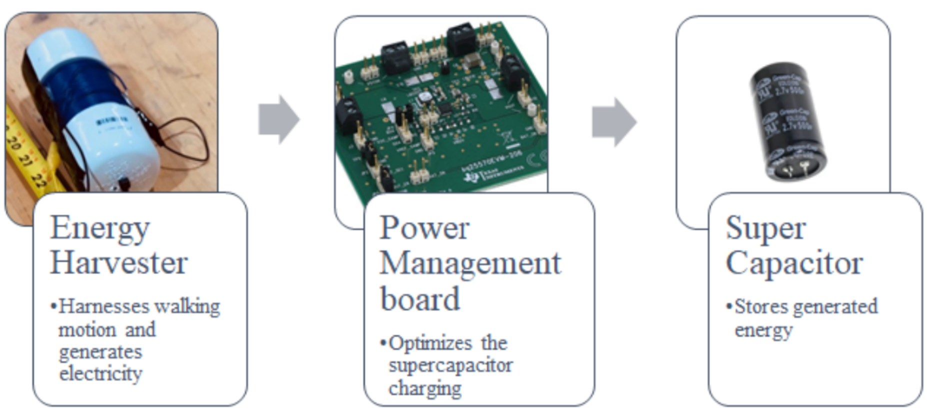

Figure 2: Block diagram of circuit connection for Energy storage and conversion.

Testing and Analysis of Energy Harvester

Testing on the initial spring-magnet system was done by oscillating the pipe body by hand at a vertical displacement of about 1". Alligator clips were attached to either side of the wire wrapped around the body center, and the voltage of the system was tracked using a multimeter. In the first test, the recorded voltage ranged from 50mV-150mV.

More in depth testing was conducted by shaking the pipe system while connected to an oscilloscope, and collecting concrete data for later analysis. With this analysis, the 14” magnet-spring system achieved alternating voltages, peaking at 50mV. The results from the oscilloscope have been digitized in Figure 3.

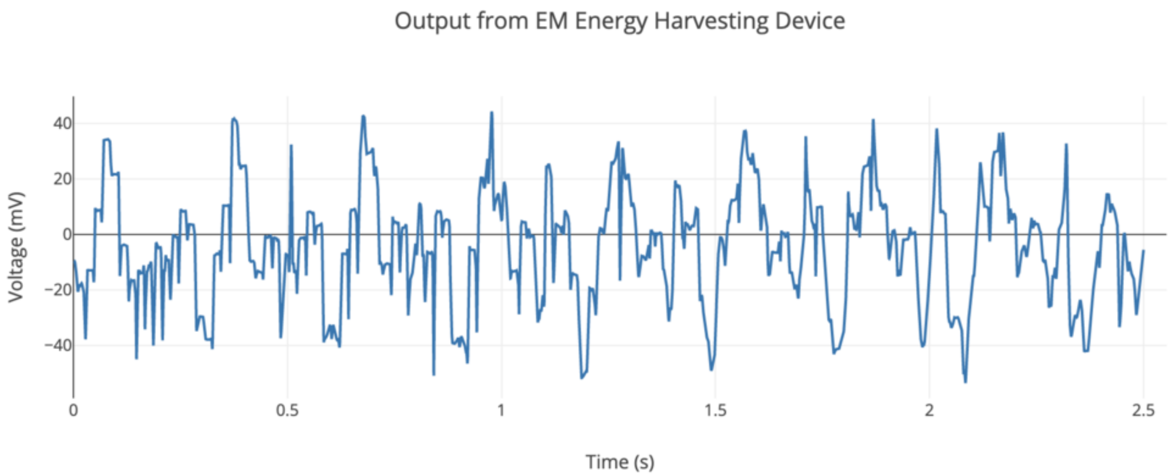

Figure 3. Output from the oscilloscope when testing the 14” electromagnetic harvesting device.

During this testing, the recorded voltage oscillated between -50 mV and 50 mV over a period of three seconds. The oscilloscope output seems to indicate that the current design may not produce enough energy to power an electronic device, so further modifications were made to the device to attempt to produce a high voltage output. There are also concerns with the negative and positive peaks canceling out, however further analysis is needed to rectify the issue.

Realistic testing was done by placing the system within a backpack and walking to simulate the actual movement the system will theoretically be harvesting. Data from this was gained by connecting the system to a multimeter to be carried by the walker. This collection was far less promising, yielding results of approximately 10mV.

In order to optimize the device, the team experimented with a longer tube, a lighter magnet (in order to lower the resonant frequency of the system closer to human motion), more turns on the coil, springs with smaller k values and winding the coil at the ends of the tube rather than the middle to remove the symmetric flux cancellation effect. A lighter magnet yielded lower outputs (Fig. 4); however, using a 12” tube to house the device with stressed springs with smaller values led to better outputs (Fig. 5).

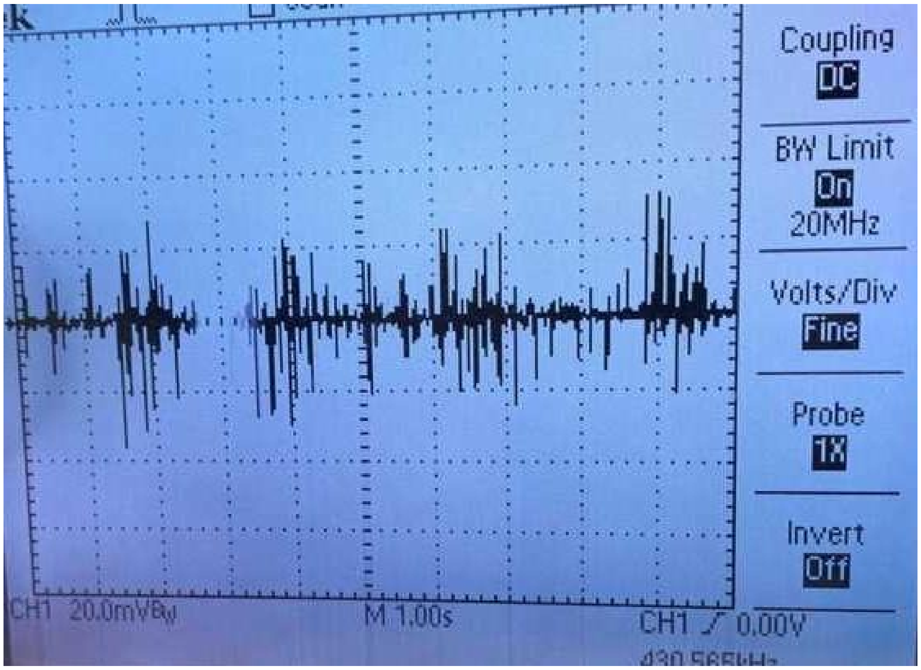

Figure 4. The output from the oscilloscope when testing the electromagnetic harvesting device with a lighter magnet.

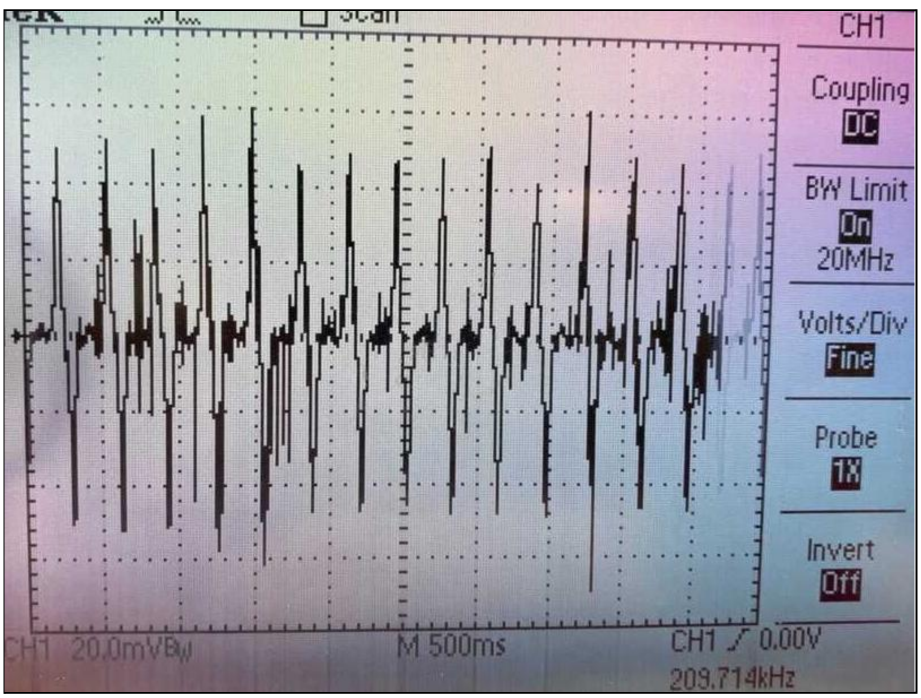

Figure 5. The output from the oscilloscope when testing the electromagnetic harvesting device with a 12" tube.

Electricity Generating Potential of Harvester and Circuit

Our initial testing showed that the harvester could successfully generate a measurable voltage. The next step in the analysis was determining if this generated electricity was sufficient to power the circuitry and charge a supercapacitor. For supercapacitors, as the level or stored energy or charge increases, the voltage across their terminals also increases. The team devised an experimental set-up that would measure the charge difference under a given excitation of the energy harvester.

Experimental Set-up

The energy harvester was connected to previously described IC evaluation board and a supercapacitor. The magnet and spring harvester was the only prototype tested in this experiment. The harvester was excited (shaken by hand) for one (1) minute, and a colorful object was attached to the end of the oscillating magnet. This was so that so that the frequency and amplitude of the excitation could be measured from videos recorded of the harvester during the experimental trials. The setup can be seen in Figure 6 below.

At the start of each trial, the voltage of the disconnected supercapacitor was measured to determine the initial charge state. The capacitor was then connected to the evaluation board, with the harvester disconnected, and then its voltage was also measured. This was done to determine the state of the IC chip before charging, and if it had any residual charge.

During the excitation of the harvester, it was determined that the supercapacitor was charging, by measuring the voltage at the energy storage terminal of the energy harvester. After the 1 minute excitation, the voltage level of the supercapacitor was measured again to determine the final state of charge. Two types of supercapacitors, differing in both capacitance and voltage rating were used in this experiment, to check if those properties impacted the supercapacitor charging.

To measure frequency, the oscillations of the colorful object attached to the magnet were counted and divided by the time (in seconds). For the amplitude, the team attached a scale to the tube and determined the position of rest of the colorful object. The team went frame by frame, found the displacement of ten oscillations and averaged them to obtain the average amplitude of excitation.

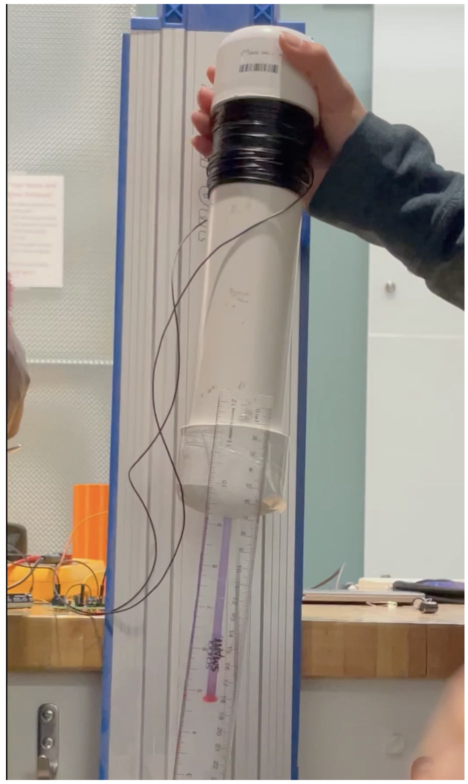

Figure 6. The experimental setup with the coil at the end (to prevent symmetric cancellation of magnetic flux) and each end connected to circuit. Red object attached to a straw attached to a magnet and thus moves with it. A scale is attached to measure amplitudes

Results

A total of 9 experimental trials were conducted. The team observed that when the same supercapacitor was continually used in multiple testing trials, it appeared to lose charge (i.e. the voltage of the supercapacitor decreased). This was the case in 6 of the experimental trials. But when it was swapped for a new capacitor after each trial, the harvester was successfully able to charge the capacitor. The team suspects that this trend could be due to the discharge of the capacitor into the IC chip, but further research would be necessary in determining the factors causing this. The team was unable to determine if this trend was correlated with the capacitor rating due to the limited availability of circuit components at the time of testing.

The team attempted to determine the state of charge of the IC chip after each excitation of the harvester. This was done by connecting a supercapacitor to the evaluation IC board before each new trial and measuring how the capacitor's voltage (and thus state of charge changed). The team obtained that to inconclusive results as in some cases, the voltage of the supercapacitor increased after being connected to the chip, and in other cases the voltage of the supercapacitor decreased. This distribution seemed to be random and not have any correlation with the experimental modifications (such as using the same supercapacitor, or using a different supercapacitor rating). To avoid this causing discrepancies in the measurements and analysis, The voltage state of the supercapacitor after a brief connection to the IC chip board was used as the initial charge state of the supercapacitor.

The data from the successful three trials is shown below in Tables 1, 2, and 3. In all of these cases, a new capacitor was used. As stated earlier, the team was only able to test this with a specific type of supercapacitor. The capacitor used was rated at 1000μF, 50V. The duration for the excitation is 1 minute.

The energy stored in the capacitor is calculated as

$$E = \frac{C(V_2 - V_1)^2}{2} \quad \text{(Equation 4)}$$

Table 1: Experimental Trial 9 - Capacitor rating: 1000uF, 50V

Average excitation frequency	1.97 Hz
Average excitation amplitude	3.35 in
Capacitor voltage before charging V_1	0.025V
Capacitor voltage after charging V_2	0.794V
Energy stored in supercapacitor (E)	2.956×10^{-4} J

Table 2: Experimental Trial 7 - Capacitor rating: 1000uF, 50V

Average excitation frequency:	1.83 Hz
Average excitation amplitude:	3.54 in
Capacitor voltage before charging V_1	0.03V
Capacitor voltage after charging V_2	0.497V
Energy stored in supercapacitor (E)	1.0904×10^{-4} J

Table 3: Experimental Trial 4 - Capacitor rating: 1000uF, 50V

Average excitation frequency:	2.02 Hz
Average excitation amplitude:	3.74 in
Capacitor voltage before charging V_1	0.39V
Capacitor voltage after charging V_2	0.711V
Energy stored in supercapacitor (E)	5.152×10^{-5} J

Discussion of Results and Next Steps

The results show that the supercapacitor is successfully charged by the present iteration of the magnet and spring harvester. This is an important proof of concept as it shows that the design configuration can power a circuit and charge a supercapacitor.

However, the results show that the supercapacitor is charged by the harvester at a very slow rate. Based on the current results, and assuming a constant rate of charging determined by the average energy transfer from the trials, it would take 16,836 days to generate enough stored energy to fully charge the most recent model of the Apple Watch™ (battery capacity of 1.024Wh or 3690J). At its current stage, the prototype is not suitable for generating sufficient electricity to charge electronic devices. The goal in this project was to explore new ways of generating energy from daily activities, and in this case walking. The team has achieved this goal by showing that a kinetic energy harvester can generate electricity, at least enough to power its own circuit. With further improvements, it shows promise for powering small devices with lower energy demands

For the device to attain its intended purpose of charging small devices, the team would need to make modifications to it that would increase its energy generation output. Such improvements include increasing the number of turns in around the harvester or increasing the strength of the magnet. The team could also integrate existing research on electromagnetic induction in modifying the prototype to increase its energy output. It would also be beneficial to investigate the aforementioned circuit charging trends that the team observed in the testing phase of the project.

Preliminary Pendulum Testing

The team tested the second iteration of the pendulum by connecting the generator to a digital multimeter (see Figure 6). The current ranged 50-70 mA while the peak voltage altered between 200-500 mV. The voltage did not drop below 0 mV as the system includes mechanical rectification; however, current does drop to 0 mV as movement temporarily halts at the ends. These results show that the pendulum also has the potential to produce significant voltage however it does not move as freely: in this case, the arm was moved with force since it produced less than 10 mV when left to move freely.

Figure 7. Setup to test output of pendulum

Environmental Benefit Analysis

The energy-harvesting backpack is expected to have significant environmental benefits as well. Though the backpack does not grant users direct access to the grid, the design harvests energy through routine interactions and stores the energy in supercapacitors. This design limits the reliance on solar-powered packs and batteries, thus reducing electrochemical waste. In the US alone, less than 5% of lithium batteries are recycled (Jacoby), and although rechargeable batteries are a current solution to this environmental problem, these too have limits of lifetime. According to a study that surveyed university students, 87% of students use power banks to keep their devices charged, especially when an outlet is not available nearby (Chen, Minghao, et al). Under these assumptions, Duke students (both undergraduate and graduate) own nearly 14,447 power banks, of which only 722 are properly recycled. The remaining power banks are disposed of inappropriately, leading to detrimental environmental effects. Specifically, the cobalt, nickel, manganese, and other metals found in these batteries leak from the casing, contaminate the soil and groundwater, and can ultimately threaten ecosystems and human health (Jacoby). Even the battery's electrolytic solution ($LiPF_6$) can leak and cause just as much harm (Jacoby). Therefore, this design minimizes the reliance on these power banks because this design utilizes supercapacitors, which also have longer life cycles than rechargeable batteries ("New Findings Pave the Way to Environmentally Friendly Supercapacitors"). Even if only two-thirds of Duke students replace their power bank for the energy-harvesting backpack as their primary convenient energy source, the design still prevents over 500 power banks from being improperly disposed of.

Furthermore, this design will minimize reliance on the grid, as more users can charge small devices on the go instead of using a conventional power outlet. According to the U.S. Energy Information Administration, an average mobile phone consumes 11 kWhs annually ("*Frequently Asked Questions (FAQs) - U.S. Energy Information Administration (EIA)").* In North Carolina, the electricity generation is 30.33% by natural gas and 26.3% by coal ("NC's Energy Mix"). Given there are 15,192 students (graduate, undergraduate, and part-time) enrolled at Duke in 2019 ("Duke University.") and assuming each student has one smart phone, Duke students require 167,112 kWh to charge their phones over the course of a year. Under the energy generation distribution in North Carolina, 50,685 kWh are obtained from natural gas, while 43,950 kWh are obtained from coal. According to the U.S. Energy Information Administration ("*Frequently Asked Questions (FAQs) - U.S. Energy Information Administration (EIA)*"), natural gas releases 117 pounds of CO_2 per million British thermal units (Btu) of energy and coal releases, on average, 216 pounds of CO_2 per million Btu. Thus, nearly 20,234 pounds of CO_2 are emitted from natural gas and 32,392 pounds of CO_2 are emitted from coal. Therefore, Duke's campus releases roughly 52,626 pounds of CO_2 to charge cell phones over the course of a year. Even though the backpack is not intended to completely replace outlets, the backpack can still offset roughly 26,313 pounds of CO_2 if used even 50% of the time and still provide adequate energy on the go.

Social Benefit Analysis

The concept of human energy harvesting points to taking advantage of all the expenditures of energy that humans do as they go about their daily lives. The goal of this project is to create a device that harvests the energy of some daily human action without any apparent negative effect on lifestyle.

Initial research for this project focused on past solutions that involve piezoelectric technology. Piezoelectric tiles have been used to harvest energy from foot traffic and essentially captures energy that would be expended. Devices like this have raised social awareness for the different ways this "free" energy can be harvested and reused to power other devices (Diamond). In a study conducted by the University of British Columbia, the potential social impact of these tiles were quantified. From these studies, 79% of the survey population would "go out of their way to generate green energy" and 62% believe the tiles will "alter their behavior elsewhere" (Cramm et al.). After taking inspiration from piezoelectric applications, this project tackled energy harvesting through the form of a backpack.

Introducing an energy-harvesting backpack to the market will also have a significant influence on the consumers and their attitude towards sustainable lifestyles. In particular, the design requires more action (i.e., walking) to generate more power, so users are encouraged to stay active and exercise more frequently to generate enough power to charge their devices. Furthermore, purchasing this backpack encourages and reminds customers to actively work towards a sustainable lifestyle. Cramm et al.'s study on social impact generated statistics quantifying social impact that the team believes can be analogously applied to the product. The team expects similar numbers can be related to increased movement, altered behaviors regarding sustainability, and increased environmental awareness in the target audiences.

The social benefits also reach beyond casual use in the case of emergency situations. During periods of power loss or in areas where energy access is limited, the energy harvesting backpack can supply energy that may be difficult to come across otherwise. It can power essentials like flashlights, radios, and GPS, and potentially have a significant impact on one's livelihood. A hiker who's electronics have been drained would be provided with an extra pump of electricity to keep their flashlight charged. Someone who lives in an energy-scarce country can charge devices as they move around with the backpack. The social benefits of this device do not stop at providing a quick charge—this backpack add-on could provide an extra tool to secure human safety and health.

Target Market

Determining the Target Market

Due to the aforementioned projected social and environmental benefits, the energy generating backpack has strong market potential, especially considering the shift towards clean energy and reusable products that seems to be happening in modern times.

The design team initially planned to market the energy generating backpack to three main groups of consumers: students and casual backpack users, intermediate and professional backpackers, and first responders and emergency service employees. However, after some deliberation, the team decided to avoid prototyping for first responders and emergency service employees, as similar technologies already exist in military and first responder spaces, and it would be a harder market for the prototype to break into. Additionally, marketing to first responders would place several restrictions on the team's harvesting and prototyping methods, and could potentially prevent the exploration of new, innovative methods that work efficiently but are not acceptable for high-risk situations.

The design team also decided to move away from marketing to intermediate and professional backpackers, as more experienced backpackers tend to be very particular about the weight they carry on their ventures. Marketing to backpackers would put a significant weight restriction on the prototyping process, which is not feasible given the current resources and existing energy harvesting methods. And even if a backpack within the weight restrictions was created, there is no guarantee that backpackers would consider it a worthwhile investment, as many of them may still consider the battery/power source an unnecessary waste of space and weight, and may also not carry electronic devices that require consistent charging, which would thus negate the function of the product.

It was ultimately decided that students and casual users would be the best market for the current prototype, as the demographic seems willing to accept more tradeoffs (heavier weight, etc.) for a more robust energy generating device. Additionally, marketing to students and casual users will help promote general environmental and energy awareness, and will help encourage individual sustainability. If the backpack is later mass produced, students and casual users would make up the majority of the population, meaning there could be a massive amount of saved energy worldwide, and potentially over 167kWh on Duke University's campus from charging phones alone.

Survey Results

After deciding to market to students and casual users, the design team sent out a consumer survey to better understand the needs and desires of the target market. The online survey was administered to several relevant student groups and a few public forums, including: Duke Outdoor Adventures, the Duke Outing Club, the Innovation Co-Lab Newsletter, and r/SampleSize. The survey collected 48 responses over the three weeks it was active (Appendix E).

The majority of survey respondents were students from ages 18 - 24 who use backpacks regularly. When asked about what they prioritized when shopping for a backpack, respondents said that function, quality, and comfort were their greatest concerns (Appendix E1). To ensure that the prototype is a manageable size for the projected users, the survey also inquired about the weight respondents carry in their backpacks daily, which appears to be around 5-10 lbs on average (Appendix E2). Finally the survey asked about the participants' greatest concerns regarding the product, with a majority responding with price and feasibility, as there was concern that the energy harvesting system would not work reliably or that the cost would be well above that of a normal backpack. Overall, 11 survey respondents said they would be interested in purchasing the product, while 32 respondents said they would consider it (Appendix E3).

Basic Business Plan

This developed prototype, the portable backpack energy harvester has potential to be a commercially viable product that can drive a profitable business venture. At its current iteration of development, it is able to generate electricity and charge a supercapacitor, but to become a product that is commercially attractive and viable, the team needs to implement further development that improves the durability and resiliency of the product. There also needs to be intentional development of its packaging in order for it to be easily removable and to allow flexibility for its user. Beyond this, the team's approach to this goal is to make this product competitive with alternative similar products in the market in terms of functionality and consumer cost.

Competitors

An obvious competitor for this product in terms of functionality would be batteries, a battery pack, or a portable phone charger. The non-sustainable alternative has an advantage in cost, but the selling point of the product in this paper is the fact that it is a sustainable alternative. Competitors in the personal sustainable energy generation field would be electricity generating backpacks that are already in use and production. In this field, the team's product has a distinct advantage in portability and price, increasing its accessibility for its target market—young adults. The competition against battery packs is reliant on the consumer choosing to go green, and the team has made efforts in the design process to streamline that decision. Further efforts will be made in the marketing phase.

Current Advantage

The product has a unique function as a device that is able to continuously generate energy and store energy. The product can replenish itself when its energy is depleted, which is a significant advantage over standard lead acid batteries. Likewise, the product can be charged in the absence of an electric outlet, allowing the storage component (supercapacitor) to have a longer usage cycle. This presents a significant advantage over rechargeable batteries.

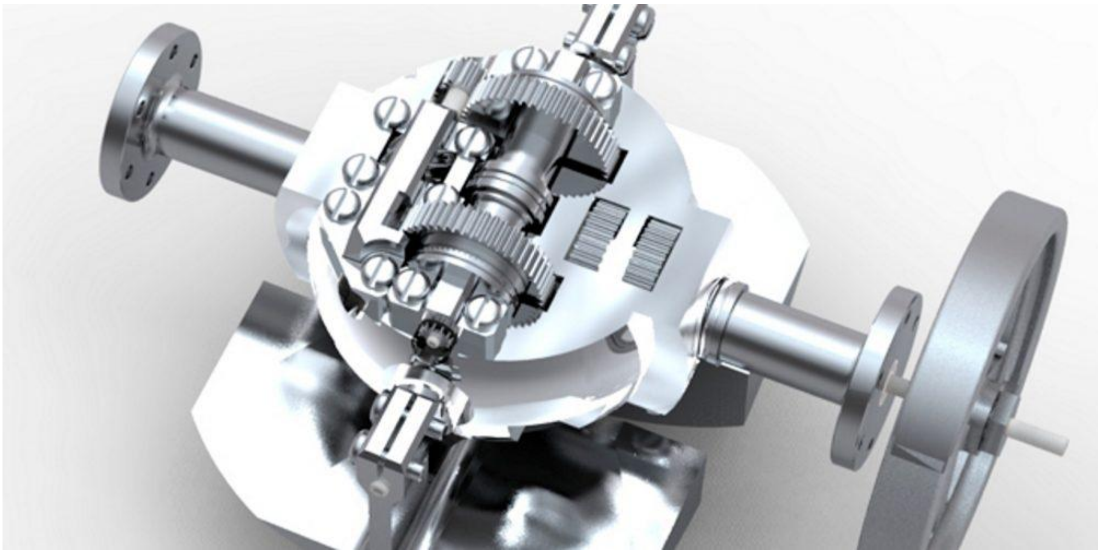

Figure 8. WITT harvester for six degrees of motion.

There exists another product in the development stage called the WITT, a device that harnesses complex six degree motion to drive a pendulum that then generates electricity ("How It Works: WITT Energy Power from Motion."). However, as seen in Figure 8, the WITT is heavy, and has a bulky frame that has to be mounted on the surface of the backpack. The prototype has the advantage of being sleek, lightweight and discreet.

Further Distinguishing From the Competition

To establish preeminence in the market of portable energy harvesters, the product has to be further improved in a couple of ways. First, the team needs to integrate additional charging functionality in the device that would allow the prototype to charge from a conventional wall outlet. This would also enable us to serve as a conventional power bank, and expand the market base to people who spend parts of their day in indoor settings.

Another value-add that could be integrated is features that would enable the harvester to be insertable into a backpack or even a wide assortment of bags. This could be in the form of detachable straps that can easily fasten to the interior of any bag, as well as more space conservative casing for the circuitry and energy harvesting components of the prototype. This would enable the user to switch the bag they might use while still keeping the energy harvesting feature

Marketing Plan

The target market is composed of college students and casual backpackers. It's expected that people in this demographic would be between ages 17 and 40. To ensure that the product can be effectively marketed to this demographic, the team needs to ensure that the final product packaging and functionality is appealing to prospective users. The product features like charging flexibility, promoting energy conservation awareness and sustainability make it attractive to this group. To capitalize on the college student sub-market, the team could employ strategies such as social media advertising and influencers, promos and coupons to encourage the sale of the product. The team will also utilize existing channels of retail that where the target demographic would be likely to shop for school or backpacking supplies. This would include corporations such as Target, Amazon, Dick's sporting goods, Walmart, etc. In the college context, the opportunity to partner with the university itself would also target the demographic, and open pathways for branding that may be attractive to students. The university may further be interested in subsidizing the product for its sustainability impact. Partnering with online content creators that rate and review commercial products like backpack and essential school supplies could also help build the reputation of the product and promote its sales.

Cost

The current cost of purchased materials in the prototype iteration is \$50.32. The team has also employed other materials that were sources at no cost from workshops and laboratories at Duke. The comprehensive bill of materials for the product is found in Appendix F, and the estimated cost per unit is \$50.32.

The team anticipates that with increased volume of production, the team would be able to find cheaper and competitive sourcing of raw materials based on wholesale purchase. This may significantly reduce material costs. This would harness the economies of scale of mass production and further lower the cost of producing each unit. Note that this estimate is non-inclusive of other anticipated costs such as taxation, administration and management fees, and fees for the protection of intellectual property. However, it forms a basis for estimating what the costs of production are and provides valuable information for setting the selling price of the product.

Other Considerations

When designing this model, the team must also consider how to protect electrical elements from moisture as well as from overheating. If the team pursues the electromagnetic system, the magnet poses a large safety hazard, as a magnet of this strength can damage electronics and can also exert a significant force. Beyond safety, the team is also considering how to make this backpack convenient for the intended audience; that is, this backpack should not cause any alarm in security measures (i.e. during travel, in public spaces, or at large events). Furthermore, the backpack should also not compromise its primary function: to provide a space for carrying materials. The team must consider how to design an energy-harvesting device that is both efficient and is also light and small enough so that the backpack can be used to carry materials.

The team must also consider the comfort of the design, especially with regards to weight and the flexibility/rigidity of the design. Though the pendulum design is more rigid, the team is actively brainstorming ways to modify the design to optimize comfort and energy-harvesting potential. Likewise, the team is considering how to optimize efficiency within the backpack - although the backpack can provide convenient energy, the team is strongly considering how long it takes to charge/power a device. If given another option to charge a device, the customer should ideally select the backpack. Finally, the team is considering how the backpack can be designed in a durable fashion. Beyond physical strength, the team is considering the durability of the energy-harvesting system over time (i.e., does the system become more inefficient over time, and does the system require regular maintenance?). The team intends to analyze what component of the design is most likely to fail first, and a more in-depth analysis will be conducted to study how this component can be strengthened and made more efficient.

Conclusion

The energy-harvesting device allows consumers to harness energy from interactions with the environment, and ultimately allows the user to access clean, off-grid energy to charge their small devices. The team is focusing on harnessing ambient energy from routine walking motion, and after studying the walking motion at varied tempos and terrains, the team narrowed the scope of the design and selected primary energy-harvesting systems to consider. The team developed two prototypes: one with an electromagnetic system and one with a pendulum (mechanical) system. The electromagnetic system is composed of an add-on feature that is comparable to the size of a soda can, and within this model, a magnet oscillates through a tube wrapped in coils. Through this mechanism, current is induced in the coil around the tube due to the changing magnetic flux due to the motion of the magnet. The team also considered a mechanical system, which includes a pendulum oscillating on the input axle of a mechanical rectifier, where the output axle is connected to a DC motor for the creation of usable power. Beyond the technical design, the team is focusing on marketing to recreational backpackers and college students.

This design has several environmental benefits, many of which can be recognized beginning at small scales. Introducing the backpack to Duke's campus could minimize electrochemical waste by preventing roughly 772 power banks from being improperly recycled, and the backpacks can also provide a potential carbon offset of roughly 52,626 pounds of CO_2 from Duke's campus over the course of the year. Besides environmental benefits, this design also offers several social benefits, including encouraging consumers to edit their lifestyles to be more sustainable. The product will ultimately encourage a more active and environmentally conscious market. Beyond lifestyle and behavioral changes, the team estimates that the backpack will also be helpful in emergency situations, as the backpack allows responders to generate energy in regions where access is limited, and the backpack can provide enough electricity to power flashlights, radios, GPS, and other small emergency devices.

At the end of the study, the team concluded that the electromagnetic design is the most efficient harvester out of the two prototypes considered, as the design operates closer to human walking frequency and has shown energy generation potential whereas the pendulum design is harder to move freely. Nevertheless, the electromagnetic design has applications in a recreational/fitness setting as well (i.e. in elliptical machines), which allows one to generate energy during fitness exercises. Improvements on the pendulum system could include the miniaturization of the gears within the mechanical rectifier to reduce weight and friction, or alternatively the replacement of a mechanical rectifier with a full-wave rectifier operating at a smaller base voltage. For the device to generate enough energy to power small devices, the team would need to increase the generation output of the harvester prototypes. Such improvements include increasing the number of turns in or around the harvester or increasing the strength of the magnet to increase the voltage and current of the induced electricity. Further literature review on electromagnetic induction could aid in integrating existing research into the model and further increase its energy output. For the circuit, investigating the supercapacitor circuit charging trends that was observed in the testing phase of the project would be crucial. The circuit may also need to be modified to include a bridge rectifier if the electricity output is increased. When the harvester prototype is modified and can then generate enough energy, adding a DC-DC converter to the supercapacitor terminal would enable the charging of devices with the stored energy.

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Appendix

Appendix A: Decision Matrix

Table A1: Decision Matrix

Criteria	**Weight**	**SOLAR**	**~~THERMAL~~ (disqualified)**	**EMag**	**Piezo**	**Flywheel**
Energy Generating Potential	0.25	5 * 1.25	0	4 * 1	2.5 * 0.625	2 * 0.5
Implementation	0.1	4 * 0.4	1 * 0.1	3 * 0.3	4 * 0.4	3 * 0.3
Durability	0.2	5 *1	4 * 0.8	3.5 * 0.7	4 * 0.8	4 * 0.8
Cost	0.1	3 * 0.3	2 * 0.2	3 * 0.3	2 * 0.2	1 * 0.1
Safety	0.25	5 * 1.25	3 * 0.75	4 * 1	5 * 1.25	1 * 0.25
Comfort	0.1	5 * 0.5	0	3 * 0.3	2 * 0.2	2 * 0.2
Total		**4.7**	**1.75**	**3.6**	**3.475**	**2.15**

Appendix B: Walking Data in Coordinate Directions

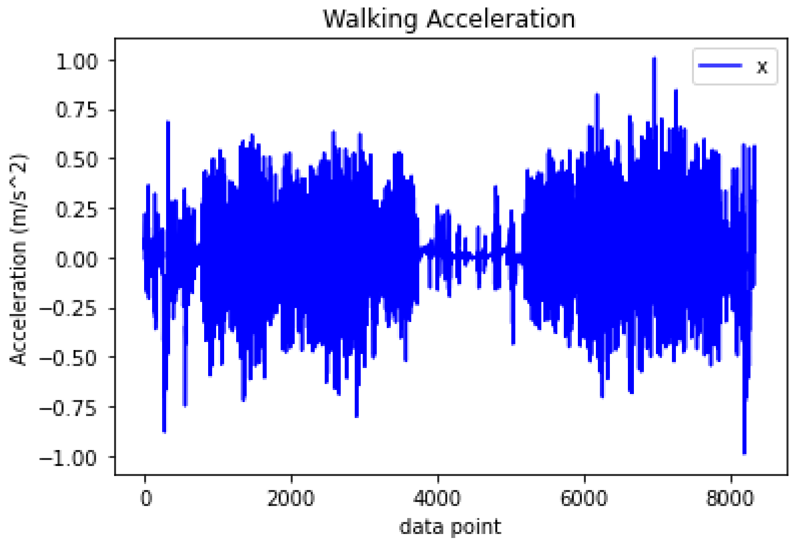

Figure B1: Walking data measured in the x-direction.

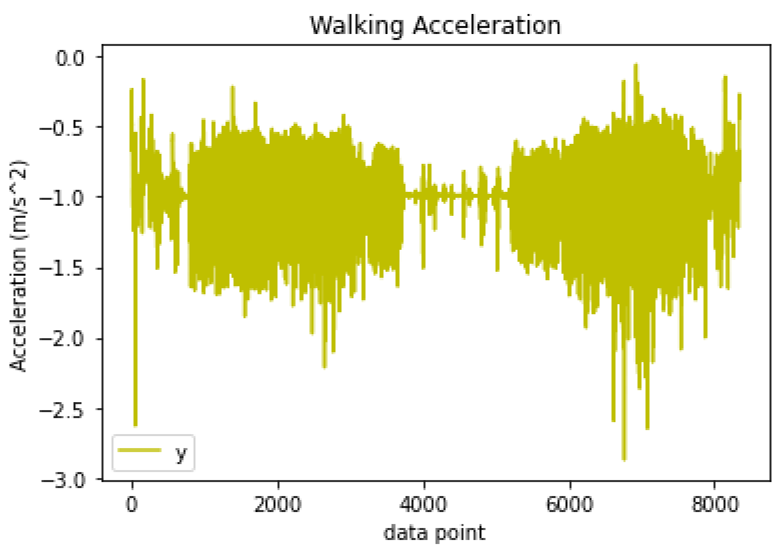

Figure B2: Walking data measured in the y-direction.

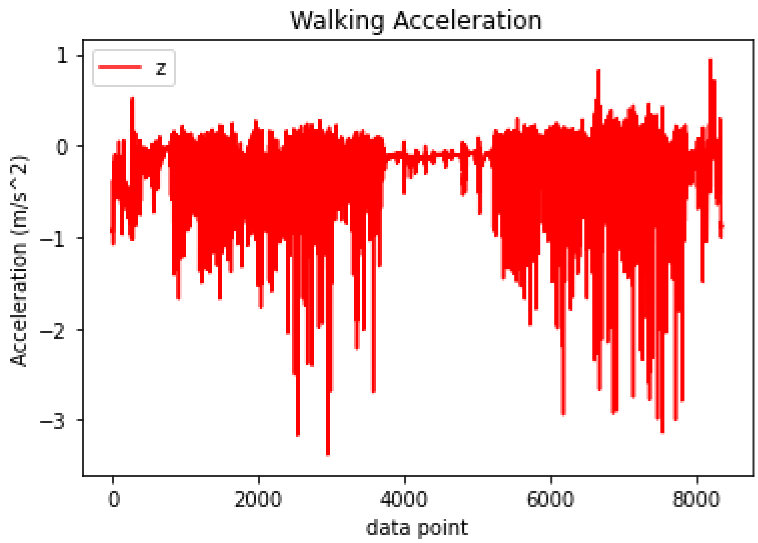

Figure B3: Walking data measured in the z-direction.

Appendix C: Tube Design with End Caps

Figure C1: CAD Model of Tube with End Caps.

Appendix D: Compiled Technical Drawings

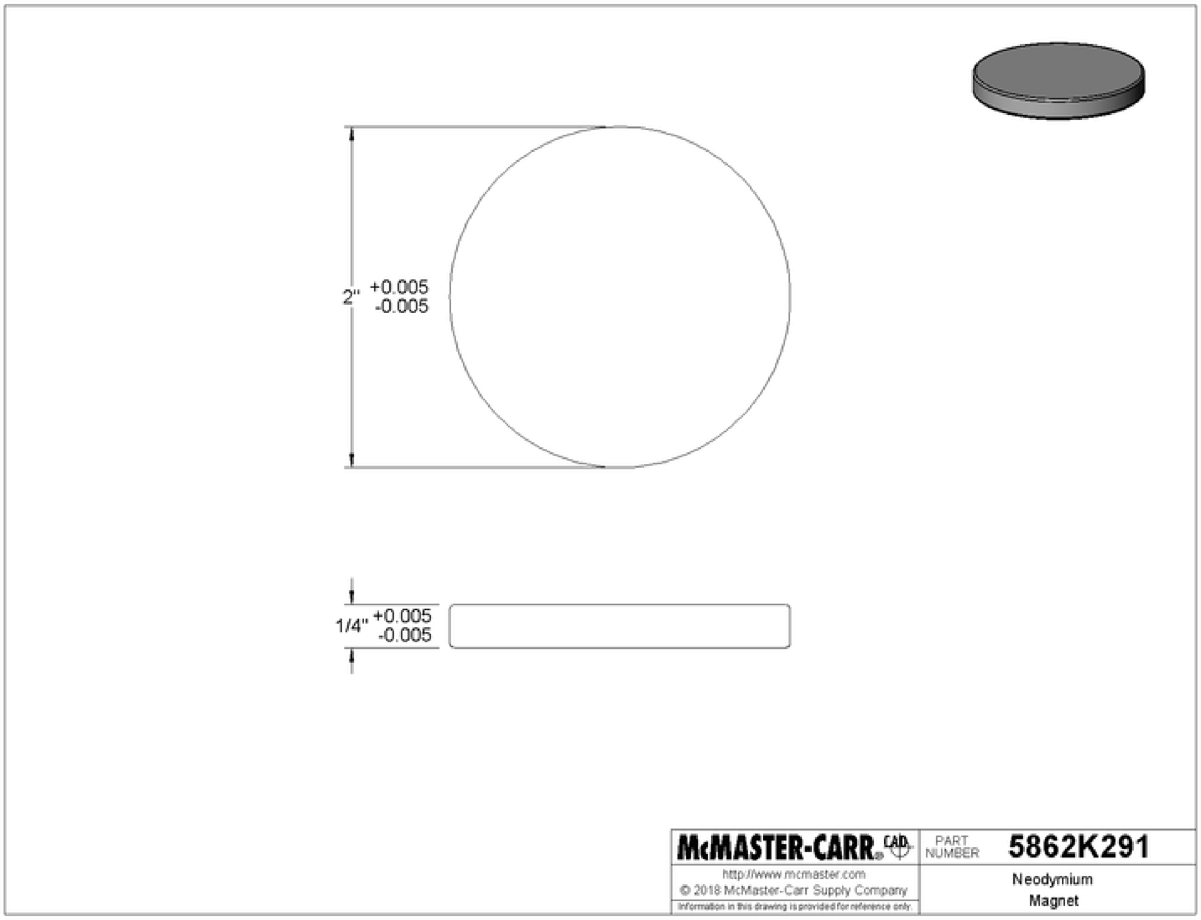

Figure D1: Neodymium Magnet.

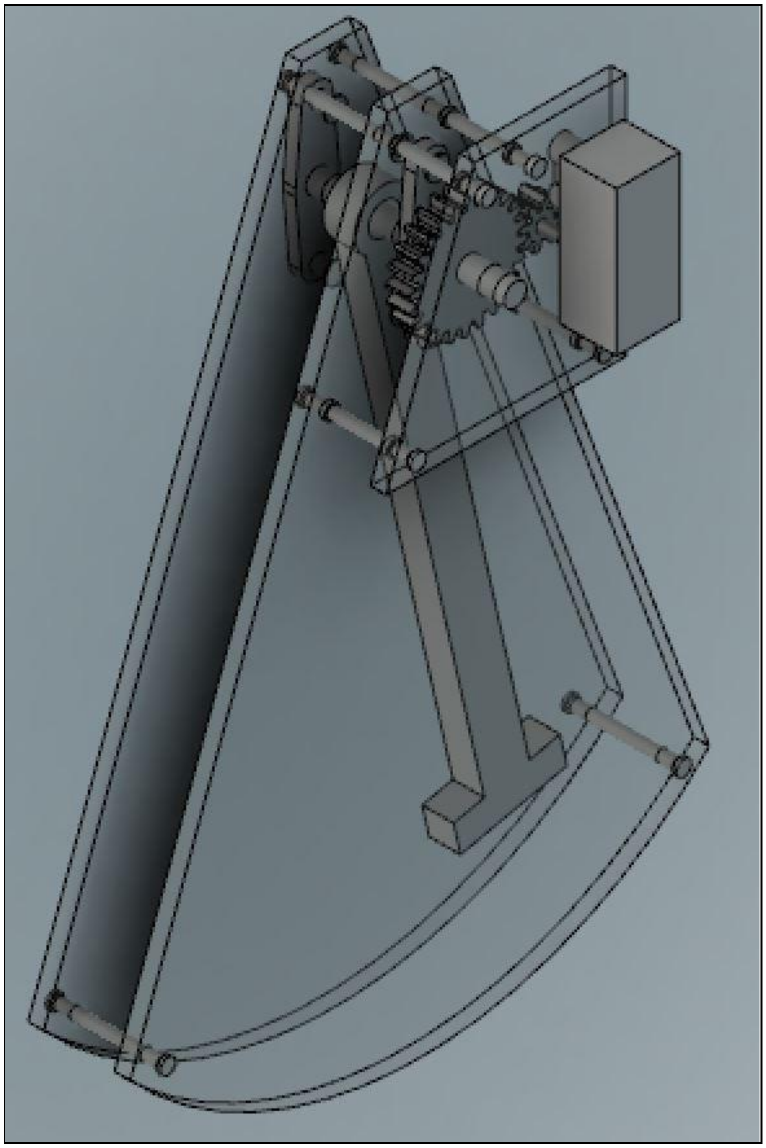

Figure D2: Pendulum Design.

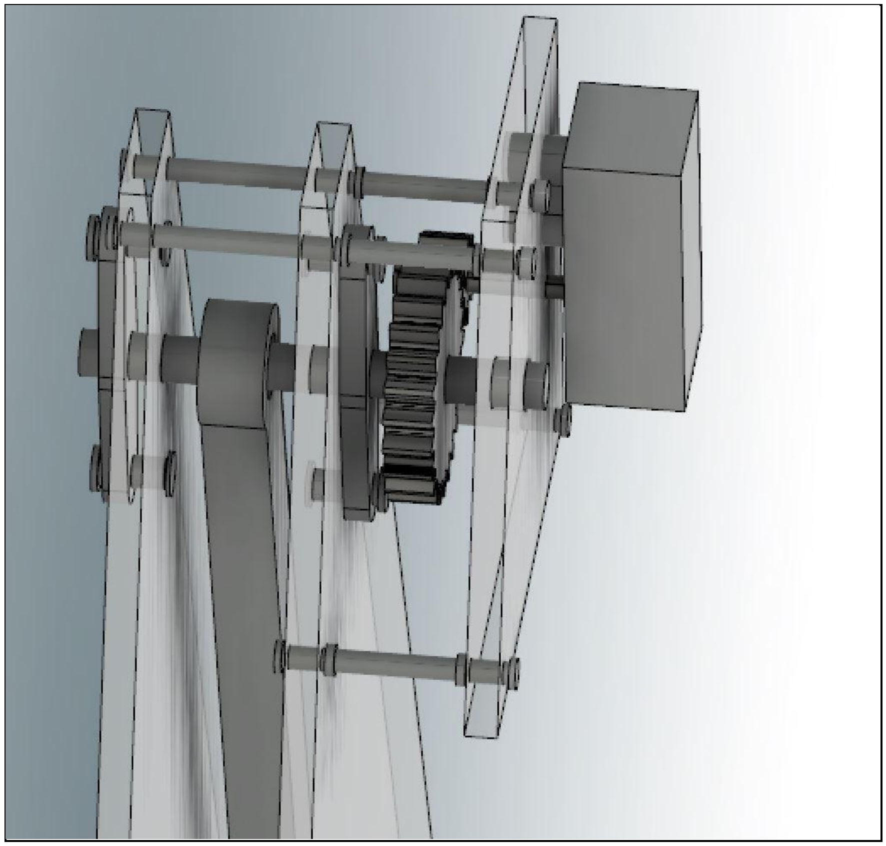

Figure D3: Gear System on Top of Pendulum Design.

Figure D4: Isometric View of Pendulum Design.

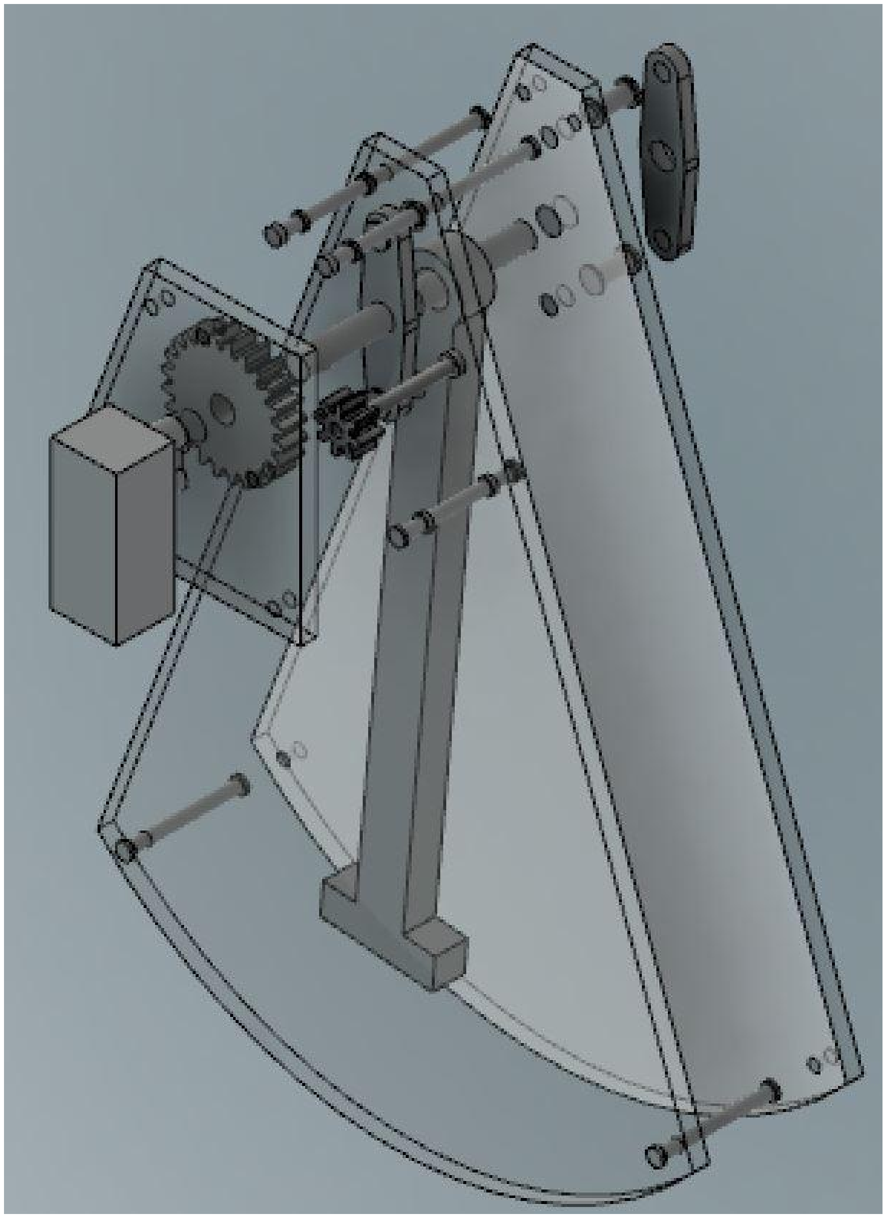

Figure D5: Partially Exploded View of Pendulum Design.

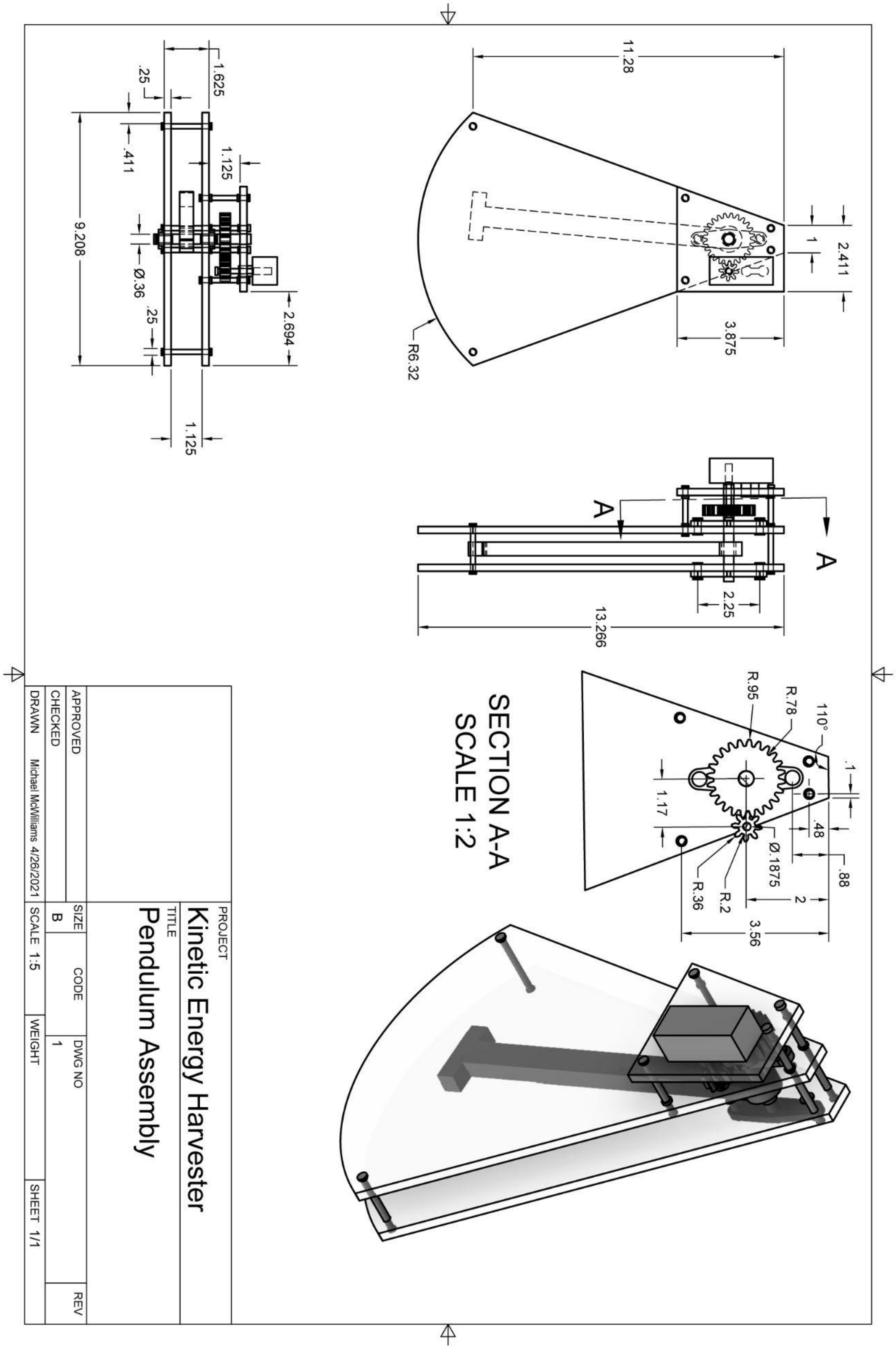

Figure D6: Engineering Drawing of Pendulum Assembly.

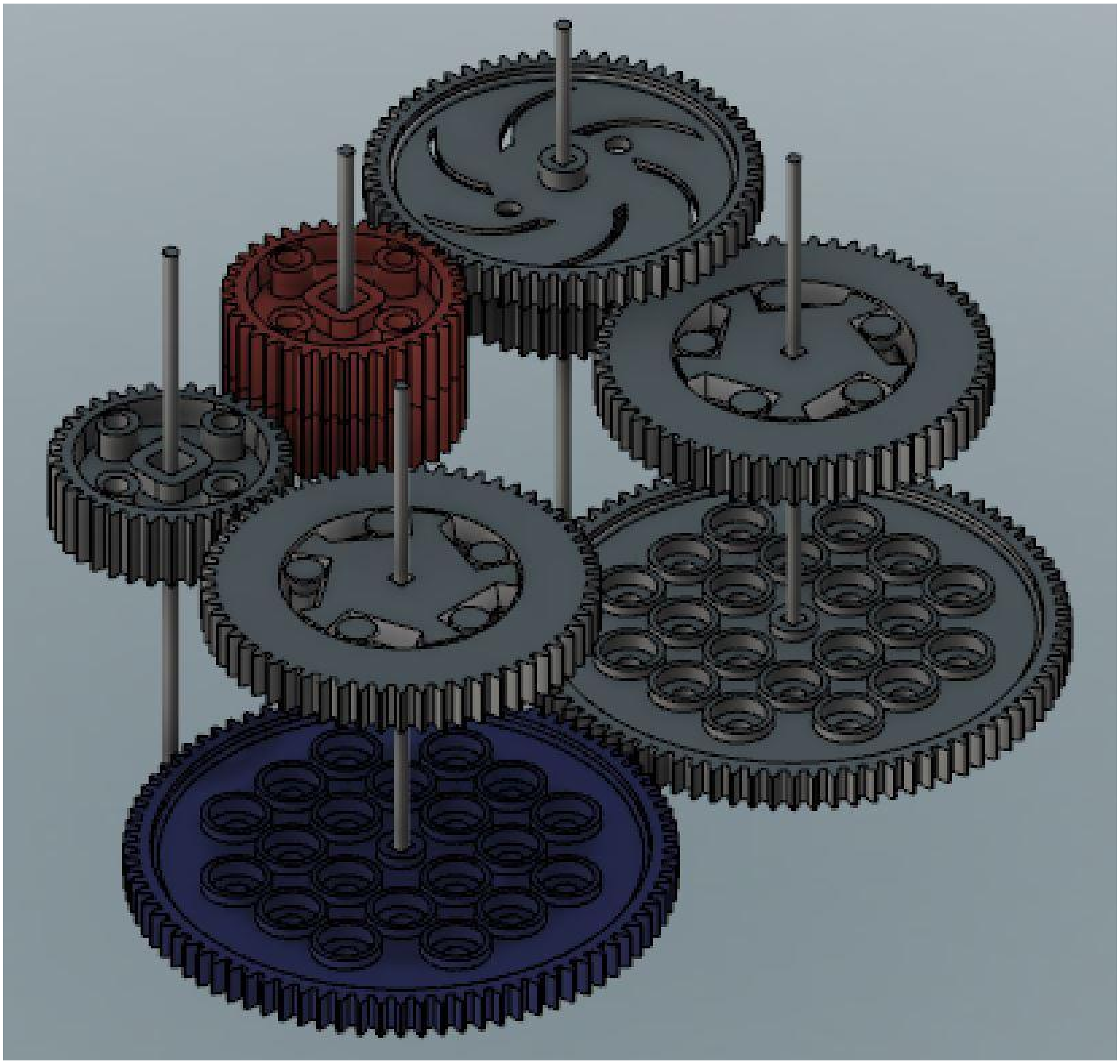

Figure D7: Mechanical Rectifier CAD Model.

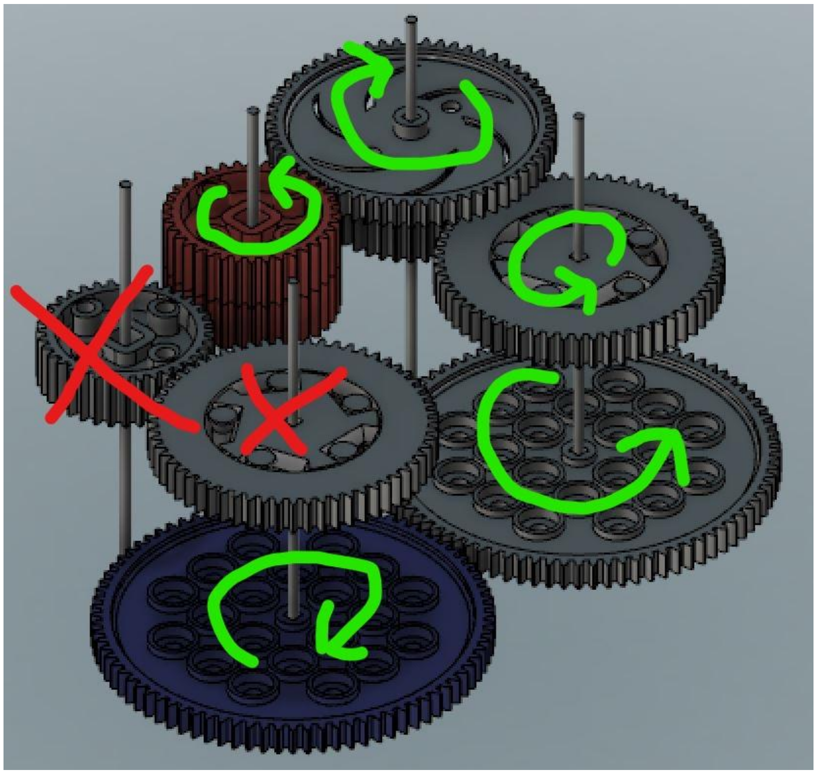

Figure D8: Mechanical Rectifier Explanation Clockwise Input.

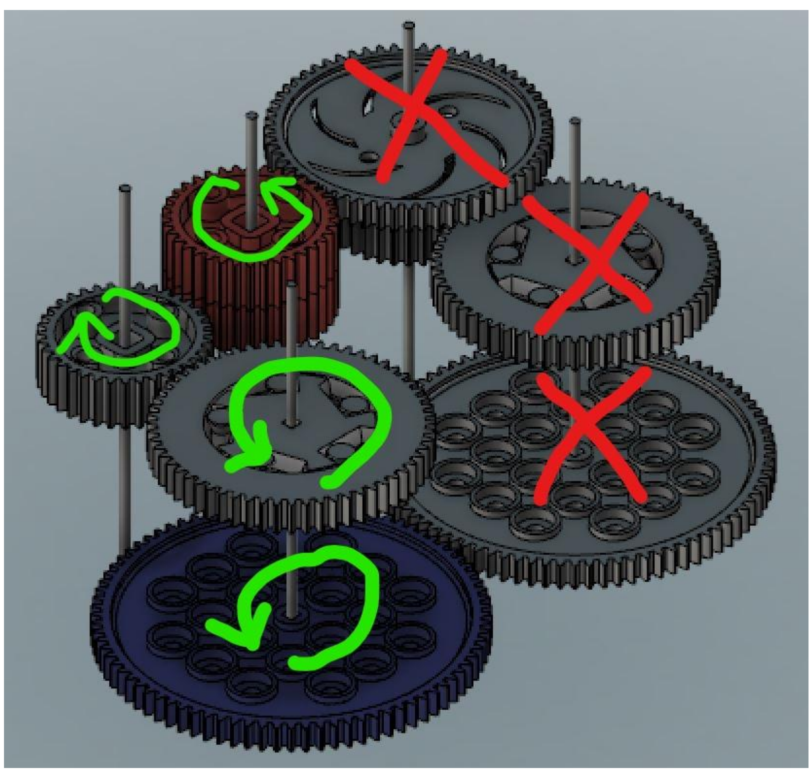

Figure D9: Mechanical Rectifier Explanation Counter-Clockwise Input.

Figure D10: Pendulum Casing prototype

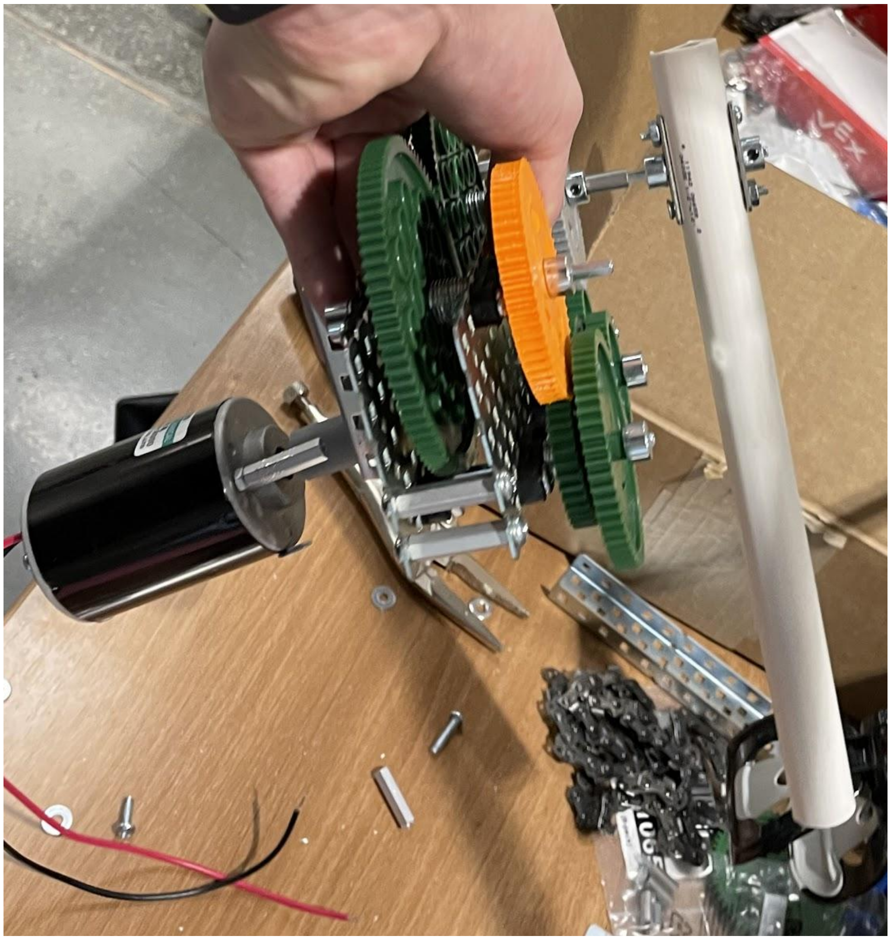

Figure D11: Mechanical Rectifier Proof of Concept.

Appendix E: Key Survey Results

Table E1: What do you prioritize when Selecting a backpack? Rank these from most important to least important

		Percentage of Respondents Who Chose the Specified Rank						
		1	***2***	***3***	***4***	***5***	***6***	***7***
Properties	***Function***	64.58	18.75	10.42	2.08	0.00	2.08	2.08
	Style	6.25	20.83	14.58	20.83	6.25	25.00	6.25
	Safety	0.00	0.00	4.17	2.08	16.67	20.83	56.25
	Quality	16.67	29.17	27.08	16.67	4.17	6.25	0.00
	Comfort	2.08	16.67	20.83	35.42	20.83	4.17	0.00
	Price	8.33	14.58	14.58	18.75	27.08	14.58	2.08
	Weight	2.08	0.00	8.33	4.17	25.00	27.08	33.33

Table E2: How much weight do you carry in your backpack on average?

Weight (lbs)	Percentage of Respondents
Less than 5	6.25%
10-May	58.33%
20-Nov	29.17%
21 - 30	6.25%
More than 30	0.00%

Table E3: Is this a product you would be interested in purchasing?

Answer	Percentage of Respondents
Yes	22.92%
Maybe	66.67%
No	10.42%

Appendix F: Bill of Materials

Item	Quantity	Cost	Function
6” long, 1/2” diameter PVC pipe	1	$0	Housing for the harvester
PVC cover for pipe	2	$0	Housing for the harvester
Neodymium Magnet	1	$28.24	Energy harvester
Spring	2	$3.28	Energy harvester
Copper wire, 28 gauge, .05" OD	1 (25ft)	$2.68	Energy harvester
Fixtures for the magnet	2	$0	Energy harvester
¼” thick acrylic board	2	$0	Housing for pendulum
BQ25507 evaluation board	1	$0.99	Contains critical components for charging super capacitor
IN5817 diode	4	$6.84	Bridge rectifier for generated energy
500F, 2.7V super capacitor	1	$7.99	Storage of generated energy
Terminal block	1	$0.30	Connection of generated energy to circuit board
Assorted nuts and bolts	~	$0	Pendulum attachments

Appendix G: Circuit Schematics

Figure G1: Circuit Schematic of BQ25570 Evaluation Module

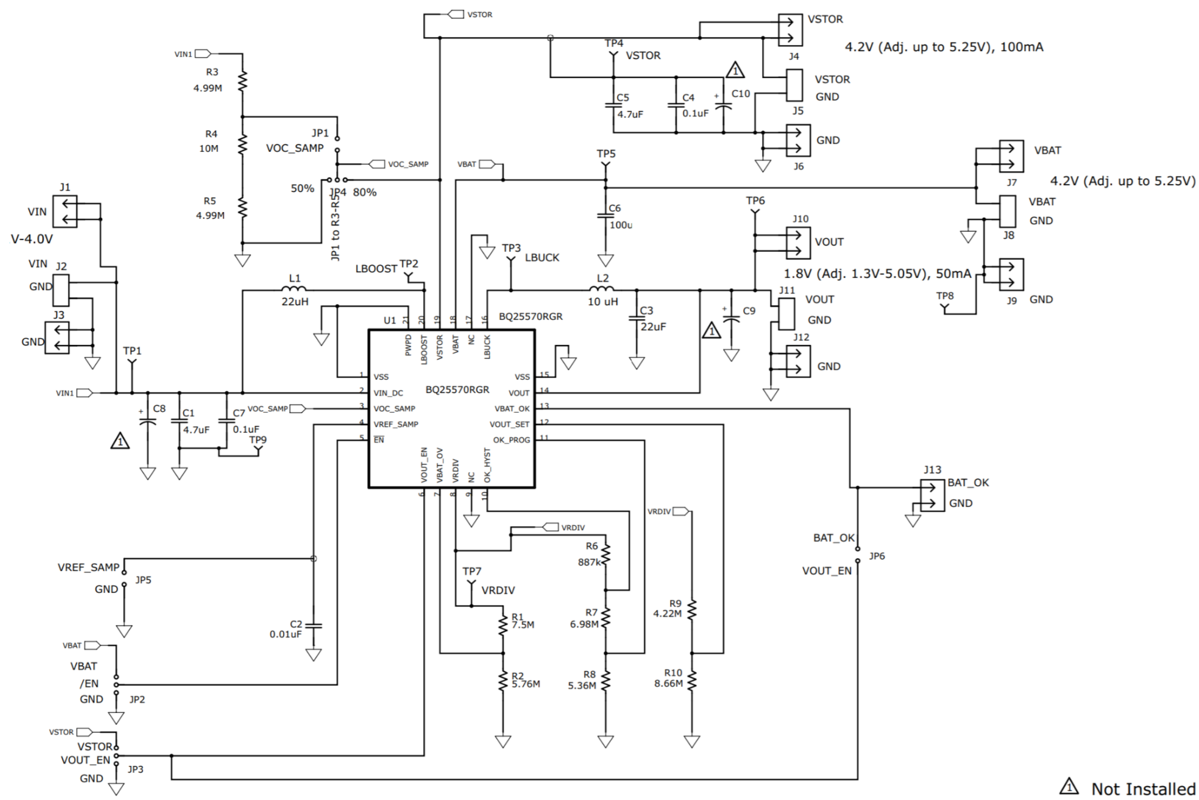

Figure G2: Internal Circuit Schematic of BQ25570 IC Chip