KINETIC ENERGY HARVESTING DEVICE
FOR LONG DISTANCE THRU-HIKERS

SENIOR PROJECT

PRESENTED BY
David Hernandez
Jarod Lyles
Ryan McLaughlin
Shaw Hawkeye Hughes

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The Warren J. Baker and Robert D. Koob Endowments

Mechanical Engineering Department
California Polytechnic State University
San Luis Obispo
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Acknowledgments

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Additionally, we thank the following people for their efforts in supporting the project:

- Charlie Refvem: His contributions to the electromechanical design of our device proved crucial. His forte in brushless DC motor operation guided motor selection, and his experience in PCB design helped us to design a board on an accelerated timeline.
- Dr. John R. Ridgely: His advice during Critical Design Review helped us to determine a feasible project scope in terms of electronics design.
- Dr. Robert Clark: His expertise in biomechanics reinforced our learnings from technical research and confirmed design direction.
- Walter Minehart: His CNC manufacturing support was critical to completing the build on time.
- Paul McLaughlin: His donation of a backpack frame allowed us to quickly develop a robust apparatus for on-trail testing.
Abstract

The intent of this project was to design and build a device capable of harnessing biomechanical energy from a thru-hiker to charge electronic devices. To begin, we ruled out any potential solutions that could be intrusive to the hiking experience, limiting us to a device that could be placed in a backpack.

After defining the scope of the project, we ideated upon potential designs, and chose to move forward with a rotational generator based design. Detailed analysis included both system dynamics and vibrations based models, and from this analysis we developed a mechanical design in SOLIDWORKS® and a custom printed circuit board (PCB) in Autodesk EAGLE® and Fusion 360.

Manufacturing of our device included both manual and CNC parts, with the most complex being a 5-axis CNC part. The circuit board was fabricated by OSH Park, as this was beyond our capabilities. System integration was highly successful, but due to higher than expected electrical/mechanical resistance, a lower than desired speed increase across the geartrain, and a variety of other issues, we were not able to produce enough power to charge a power bank.

However, low power output did not completely disprove feasibility of the concept. Both the mechanical and electrical subsystems functioned as expected, and showed promise in isolated testing. Further work related to this project should be focused on gathering informative data related to prototype performance in an on-trail setting. And lastly, although our project focused on thru-hikers as the main customer, a much larger market could be reached with the success of such a product.
Introduction

The objective of this project was to design and fabricate a device to charge portable electronics using biomechanical energy from walking. Specifically, we targeted thru-hikers as our main customers. Not wanting to intrude upon the hiking experience, we chose to limit our design to a device that could be placed in a backpack and operate without any additional user input.

Over the course of a full academic year, we took the project from problem statement to a working prototype. This report is a compilation of all four reports written for our sponsor, with the contents of each report described in detail below. Note these reports were written as individual components; each report is self-contained with their own page numbers, references, and appendices.

1. *Scope of Work (SOW):* The first report written for the project sponsor, SOW focuses on technical research and problem definition. This report also outlines the design process we would follow and the timeline upon which we would execute all tasks.

2. *Preliminary Design Review (PDR):* After performing technical research, we moved onto to design ideation, concept prototyping, and down selection. In the PDR report, we introduced two concepts, which were narrowed to a single design direction in CDR.

3. *Critical Design Review (CDR):* CDR includes analysis and justification for our final selected design, as well as all manufacturing operations and testing plans for the final prototype. The appendix for this report notably contains the full indented bill of materials (iBOM), drawings and specifications package, and detailed manufacturing plan.

4. *Final Design Review (FDR):* The final report of the project, FDR details any manufacturing operations not previously covered in CDR, a final review of specifications, and a summary of all testing and troubleshooting performed. Lastly, FDR includes a discussion of project learnings and recommendations for further work.

Note that within the body of each report, previous reports may be referred to using their full name or acronym.
KINETIC ENERGY HARVESTING DEVICE
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SCOPE OF WORK

PRESENTED BY
David Hernandez
Jarod Lyles
Shaw Hawkeye Hughes
Ryan McLaughlin

Mechanical Engineering Department
California Polytechnic State University
San Luis Obispo
20 October 2021
Executive Summary

The intent of this project is to design and build a device that harnesses the biomechanical energy from a thru-hiker to charge their electronic devices. We performed research to gauge interest for a product that captures kinetic energy from walking, and we examined various kinetic energy capture solutions, such as mechanical, electromechanical, electromagnetic, and piezoelectric. The focus of this project is the creation of a device for long distance hikers, but our technology could be extended to a broader market if proven successful.
Scope of Work

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1 Introduction

Thru-hiking is a subset of backpacking that entails hiking the entirety of an established trail system – such as the Pacific Crest Trail or the Appalachian Trail – in an end-to-end attempt. Rechargeable electronic devices are an integral part of everyday life, and many thru-hikers use rechargeable devices on the trail. Accordingly, there is a growing need for portable charging solutions in the backcountry. There are a few existing products used by thru-hikers, such as solar panels, but they require specific environmental inputs.

Thru-hikers need a consistent source of energy to charge their mobile devices that does not rely on environmental conditions or compromise their hiking experience. To fulfill this need, we aim to capture human biomechanical energy generated from hours of walking each day. Over the course of the next eight months, our team will apply a comprehensive design process to generate a functional prototype to fill this need.

Our team consists of four undergraduate mechanical engineering students studying at California Polytechnic State University, San Luis Obispo: David Hernandez, Shaw Hughes, Jarod Lyles, and Ryan McLaughlin. We will be performing this work for our sponsor, Dr. Peter Schuster, a professor of mechanical engineering at Cal Poly.

This report, the Scope of Work, is focused on the early stages of our design process: defining the problem we are solving, scoping the project, synthesizing past research related to our project, presenting a clear timeline for the completion of the project, and identifying resources we will need to be successful. In the remainder of the report, we will cover background information, objectives for our design, and a plan for project management.
2 Background

The goal of this background research was to quantify the niche market need that we intend to fill, understand why it has not yet been successfully filled, and explore existing technical research that might help us succeed.

2.1 Customer Research

Early in our design process, we decided to focus on long-distance backpackers. Thru-hikers often spend long stretches of time without access to electricity and they consistently hike for ten or more hours every day. These two factors make the thru-hiker community a perfect target market for our device.

2.1.1 Survey

To learn more about our customer needs, we created a survey and distributed it amongst the thru-hiking community. Along with some basic demographic information, our survey quantified: hiking style, current battery-powered device usage and charging methods, and preferences for a kinetic charging system. We shared the survey via our personal connections, the Cal Poly Mechanical Engineering department newsletter, and a variety of Reddit forums.

Overall, the survey responses are enthusiastic and confirm the customer need for a lightweight kinetic energy harvesting device. To date, we have received over 300 responses. From preliminary analysis of these responses, we have identified a few key inputs: thru-hikers often hike 20 to 30 miles every day for ten or more hours, and every single respondent carries at least one USB-rechargeable device with them on long trips.

2.1.2 Ongoing Customer Research

Over 100 individuals that responded to our survey offered to answer follow-up questions. Moving forward, we will be reaching out for interviews and sending periodic updates to receive more feedback from the thru-hiker community.

2.2 Existing Solutions

There are no commercially available products that satisfy the needs of our target market. Most thru-hikers – nearly 90% according to data collected on PCT thru-hikers [1] – carry a rechargeable battery pack. Some thru-hikers choose to supplement with a small solar panel. Otherwise, there are no realistic solutions for thru-hikers.

Thru-hikers and backpackers want electricity on the trail for a few primary reasons: cellular and/or satellite communication, navigation, and sometimes listening to music. The electricity needs of the devices that enable these functions are not well-met by the existing solutions mentioned above; rechargeable battery packs often take 8+ hours to charge, and solar power is not always available.
2.2.1 Product Research
We gained insight by comparing some existing products, as summarized in Table 2.1. A solar panel charger is included as benchmark, but otherwise these products all capture energy independent of environmental conditions.

**Table 2.1. Summary Table of Competitive Products and Claimed Specifications.**

<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Linear Motor [2]</td>
<td>“up to” 4</td>
<td>397</td>
<td>0.52</td>
<td>$200</td>
<td>-20 to 60 °C</td>
<td>unknown</td>
</tr>
<tr>
<td>Solar Charger [3]</td>
<td>6.12</td>
<td>213</td>
<td>0.14</td>
<td>$130</td>
<td>-7 to 50 °C</td>
<td>IPX7</td>
</tr>
<tr>
<td>Hand Crank [4]</td>
<td>5</td>
<td>425</td>
<td>0.63</td>
<td>$65</td>
<td>0 to 55 °C</td>
<td>unknown</td>
</tr>
<tr>
<td>Kinetic Watch *</td>
<td>N/A</td>
<td>61</td>
<td>0.01</td>
<td>$275</td>
<td>5 to 35 °C</td>
<td>IP68</td>
</tr>
</tbody>
</table>

* [4] and [5] have been grouped into one generic category due to specifications being similar.

It was helpful to examine the mechanisms by which these products capture energy. Only one of these existing products is a viable option for our target market: the Suntactics S5 solar charger. The K-TOR Pocket Socket hand crank charger requires unreasonably intrusive hand-crank input from the user, the nPower PEG is no longer available for purchase, and kinetic watches are included only as a reference point for a similar technological field.

The nPower PEG, as shown in Figure 2.1, is the most relevant product precedent for our target market.

![Figure 2.1. First-generation (left) and second-generation (right) nPower PEG devices [5] [6].](image)

The nPower PEG is a kinetic energy harvesting device with an internal battery and USB output. A lightweight, 255-gram, titanium version first went on sale in May of 2010 for $150 [7] [5]. At some point, a second-generation plastic device was introduced, with the specifications indicated in Table 2.1. It debuted for retail purchase in 2012 [8]. As of October 2021, the PEG is no longer
available for purchase from any vendor. The second-generation device received a favorable review by Michael Lasky of Wired Magazine in October of 2012. His personal testing was as follows:

> Starting with a depleted PEG, I carried it on a ten-minute run. This yielded about a minute of talk time on a pre-3G phone. But it took over 25 minutes of brisk walking to get just a minute on a 3G smartphone. I didn’t test how much time it takes to power a short call on a 4G phone because I have a strict no-marathons policy [8].

If the PEG consistently performs according to Lasky’s testing, a similar mechanism could hold promise for our project. The published power output of the PEG is 4-watts, but we currently have no way to verify this claim. We have reached out to the inventor, Aaron LeMieux, with hopes of learning more. The operating principle of the nPower PEG is examined in the following section, Patent Research.

The Suntactics S5, as photographed by our team member in Figure 2.2, is a 5W solar charger designed for thru-hikers. There are numerous options for solar chargers, but we chose to benchmark with the S5 for a few reasons: it is designed specifically for endurance hiking, the power output is consistent with competing products, and we have personal thru-hiking experience with the product to validate its capabilities.

![Figure 2.2. Suntactics S5 solar charger.](image)

Per our survey results, 16% of 199 self-described thru-hikers use a small solar panel. These thru-hikers often travel ten or more hours every day, so the panel is unlikely to consistently capture sunlight.
Our third product for comparison was the Pocket Socket hand-crank dynamo USB charger [4]. This model can ostensibly produce 5W of continuous power [4], albeit at twice the weight of a solar panel with similar output. A hand-crank charger functions independently of environmental conditions; however, it is unreasonably intrusive on the hiking experience, as indicated by minimal use in the thru-hiking community.

Finally, we have included two self-winding, or “automatic”, watches in our comparison: the Timex Waterbury Classic [9] and the Seiko SRPE61 [10]. Both watches capture and mechanically store tiny amounts of energy from the wearer. Neither watch can charge a phone, but nonetheless the technology can teach us something. Self-winding watch mechanisms are highly efficient, and they employ a small pendulum to capture energy, as shown in Figure 2.3.

![Figure 2.3. The Timex Waterbury Classic fully-mechanical kinetic energy capture and storage mechanism [9].](image)

The Timex model shown in Figure 2.3 is purely mechanical. Alternatively, the Seiko model, an “automatic quartz watch” converts stored energy to electricity to oscillate a quartz crystal. The pendulum mechanism operates under the same principle as a mechanical kinetic watch, but it uses the Kinetron microgenerator system (MGS), as shown in Figure 2.4, to generate electricity [11]. Kinetic watches achieve high efficiency, in part, by using “jewel bearings” at the center of most rotating components [12].

![Figure 2.4. Kinetron microgenerator system schematic and MG4.0 generator detail [11].](image)
2.2.2 Patent Research

Patents gave us insight into the operating modes of emerging and established technologies for harvesting biomechanical energy. Table 2.2 captures the most detailed, product-ready biomechanical energy harvesters from our research.

<table>
<thead>
<tr>
<th>Patent Name</th>
<th>Patent Number</th>
<th>Status</th>
<th>Design Characteristics</th>
</tr>
</thead>
<tbody>
<tr>
<td>Electrical energy generator [13]</td>
<td>7498682B2</td>
<td>Active</td>
<td>Tubular housing with spring-loaded electromagnet mass moving linearly through the surrounding coil (nPower Peg patent)</td>
</tr>
<tr>
<td>Kinetic energy harvesting methods and apparatus [14]</td>
<td>9331559B2</td>
<td>Active</td>
<td>Tubular housing with suspended magnet reciprocating through surrounding coil</td>
</tr>
<tr>
<td>Miniature kinetic energy harvester for generating electrical energy from mechanical vibrations [15]</td>
<td>10581344B2</td>
<td>Active</td>
<td>Sprung magnetic mass with surrounding coil to capture changing magnetic flux</td>
</tr>
<tr>
<td>Methods and apparatus for harvesting biomechanical energy [16]</td>
<td>9057361B2</td>
<td>Active</td>
<td>Rotary generator intended to connect to joint</td>
</tr>
<tr>
<td>Backpack based system for human electricity generation and use when off the electric grid [17]</td>
<td>7851932B2</td>
<td>Active</td>
<td>Beam sits against user’s femur and an AC dynamo converts reciprocation to power</td>
</tr>
</tbody>
</table>

A few of these compact form-factor devices utilize suspended magnetic masses reciprocating in coil systems to harvest time-varying magnetic flux [13] [14] [15]. Other patents utilize rotary AC or DC generators [16] [17]. Our patent research suggests that linear and rotary generators are a more developed mechanism for capturing biomechanical energy to power portable electronics than alternatives such as piezoelectric generators or triboelectric nanogenerators.

Specifically, we were interested to see the operating principle of LeMieux’s nPower PEG. Two variations of the mechanism are shown in Figure 2.5. In the first illustration, “an electromagnetically active mass (140) moves in a reciprocating manner along a path constrained by a guidance means (160), which is, in the embodiment shown, the interior surface (124) of the housing (120)” [13]. In the second configuration, the mass is guided by “an elongated rod engaged at either end with [the] housing (220)” instead of the housing itself [13]. It is unclear which configuration is used in the production PEG.
Ultimately, patent exploration was a minor part of our background research. The technical literature conveys far more technical details.

2.3 Technical Literature Review

In our literature review, a few technical challenges stood out to us. These technical challenges are all linked by one factor: the unpredictable nature of human motion. In the following sections, we examine the specifics of biomechanical issues and the engineering challenges to kinetic energy capture.

2.3.1 Low Frequency of Human Bipedal Motion

For one-dimensional motion at constant velocity, the basic equation for kinetic energy is

\[ KE = \frac{1}{2} m v^2 \]  

where \( m \) and \( v \) are the mass and velocity of the body, respectively. Therefore, to increase kinetic energy generation, mass and/or velocity must increase. An appropriate metric for characterizing human motion is step frequency. From studies by Berdy et al. [19], Montoya et al. [20], and Huang et al. [21] it has been repeatedly determined that typical human step frequency is less than 3 Hz. To capture energy from low frequency oscillation, a technique called “frequency up-conversion” is commonly applied in research communities [11].

Vocca and Cottone [22] present a typical up-conversion schematic, as depicted in Figure 2.6. Excitation of the primary vibrational element (\( m \)) is translated through “mechanical energy transfer teeth” to a secondary element (piezoelectric cantilever beams, in this case) with a higher resonant frequency. With a higher oscillation frequency, the piezoelectric power output of the secondary elements is higher than if they were oscillated directly by the spring.

Figure 2.5. Illustrations of the nPower PEG; Fig 1 and Fig 2 in the patent document [13].
It is important to note that this type of system can be constructed from any combination of oscillatory elements or interaction mechanisms (magnetic, mechanical, or otherwise). Unfortunately, frequency up-conversion, like many solutions for improving energy capture from low-frequency vibration, is most advantageous for a predictable source frequency [22].

2.3.2 Randomness of Gait
The basic kinematics of walking are well understood, but the manner of walking, or “gait”, differs amongst individuals [19]. For example, in testing conducted by Berdy et al. [19] with a levitating magnet energy harvester, the mean output power from 10 participants walking at the same speed varied by over 40%.

Additionally, forces that are not captured by the harvesting device vary unpredictably. In some cases, these unpredictable forces further reduce power output. As shown in Figure 2.7, the vertical and horizontal displacements of a human’s center of mass follow a sinusoidal path, but these additional directions of motion contribute negatively to power output for one-dimensional energy harvesters due to increased damping [21].
2.3.3 Energy Available at Upper Body

Another important constraint that appeared in our research was the significant impact of device location on the human body. As explained in more detail in our Problem Definition, we have limited our solution space to a device that can function inside of, or externally on, a backpack. To our knowledge, studies have not been done to quantify the acceleration of a worn backpack, but results from Huang et al. [21] and Montoya et al. [20] indicate that upper body motion provides less power output than the lower body.

In testing conducted by [21], data was taken from a tri-axial accelerometer at five different locations on the body. The experimental setup is shown in Figure 2.8. Presumably, vibrations at the waist location most closely mimic a backpack. The specific power output (energy per unit mass) was an order of magnitude greater at lower body locations [21].

![Figure 2.8. Experimental setup for the energy harvesting testing conducted by [21].](image)

Pendulum-based experiments conducted by [20] showed a similar result. Energy availability on the chest (0.05-1.2mJ) was significantly lower than that for the hip (0.5-2.5mJ) and elbow (0.5-41mJ).

These studies suggest that energy capture from the upper body is not the best solution; perhaps a hip-belt mounted device is a better solution. We will consider this possibility as we continue the design process, but we would also like to perform our own testing to determine if energy capture from a backpack location differs from direct upper body motion.

2.3.4 Power Requirements of Circuitry

Another notable technical challenge is the low margin of available power for circuitry losses. By nature, producing steady DC power from an oscillating energy source requires rectification and voltage regulation. Typical diodes have an inherent voltage drop of about 0.7V, so low voltage rectification can be especially inefficient [23].

For example, Mayer et al. [24] designed and tested a smart power unit (SPU) to maximize the power output from kinetic wearables like the Kinetron MGS. This unit utilized a low power microcontroller for dynamic state changes between sleep modes and active power modes,
management of energy harvesting, and DC-DC conversion for active voltage scaling. Although this unit was able to better capitalize on bursts of energy, the quiescent current needed to run the microcontroller during active power modes decreases the overall system efficiency [24]. The available energy is scarce to begin with, so any design with overhead like the SPU is impractical. Ultimately, we need to perform more research to design a circuit that will achieve maximum power output.

2.3.5 Further Research

Due to time constraints for the preparation of this report and the wide array of solutions available in the technical literature domain, there are some areas that we would like to further investigate.

For one, we have not come to a conclusion about the viability of utilizing resonance to capture additional energy. As discussed by [22] and Luo et al. [25], resonant systems rely heavily on a small band of input frequency. Both inquires concluded that systems relying on resonance are too inconsistent for practical deployment. However, studies by Zhang et al. [26] (using a rotary inertial harvester) and Nia et al. [27] (a piezoelectric approach) both considered achieving resonance a critical design goal.

We will further explore methods to harness energy, such as piezoelectric, magnetostictive, and triboelectric capture. Specifically, non-linear systems provoke further investigation. As discussed in [22], non-linear systems such as bistable cantilevers and buckled beams provide unique capabilities to harvest energy at wider ranges of frequency. However, the non-linearity of these solutions adds significant complexity to modeling, and these solutions have been tested far less than the techniques described in earlier sections.
3 Objectives

The objectives section establishes measurable criteria for evaluation of our final design and outlines the various deliverables that will be used to guide our design process.

3.1 Problem Definition

Our problem statement is as follows:

*Thru-hikers need a consistent source of energy to charge mobile devices used for communication and navigation. This energy source should be compatible with the hiking experience, and it must be available regardless of environmental conditions.*

As discussed in our approach to customer research, we are creating a product specifically for thru-hikers: long-distance backpackers pursuing continuous, end-to-end travel along a designated route. We considered other users such as backpackers, commuters, and people without consistent access to electricity, but we consciously chose to focus our efforts on a smaller target market.

The thru-hiking community often uses portable battery packs or solar generation for personal power in the backcountry. Elimination of environmental limitations, such as inconsistent sunlight and limited time near commercial electricity sources, will provide self-reliance and independence for thru-hikers.

The consistent exertion from a thru-hiker provides an unusually feasible opportunity to create usable, reliable electrical power from kinetic motion. The energy-capture device should not hinder a hiker’s range of motion, sacrifice comfort, or require complicated mounting or adjustment. Specifically, the device should function inside of, or externally on, a backpack. Thru-hikers should be engaged in their journey, not waiting for batteries and devices to charge.

We compiled the following customer needs from our research. The device must:

- Effectively harvest energy in all hiking conditions.
- Be lightweight and not intrusive on the hiking experience.
- Be simple to use, durable, and reliable regardless of exposure to water, dust, and shock.

Some customer desires are less critical (“wants”). The device should:

- Be compact.
- Produce power in any orientation.
- Be aesthetically pleasing.

As shown in Figure 3.1, we used a function tree to identify the desired function and scope of our solution. The primary function is to capture energy; our scope is limited to harnessing
biomechanical energy. To fulfill the needs of thru-hikers, our device must generate electricity while seamlessly integrating with the thru-hiking experience.

![Function Tree](image1.png)

**Figure 3.1.** Function tree identifying boundary scope of our project.

In addition, the boundary sketch in Figure 3.2 provides a visual representation of the function tree. The dotted lines on each figure encompass factors that we can control and are within our scope.

![Boundary Sketch](image2.png)

**Figure 3.2.** Boundary sketch used for problem definition.
3.2 Quality Function Deployment

Quality Function Deployment (QFD) is a methodical process that helped us accurately constrain our problem. We carefully considered the customer (who), customer needs (what), and engineering specifications (how). From the QFD process, we were able to identify customer wants and needs that either could not be tested or were not critical enough to warrant inclusion in further analysis. Wants such as aesthetic appeal and waterproofing were removed due to their low level of importance, and the need for a long lifespan was ruled out based on the inability to test with available equipment.

We also determined that only a few critical specifications (namely power output, weight, and cost) could clearly define the success of our work. QFD also pushed us to identify our main competitors: solar panel chargers, hand crank chargers, kinetic watches, and past failed kinetic chargers such as the nPower Peg. The final output of QFD is the “House of Quality” table, included as Appendix A. We will revisit the House of Quality throughout our conceptual design phase.

3.3 Engineering Specifications

From Quality Function Deployment (QFD) analysis, we synthesized our customer wants and needs into engineering specifications. Engineering specifications are testable, measurable parameters, as shown in Table 3.1.

Table 3.1. Engineering specifications, in order of importance.

<table>
<thead>
<tr>
<th>Spec.</th>
<th>Parameter Description</th>
<th>Target</th>
<th>Tolerance</th>
<th>Risk*</th>
<th>Compliance †</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Power Output</td>
<td>5W</td>
<td>Min.</td>
<td>H</td>
<td>A, T</td>
</tr>
<tr>
<td>2</td>
<td>Weight</td>
<td>250g</td>
<td>Max.</td>
<td>M</td>
<td>A, I</td>
</tr>
<tr>
<td>3</td>
<td>Manufacturing Cost</td>
<td>$100</td>
<td>Max.</td>
<td>M</td>
<td>A</td>
</tr>
<tr>
<td>4</td>
<td>Volume</td>
<td>0.5L</td>
<td>Max.</td>
<td>M</td>
<td>A, I</td>
</tr>
<tr>
<td>5</td>
<td>Drop Resilience</td>
<td>Ten drops from 2m</td>
<td>Min.</td>
<td>M</td>
<td>T</td>
</tr>
<tr>
<td>6</td>
<td>IP Rating</td>
<td>IP54</td>
<td>Min.</td>
<td>L</td>
<td>I, T</td>
</tr>
</tbody>
</table>

* Risk of meeting specification: (H) High, (M) Medium, (L) Low
† Compliance Methods: (A) Analysis, (I) Inspection, (S) Similar to Existing, (T) Test

Explanations of each engineering specification are included as follows, in order of importance:

1. A solar panel like the Suntactics S5 is our most notable competitor in this product space. If we can match or exceed the **power output** of a small solar panel, our device will be a desirable alternative for thru-hikers. Specifically, we will conservatively assume that a 5W panel continuously produces power, as use 5 watts as our benchmark.

2. Minimizing **weight** is a priority for thru-hikers. Based on the weight of competitive systems (as shown in Table 2.1) and results from our survey, we will target 250 grams (8.8 oz).
3. **We will target a cost** of less than $100 to manufacture the device. Again, this consensus is based on survey results and the pricing of competitive products. Cost is closely related to the weight of the device; most likely, minimizing device weight will involve lightweight, expensive materials.

4. **Volume**, like weight, is important to thru-hikers, albeit slightly less so. We will target a realistic 0.5L device volume based on survey results. Most likely, we will not be able to compete with the volume of a solar panel (roughly 0.15L).

5. Regardless of our final design direction, the device must be able to withstand extended use by a thru-hiker. We defined a target value for **drop resilience** as ten drops from 2m onto hard-packed dirt, to ensure that the device strikes the ground in multiple orientations. The device must produce at least 90% of the original power after the drop test to meet this target.

6. **IP ratings** quantify enclosure resistance to moisture and debris ingress. The numerals signify resistance to solid foreign objects and water, respectively. IP54 indicates that dust particles smaller than 1.0mm diameter must not damage the device and that water splashed against the enclosure in any direction must have no harmful effects [28]. These conditions are explained clearly in the IEC IP code: “ingress of dust is not totally prevented, but dust shall not penetrate in a quantity to interfere with satisfactory operation of the apparatus or to impair safety”. [29] Test conditions are explained in detail in section 11 of the IP code; we will refer to these details when we test our prototype. [29]
4 Project Management

We will utilize a few tools to maintain efficient progress and focus throughout the design process: human-centered design, a detailed Gantt chart for schedule tracking, and clear definition of deliverables for our sponsor.

4.1 Design Process

To produce a design that meets the foundational needs of the thru-hiking community, we will follow the human-centered design process: inspiration, ideation, and implementation [30]. Figure 4.1 captures the essence of the human-centered design process.

![Figure 4.1. Human-Centered Design Process [30].](image)

This project is especially open-ended; there are numerous design avenues to pursue. Each phase of the process will involve stages of convergence and divergence, where we swing between narrowing in on our design and reconsidering design features and options. We will maintain communication with our customer basis through surveys and interviews to ensure alignment with the needs of the thru-hiking community and avoid fixation on a single design.

The three phases of human-centered design include:

- **Inspiration**: Understand and empathize with the desires and needs of thru-hikers via additional surveys and detailed interviews. In this phase, we define our problem and understand those we aim to serve.
- **Ideation**: Generate ideas, experiment with existing solutions, test our conceptual solutions, and refine them into functional prototypes.
- **Implementation**: Perform detailed analysis and engineering design to manufacture a suitable solution.

The completion of this report marks the transition from the inspiration phase to the ideation phase. Human-centered design is not a linear process, so we will revisit phases throughout our project while maintaining focus on our goal and being cognizant of our tight schedule.
4.2 Timeline & Deliverables

The schedule of our project is constrained by the timeline of the Cal Poly Mechanical Engineering Fall 2021 through Spring 2022 senior project schedule. The milestones that we must meet are captured in the Gantt chart included in Appendix B.

We are utilizing a Gantt chart for detailed schedule tracking. The first third of our Gantt Chart, from project inception through Preliminary Design Review, is included in Appendix B. The Gantt chart provides visualization of task dependencies, project progress, and the individuals responsible for each task. If milestones must change, justification will be approved by our sponsor.

We will have weekly meetings and create detailed written reports for our sponsor, Dr. Schuster. These reports will document our validation of the design, overall project progress, and the results of our solution. Table 4.2 tabulates major deliverables with a brief description and expected submission date for each.

<table>
<thead>
<tr>
<th>Deliverable</th>
<th>Description</th>
<th>Submission Date(s)*</th>
</tr>
</thead>
<tbody>
<tr>
<td>Scope of Work (SOW)</td>
<td>Outlines problem definition, research, and project management plan.</td>
<td>October 13, 2021</td>
</tr>
<tr>
<td>Preliminary Design Review (PDR)</td>
<td>Provide justification for chosen design with a conceptual prototype.</td>
<td>November 16, 2021 (Presentation) November 18, 2021 (Report)</td>
</tr>
<tr>
<td>Critical Design Review (CDR)</td>
<td>Provide detailed analysis and design with a structural prototype.</td>
<td>February 8, 2022 (Presentation) February 11, 2022 (Report)</td>
</tr>
<tr>
<td>Bill of Materials &amp; Purchase Order</td>
<td>Provide budgeted list of materials needed for verification prototype.</td>
<td>February 14, 2022</td>
</tr>
<tr>
<td>Senior Project Expo</td>
<td>Provide capstone presentation with verification prototype.</td>
<td>May 26, 2022</td>
</tr>
<tr>
<td>Final Design Review</td>
<td>Provide final report summarizing project.</td>
<td>June 3, 2022</td>
</tr>
</tbody>
</table>

* Submission dates may change. Sponsor will approve any changes in advance.

4.3 Preparation for Preliminary Design Review

Following this report, our next milestone and major deliverable is the Preliminary Design Review (PDR). In our PDR report and presentation, we will explain our chosen conceptual design(s). Due to the unique nature of this project, it is possible that we will have multiple design avenues at this stage. We will iterate with the ideation and inspiration phases to choose and develop the most promising concept(s).
5 Conclusions

We have resolved to design a device for thru-hikers that captures kinetic energy from walking to charge electronic devices. This device will not intrude on hiking experience. It must be lightweight and reliable. Our most critical design specifications are as follows: a power output of 5 watts at a mass of 250 grams, and a volume of 0.5 liters or less.

Technical challenges include: the random nature of low frequency human walking motion, the potential limitations of harnessing energy from the upper body region, the lack of available data concerning the acceleration of various regions in a worn backpack, and the need for efficient circuitry. Further research will be conducted as needed in these areas.

Once given approval by our sponsor, Dr. Schuster, this document will serve as an agreement outlining the scope of work for which we are responsible. Any significant changes must be discussed with and approved by Dr. Schuster and documented in subsequent reports. We will provide our next major deliverable to Dr. Schuster, the Preliminary Design Review (PDR) on November 18th, 2021. The PDR will focus on justification for our chosen design direction based on continued research, preliminary analysis, and a concept prototype.
References


Appendix

Appendix A: House of Quality
Appendix B - Gantt Chart
KINETIC ENERGY HARVESTING DEVICE
FOR LONG DISTANCE THRU-HIKERS

PRELIMINARY DESIGN REVIEW

PRESENTED BY
David Hernandez
Jarod Lyles
Shaw Hawkeye Hughes
Ryan McLaughlin

Mechanical Engineering Department
California Polytechnic State University
San Luis Obispo
19 November 2021
Executive Summary

The intent of this project is to design and build a device that harnesses the biomechanical energy from a thru-hiker to charge their electronic devices. Through extensive research, we summarized our device in three major functions: capture motion, transduce motion into usable energy, and convert to electricity.

Ideating for these functions led to the development of three concepts that could theoretically take our customer’s walking motion and mechanically convert it into electricity. Our selection process led to the pursuit of two oscillating motion concepts.

The first device is the “Rotational Generator”, which uses a gear train to convert vertical oscillations of the user’s backpack to rotary motion. This rotation is captured by a generator. The second device is the “Linear Generator”, in which a permanent magnet oscillates through fixed windings and induces an electric current. Moving forward, we will select one final concept from the two described to develop as our verification prototype.
Preliminary Design Review

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1 Introduction

Our objective is to design and fabricate a device for charging portable devices using biomechanical energy from walking. More specifically, we are targeting thru-hikers as our main customer. The Preliminary Design Review report is the second of four major reports for this project. In it, we detail our ideation, concept selection, and early prototyping efforts. Critically, we have chosen two concept designs: the “Linear Generator” and the “Rotational Generator”. We explain some of our preliminary calculations to assess the feasibility of our designs and the next steps for our project.
2  Learnings Since Scope of Work

The scope and goals of our project have changed slightly since the submission of our Scope of Work (SOW) report. As explained in our SOW, we created a survey and distributed it amongst the thru-hiking community. Along with some basic demographic information, our survey quantified: hiking style, battery-powered device usage, current charging methods, and preferences for a kinetic charging system. We have examined the results from this survey, and the results are presented here. Additionally, feedback from our sponsor, Dr. Schuster, and our ongoing research effort guided the changes and learnings presented in this section.

2.1  Engineering Specification Changes

Based on feedback from our sponsor and a more thorough review of our survey data, we have added two additional engineering specifications. First, device usability is an important factor in customer satisfaction; we will ensure that a user can pick up the device and use it with minimal instructions. Secondly, we have included a thermal operating range that the device must function properly within. For full details, refer to Appendix A.

2.2  Additional Research

The nPower PEG is the only product in direct alignment with our goals that made it to market. It has since been discontinued, but an article cited in our SOW claimed that the PEG could generate up to 4W [1]. This claim directly contradicts other available information online; in fact, the same article mentions “5.0V DC @ 200 mA”, or only 1W. We have been skeptical of the nPower claims since we first discovered the PEG. Unfortunately, we were unable to obtain a PEG unit for testing, and further research suggests that the 4W power output claim was severely inflated.

Most significantly, we came across a 2015 senior project report about creating a device to harness energy from mountain biking [2]. The team acquired, tested, and tore down a PEG. They measured 1.6W of power output when vigorously shaking the device, but the report is lacking a detailed testing procedure or any detailed results. The report also does not include any photos of the torn-down PEG, but the team found that it consists of a simple linear generator, rectifier circuit, and capacitor [2].

They also cite an October 2012 interview by the Section Hikers Backpacking Blog with Aaron LeMieux, the inventor of the PEG. The interview is no longer hosted online, but their team deduced that “in terms of energy generation, the device will recharge an iPhone to about 20% after a full day of walking” [2]. At the time of this interview, the iPhone 4S was the most recent release from Apple [3]. The iPhone 4S had a 1432mAh lithium polymer battery [4]. As calculated in Appendix B, this claim suggests a power output of only 0.1W. Ultimately, the available data about the nPower PEG suggests caution in pursuing a similar design.
2.3 Survey Result Analysis

To better understand the thru-hiking community, we distributed a survey inquiring about hikers’ interests in a kinetic energy harvester. The survey was distributed to thru-hiking and backpacking forums on Reddit, the Cal Poly Mechanical Engineering Department Weekly Newsletter, and personal family and friend connections. After data filtering, we received valuable input from 304 self-proclaimed backpackers and thru-hikers.

In Appendix C, the results of our survey are represented in histogram form. We found the following insights from our survey:

- Our respondents identified 35% as backpackers and 65% as thru-hikers.
- The average hiker is between the age of 20 to 29 years old, hikes between 10 and 19 miles per day (between 5 and 10 hours) on an average trip and carries 10 to 20 pounds of base weight gear.
- Rechargeable battery packs are carried by about 91% of hikers. Batteries in the 5,000 to 10,000mAh range are most common.
- Solar panels are carried by about 16% of hikers.
- Approximately 70% of hikers are unsure of the power output needed to supplement their devices while on the trail.
- Hikers would prefer a device on the order of 100 to 500mL in volume at a price point of $100 or less.

These results provide better insight into the needs of thru-hikers. In our SOW, we used Quality Function Deployment to define engineering specifications according to researched competition, not the expectations of our customer. Though we do not intend to change engineering specifications defined in our SOW, the survey results suggest we may reconsider the requirement for our most critical function – power output. As discussed later in the Feasibility Assessment of Section 5.1, thru-hikers may not need 5W to sufficiently charge a phone or other device partially or fully over the course of a day.
3 Concept Development

With minds filled with research and a fully-constrained problem from our Scope of Work, we set out on concept development. We initiated development with ideation, whittled down to system-level designs through Pugh and morphological matrices, and selected our design direction with a weighted decision matrix.

3.1 Ideation

In ideation, we performed intensive team brainstorming sessions. We summarized our device with three major functions – capture acceleration, transduce acceleration to a usable form of energy, and convert to electricity. Early in ideation, we made low-resolution system and function prototypes. These designs can be seen in Appendix D.

Throughout the ideation process, we had difficulty isolating independent functions due to the interdependent system-level nature of energy capture, transduction, and conversion methods. Figure 3.1 depicts a system-level design flow tree for our device. This ideation tree was a critical turning point in brainstorming a solution to our problem.

![System-level design flow diagram](image)

**Figure 3.1.** System-level design flow diagram.

The tree identifies possible locations of the device in or on a backpack, predicts the experienced acceleration, and feeds into paths for energy system design. Once we developed this tree, procedural brainstorming sessions were more focused and intentional towards system-level design paths.
Ultimately, we focused on two primary functions to build system-level designs – capture acceleration and transduce energy into a usable form. Electrical energy conversion had few avenues of ideation. From our research, Faraday’s Law – in the form of a linear or rotary generator – provides the most efficient and effective method to produce substantial electrical power. Ultimately, use of a linear or rotary electrical power generation relies upon the transduction method of choice.

3.2 Top Concepts

Using the Pugh matrices of Appendix E, we scored forms of acceleration capture and energy transduction. The best performing functions fed into morphological matrices; the matrices for our two chosen concepts are shown in Appendix F. Our morphological matrices fleshed out three primary system-level design choices: the Linear Generator, the Pendulum Mechanism, and the Rotational Generator.

The Linear Generator uses Faraday’s Law, converting the linear motion of a permanent magnet into an induced voltage in coiled wiring. Figure 3.2 captures the concept of the Linear Generator. We expect a linear generator to be oriented vertically in a backpack, capturing up-and-down motion of walking. However, this design may also function if oriented horizontally (length-wise).

![Figure 3.2. Linear Generator concept sketch.](image)

The Pendulum Mechanism in Figure 3.3 is another system-level design we considered. The pendulum uses the hiker’s walking motion to swing a mass-loaded pendulum arm, providing torque input into a rotary generator.
The Rotational Generator aims to convert linear motion from walking into rotational motion through a rack-and-pinion gear system that spins a generator for electrical energy production. Figure 3.4 captures a sketch of the Rotational Generator concept.

Figure 3.3. Pendulum Mechanism concept sketch.

Figure 3.4. Rotational Generator concept sketch.
These three concepts use oscillating motion to capture acceleration. The captured motion is transduced through the respective spring, gear, and pendulum mechanisms for conversion to electricity.

3.3 Idea Selection

Using the weighted decision matrix (WDM) of Table 3.1, we chose our best concepts. The specifications in the WDM were decided to be the most important to thru-hikers and to our design. We relied on our research and intuition to make scores for each specification. The values for each concept were evaluated by multiplying the score of each criterion by the assigned weight. The final scoring led to the elimination of the pendulum.

<table>
<thead>
<tr>
<th>Specifications (Target)</th>
<th>Power Output (5W)</th>
<th>Weight (250g)</th>
<th>Cost ($100)</th>
<th>Volume (0.5L)</th>
<th>Usability (N/A)</th>
<th>Total</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Weight</strong></td>
<td>5</td>
<td>4</td>
<td>2</td>
<td>3</td>
<td>2</td>
<td><strong>47</strong></td>
</tr>
<tr>
<td>Linear Generator</td>
<td>3</td>
<td>2</td>
<td>3.5</td>
<td>3</td>
<td>4</td>
<td><strong>47</strong></td>
</tr>
<tr>
<td>(15)</td>
<td>(8)</td>
<td>(7)</td>
<td>(9)</td>
<td>(8)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Pendulum Mechanism</td>
<td>2</td>
<td>3</td>
<td>3</td>
<td>4</td>
<td>2.5</td>
<td><strong>45</strong></td>
</tr>
<tr>
<td>(10)</td>
<td>(12)</td>
<td>(6)</td>
<td>(12)</td>
<td>(5)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Rotational Generator</td>
<td>3</td>
<td>2.5</td>
<td>2.5</td>
<td>3.5</td>
<td>4</td>
<td><strong>48.5</strong></td>
</tr>
<tr>
<td>(15)</td>
<td>(10)</td>
<td>(5)</td>
<td>(11)</td>
<td>(8)</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Ultimately, we selected the Linear Generator and the Rotational Generator as our two concept design directions. Aside from the high mass requirement and low power output, the Pendulum Mechanism has stringent orientation rules for operation, meaning thru-hikers would need to pay close attention to the device setup. The need for critical setup made the Pendulum Mechanism much too intrusive on the hiking experience. The Linear Generator and Rotational Generator had the two highest scores and matched up with our intuition from research. We decided to pursue these concepts in further development.
4 Concept Designs

Through the process of ideation, two final concepts have been selected for concept prototyping. These two concepts were selected based on results from our system-level weighted decision matrix. The following sections present detailed descriptions and a discussion of each concept prototype.

4.1 Rotational Generator

The first concept selected is the Rotational Generator. This design was first considered during the ideation process while exploring conversion from linear to rotational kinetic energy using a rack and pinion mechanism. The device consists of a fixed rack mated to a moving mass by a pinion gear. Within this moving mass is a gear train for increasing rotational velocity from the input (pinion shaft) to the output (generator), as well as the generator itself. By including the generator and gear train as a part of the oscillating mass, the system utilizes more of the total mass for kinetic energy capture, as explained further in Section 5. Figure 4.1 shows preliminary system CAD of the Rotational Generator design. Note that the generator itself has not been included in this preliminary model.

![Rotational Generator Preliminary CAD Model](image)

**Figure 4.1.** Rotational Generator Preliminary CAD Model.

In addition to CAD, basic mechanisms of the system have been demonstrated using LEGO® components and springs. Due to lack of access to a LEGO® motor, the generator portion of this design was not included. Furthermore, the form factor – circular versus rectangular cross section
– for this concept has not yet been determined. Form factor will be determined when a generator is incorporated into the system-level design.

![Figure 4.2. System-level view of LEGO model of the Rotational Generator.](image)

As shown in the close-up view of Figure 4.3, the pinion (darker grey gear) translates relative to the rack (left-most worm gear¹), in turn driving the gear train. The shaft with a wheel attached (right) would be connected to the generator for the final design, but for this concept prototype, a wheel more clearly showed the increase in rotational velocity at the output shaft.

![Figure 4.3. Close-up view of rack and gearing used in the Rotational Generator prototype.](image)

¹ Due to available parts, a fixed worm gear was used as the rack gear in this design.
Although this gear train and generator may add complexity to modeling and design, these parts can be purchased and directly integrated into a system, potentially leading to a lower overall manufacturing cost.

4.2 Linear Generator

In parallel to the Rotational Generator, we are pursuing conceptual design of a Linear Generator. The idea originated from the exploration of linear motors and the nPower PEG – the only significant commercial attempt at a kinetic energy harvester for hikers. As described by Faraday’s Law of time-varying magnetic flux, linear generators use an oscillating magnetic mass to develop a voltage difference in induction coiling. In our conceptual design, a permanent magnet attaches to a spring, suspending the mass and allowing for oscillation of the magnetic field through the external induction coils. The orientation of the mass-spring system allows for capture of linear, oscillatory motion in vertical plane of walking. Figure 4.4 is a primitive CAD model of the Linear Generator.

Figure 4.4. Preliminary CAD of the Linear Generator mechanism.

Figure 4.5 captures the physical prototype model. Our concept prototype for the Linear Generator was primarily constructed from clear polycarbonate tubing, a neodymium magnetic mass, extension springs, copper magnet wire, and 3D-printed retainers and caps.
The form of the design is likely to adopt a cylindrical body to minimize volume and accommodate free movement and suspension of the magnetic mass. Because of cost constraints and availability of parts, much of the design may consist of commercially, off-the-shelf components. The housing and oscillating mechanism will require in-house development and manufacturing. Dimensions and materials for the housing will be selected through detailed analysis. Additional circuitry for rectification and output of the electrical signal from the inductions coils is not pictured in the prototype of Figure 4.5.
5 Concept Justification

Our preliminary analysis and engineering judgement suggests that we can satisfy the needs of thru-hikers with one of these two approaches. In this section, we explain how we arrived at these concepts, the feasibility of each design, and the challenges we expect to face as we work towards our final design. We have performed some preliminary analysis, but rigorous engineering calculations, simulation, and testing will be used to guide the selection of one detailed design that will be presented at our Critical Design Review (CDR).

5.1 Feasibility Assessment

In our Scope of Work report, we defined our goals for this project with a set of engineering specifications. For more details, refer to Appendix A. Power output is our most important specification; we will choose the design that can make the most power within our mass and volume limitations. For an oscillating linear mass, the theoretical maximum power output is simple to quantify. The work done on an oscillating mass is

\[ W = F\delta \]  

where \( F = mg \), and \( \delta \) is the distance traveled by the oscillating mass \( m_{osc} \) in one cycle. Power, in this case, is the amount of work that can be done per cycle. Thus,

\[ Power \propto m_{osc}\delta f \]

where \( f \) is the frequency of oscillation. We have employed significant simplifying assumptions in this calculation, but it is valid for both the Linear Generator and the Rotational Generator and gives us a basic idea of how much power we can expect to produce in an absolute best-case scenario. Based on our engineering specifications, we estimated realistic values of \( m_{osc} = 200 \) grams and \( \delta = 40\) cm; we performed this calculation for a 2Hz walking frequency, as indicated by research presented in our SOW. As shown in Appendix G, we can expect to produce no more than about 1.6W of power with these concept designs.

Power output, mass, and volume are closely interrelated: power output will be maximized within these constraints. Our theoretical power calculation in Appendix G has elucidated a core issue; the concept designs presented in this report will not produce 5W at less than 250g and 500mL. When we set this specification, our logic was simple: if we can match or exceed the power output of a small solar panel, our device will be a desirable alternative for thru-hikers. Moreover, our perception of realistic power output was skewed by our understanding of the nPower PEG, as explained in Section 2 of this report.

Regardless, other facets of our preliminary analysis suggest that the device power output could satisfy our customer need at less than 5W. Based on our survey results, thru-hikers consistently hike for ten or more hours every day, and our device will reliably produce consistent power during
this entire period, unlike a solar panel. As shown in Appendix H, preliminary calculations show that a modern smartphone could potentially be charged under ideal conditions in a ten-hour period with only 1.4W.

Ultimately, power output, mass, and volume are the most important drivers of our design process. We have elected to maintain our lofty 5W specification to encourage innovation and creative solutions as we continue our ideation process. We believe that these two designs are the most promising approaches, and our remaining specifications (cost, drop resilience, IP rating, usability, and thermal operating range) are similar for both designs and should be simple to achieve as we continue the design process.

5.2 Preliminary Concept Comparison

Our concept designs are similar in function, and at this point it is unclear which device is more capable of satisfying our customer need. The added complexity of the Rotational Generator allows for several potential advantages, but the simplicity of the Linear Generator has benefits as well. Moving forward, we will perform more detailed analysis to choose the strongest design.

The main advantage of the Rotational Generator is the high ratio of oscillating mass, \( m_{osc} \), to total device mass. Minimizing total device mass is critical, and power is proportional to the magnitude of \( m_{osc} \). Both devices generate power in accordance with Faraday’s law of induction, but the design of the Linear Generator precludes the mass of the copper coils from contributing to \( m_{osc} \). Moreover, the oscillating mass of the Linear Generator must be comprised entirely of a large rare-earth magnet. In the Rotational Generator, the only significant fixed mass not shared with the Linear Generator is the gear rack, which is likely to be less than that of fixed copper coils.

In this same vein, the diameter of the oscillating mass in the Rotational Generator is constrained by the size of the components contained within it. The Linear Generator does not have this restriction, and smaller diameter allows for greater device length and thus greater \( \delta \) for the same volume. From a simple examination of power relations, this could be advantageous. From Appendix G,

\[
dev \text{device length} \approx \frac{4V}{\pi \varnothing^2}
\]

such that \( \delta \) is inversely proportional to diameter, \( \varnothing \), squared and \( \delta \) is directly proportional to power output. However, we need to quantify the relation of magnet diameter to power output, and it is unclear if higher \( \delta \) will be difficult to consistently achieve with the vertical acceleration in a backpack. As discussed in our SOW, we intend to perform testing to quantify this acceleration.

Another potential benefit of the Rotational Generator is decreased vulnerability to placement near magnetic objects. As discussed in the WIRED review of the nPower PEG, “the manual warns against positioning the PEG close to items that are attracted to magnets, as this will limit its amount
of movement and thus reduce the amount of charge it can collect” [6]. The Rotational Generator does not have a large permanent magnet like the Linear Generator and should be less susceptible to this issue.

The linear-to-rotational conversion of the Rotational Generator also allows for conversion to higher-frequency oscillatory motion, and even conversion to consistent rotation in one direction. As discussed in our Scope of Work, low frequency oscillatory motion is notoriously difficult to capture, and we believe there may be potential for increased system efficiency if the output shaft experiences continuous rotation at a higher frequency. This transduction is common and straightforward in the rotational domain: a simple set of gears can increase rotational velocity manyfold with high efficiency. Our preliminary research revealed many possible mechanisms for converting oscillatory rotation to one direction. A book by Nguyen Thang includes several mechanisms, one of which is shown in Figure 5.1 [7].

![Figure 5.1. Mechanism for converting two-way rotation to one-way rotation. [7]](image)

Mechanical losses like backlash and sliding friction could make a bi-directional geared system less favorable. Potentially, a flywheel could be incorporated into the oscillating mass of the Rotational Generator to improve the consistency of rotation. Ultimately, the potential advantages of the Rotational Generator come with added complexity, which may manifest as efficiency losses and increased cost. We will work to analytically quantify these losses to objectively compare both devices.

### 5.3 Design Hazards and Expected Challenges

As shown in Appendix I, we performed a preliminary analysis of potential design hazards inherent to our design. Two features stood out as potentially problematic. For one, like any portable electronic device, our concept designs do not incorporate any connection to earth ground. To correct for this risk, we will ensure that any electronic components are grounded to the outer...
housing of the device. Secondly, we are still considering the use of a flywheel to store energy, which is a potential hazard. However, the overall system mass is constrained to ~250g, so we do not believe a flywheel could be dangerous, and no corrective action is needed.

In terms of potential challenges, we see three main risks – power output, user inconsistency, and mechanical losses. Table 5.1 captures the top issues that we have identified and the corrective actions we will implement to address these concerns.

Table 5.1. Challenges going forward.

<table>
<thead>
<tr>
<th>Challenge</th>
<th>Risk</th>
<th>Description</th>
<th>Corrective Actions</th>
</tr>
</thead>
<tbody>
<tr>
<td>Power Output</td>
<td></td>
<td>How much power can we produce? Is this enough?</td>
<td>Pursue linear and rotary motor testing; develop model for power generation; design for efficiency.</td>
</tr>
<tr>
<td>User Inconsistency</td>
<td></td>
<td>Will the device function for any user in varying trail conditions?</td>
<td>Test backpack acceleration with many hikers under various loads and trail conditions.</td>
</tr>
<tr>
<td>Transduction Losses</td>
<td></td>
<td>What percent of input power will be lost through transduction?</td>
<td>Investigate losses in transduction mechanisms of the concept designs both theoretically and experimentally.</td>
</tr>
</tbody>
</table>

Low Risk  Med Risk  High Risk
6 Project Management

Preliminary Design Review has confirmed the two concept directions we will pursue. We must validate our initial concepts, perform detailed analysis, and design a verification prototype in a timely manner before Critical Design Review (CDR).

6.1 Timeline to Critical Design Review

Table 6.1 explains the general workflow up to CDR. The Gantt Chart in Appendix J further breaks out the schedule and details leading to CDR.

<table>
<thead>
<tr>
<th>Category</th>
<th>Item</th>
<th>Description</th>
<th>Expected Completion Date</th>
</tr>
</thead>
<tbody>
<tr>
<td>Initial Concept Validation</td>
<td>Failure Modes and Effects Analysis (FMEA)</td>
<td>Identify the design failure mechanisms and the associated consequences of those failures.</td>
<td>November 30th, 2021</td>
</tr>
<tr>
<td></td>
<td>Design for Manufacture and Assembly (DFMA)</td>
<td>Constrain manufacturing and assembly and eliminate inefficiencies in product design.</td>
<td>January 7th, 2022</td>
</tr>
<tr>
<td>Detailed Design and Analysis</td>
<td>Design Analysis</td>
<td>Quantify the mechanical design – power output, size, mass, form, and function of the device.</td>
<td>January 11th, 2022</td>
</tr>
<tr>
<td></td>
<td>Concept Down-Selection</td>
<td>Down-select to design direction.</td>
<td>January 12th, 2022</td>
</tr>
<tr>
<td></td>
<td>Interim Design Review (IDR)</td>
<td>Presentation of the major subsystems and any related design concerns.</td>
<td>January 13th, 2022</td>
</tr>
<tr>
<td>VerificationPrototype Development</td>
<td>Structural Prototype</td>
<td>Build a functional, system-level prototype to validate the design.</td>
<td>January 25th, 2022</td>
</tr>
<tr>
<td></td>
<td>Engineering Drawings</td>
<td>Make engineering drawings for the Design Verification Prototype (DVP).</td>
<td>February 3rd, 2022</td>
</tr>
<tr>
<td></td>
<td>Manufacturing Plan</td>
<td>Develop a manufacturing plan for DVP.</td>
<td></td>
</tr>
</tbody>
</table>

Our concept down-selection is a critical date as we progress to CDR. Before IDR, we intend to down select to a single design. Table 6.2 presents the major deliverables through the remainder of the project.
Table 6.2. Project deliverables to sponsor.

<table>
<thead>
<tr>
<th>Deliverable</th>
<th>Description</th>
<th>Submission Date</th>
</tr>
</thead>
<tbody>
<tr>
<td>Critical Design Review (CDR)</td>
<td>Provide detailed analysis and design with a structural prototype.</td>
<td>February 11th, 2022</td>
</tr>
<tr>
<td>Bill of Materials &amp; Purchase Order</td>
<td>Provide budgeted list of materials needed for verification prototype.</td>
<td>February 14th, 2022</td>
</tr>
<tr>
<td>Senior Project Expo</td>
<td>Provide capstone presentation with verification prototype.</td>
<td>May 26th, 2022</td>
</tr>
<tr>
<td>Final Design Review</td>
<td>Provide final report summarizing project.</td>
<td>June 3rd, 2022</td>
</tr>
</tbody>
</table>

6.2 Analyses and Testing for Detailed Design

For mechanical design, we expect to perform detailed energy and forces analysis on both conceptual designs. Since our device will be stored on or inside of a backpack, we need to better understand backpack kinematics during hiking. We intend to pursue acceleration testing on both internal framed and frameless backpacks with various loading configurations. Such testing may determine optimal device location in or on a backpack to best capture translated biomechanical acceleration.

For both design directions, we plan to constrain the mass and model power output. This analysis will define power generation and the mechanisms of energy transduction for both concepts. The calculated specific power output – power output per unit mass – will provide us insight into the most effective solution. By IDR, we will down select to our design direction. After IDR, system-level detailed design will be pursued such as circuit and housing design.

6.3 Preliminary Manufacturing and Testing Plans

From early analysis of our conceptual prototypes, we anticipate manufacturing parts in the Cal Poly Mechanical Engineering Machine Shops and purchasing off-the-shelf parts. After IDR, we will develop a parts list and more intentionally consider our material suppliers. We do not foresee part lead times placing our structural or design verification prototype at risk.

We are encouraged to get into preliminary testing as soon as possible. We intend to experiment with power generation methods to home in on important modeling factors.
7 Conclusions

We have completed significant steps in design of a biomechanical energy harvesting device for thru-hikers, including ideation, concept selection, and preliminary analysis. Completion of these steps has defined the qualitative design concepts we will pursue further: the Linear Generator and Rotational Generator. Down-selection between our two design concepts take place before IDR based upon comparison of theoretical power output.

In our Preliminary Design Review, we identified technical challenges of our designs. These challenges include power output, user inconsistency, and transduction losses. We will implement appropriate theoretical and experimental analysis to address these concerns.

Once given approval by our sponsor, Dr. Schuster, this document will serve as an agreement for the proceeding design direction of our kinetic energy harvesting device. Any significant changes must be discussed with and approved by Dr. Schuster and documented in subsequent reports. We will provide our next major deliverable for Critical Design Review (CDR) on February 11th, 2022. The CDR will focus on the detailed analysis and design of our functional verification prototype.
References


Appendix

Appendix A – Engineering Specifications

Table A.1. Engineering specifications.

<table>
<thead>
<tr>
<th>Spec.</th>
<th>Parameter Description</th>
<th>Target</th>
<th>Tolerance</th>
<th>Risk*</th>
<th>Compliance †</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Power Output</td>
<td>5W</td>
<td>Min.</td>
<td>H</td>
<td>A, T</td>
</tr>
<tr>
<td>2</td>
<td>Mass</td>
<td>250g</td>
<td>Max.</td>
<td>M</td>
<td>A, I</td>
</tr>
<tr>
<td>3</td>
<td>Manufacturing Cost</td>
<td>$100</td>
<td>Max.</td>
<td>M</td>
<td>A</td>
</tr>
<tr>
<td>4</td>
<td>Volume</td>
<td>0.5L</td>
<td>Max.</td>
<td>M</td>
<td>A, I</td>
</tr>
<tr>
<td>5</td>
<td>Drop Resilience</td>
<td>Ten drops from 2m</td>
<td>Min.</td>
<td>M</td>
<td>T</td>
</tr>
<tr>
<td>6</td>
<td>IP Rating</td>
<td>IP54</td>
<td>Min.</td>
<td>L</td>
<td>I, T</td>
</tr>
<tr>
<td>7</td>
<td>Usability</td>
<td>Hands-on Survey</td>
<td>Min.</td>
<td>L</td>
<td>I</td>
</tr>
<tr>
<td>8</td>
<td>Thermal Operating Range</td>
<td>-20 to 50 °C</td>
<td>Max.</td>
<td>M</td>
<td>A, T</td>
</tr>
</tbody>
</table>

* Risk of meeting specification: (H) High, (M) Medium, (L) Low
† Compliance Methods: (A) Analysis, (I) Inspection, (S) Similar to Existing, (T) Test

Updated explanations of each engineering specification are included as follows. As explained in the main body of this report, specifications 7 and 8 (highlighted above) have been added since our Scope of Work report.

1. A solar panel is our most notable competitor in this product space. If we can match or exceed the power output of a small solar panel, our device will be a desirable alternative for thru-hikers. Specifically, we will conservatively assume that a 5W panel continuously produces power, as we use 5 watts as our benchmark. The power output of our device will be measured by charging a battery of known capacity for a fixed period.

2. Minimizing mass is a priority for thru-hikers. Based on the mass of competitive systems and results from our survey, we will target 250g (8.8 oz).

3. We will target a cost of less than $100 to manufacture the device. Again, this consensus is based on survey results and the pricing of competitive products. Cost is closely related to the weight of the device; most likely, minimizing device weight will involve lightweight, expensive materials.

4. Volume, like weight, is important to thru-hikers, albeit slightly less so. We will target a realistic 0.5L device volume based on survey results. Most likely, we will not be able to compete with the volume of a solar panel (roughly 0.15L). Our measurement method for volume will depend on the form factor of our prototype.

5. Regardless of our final design direction, the device must be able to withstand extended use by a thru-hiker. We defined a target value for drop resilience as ten drops from 2m, to ensure that the device strikes the ground in multiple orientations. The device must produce
at least 90% of the original power after the drop test to meet this target. Since hikers are most commonly on dirt trails, the device will be dropped on dirt.

6. **IP ratings** quantify enclosure resistance to moisture and debris ingress. The numerals signify resistance to solid foreign objects and water, respectively. IP54 indicates that dust particles smaller than 1.0mm diameter must not damage the device and that water splashed against the enclosure in any direction must have no harmful effects [8]. These conditions are explained clearly in the IEC IP code: “ingress of dust is not totally prevented, but dust shall not penetrate in a quantity to interfere with satisfactory operation of the apparatus or to impair safety” [8]. Test conditions are explained in detail in section 11 of the IP code; we will refer to these details when we test our prototype [8].

7. **Usability** is the ease of use of the product. Any thru-hiker should be able to pick up our device, without instructions, and figure out how to use it in five minutes or less. This will be tested via hands-on surveys and visual observations.

8. As demonstrated by our survey data, thru-hikers travel in a variety of extreme conditions. Our device must function adequately in a wide **thermal operating range**. We will perform this test by “hot soaking” and “cold soaking” the device and verifying that power output is not reduced by more than 20%.
Appendix B – nPower PEG Claim

IN AN OCTOBER 2012 INTERVIEW, LEMIEUX APPARENTLY CLAIMED THAT THE nPOWER PEG COULD CHARGE AN iPHONE 20% AFTER A "FULL DAY" OF WALKING.

WHAT POWER OUTPUT, IN WATTS, DOES THIS CORRESPOND TO?

FROM RESEARCH

IPHONE 4S WAS THE MOST RECENT
1432 mAh LIPO BATTERY

ASSUME

1) CONSTANT 3.7V CELL VOLTAGE
2) TEN HOURS OF WALKING

ANALYSIS

TOTAL STORED ENERGY = (1.432 Ah)(3.7 V)
= 5.3 Wh

20% CHARGE = 0.2(5.3 Wh)
= 1.06 Wh

INSTANTANEOUS POWER OVER TEN HOURS = \frac{1.06 \text{ Wh}}{10 \text{ hr}} = 0.1 \text{ W}
Appendix C – Survey Results

**With what gender do you identify?**

<table>
<thead>
<tr>
<th>Level</th>
<th>Count</th>
<th>Prob</th>
</tr>
</thead>
<tbody>
<tr>
<td>Female</td>
<td>88</td>
<td>0.29236</td>
</tr>
<tr>
<td>Male</td>
<td>208</td>
<td>0.69103</td>
</tr>
<tr>
<td>Other</td>
<td>5</td>
<td>0.01661</td>
</tr>
<tr>
<td>Total</td>
<td>301</td>
<td>1.00000</td>
</tr>
</tbody>
</table>

**How old are you?**

<table>
<thead>
<tr>
<th>Level</th>
<th>Count</th>
<th>Prob</th>
</tr>
</thead>
<tbody>
<tr>
<td>under 20</td>
<td>20</td>
<td>0.06601</td>
</tr>
<tr>
<td>20 - 29</td>
<td>130</td>
<td>0.42904</td>
</tr>
<tr>
<td>30 - 39</td>
<td>85</td>
<td>0.28053</td>
</tr>
<tr>
<td>40 - 49</td>
<td>34</td>
<td>0.11221</td>
</tr>
<tr>
<td>50 - 59</td>
<td>26</td>
<td>0.08581</td>
</tr>
<tr>
<td>60 - 69</td>
<td>8</td>
<td>0.02640</td>
</tr>
<tr>
<td>Total</td>
<td>303</td>
<td>1.00000</td>
</tr>
</tbody>
</table>

**Do you consider yourself a backpacker or a thru-hiker?**

<table>
<thead>
<tr>
<th>Level</th>
<th>Count</th>
<th>Prob</th>
</tr>
</thead>
<tbody>
<tr>
<td>thru-hiker</td>
<td>199</td>
<td>0.65461</td>
</tr>
<tr>
<td>backpacker</td>
<td>105</td>
<td>0.34539</td>
</tr>
<tr>
<td>Total</td>
<td>304</td>
<td>1.00000</td>
</tr>
</tbody>
</table>
What is your longest trip?

<table>
<thead>
<tr>
<th>Level</th>
<th>Count</th>
<th>Prob</th>
</tr>
</thead>
<tbody>
<tr>
<td>not sure</td>
<td>2</td>
<td>0.00658</td>
</tr>
<tr>
<td>0 - 20 miles</td>
<td>11</td>
<td>0.03618</td>
</tr>
<tr>
<td>20 - 50 miles</td>
<td>36</td>
<td>0.11842</td>
</tr>
<tr>
<td>50 - 100 miles</td>
<td>52</td>
<td>0.17105</td>
</tr>
<tr>
<td>100 - 500 miles</td>
<td>64</td>
<td>0.21053</td>
</tr>
<tr>
<td>500+ miles</td>
<td>139</td>
<td>0.45724</td>
</tr>
<tr>
<td>Total</td>
<td>304</td>
<td>1.00000</td>
</tr>
</tbody>
</table>

What is your average mileage per day on a trip?

<table>
<thead>
<tr>
<th>Level</th>
<th>Count</th>
<th>Prob</th>
</tr>
</thead>
<tbody>
<tr>
<td>0 - 4 miles</td>
<td>3</td>
<td>0.00990</td>
</tr>
<tr>
<td>5 - 9 miles</td>
<td>33</td>
<td>0.10891</td>
</tr>
<tr>
<td>10 - 19 miles</td>
<td>161</td>
<td>0.53135</td>
</tr>
<tr>
<td>20 - 29 miles</td>
<td>97</td>
<td>0.32013</td>
</tr>
<tr>
<td>30 - 39 miles</td>
<td>8</td>
<td>0.02640</td>
</tr>
<tr>
<td>40 - 49 miles</td>
<td>1</td>
<td>0.00330</td>
</tr>
<tr>
<td>Total</td>
<td>303</td>
<td>1.00000</td>
</tr>
</tbody>
</table>

What are the average hours hiked per day on a trip?

<table>
<thead>
<tr>
<th>Level</th>
<th>Count</th>
<th>Prob</th>
</tr>
</thead>
<tbody>
<tr>
<td>0 - 2 hours</td>
<td>1</td>
<td>0.00329</td>
</tr>
<tr>
<td>2 - 5 hours</td>
<td>29</td>
<td>0.09539</td>
</tr>
<tr>
<td>5 - 10 hours</td>
<td>180</td>
<td>0.59211</td>
</tr>
<tr>
<td>10+ hours</td>
<td>94</td>
<td>0.30921</td>
</tr>
<tr>
<td>Total</td>
<td>304</td>
<td>1.00000</td>
</tr>
</tbody>
</table>
**What size battery pack do you carry?**

<table>
<thead>
<tr>
<th>Level</th>
<th>Count</th>
<th>Prob</th>
</tr>
</thead>
<tbody>
<tr>
<td>Not sure</td>
<td>35</td>
<td>0.11513</td>
</tr>
<tr>
<td>No battery</td>
<td>28</td>
<td>0.09211</td>
</tr>
<tr>
<td>&lt;5,000mAh</td>
<td>18</td>
<td>0.05921</td>
</tr>
<tr>
<td>5,001-10,000mAh</td>
<td>120</td>
<td>0.39474</td>
</tr>
<tr>
<td>10,001-20,000mAh</td>
<td>92</td>
<td>0.30263</td>
</tr>
<tr>
<td>&gt;20,000mAh</td>
<td>11</td>
<td>0.03618</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td>304</td>
<td>1.00000</td>
</tr>
</tbody>
</table>

**Do you carry a solar panel or other device for energy generation?**

<table>
<thead>
<tr>
<th>Level</th>
<th>Count</th>
<th>Prob</th>
</tr>
</thead>
<tbody>
<tr>
<td>None</td>
<td>253</td>
<td>0.83224</td>
</tr>
<tr>
<td>Solar Panel</td>
<td>50</td>
<td>0.16447</td>
</tr>
<tr>
<td>Thermoelectric Generator</td>
<td>1</td>
<td>0.00329</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td>304</td>
<td>1.00000</td>
</tr>
</tbody>
</table>

**What expected power output do you need to supplement your electronics?**

<table>
<thead>
<tr>
<th>Level</th>
<th>Count</th>
<th>Prob</th>
</tr>
</thead>
<tbody>
<tr>
<td>not sure</td>
<td>206</td>
<td>0.70307</td>
</tr>
<tr>
<td>&lt;2W</td>
<td>7</td>
<td>0.02389</td>
</tr>
<tr>
<td>~5W</td>
<td>45</td>
<td>0.15358</td>
</tr>
<tr>
<td>~7.5W</td>
<td>8</td>
<td>0.02730</td>
</tr>
<tr>
<td>~10W</td>
<td>20</td>
<td>0.06826</td>
</tr>
<tr>
<td>~15W</td>
<td>7</td>
<td>0.02389</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td>293</td>
<td>1.00000</td>
</tr>
</tbody>
</table>
What is the maximum volume range you would expect for this device?

<table>
<thead>
<tr>
<th>Level</th>
<th>Count</th>
<th>Prob</th>
</tr>
</thead>
<tbody>
<tr>
<td>not sure</td>
<td>21</td>
<td>0.07368</td>
</tr>
<tr>
<td>0-100mL</td>
<td>64</td>
<td>0.22456</td>
</tr>
<tr>
<td>101-500mL</td>
<td>164</td>
<td>0.57544</td>
</tr>
<tr>
<td>501-1000mL</td>
<td>31</td>
<td>0.10877</td>
</tr>
<tr>
<td>1000mL+</td>
<td>5</td>
<td>0.01754</td>
</tr>
<tr>
<td>Total</td>
<td>285</td>
<td>1.00000</td>
</tr>
</tbody>
</table>

What is your average base gear weight?

<table>
<thead>
<tr>
<th>Level</th>
<th>Count</th>
<th>Prob</th>
</tr>
</thead>
<tbody>
<tr>
<td>not sure</td>
<td>9</td>
<td>0.03010</td>
</tr>
<tr>
<td>5-10 pounds</td>
<td>51</td>
<td>0.17057</td>
</tr>
<tr>
<td>10-20 pounds</td>
<td>163</td>
<td>0.54515</td>
</tr>
<tr>
<td>20-30 pounds</td>
<td>60</td>
<td>0.20067</td>
</tr>
<tr>
<td>30-40 pounds</td>
<td>16</td>
<td>0.05351</td>
</tr>
<tr>
<td>Total</td>
<td>299</td>
<td>1.00000</td>
</tr>
</tbody>
</table>

At what price point would you consider such a device?

<table>
<thead>
<tr>
<th>Level</th>
<th>Count</th>
<th>Prob</th>
</tr>
</thead>
<tbody>
<tr>
<td>$50 or less</td>
<td>36</td>
<td>0.12371</td>
</tr>
<tr>
<td>$100 or less</td>
<td>141</td>
<td>0.48454</td>
</tr>
<tr>
<td>$150 or less</td>
<td>61</td>
<td>0.20962</td>
</tr>
<tr>
<td>$200 or less</td>
<td>42</td>
<td>0.14433</td>
</tr>
<tr>
<td>More than $200</td>
<td>11</td>
<td>0.03780</td>
</tr>
<tr>
<td>Total</td>
<td>291</td>
<td>1.00000</td>
</tr>
</tbody>
</table>
Appendix D – Ideation Models

This appendix contains images of our ideation prototypes, presented in the following categories: linear motion, rotational motion, fluid motion, piezoelectric, and user feedback.

**Linear Motion Capture**

![Linear motion low-resolution prototypes](image)

*Figure D.1. Linear motion low-resolution prototypes.*

**Rotational Motion Capture**

![Rotary motion low-resolution prototypes](image)

*Figure D.2. Rotary motion low-resolution prototypes.*
**Figure D.3.** Pendulum low-resolution prototype

**Fluid Motion Capture**

**Figure D.4.** Fluid motion low-resolution prototypes.
Piezoelectric

Figure D.5. Piezoelectric and vertical vane low-resolution prototypes.

User Feedback

Figure D.6. Feedback low-resolution prototypes that use LEDs as visual feedback to the user.
### Table E.1. Pugh matrix with sketches for capturing acceleration.

<table>
<thead>
<tr>
<th>Criteria</th>
<th>Relevant to Function?</th>
<th>Solar Charger</th>
<th>Pendulum</th>
<th>Linear Mechanical</th>
<th>Linear Electromechanical</th>
<th>Fluid Motion</th>
</tr>
</thead>
<tbody>
<tr>
<td>Harvest Energy</td>
<td>Y</td>
<td>S</td>
<td>S</td>
<td>S</td>
<td>S</td>
<td>-</td>
</tr>
<tr>
<td>Effectively</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Non-Intrusive</td>
<td>N</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Reliable</td>
<td>Y</td>
<td>S</td>
<td>+</td>
<td>+</td>
<td>+</td>
<td>-</td>
</tr>
<tr>
<td>Light Weight</td>
<td>Y</td>
<td>S</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>S</td>
</tr>
<tr>
<td>Durable</td>
<td>Y</td>
<td>S</td>
<td>S</td>
<td>S</td>
<td>S</td>
<td>S</td>
</tr>
<tr>
<td>Dust Resistant</td>
<td>N</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Water Resistant</td>
<td>N</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Easy to Make</td>
<td>Y</td>
<td>S</td>
<td>+</td>
<td>+</td>
<td>S</td>
<td>S</td>
</tr>
<tr>
<td>Safe</td>
<td>Y</td>
<td>S</td>
<td>S</td>
<td>S</td>
<td>S</td>
<td>S</td>
</tr>
<tr>
<td>Compact</td>
<td>Y</td>
<td>S</td>
<td>-</td>
<td>+</td>
<td>+</td>
<td>+</td>
</tr>
</tbody>
</table>

ΣS   | 7       | 3       | 3       | 4       | 4       |
Σ+   | 0       | 2       | 3       | 2       | 1       |
Σ-   | 0       | 2       | 1       | 1       | 2       |
Total| **0**   | **0**   | **2**   | **1**   | **-1**  |

*Image from Microsoft 2020*
Table E.2. Pugh matrix with sketches for transducing energy for the first four of our seven ideas.

<table>
<thead>
<tr>
<th>Criteria</th>
<th>Solar Charger - No Transduction</th>
<th>Rack &amp; Pinion (lin-rot)</th>
<th>Reciprocator (rot-lin)</th>
<th>Gear Ratio (rot-rot)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Description</td>
<td>![Solar Charger Sketch]</td>
<td>![Rack &amp; Pinion Sketch]</td>
<td>![Reciprocator Sketch]</td>
<td>![Gear Ratio Sketch]</td>
</tr>
<tr>
<td><strong>Relevant to Function?</strong></td>
<td>Y</td>
<td>S</td>
<td>+</td>
<td>S</td>
</tr>
<tr>
<td>Harvest Energy Effectively</td>
<td>Y</td>
<td>S</td>
<td>+</td>
<td>S</td>
</tr>
<tr>
<td>Non-Intrusive</td>
<td>N</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Reliable</td>
<td>Y</td>
<td>S</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Lightweight</td>
<td>Y</td>
<td>S</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Durable</td>
<td>N</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Dust Resistant</td>
<td>N</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Water Resistant</td>
<td>N</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Easy to Make</td>
<td>Y</td>
<td>S</td>
<td>S</td>
<td>S</td>
</tr>
<tr>
<td>Safe</td>
<td>N</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Compact</td>
<td>Y</td>
<td>S</td>
<td>S</td>
<td>S</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th></th>
<th>ΣS</th>
<th>Σ+</th>
<th>Σ-</th>
<th>Total</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>5</td>
<td>2</td>
<td>2</td>
<td>+</td>
</tr>
<tr>
<td>2</td>
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</tr>
<tr>
<td>3</td>
<td>0</td>
<td>2</td>
<td>2</td>
<td>-</td>
</tr>
<tr>
<td>4</td>
<td>0</td>
<td>-1</td>
<td>-3</td>
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</tbody>
</table>

*Image from Microsoft 2020*
Table E.3. Pugh matrix with sketches for transducing energy for the last three of our seven ideas.

<table>
<thead>
<tr>
<th>Criteria</th>
<th>Description</th>
<th>Linear Form of Faraday’s Law</th>
<th>Rotational Form of Faraday’s Law</th>
<th>Mechanical rectification (AC to DC)</th>
<th>Piezoelectric</th>
</tr>
</thead>
<tbody>
<tr>
<td>Harvest Energy Effectively</td>
<td>Y</td>
<td>S</td>
<td>S</td>
<td>+</td>
<td>S</td>
</tr>
<tr>
<td>Non-Intrusive</td>
<td>N</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Reliable</td>
<td>Y</td>
<td>S</td>
<td>S</td>
<td>S</td>
<td>S</td>
</tr>
<tr>
<td>Lightweight</td>
<td>Y</td>
<td>-</td>
<td>S</td>
<td>S</td>
<td>S</td>
</tr>
<tr>
<td>Durable</td>
<td>N</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Dust Resistant</td>
<td>N</td>
<td></td>
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<td></td>
<td></td>
</tr>
<tr>
<td>Water Resistant</td>
<td>N</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Easy to Make</td>
<td>Y</td>
<td>S</td>
<td>+</td>
<td>S</td>
<td>-</td>
</tr>
<tr>
<td>Safe</td>
<td>N</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Compact</td>
<td>Y</td>
<td>S</td>
<td>S</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td></td>
<td>ΣS</td>
<td>4</td>
<td>4</td>
<td>3</td>
<td>3</td>
</tr>
<tr>
<td></td>
<td>Σ+</td>
<td>0</td>
<td>1</td>
<td>1</td>
<td>0</td>
</tr>
<tr>
<td></td>
<td>Σ-</td>
<td>1</td>
<td>0</td>
<td>1</td>
<td>2</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td>-1</td>
<td>1</td>
<td>0</td>
<td>-2</td>
<td></td>
</tr>
</tbody>
</table>
## Linear to Rotational Dynamo

<table>
<thead>
<tr>
<th>Functions/Attributes</th>
<th>Idea 1</th>
<th>Idea 2</th>
<th>Idea 3</th>
<th>Idea 4</th>
<th>Idea 5</th>
</tr>
</thead>
<tbody>
<tr>
<td>Capture Acceleration</td>
<td>Pendulum</td>
<td>Linear Mechanical</td>
<td>Linear Electromechanical</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Transduce</td>
<td>Faraday Linear</td>
<td>Dynamo</td>
<td>Gearing</td>
<td>Rack &amp; Pinion</td>
<td>Mechanical Rectification</td>
</tr>
<tr>
<td>Device Location</td>
<td>In Backpack</td>
<td>On Backpack</td>
<td>Hip Belt Mounted</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Form</td>
<td>Cylindrical</td>
<td>Flat</td>
<td>Box</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Feedback</td>
<td>LED</td>
<td>Display</td>
<td>Vibration</td>
<td>Noise</td>
<td></td>
</tr>
<tr>
<td>Extra Functions</td>
<td>Cord Strain Relief</td>
<td>2 Ports</td>
<td>Mounting Points</td>
<td>Mass Incorporates Battery</td>
<td></td>
</tr>
</tbody>
</table>

**Figure F.3.** A linear mechanical system that converts the linear motion to rotational through multiple transducers.

## Internal Electromechanical Linear Generator

<table>
<thead>
<tr>
<th>Functions/Attributes</th>
<th>Idea 1</th>
<th>Idea 2</th>
<th>Idea 3</th>
<th>Idea 4</th>
<th>Idea 5</th>
</tr>
</thead>
<tbody>
<tr>
<td>Capture Acceleration</td>
<td>Pendulum</td>
<td>Linear Mechanical</td>
<td>Linear Electromechanical</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Transduce</td>
<td>Faraday Linear</td>
<td>Dynamo</td>
<td>Gearing</td>
<td>Rack &amp; Pinion</td>
<td>Mechanical Rectification</td>
</tr>
<tr>
<td>Device Location</td>
<td>In Backpack</td>
<td>On Backpack</td>
<td>Hip Belt Mounted</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Form</td>
<td>Cylindrical</td>
<td>Flat</td>
<td>Box</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Feedback</td>
<td>LED</td>
<td>Display</td>
<td>Vibration</td>
<td>Noise</td>
<td></td>
</tr>
<tr>
<td>Extra Functions</td>
<td>Cord Strain Relief</td>
<td>2 Ports</td>
<td>Mounting Points</td>
<td>Mass Incorporates Battery</td>
<td></td>
</tr>
</tbody>
</table>

**Figure F.5.** A linear motion system that uses electromagnetic induction inside the backpack or on a hip belt.
Appendix G – Theoretical Maximum Power Available

USING OUR ENGINEERING SPECIFICATIONS AS CONSTRAINTS, WE CAN ESTIMATE THE THEORETICAL MAXIMUM AVAILABLE POWER.

OUR TARGET SPECIFICATIONS ARE AS FOLLOWS:

TOTAL MASS = 250 g
TOTAL VOLUME = 0.5 L

ASSUMING A REASONABLE BEST-CASE SCENARIO

OSCILLATING MASS ~ 200 g

IF THE DEVICE DIAMETER IS \( \varnothing = 50 \text{mm} \)

LENGTH = \( \frac{4 \varnothing}{\pi \varnothing^2} \)

= \( \frac{4}{\pi \left(500 \text{ cm}^3\right)} \)

= \( \frac{4}{\pi \left(5 \text{ cm}^3\right)} \)

LENGTH ~ 25 cm

EACH CONCEPT FEATURES A MASS THAT OSCILLATES WITH HUMAN WALKING FREQUENCY. ASSUME 2 Hz.

ASSUME THE MASS CAN OSCILLATE \( \delta = 40 \text{ cm} \) PER CYCLE

OUTPUT POWER, NEGLECTING ANY LOSSES:

\[
P = \frac{\text{ENERGY}}{\text{TIME}}\quad \text{WHERE ENERGY IS WORK} = F \delta
\]

ON EARTH, \( F = (2 \text{ kg})(9.81 \text{ m/s}^2) \)

\( F \approx 2 \text{ N} \)

WORK PER CYCLE \( W = F \delta \)

\( W = (2 \text{ N})(0.4 \text{ m}) \)

\( W = 0.8 \text{ Nm} \)

AT 2 Hz, THIS MUCH WORK IS DONE TWICE PER SECOND.

\[
P = \frac{0.8 \text{ Nm}}{0.8 \text{s}} \quad \rightarrow \quad P = 1.6 \text{ W}
\]
### Appendix H – Power Output Required

<table>
<thead>
<tr>
<th>CHARGING TIME / REQUIRED POWER OUTPUT</th>
</tr>
</thead>
<tbody>
<tr>
<td>WANT TO DETERMINE POWER OUTPUT NEEDED</td>
</tr>
<tr>
<td>FIXED VARIABLES</td>
</tr>
<tr>
<td>( \Delta t_w = 10 \text{ hrs} )</td>
</tr>
<tr>
<td>TIME SPENT WALKING PER DAY</td>
</tr>
<tr>
<td>( V = 5.0 \text{ V} )</td>
</tr>
<tr>
<td>REQUIRED VOLTAGE</td>
</tr>
<tr>
<td>( C_{\text{Bat}} = 10000 \text{ mAh} )</td>
</tr>
<tr>
<td>POWER BANK CAPACITY</td>
</tr>
</tbody>
</table>

**USING THE BASIC FORMULA**

\[
\Delta t_{\text{CH}} = \frac{C_{\text{Bat}}}{I_{\text{Dev}}} f_{\text{Noise}}
\]

Where:
- \( \Delta t_{\text{CH}} \) = TIME TO CHARGE
- \( I_{\text{Dev}} \) = INPUT CURRENT FROM CHARGER
- \( f_{\text{Noise}} \) = FACTOR FOR NOISE (DECREASES IN EFFICIENCY)

\[
I_{\text{Dev}} = \frac{C_{\text{Bat}} f_{\text{Noise}}}{\Delta t_{\text{CH}}}
\]

**LET** \( f_{\text{Noise}} = 1 \) (ASSUME NO LOSSES)

\[
\Delta t_{\text{CH}} = \Delta t_w
\]

\[
I_{\text{Dev}} = \frac{10,000 \text{ mAh}}{10 \text{ hrs}} (1.0) = 1000 \text{ mA}
\]

\[
P_{\text{Dev}} = \frac{V I_{\text{Dev}}}{1000 \text{ mA}} (1000 \text{ mA}) = \frac{1 \text{ A}}{1000 \text{ mA}}
\]

\[
P_{\text{Dev}} \approx 5.0 \text{ W}
\]

\( C_{\text{Bat}} = 10000 \text{ mAh} \)

(Cont'd)
However, this calculation is very conservative. A typical phone does not require a full power bank to charge.

For example, take an iPhone X:

\[ C_x = 2716 \text{ mAh} \quad \text{[Know Your Mobile, com]} \]

Assuming 100% efficiency from bank to phone,

\[ C_{\text{bank, needed}} = \frac{C_x}{\text{efficiency}} = \frac{C_x}{1.00} \]

\[ = 2716 \text{ mAh} \]

Repeating the same calculation for

\[ I_{\text{dev}} \]

\[ I_{\text{dev}} = \frac{2716 \text{ mAh}}{10 \text{ hrs}} = 272 \text{ mA} \]

\[ P_{\text{dev}} = VI_{\text{dev}} \]

\[ = (5 \text{ V})(272 \text{ mA}) \left| \frac{1 \text{ A}}{1000 \text{ mA}} \right| \]

\[ P_{\text{dev}} \approx 1.4 \text{ W} \]

Although both of these calculations are full of assumptions that have not yet been justified, it gives reason to believe our device may not need to output 5 W to be considered a success.
## DESIGN HAZARD CHECKLIST – ROTATIONAL GENERATOR

**Team:** F24 - Power Walking  
**Faculty Coach:** Sarah Harding

<p>| | |</p>
<table>
<thead>
<tr>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Y</td>
<td>N</td>
</tr>
<tr>
<td>□</td>
<td>■</td>
</tr>
<tr>
<td>1. Will any part of the design create hazardous revolving, reciprocating, running, shearing, punching, pressing, squeezing, drawing, cutting, rolling, mixing or similar action, including pinch points and sheer points?</td>
<td></td>
</tr>
<tr>
<td>□</td>
<td>■</td>
</tr>
<tr>
<td>2. Can any part of the design undergo high accelerations/decelerations?</td>
<td></td>
</tr>
<tr>
<td>□</td>
<td>■</td>
</tr>
<tr>
<td>3. Will the system have any large moving masses or large forces?</td>
<td></td>
</tr>
<tr>
<td>□</td>
<td>■</td>
</tr>
<tr>
<td>4. Will the system produce a projectile?</td>
<td></td>
</tr>
<tr>
<td>□</td>
<td>■</td>
</tr>
<tr>
<td>5. Would it be possible for the system to fall under gravity creating injury?</td>
<td></td>
</tr>
<tr>
<td>□</td>
<td>■</td>
</tr>
<tr>
<td>6. Will a user be exposed to overhanging weights as part of the design?</td>
<td></td>
</tr>
<tr>
<td>□</td>
<td>■</td>
</tr>
<tr>
<td>7. Will the system have any sharp edges?</td>
<td></td>
</tr>
<tr>
<td>■</td>
<td>□</td>
</tr>
<tr>
<td>8. Will you have any non-grounded electrical systems?</td>
<td></td>
</tr>
<tr>
<td>□</td>
<td>■</td>
</tr>
<tr>
<td>9. Will there be any large batteries or electrical voltage (above 40 V) in the system?</td>
<td></td>
</tr>
<tr>
<td>■</td>
<td>□</td>
</tr>
<tr>
<td>10. Will there be any stored energy in the system such as batteries, flywheels, hanging weights or pressurized fluids?</td>
<td></td>
</tr>
<tr>
<td>□</td>
<td>■</td>
</tr>
<tr>
<td>11. Will there be any explosive or flammable liquids, gases, or dust fuel as part of the system?</td>
<td></td>
</tr>
<tr>
<td>□</td>
<td>■</td>
</tr>
<tr>
<td>12. Will the user of the design be required to exert any abnormal effort or physical posture during the use of the design?</td>
<td></td>
</tr>
<tr>
<td>□</td>
<td>■</td>
</tr>
<tr>
<td>13. Will there be any materials known to be hazardous to humans involved in either the design or the manufacturing of the design?</td>
<td></td>
</tr>
<tr>
<td>□</td>
<td>■</td>
</tr>
<tr>
<td>14. Could the system generate high levels of noise?</td>
<td></td>
</tr>
<tr>
<td>□</td>
<td>■</td>
</tr>
<tr>
<td>15. Will the device/system be exposed to extreme environmental conditions such as fog, humidity, cold, high temperatures, etc.?</td>
<td></td>
</tr>
<tr>
<td>□</td>
<td>■</td>
</tr>
<tr>
<td>16. Is it possible for the system to be used in an unsafe manner?</td>
<td></td>
</tr>
<tr>
<td>□</td>
<td>■</td>
</tr>
<tr>
<td>17. Will there be any other potential hazards not listed above? If yes, please explain on reverse.</td>
<td></td>
</tr>
</tbody>
</table>

For any “Y” responses, complete a row in your Design Hazard Plan including (a) a description of the hazard, (b) a list of corrective actions to be taken, and (c) the date you plan to complete the actions.

**Figure I.1.** Design Hazard Checklist for the Rotational Generator.
Table I.1. Corrective Actions Plan for the Rotational Generator.

<table>
<thead>
<tr>
<th>Description of Hazard</th>
<th>Planned Corrective Action</th>
<th>Planned Date</th>
<th>Actual Date</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ungrounded Electrical Connection</td>
<td>We will ensure that the ground connection for the oscillating element is connected to the housing of the overall device.</td>
<td>1/05/21</td>
<td></td>
</tr>
<tr>
<td>Potential Use of Flywheel</td>
<td>The Rotational Generator may potentially have a flywheel as a part of the oscillating mass, but because we are limited in total mass by our engineering specifications, the flywheel will not be massive enough to be dangerous (&lt;200g).</td>
<td>N/A</td>
<td></td>
</tr>
</tbody>
</table>
**DESIGN HAZARD CHECKLIST - LINEAR GENERATOR**

Team: **F24 - Power Walking**  
Faculty Coach: **Sarah Harding**

| Y | N | 1. Will any part of the design create hazardous revolving, reciprocating, running, shearing, punching, pressing, squeezing, drawing, cutting, rolling, mixing or similar action, including pinch points and sheer points? |
| Y | N | 2. Can any part of the design undergo high accelerations/decelerations? |
| Y | N | 3. Will the system have any large moving masses or large forces? |
| Y | N | 4. Will the system produce a projectile? |
| Y | N | 5. Would it be possible for the system to fall under gravity creating injury? |
| Y | N | 6. Will a user be exposed to overhanging weights as part of the design? |
| Y | N | 7. Will the system have any sharp edges? |
| Y | N | 8. Will you have any non-grounded electrical systems? |
| Y | N | 9. Will there be any large batteries or electrical voltage (above 40 V) in the system? |
| Y | N | 10. Will there be any stored energy in the system such as batteries, flywheels, hanging weights or pressurized fluids? |
| Y | N | 11. Will there be any explosive or flammable liquids, gases, or dust fuel as part of the system? |
| Y | N | 12. Will the user of the design be required to exert any abnormal effort or physical posture during the use of the design? |
| Y | N | 13. Will there be any materials known to be hazardous to humans involved in either the design or the manufacturing of the design? |
| Y | N | 14. Could the system generate high levels of noise? |
| Y | N | 15. Will the device/system be exposed to extreme environmental conditions such as fog, humidity, cold, high temperatures, etc.? |
| Y | N | 16. Is it possible for the system to be used in an unsafe manner? |
| Y | N | 17. Will there be any other potential hazards not listed above? If yes, please explain on reverse. |

**Figure I.2.** Design Hazard Checklist for the Linear Generator.
Table I.2. Corrective Actions Plan for the Linear Generator.

<table>
<thead>
<tr>
<th>Description of Hazard</th>
<th>Planned Corrective Action</th>
<th>Planned Date</th>
<th>Actual Date</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ungrounded Electrical Connection</td>
<td>We will ensure that the ground connection for the oscillating element is connected to the housing of the overall device. Proper consumer electronic grounding procedures will be followed.</td>
<td>1/05/21</td>
<td></td>
</tr>
<tr>
<td>Potential Use Batteries</td>
<td>The Linear Generator may incorporate a battery. We will ensure proper seal of the batteries to prevent damage from conditional exposure.</td>
<td>N/A</td>
<td></td>
</tr>
</tbody>
</table>
Appendix J – Gantt Chart

<table>
<thead>
<tr>
<th>Activity</th>
<th>Milestone 1 (11/03)</th>
<th>Milestone 2 (12/03)</th>
<th>Milestone 3 (01/02)</th>
<th>Milestone 4 (02/02)</th>
<th>Milestone 5 (03/02)</th>
<th>Milestone 6 (04/02)</th>
</tr>
</thead>
<tbody>
<tr>
<td>F24 - Power Walking</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Administrative</td>
<td>0h</td>
<td>100%</td>
<td></td>
<td></td>
<td></td>
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</tr>
<tr>
<td>Write Proposal</td>
<td>0h</td>
<td>100%</td>
<td></td>
<td></td>
<td></td>
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</tr>
<tr>
<td>Write Letter</td>
<td>0h</td>
<td>100%</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Letter of Support</td>
<td>0h</td>
<td>100%</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Revise Baker-Knoebel Proposal</td>
<td>0h</td>
<td>100%</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Submit Baker-Knoebel Proposal</td>
<td>0h</td>
<td>100%</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Revise CPConnect Proposal</td>
<td>0h</td>
<td>100%</td>
<td></td>
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<td></td>
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</tr>
<tr>
<td>Submit CPConnect Proposal</td>
<td>0h</td>
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KINETIC ENERGY HARVESTING DEVICE FOR LONG DISTANCE THRU-HIKERS

CRITICAL DESIGN REVIEW

PRESENTED BY
David Hernandez
Jarod Lyles
Ryan McLaughlin
Shaw Hawkeye Hughes

Mechanical Engineering Department
California Polytechnic State University
San Luis Obispo
24 February 2022
Executive Summary

The intent of this project is to design and build a device that harnesses the biomechanical energy from a thru-hiker to charge their electronic devices. For Critical Design Review, we chose a design direction, performed engineering analysis, designed a rotational generator concept, and manufactured preliminary structural prototype elements to demonstrate feasibility of our mechanical and electrical systems.

We aim to produce a rotational generator system in the form of a test platform, allowing for ease of modification, tuning, and improvement. System dynamics and base excitation models provided the fundamental theory behind our concept, and detailed design manifested our rotational generator concept in a cost-effective, manufacturable form.

So far, we have manufactured the skeleton and guidance assembly, performed electrical testing to verify our rectification and smoothing circuitry, and modified our selected motor. We made a few revisions to the skeleton based on the machining process and gained confidence in our circuitry design. Moving forward, we will manufacture, test, refine, and iterate upon our rotational generator design in the form of a verification prototype.
Critical Design Review

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1 Introduction

The objective of this project is to design and fabricate a device to charge portable electronics using biomechanical energy from walking. More specifically, we are targeting thru-hikers as our main customers. Since our previous report, Preliminary Design Review, we have down-selected from two distinct concepts to a single design: the rotational generator. This report, the Critical Design Review, is the third of four major reports for this project. The purpose of this report is to provide detailed engineering justification for our final design and sufficient detail such that our work could be recreated. This includes analysis, testing, manufacturing, and plans for design verification.
2 Learnings Since Preliminary Design Review

Since Preliminary Design Review (PDR), the direction and intentions of our verification prototype development have shifted. After PDR, we intended to pursue an in-depth comparative analysis of two systems – a linear generator and a rotational generator. However, considering the complex multi-domain nature of our system design and constrained project timeline, we decided to expedite the decision process and move forward with the rotational generator concept.

2.1 Down Selection

Initially, we intended to perform analysis to compare the two concepts, but we had difficult defining the inefficiencies of the linear and rotary generator systems in equivalent terms. Ultimately, an accurate comparison of our two concepts would be a time-consuming estimation of system dynamics and losses. Thus, we down-selected to the rotational generator design based on our engineering judgment and the following criteria:

- The primary linear generator design of our research – the nPower Peg – proved to be an ineffective solution. As previous calculations in our PDR report showed, the nPower Peg never achieved its advertised output of 4 Watts.

- As a team, we desired to pursue a unique and innovative solution. Rather than repeating the solution of a linear motor design, the rotational generator offered greater opportunity for original design and exploration.

2.2 Rescue of Verification Prototype

Initially, we intended to build a lightweight, polished prototype of a final product. Ultimately, we realized that our concepts need experimental validation. Shifting focus from the development of a market-ready product, we moved towards building an adaptable test platform that allows for easy modification, tuning, and troubleshooting.
3 System Design and Justification

Our goal for the testing platform is to efficiently convert linear oscillation to rotational motion – and ultimately electricity – in a manner that could be implemented in a final product. It is more than just a robust proof of concept; iterative testing with this platform will fill in gaps in our theoretical analysis and inform design decisions like spring rate and gear ratio.

This design will simulate a final product, but the physical incarnation is a far cry from the lightweight, polished design that might be desirable to thru-hikers. We will refrain from delving too deep into specific deviations from the design of a final product, but they were at the forefront of our minds throughout the design process. In general, the platform is as modular as possible to accommodate the iterative changes that we expect to make.

3.1 Overview

A CAD model of our test platform design is shown in Figure 3.1. The carriage is constrained in a clear tube by six guide wheels and suspended between a pair of extension springs. It oscillates linearly along the length of the tube, and a pair of rubber bumpers limit the oscillation envelope.

Figure 3.1. Test platform assembly.

One of the guide wheels drives the shaft of a brushless DC motor\(^1\) via a two-stage gearset and a pair of bevel gears. The generator is positioned axially in the carriage for maximum packing efficiency, and the rectification circuit board is mounted to the carriage behind the motor.

To facilitate clear discussion, we have broken the test platform into two subsystems: a housing assembly and a carriage assembly. Please refer to our Indented Bill of Materials (iBOM) in

\(^1\) We will refer the motor interchangeably as a “motor” or “generator” throughout this report.
Appendix A for a breakdown of these subsystems. Detailed drawings and spec sheets for each component are included in the Drawing and Spec Package of Appendix B.

3.2 Housing Assembly

The housing assembly, as shown in Figure 3.2, encompasses the base, tube, threaded bumpers, spring studs and springs. A detailed drawing of this assembly is included in Appendix B.

![Figure 3.2. Housing assembly.](image)

In a finished product, the housing would be much more straightforward; we envision a standalone tube with two end caps. This design emulates such a configuration but prioritizes ease of access for swapping components. The clear polycarbonate tube allows for visual observation of oscillation frequency and any issues that might arise during testing; it is secured to the base with a pair of clamps for easy removal. We will enclose the ends of the housing with a pair of 3D printed covers for testing in a backpack.

3.2.1 Extension Springs

Unfortunately, the extensive analysis presented in the following section of this report did not lead us to a clear starting point for the spring rate. Critically, the damping coefficient and inertial effects in the system are unknown. We expect to quantify this damping experimentally and iteratively tune the spring rate of the system. Nonetheless, we need a starting point. We can roughly define a desirable spring rate, \( k \), using the fundamental relationship for the natural frequency of a sprung-damped mass system,

\[
    k = (\omega_n^2)(m_{osc}),
\]

where \( \omega_n \) is the system natural frequency and \( m_{osc} \) is the total oscillating mass. Through our base excitation modeling, covered in greater detail later, we can expect peak transmissibility when the frequency ratio \( r = \omega_b / \omega_n \) is equal to one (or slightly less than one for high damping ratios). Thus, since we want to maximize transmissibility, the natural frequency of the system should be about equal to the base excitation frequency. We are still working on quantifying base excitation
for an average thru-hiker, but the 2 Hz figure quoted in our Scope of Work report is a decent starting point. The mass of the carriage, \( m_{osc} \), can be estimated as the sum of the motor (200 g) and the carriage (50 g) for a total of \( m_{osc} = 0.250 \) kg.

According to this simple calculation, the spring rate should be at least 40 N/m, or 0.2 lb/in. The pair of springs are in parallel, so each spring should be about 0.4 lb/in. Notably, this calculation neglects rotational inertia of the motor and transmission, as well as electrical inertia from capacitance. These effects are difficult to quantify, so we chose this simplified model to set our initial spring rate. However, additional inertia in the system should decrease the natural frequency, so we expect peak transmissibility at a lower spring rate than this simplified calculation suggests. Ultimately, we ordered a pair of 30 N/m springs for our first iteration, fully expecting to change them as we learn more.

3.2.2 Stud Lengths

As we iterate the spring rate, each set of springs that we swap into the test platform will have different static and extended lengths. To take advantage of the entire linear-elastic region of a variety of extension springs, the threaded bumper, a soft rubber stop to prevent carriage over extension, and spring studs, hooks that aid in retaining and locating springs on the housing base, are swappable. A MATLAB script that finds the bumper and spring stud lengths for a given spring, populated with sample values for our first spring revision, is attached as Appendix C.

3.3.3 Housing Electrics

We are including a micro-USB breakout board on the base as a compact and tidy solution for power output. The connector is recessed, and there is a wire-routing channel on the bottom of the base, as shown in Figure 3.3. This channel will be taped-over once the wires are installed.

![Figure 3.3. Wiring channel and micro-USB detail.](image)

Additionally, we are concerned about friction created by loose wires running from the oscillating carriage to the housing, and a potential solution is using the pair of springs to pass positive and negative DC power to the base. Assuming the electrical resistance of the springs is not excessive, this voltage drop should be more constant.
Thin-wire steel springs like those chosen for our first revision have significant resistance – on the order of 5 ohms – but this fixed resistance might be preferable to the unknown effects of wire friction. Moreover, this voltage drop could become negligible with custom springs once the spring rate is finalized. As shown in Appendix D, a larger diameter beryllium-copper spring with an equivalent spring rate would have a resistance of only 0.1 ohms.

Thus, we have included provisions to use the springs as DC conductors. This possibility is discussed in further detail in Section 3.3.4. In the housing subassembly, this means that the wire channel runs to both sides of the base, and the spring studs are isolated from the endcaps with threaded Delrin insulators, as shown in Figure 3.4. Note that the wires are not modeled.

![Figure 3.4. Insulated wire stud and hole for wire routing.](image)

### 3.3 Carriage Assembly

The carriage houses the generator and rectification circuit, and it transduces linear motion into rotation to drive the generator. It is constrained in the housing tube by five idler wheels and one drive wheel. Our solid model of the carriage is shown in Figure 3.5, and a drawing is included in Appendix B.

![Figure 3.5. Carriage assembly.](image)
We have broken our discussion of the carriage into several subassemblies: the skeleton, guidance assembly, transmission, generator, and circuit board assembly.

### 3.3.1 Skeleton Subassembly

The structure of the carriage, the “skeleton”, is a one-piece machined aluminum part. A pair of interchangeable plates, as shown in Figure 3.6, bolt to the skeleton. These bearing plates are located by machined surfaces and a pair of dowel pins. The bearing plates can be re-machined with relative ease so we can accommodate different gear ratios and/or drive wheel diameters.

![Figure 3.6. Skeleton sub-assembly.](image)

A thin aluminum plate (green in Figure 3.6) bolts to the front of the skeleton and serves two purposes: it provides a consistent surface for the rubber bumper, and it forces the bearing plates into place against the machined face of the skeleton. Finally, a spring mount shaft with a lateral hole is slip fit into the bearing plates.
3.3.2 Guidance

The carriage guidance assembly consists of five “idler” wheel assemblies. These idlers, in tandem with the drive wheel, constrain the motion of the carriage in the housing tube.

![Figure 3.7. Guidance sub-assembly.](image)

Small, lightweight wheels suitable for this application were not readily available in market, so we designed aluminum wheels with an o-ring “tire”. The idler wheel assembly is shown in a quasi-exploded view in Figure 3.8. The idler shafts are a light press fit into the bearing, and the outer race of the bearing is a light press fit into the aluminum wheel.

![Figure 3.8. Idler wheel assembly.](image)

Two spring washers allow the wheel assembly to float laterally in the carriage slot, and a pair of .010” shims support the spring washers and prevent the wheel surface from contacting the carriage.

3.3.3 Transmission

A sixth wheel, the “drive wheel” is an integral part of carriage guidance, but it also drives the generator via a two-stage gear train. This gear train is facilitated by three custom shafts, which are supported at both ends with roller bearings. The customs shafts maintain the gears and drive wheel in a rigid location. The motor axis is perpendicular to these shafts, so we employed a set of bevel gears to drive the motor at the transmission output. One configuration of the first-revision transmission is shown in Figure 3.9.
Spur gears were used to transduce the linear motion to rotational motion in the transmission. The mating pairs of spur gears can both be swapped to change the overall gear ratio, and further gear ratios can be achieved relatively easily by re-machining the bearing plates with different center-to-center distances, as explained in section 3.3.1.

To set the drive wheel o-ring seat diameter, we turned a shaft to various diameters until a tight, no-slip fit was achieved. An ~15% increase in inner diameter of the o-ring was found to be the minimum amount of stretch for a no-slip fit on a machined aluminum surface. Then, the drive wheel was machined, the o-ring installed, and outer o-ring diameter measured; the diameter was .005” larger than expected, so the solid model was updated before the bearing plates were machined to ensure an accurate nominal fit within the housing tube.

### 3.3.3 Generator

There are two main electrical components in the carriage. The first is the generator, a Maxon EC 45 Flat 42.8 mm diameter brushless DC motor (see Figure 3.10 below).
This specific model was chosen for three main reasons: motor type, form factor and voltage density. We chose a brushless DC (BLDC) motor\textsuperscript{2} over a brushed option to minimize system losses. Driven at a constant shaft speed, a brushed DC motor produces relatively steady current, and the equivalent output of a brushless motor is an AC signal. Thus, a brushless generator signal must be rectified electrically, which adds complexity but is generally more efficient than the mechanical rectification of a brushed generator. Most importantly, in our application, a brushed generator would still produce a fully reversed AC signal because the shaft speed is roughly sinusoidal. This relationship is discussed in further detail in Section 4.3.2.

In terms of form factor, the EC 45 Flat has a cylindrical body with a diameter of 42.8 mm, which is in alignment with our expected diameter for this device.\textsuperscript{3} The motor is oriented with the motor body concentric to the housing tube to maximize packing efficiency of components. However, the extended power signal tab was a drawback for our design. Therefore, we had to modify the tab into a form that would best fit within the tube housing while retaining access to the power traces on the circuit board. A complete explanation of modification is later discussed.

Lastly, we developed a metric called voltage density to combine the two most important motor characteristics we were seeking: low mass and high back-emf constant (or low speed constant). In equation form, voltage density, $VD$, is calculated as

$$VD = m \cdot K_v,$$

(3.2)

where $m$ is the motor mass in grams and $K_v$ is the motor speed constant in RPM/V. The EC 45 has a voltage density of 9420 g-RPM/V, or approximately 50% better than the next best in-stock option. For a full table of motor options considered and their respective characteristics, see Appendix E.

### 3.3.4 Circuit Board Assembly

Since the generator output is an AC signal, additional circuitry is needed to produce a regulated, DC voltage that can charge a battery. For compact packaging, we designed a custom printed circuit board (PCB). The PCB has three main subfunctions, each of which require a specific set of components. These subfunctions and their respective components are summarized in Table 3.1.

---

\textsuperscript{2} The name “brushless DC motor” is a bit of a misnomer. A brushless DC motor must be driven with alternating current (often produced from a DC supply with an electronic speed control circuit). Specifically, the EC45 motor employed in our design produces a three-phase alternating signal when driven as a generator.

\textsuperscript{3} At this juncture, we are uncertain how much displacement we can expect from the carriage under average hiking conditions – we will learn more from testing. If the displacement is small, it might be desirable to pursue a larger diameter motor with a higher voltage density.
Table 3.1. Custom PCB design overview by subfunctions.

<table>
<thead>
<tr>
<th>Subfunction</th>
<th>Circuit Form</th>
</tr>
</thead>
<tbody>
<tr>
<td>AC to DC conversion</td>
<td>Three-phase bridge rectifier with Schottky diodes</td>
</tr>
<tr>
<td>Signal Smoothing</td>
<td>Parallel ceramic/electrolytic capacitors</td>
</tr>
<tr>
<td>Regulation</td>
<td>Voltage regulator composed of a Regulator IC, coil inductor, ceramic capacitors, and resistors</td>
</tr>
</tbody>
</table>

From a big picture perspective, the goal for circuitry design was simplicity and minimization of risk to overall system functionality. The design employed in our verification prototype is by no means the most efficient electrical system possible. A reasonable effort at maximizing electrical efficiency could be an entire senior project on its own.

After simple solutions for each subfunction were identified, Autodesk’s EAGLE® software was used to design the final circuit board. The circuit board consists of a mix of surface mount and through hole parts. To find a suitable voltage regulator circuit design, Texas Instruments’ WEBBENCH® Power Developer tool [2] was utilized.

A screen capture of the board file and manufacturing view of the PCB are shown in Figure 3.11 below. For full details of all board components, as well as a schematic diagram for the board, see the iBOM of Appendix A and the drawing for CA-PB-01B within Appendix B, respectively.

![Autodesk EAGLE® screen capture.](image1)

![Manufacturing preview](image2)

(a) Autodesk EAGLE® screen capture. 
(b) Manufacturing preview

Figure 3.11. Multiple representations of the final PCB design.

---

4 IC stands for integrated circuit and refers to a small chip containing multiple components working together.
The circuit board mounts directly to the carriage; the board footprint is based off the carriage outline. To reduce part count and simplify the design, we are using the circuit board as a bumper surface, and the spring stud is mounted to the PCB as shown in Figure 3.12.

![Figure 3.12. Integration of the PCB with the carriage assembly.](image)

As discussed in Section 3.3.3, we have not solidified our strategy for transferring power from the oscillating carriage to the housing base. We have explored multiple options, such as spring-loaded brush contacts along the length of the tube, but we ultimately included provisions for two configurations in this final design.

In the first configuration, a pair of loose wires are connected to the terminal block, routed through the wire clamp as shown in Figure 3.13, and passed to the housing through the pair of slots.

![Figure 3.13. Loose wire routing.](image)

As discussed in Section 3.3.3, these loose wires might introduce undesirable variation to our test platform, so our second configuration uses the pair of extension springs to pass regulated DC voltage from the carriage to the base. We have included pads at mechanical interface points on the
PCB for this purpose. As shown in Figure 3.11b, there are three ground pads on the perimeter of the PCB where it bolts to the skeleton; there should be negligible resistance between these bolts and the spring stud on the opposite side of the carriage. Another pad around the center hole will conduct to the spring that is attached directly to the PCB and is connected to the output voltage trace. For further discussion of using springs as conductors, see Section 3.3.3 and Section 4.3.1.

Finally, we have included a Double-Pole Double-Throw (DPDT) switch to allow for testing flexibility (see Figure 3.14 below).

![DPDT switch wiring diagram](image)

**Figure 3.14.** DPDT switch wiring diagram.

When the switch is in the closed position, the output of the bridge rectifier/smoothing sub-circuit is routed through the regulator, providing a regulated output signal. However, when the switch is open, the regulator portion of the circuit is fully isolated from the rest of the circuit, and the output is an unregulated signal. A DPDT switch is needed to fully isolate the regulator input and output in the open position, otherwise current in the reverse direction could damage components.

### 3.4 Safety, Maintenance, and Repair

As discussed above, the verification prototype has changed scope since initial project formulation, such that the device will not be a full representation of a market-ready product. However, safety has still been at the forefront of our design. For a full breakdown of our Failure Modes and Effects Analysis, see Appendix F, and for specific potential design hazards, see Appendix G.

To begin, voltage from the motor could potentially be as high as 60 V (the rated motor voltage), but this is unlikely to occur. To achieve this voltage, we would need shaft speeds upwards of 3000 RPM, which we do not expect (see Section 4.1.3 for a discussion of modeling results). Furthermore, current will be low (on the order of 100-500 mA).

From a mechanical safety standpoint, the only concern is pinch points from rotating gears, but with controlled testing and assembly conditions this is of minimal concern. The only high-risk item in
the Design Hazard Checklist we identified was falling down with the device in a backpack, causing harm to the user, so we will ensure safe hiking conditions for any on-trail testing.

As far as maintenance and repair go, we have designed the entire device to be as modular as possible, allowing for ease of iteration and maintenance. As this device is only a proof of concept for the final market-ready product, repairability is also of low importance, but the off-the-shelf-parts can be replaced from McMaster-Carr as detailed in Appendix A.

3.5 Cost Breakdown

The cost breakdown was determined from the three main assemblies composing our verification prototype: the housing, the carriage, and the circuit board. A complete parts list with part numbers, nomenclature, prices, quantity, and corresponding assembly hierarchy is available in our Indented Bill of Materials (iBOM) in Appendix A. A comprehensive list of vendors and part information can also be found in Appendix H. It is important to note that many parts are typically not sold as piece parts. Therefore, our total budget costs are greater than that of a single verification prototype build.

The housing assembly’s main costs were from the aluminum stock required to make our custom components. The overall price to develop the housing as of now is $262.15.

Our carriage was by far the most expensive and time-consuming assembly. The largest expenditures for this assembly came from the aluminum stock for the skeleton, as well as the motor, bearings, and gears. This overall price came out to $787.

The third assembly of our device is the circuit board. This was the most inexpensive to build, but potentially the most challenging in terms of analysis, research, and part selection. The primary costs came from the breakout board, DPDT switch, Schottky diodes, and shipping. The total circuit board assembly cost can be found in Table 3.2.

Table 3.2. Total price, including shipping and taxes, to construct a single verification prototype.

<table>
<thead>
<tr>
<th>Assembly</th>
<th>Cost</th>
</tr>
</thead>
<tbody>
<tr>
<td>Housing</td>
<td>$(262.15)</td>
</tr>
<tr>
<td>Carriage</td>
<td>$(787.00)</td>
</tr>
<tr>
<td>Circuit Board</td>
<td>$(39.94)</td>
</tr>
<tr>
<td><strong>Budget</strong></td>
<td><strong>$1,780.00</strong></td>
</tr>
<tr>
<td><strong>Expenses</strong></td>
<td><strong>$(1,089.09)</strong></td>
</tr>
<tr>
<td><strong>Balance</strong></td>
<td><strong>$690.91</strong></td>
</tr>
</tbody>
</table>
4 Modeling, Preliminary Testing, and Remaining Risks

Initially, we developed engineering specifications for our verification prototype. However, as discussed in Section 2.2, the scope of the verification prototype has changed. Specifically, our goal has shifted to developing a modifiable test platform, so specifications related to a final product such as IP rating and drop resilience are no longer relevant for the current prototype state. For a full discussion of these changes, see Section 6, Design Verification Plan.

Furthermore, due to the exploratory nature of our project, complete engineering justification for power output is unreasonably complex. Instead, we attempted to model the system using multiple techniques, and two of these avenues led to useful learnings.

4.1 Modeling

To model the Rotational Generator device, we employed both a system dynamics and mechanical vibrations approach. In the end, each model had merits, and the process of developing each model gave us invaluable insight into the complexities of the system.

4.1.1 System Dynamics

Our first major attempt at modeling the entire system was a system dynamics approach based on the methods of Rowell and Wormley in *System Dynamics* (1st Ed.) [3]. System dynamics is a multi-domain approach based on the theory of linear graph and normal tree modeling. The goal of this approach was to directly relate our output, electrical power, to the system input—the linear velocity and acceleration of the hiker’s backpack. Figure 4.1 below shows the linear graph and normal tree for the complete system.

![Linear graph and normal tree for the rotational generator model.](image)

Initially, energy comes into the system as mechanical translational energy in the form of a backpack oscillating in the vertical plane. This energy is first converted to the rotational domain by the drive wheel rolling along the housing (modeled as a rack and pinion transformer according to Rowell and Wormley [3]). Finally, a generator converts rotational energy to electrical energy by the principle of Faraday’s law. For a full derivation of the system state equations, see Appendix I.
Although this model was initially proposed to obtain quantitative results, characterizing a completely theoretical system became too difficult to warrant further work. Specifically, trying to define damping (or friction) coefficients in the mechanical translational and rotational domains would require significant testing efforts, a luxury we did not have time for. Thus, after deriving and setting up a state-space model in MATLAB®, we decided to pursue a simpler model.

Despite our disappointment, we still learned a lot from a high-level perspective about the multi-domain nature of this problem. The total system damping depends on “friction” in all three domains. The “mass” of the system could better be considered as a generalized inertia made up of the mass of the oscillatory components, the rotational inertia of the gears and motor, and any capacitance in the electrical domain, and much more.

4.1.2 Base Excitation

After failing to obtain any quantitative results from the system dynamics modeling approach, we turned to a more simplified model based on ideas presented in *Engineering Vibration* by Inman [4]. The premise was to model the system as a base excitation problem, where the “base” is the device body anchored to the hiker’s backpack, and the oscillatory mass is the carriage. Figure 4.2 below shows a system schematic for this model.

![Figure 4.2. Schematic of the mechanical base excitation model.](image-url)
In this simplified model, the input displacement is $x_h$, the oscillating mass displacement is $x_m$, the wheel and shaft angular displacements are $\theta_w$ (not pictured) and $\theta_s$ respectively, the wheel radius is $r_w$, and the gear ratio between the wheel and shaft is $N$. Furthermore, the damping ratio, $\zeta$, is critical to the system response.

To begin, we note that the motion of the wheel is based on relative motion between the oscillatory mass (the carriage) and the housing. This leads to a kinematic relation for shaft speed of the form, 

$$\dot{\theta}_s = \frac{N}{r_w}(x_m - x_h) \quad (4.1)$$

To remove $x_m$ from this equation, we can approximate both velocities as sinusoidal waveforms [4],

$$\dot{x}_h = Y\omega_b \sin(\omega_b t) \quad \text{and}$$
$$\dot{x}_m = X\omega_b \cos(\omega_b t - \theta_1 - \theta_2). \quad (4.2)$$

Finally, since we only have information about the input amplitude, $Y$, we can relate $X$ and $Y$ using displacement transmissibility, such that

$$(DT) = \frac{X}{Y} = \left[\frac{1 + (2\zeta r)^2}{(1 - r^2)^2 + (2\zeta r)^2}\right]^{1/2} \quad (4.3)$$

where $r$ is the frequency ratio ($\omega_b/\omega_n$) and $\zeta$ is the damping ratio. Putting this all together, the final kinematic equation for shaft speed is

$$\dot{\theta}_s = \frac{N}{r_w} \frac{A_{\text{accel}}}{\omega_b} [(DT)\cos(\omega_b t - \theta_1 - \theta_2) - \sin(\omega_b t)] \quad (4.4)$$

where $A_{\text{accel}}$ is the average amplitude of acceleration, and $\theta_1$ and $\theta_2$ are phase shifts. For the full derivation, see Appendix J. With this model, we can use data for frequency and amplitude from an accelerometer to obtain estimates of shaft speed at the motor. However, there are a few important limitations on the accuracy of this model. First, the value of displacement transmissibility, $(DT)$, is dependent on both the frequency ratio, $r$, and the damping ratio, $\zeta$, as shown in Figure 4.3 from Inman [4].
Figure 4.3. Displacement transmissibility as a function of frequency and damping ratio [4].

Looking more closely at these parameters, both $r$ and $\zeta$ are difficult to predict. Starting with the frequency ratio, $r$, this value is dependent on the system natural frequency and the driving frequency. We are aiming for both values to be as close to 2 Hz as possible based on past research regarding normal human walking frequency, but we can only estimate what our real system natural frequency will be as the mechanical and electrical dynamics of the system are coupled.

The damping ratio, $\zeta$, is also dependent on mechanical and electrical dynamics of the system. Thus, instead of attempting to develop a complex analytical model with many parameters, we will experimentally determine the displacement transmissibility by performing tests at various frequencies of base excitation to input into the model. For a complete description of this testing, see Section 6.2.2.
4.1.3 Preliminary Modeling Results
Building off the derivation outlined in the previous section for the base excitation model, an initial simulation was run for expected device operating conditions. For full results, see Appendix K.

4.2 Preliminary Testing
In terms of testing our Structural Prototype for CDR, we initially wanted to develop a fully integrated system and perform testing using a shake table. However, we realized it would be more reasonable to prove basic functionality for our two critical subsystems: mechanical and the electrical.

4.3.1 Mechanical Testing
Our goal for mechanical testing was to machine the skeleton and idler wheels to test fit the carriage assembly in the housing tube. As explained above, the skeleton is the most complex part of our assembly, so we wanted to machine it as early as possible to front-load any potential issues.

As detailed in Section 5, we have machined and partially assembled the skeleton, idler wheels, drive wheel, bearing plates, and bumper surface. Our learnings from this process prompted revision D of the skeleton, and we are confident that this assembly will be successful. However, we have not performed any substantive mechanical testing yet; the fit of the carriage assembly is an outstanding risk until the skeleton is modified to revision D and additional testing is performed.

4.3.2 Electrical Testing
To test the EC 45 Flat motor, we designed and fabricated a 3D-printed generator testing stand (see Figure 4.4 below).

![EC 45 Flat Motor](image)

**Figure 4.4.** Assembled test stand for testing a brushless DC motor as a generator.
As shown in Figure 4.4, a brushed DC motor (left) is driven by a DC voltage supply (not pictured). This motor is connected to the EC 45 motor (right) with a flexible coupling. In the event of a change of motor, all parts are easily swappable and snap into the bottom baseplate.

To begin, we measured phase voltage signals for two of the three leads for a constant shaft speed profile, and results were as expected. As shown in Figure 4.5, the two phases are identical in frequency and magnitude, but phase shifted.

![Figure 4.5. Phase voltage signals from a Tektronix TDS 2022B Oscilloscope for two BLDC motor leads referenced to the third lead.](image)

From the signal frequency, we can calculate shaft speed using the following equation,

\[
n = f \cdot \frac{2}{N} \cdot 60,
\]

where \(n\) is shaft speed in RPM, \(f\) is the signal frequency in Hz, and \(N\) is the number of pole pairs. Furthermore, predicted peak-to-peak voltage can be calculated based off measured speed and the motor speed constant (in RPM per volts), \(K_v\), as the following,

\[
V_{pk-pk} = \frac{2}{\sqrt{3}} \frac{n}{K_v},
\]

5 Only two leads could be measured simultaneously because the oscilloscopes in the Cal Poly Mechatronics lab are two-channel only. The two phases are referenced to the third phase to get a clean waveform.
where the 2 in the numerator is for conversion to a peak-to-peak value, and the factor of $\sqrt{3}$ is to convert from phase voltage to line voltage\(^6\). Testing results have been included in Appendix L.

After verifying motor performance as a generator, we moved on to proving out our bridge rectifier circuit using the test setup shown in Figure 4.6.

![Test apparatus for rectification and smoothing of a BLDC generator output.](image)

**Figure 4.6.** Test apparatus for rectification and smoothing of a BLDC generator output.

This circuit consisted of six Schottky diodes forming a three-phase bridge rectifier, followed by one to four (three shown) capacitors in parallel for signal smoothing. The circuitry used for this test was based on a portion of the final board schematic as shown in Figure 4.7.

![Bridge rectifier and smoothing schematic from EAGLE®.](image)

**Figure 4.7.** Bridge rectifier and smoothing schematic from EAGLE®.

\(^6\) Although the Maxon datasheet provided online does not explicitly state the winding configuration, analysis provided justification for a Wye winding motor.
In this test, we first looked at the output directly from the bridge rectifier with no smoothing (Figure 4.8a). With no smoothing, the signal has a positive mean DC value, but significant ripple is present. However as expected, parallel capacitors greatly reduce ripple voltage to produce a steady DC signal.

![Figure 4.8](image)

(a) Without Smoothing  (b) With Smoothing

**Figure 4.8.** Effects of including smoothing capacitors to a bridge rectifier circuit, as measured on a Tektronix TDS 2022B Oscilloscope.

Although this is promising, the testing conditions were not fully representative of the expected generator output. Specifically, these tests were run at constant shaft speeds. However, with the final verification prototype device, shaft rotation will be roughly sinusoidal, so the voltage signal from the motor will vary in frequency and amplitude, similar to a combination of AM & FM. A visualization of this idea is shown in Figure 4.9.

![Figure 4.9](image)

**Figure 4.9.** Approximate visualization of a combination AM/FM signal.
4.3 Remaining Risks

Although there are numerous risks involved with a research-focused endeavor such as the rotational generator concept, we have identified three main risks.

4.3.1 Wire Friction

Our biggest concern is getting electricity from the oscillating carriage to the Micro-USB breakout board without incurring major losses. Relative motion between the moving carriage, where DC power is produced, and the stationary housing is unavoidable, and we don’t have a concrete plan for minimizing wire friction and/or interference with the carriage. Furthermore, due to space limitations inside the housing tube, we do not have room for the wires to change form significantly (as is the case with scissor lift arms, for example).

Multiple options are being considered. The most desirable is using the pair of extension springs as conductors (thus eliminating the need for loose wires). We would prefer to avoid the voltage drop of high resistance springs. However, we are also considering the use of a channel to house the wires. Our final design will be based mainly on preliminary experimentation.

4.3.2 Carriage Wheel Fitment

As discussed in Section 4.3.1, Mechanical Testing, we have not checked the fitment of the carriage wheels in the housing tube. These guide wheels must provide sufficient normal force such that the drive wheel does not slip on the tubing wall, but they should also introduce minimal rolling friction. We expect to achieve this balance with measurements, re-machining the drive and idler wheel bodies, and some trial and error, but the concept remains untested thus far.

Moreover, the guide wheels must roll smoothly along the entire length of the main tube; any changes in diameter or cylindricity of the polycarbonate tube may be problematic. As detailed in the specification sheet for HO-TU-01A, the inner diameter of the polycarbonate tube is guaranteed to ±0.020” – a concerningly wide tolerance for our application. However, this risk is of low concern based on our knowledge of the manufacture process for extruded plastic tubing; the nominal ID of any individual tube will fall somewhere within ±0.020”, but variation along its length should be an order of magnitude lower. Moreover, we have also ordered an equivalent section of extruded acrylic tubing (with the same ±0.020” ID tolerance) as a second option.

4.3.3 Power Output

Although we have successfully demonstrated the ability to convert rotation of a brushless DC motor shaft to a steady DC voltage signal, we have not tested power output yet. We will test this capability by measuring the power output with a DAQ, and/or by attempting to trickle-charge a power bank. Furthermore, even if the electrical subsystem performs as expected, mechanical system performance is yet to be verified; it cannot be until the verification prototype build is complete.
5 Manufacturing Plan

We have procured many parts for our structural prototype through many reputable vendors and plan to reuse many of those components in our verification prototype. Through our structural prototype, we have successfully manufactured the motor carriage. We have also modified the circuit board for use in our verification prototype, as detailed in Appendix M. Further details on future plans and processes are discussed below.

5.1 Procurement

Since our device is exploratory and unique, finding off-the-shelf parts to build and assemble immediately is only reasonable for a subset of parts. Several parts have been or will be fabricated in-house from raw materials or customized to meet our needs. After submitting multiple applications for funding, we were awarded $1500 from the Baker-Koob Endowments and $280 from the ME Student Fund Allocation Committee (MESFAC).

5.1.1 Mechanical Components

Most off-the-shelf mechanical components and raw materials used to develop the housing and carriage assemblies have been purchased from McMaster-Carr. We purchased our motors from Maxon. Procuring a motor was difficult, but through a sales engineer we obtained information on the current catalog and were given a student discount. These purchases were covered by our Baker-Koob and MESFAC funds.

5.1.2 Electrical Components

The majority of electrical components will be purchased through Digi-Key, an electronics vendor with an easy-to-use catalog, low-cost parts, and adequate shipping speeds. The only circuit board component not from Digi-Key was the voltage regulator IC chip, which was ordered from Texas Instruments. Lastly, the custom PCB will be ordered from JLCPCB, a manufacturer located in China. This company offers high quality boards with quick lead times, flexibility in board outline design, and a high level of reputability.

5.2 Manufacturing Operations and Assembly

The first revision of our test platform includes 171 components, as detailed in Appendix A. Fifteen of these components require modification, and we will machine 24 parts from raw material. Of these machined parts, 14 require a CNC mill and/or lathe. These components are broken out into “built”, “modified”, and “purchased” categories in Appendix N with more details in Appendix O.

5.2.1 CNC Parts

We are fortunate to have access to a handful of Haas CNC mills and lathes in the Cal Poly Mechanical Engineering machine shops. Our most complex CNC part, the skeleton, has already been machined. A solid model of the skeleton is shown in Figure 5.1.
The skeleton is machined in three operations: a lathe operation and two five axis mill operations. The completed state of each operation is shown in Figure 5.2. The mill operations were done on a VF3-SS with a TR160 trunnion and a 4-jaw lathe chuck.

The current machined skeleton, CA-SK-01C, will be modified to CA-SK-01D by opening the front idler shaft bores into slots. The rear idler shaft bores were designed as slots for machinability, and we discovered that the assembly process is vastly simplified with slots. This modification is explained in Figure 5.3.
Figure 5.3. Skeleton modification from revision C to revision D, and an image of the toolpath where this feature was machined. The modified part will be functionally (but not aesthetically) identical to the center image. The CAM will be updated with the exact revision if we machine another skeleton.

Most of the complexity in the carriage design is contained within the skeleton, and we do not expect to make any additional changes to it. Thus, the remaining CNC parts are simple and easily iterated as we learn more about gear ratio, fitment, and other dimensions. These additional parts are detailed in the Appendix A iBOM and part drawings in Appendix B.

5.2.2 Manual and Modified Components
There are three manual mill parts, five unique lathe parts, and one part that requires both lathe and mill work. Please refer to the iBOM, individual part drawings, and our detailed manufacturing plan in Appendices A, B, N, and O.

5.2.3 Motor Modifications
Per previous explanation, we selected the Maxon EC 45 Flat motor as a fit for our system design. However, because of an excessive lead time, we had to select the V1 configuration of Maxon’s motor, as shown in Figure 5.4a below.
The V1 configuration features an unfavorable Molex adapter that would significantly increase the diameter of our design. We decided to purchase the V1 motor and modify it to replicate a form factor closer to that of the V2 configuration.

Modification of the motor involved removing the Molex adapter, cutting and sanding the circuit board to a radius that fit within the inner diameter of the skeleton, drilling holes for routing wire through the circuit border, and soldering 16-gauge wire to the power traces. The results of these modification are shown in Figure 5.5, and Appendix M describes the modification procedure and results in detail.

The motor functioned successfully as a generator (see Appendix L) with no clear evidence of changes in performance.
5.2.4 Printed Circuit Board
To assemble the printed circuit board, we will need to solder components onto our PCB. This will involve thru-hole and reflow soldering. Reflow assembly involves the use of a controlled heat source to attach electrical – typically surface mount – components to their respective contact pads using solder paste (a mixture of powdered solder metals and flux).

First, the diodes, capacitors, and voltage regulator will be attached by way of solder paste stenciling on the board. Heat will be applied until solder flow is achieved. We will use a hot plate in the Cal Poly Mechatronics Lab as the heat source for the reflow process. Once flow-out of the solder is achieved, the board will be removed from heat and electrical connections will be tested for continuity. Lastly, our thru-hole components – switch, wire adapter, and larger capacitor (if desired) – will be joined to appropriate contact pads using a soldering iron. Cleaning of residue flux from the border will follow.
6 Design Verification Plan

This section covers, in detail, the methods we will employ to test each engineering specification. We have also included a concise Design Verification Plan (DVP) table in Appendix P as a summary of our tests and evaluations. Since our final prototype is a concept platform, we are not expecting to meet all engineering specifications.

6.1 Evaluation of Specifications

The engineering specifications in Table 6.1 have not been changed since PDR; however, the change in scope for the verification prototype makes power output our main goal. Specifications 2 through 4 can still be evaluated through inspection/calculation. Greyed-out specifications (5-8) will not be tested with the verification prototype but are still relevant for a production-ready product.

Table 6.1. Engineering specifications.

<table>
<thead>
<tr>
<th>Spec.</th>
<th>Parameter Description</th>
<th>Target</th>
<th>Tolerance</th>
<th>Risk*</th>
<th>Compliance †</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Power Output</td>
<td>5W</td>
<td>Min.</td>
<td>H</td>
<td>A, T</td>
</tr>
<tr>
<td>2</td>
<td>Mass</td>
<td>250g</td>
<td>Max.</td>
<td>M</td>
<td>A, I</td>
</tr>
<tr>
<td>3</td>
<td>Manufacturing Cost</td>
<td>$100</td>
<td>Max.</td>
<td>M</td>
<td>A</td>
</tr>
<tr>
<td>4</td>
<td>Volume</td>
<td>0.5L</td>
<td>Max.</td>
<td>M</td>
<td>A, I</td>
</tr>
<tr>
<td>5</td>
<td>Drop Resilience</td>
<td>Ten drops from 2m</td>
<td>Min.</td>
<td>M</td>
<td>T</td>
</tr>
<tr>
<td>6</td>
<td>IP Rating</td>
<td>IP54</td>
<td>Min.</td>
<td>L</td>
<td>I, T</td>
</tr>
<tr>
<td>7</td>
<td>Usability</td>
<td>Hands-on Survey</td>
<td>Min.</td>
<td>L</td>
<td>I</td>
</tr>
<tr>
<td>8</td>
<td>Thermal Operating Range</td>
<td>-20 to 50 °C</td>
<td>Max.</td>
<td>M</td>
<td>A, T</td>
</tr>
</tbody>
</table>

* Risk of meeting specification: (H) High, (M) Medium, (L) Low
† Compliance Methods: (A) Analysis, (I) Inspection, (S) Similar to Existing, (T) Test

6.2 Planned Testing

The following tests will be carried out to measure power output directly and measure intermediate quantities related to the net effects of the system. For now, only general descriptions of each test are provided, but for the Final Design Review and Design Verification Reports, thorough test procedures and analysis methods will be documented and presented.

6.2.1 Net Power Output

The first test that will be performed using the verification prototype is a laboratory simulation of hiking conditions, with the rotational generator device mounted to a shake table in the Cal Poly Vibrations Lab. Based on data collected by one of our group members, we will run the shake table at a range of input frequencies and amplitudes to best simulate a range of hiking conditions. At each frequency and amplitude, power output from the device will be measured using either the
OMEGA OM-DAQ-USB-2400 [5] supplied by the Cal Poly Mechanical Engineering department or a custom Arduino-based DAQ. This data will be analyzed for trends in power output as a function of frequency and/or amplitude of vibration, and uncertainty propagation calculations will be performed to further validate the testing methods utilized. For a testing timeline, see the project Gantt Chart of Appendix Q.

6.2.2 Displacement Transmissibility
Along with measuring the net power output, we intend to perform intermediate testing to validate the system performance. These next two tests are not directly related to a specification. Therefore, they are not as relevant for a production product, but they are critical in the development phase.

We want to test the system kinematics to refine our base excitation model (see Appendix K). One of the key parameters in achieving higher shaft speeds (and thus greater power output) is maximizing displacement transmissibility. As was shown in Figure 4.3, displacement transmissibility is dependent on both the overall damping in the system, and how well the natural frequency of the system matches the base excitation frequency. These parameters are challenging to predict analytically, so empirical measurement and iteration will be critical to improving our models.

For this intermediate testing, a similar setup to the Net Power Output test of Section 6.2.1 will be used with additional equipment. To measure both the displacement of the device housing and the displacement of the oscillating carriage, video footage of the device will be taken. A scale will be included in the background of the video to determine a relationship between image pixels and displacement. Once video is recorded, the MATLAB image processing toolbox will be used to perform analysis on the video footage to calculate displacements.

6.2.3 Circuit Efficiency
Our third test requires a subset of the electrical components. Because of the limited timeline for development of the verification prototype, the circuitry used in our design is simple, so efficiency will be lower than a final market product. To quantify this discrepancy, we will be running a series of tests involving the custom PCB, looking at voltage and power output. All tests will be performed using the custom-built motor testing stand (see Section 4.3.2 for a full description) and custom PCB. The specific details of each test are shown below in Table 6.2.

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<th>Test No.</th>
<th>Shaft Speed Profile</th>
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<td>On</td>
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</table>
For each test, we will measure power at the motor leads, then at the output of the circuit board for comparison and calculation of efficiency. Our custom PCB has been designed with a DPDT switch (see Section 3.3.4 for a full description) to allow output to be measured both with and without voltage regulation.
In conclusion, this document described the system design for a rotational generator device. We provided justification for our high-level approach and component-level selections. In building our structural prototype for the mechanical subsystem, we gained confidence in our ability to manufacture the most complex part and began working through assembly troubleshooting early in the manufacturing process. In terms of the electrical subsystem, we verified system behavior for our BLDC motor as a generator and displayed the ability to rectify and smooth a three-phase signal to a steady DC output.

Moving forward, we will continue manufacturing to complete the verification prototype build as soon as possible, while simultaneously preparing test procedures for design verification. We will use measured data and qualitative observations to iterate upon our design and swap components as needed. Finally, we ask for affirmation from our sponsor, Dr. Peter Schuster of the Cal Poly Mechanical Engineering department, to continue this project as outlined by this report.
References


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Appendix A: Indented Bill of Materials (iBOM)

The following is a brief explanation of the part numbering convention utilized for this project. Using a letter abbreviation based scheme allows for part numbers to hold more intuitive meaning than would be possible with a numbers only system.

<table>
<thead>
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<th>Part Number System</th>
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</thead>
<tbody>
<tr>
<td>_ _ _ _ - XX _</td>
</tr>
</tbody>
</table>

First two letters: Subsystem  
Second two letters: Sub-Assembly  
Numbers: Part Number  
Letter: Revision

Example 1: Subsystem - Sub-Assembly

| CA-GT |
| CArriage Subsystem | Gear Train |

Example 1 Continued: Subsystem-Sub-Assembly-Part Number

| CA-GT-001A |
| CArriage Subsystem | Gear Train | Part 001 | Revision A |

The following two pages contain our Indented Bill of Materials (iBOM).
# Rotational Generator Test Platform

## Indented Bill of Material (iBOM)

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<td>custom</td>
<td>dwg - cut to length, manual mill</td>
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<td>CA-PB-04A</td>
<td>Nut M6x1.0</td>
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<td>McMaster spc sht 98689A115</td>
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<tr>
<td>CA-PB-06A</td>
<td>Assorted Wires</td>
<td>N/A</td>
<td>1</td>
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<td>CA-PB-07A</td>
<td>Screw terminals</td>
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<td>Schottky diode</td>
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<td>$0.68</td>
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<td>Buck Regulator</td>
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<td>$ -</td>
<td>custom dwg 3D printed</td>
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</table>
Appendix B: Drawings and Specifications Package

Title Page for Drawings and Specifications Package
NOTES:
1. DEBURR AND BREAK SHARP EDGES, .015 MAX.
2. THIS PART WAS GENERATED USING SOLIDWORKS. DRAWING TO BE USED IN CONJUNCTION WITH ELECTRONIC MEDIA.
3. SCALE 1:4
M6 X 1.0 THRU
φ .625" .197

φ .625" .100

2X R.25

2X 37°

φ .500" +.000
-.001 THRU

2X R.50

2X φ .213 THRU
φ .413" .118

NOTES:
1. DEBURR AND BREAK SHARP EDGES, .015 MAX.
2. FAO
3. THIS PART WAS GENERATED USING SOLIDWORKS.
DRAWING TO BE USED IN CONJUNCTION WITH ELECTRONIC MEDIA.

MATERIAL: AL6061
SCALE: 1=1
UNLESS OTHERWISE SPECIFIED:
DIMENSIONS ARE IN INCHES
TOLERANCES:
FRACTIONAL: ±1/16
ANGULAR: MACH ±1° BEND ±2°
XXX: ±.001
TOLERANCING PER MMC

POWER WALKING SENIOR PROJECT

Drawn By: JAROD LYLES
Checked By: SHAW HUGHES

BASE END PLATES

TITLE:

DWG. NO.
HO-BA-02A

DATE: 02/22/2022

SOLIDWORKS Educational Product. For Instructional Use Only.
M6 THREADED ROD STOCK

φ.118
R.09
1.032
1.150

.050
M6 THREADED ROD STOCK

POWER WALKING SENIOR PROJECT

MATERIAL: 304SS
SCALE: 2=1
UNLESS OTHERWISE SPECIFIED: DIMENSIONS ARE IN INCHES
TOLERANCES:
FRACTIONAL: ±1/16
ANGULAR: MACH ±1° BEND ±1°
XXX: ±.01
XXX: ±.005
TOLERANCING PER MMC

TITLE: FRONT BUMPER STUD

DRAWN BY: JAROD LYLES
CHECKED BY: SHAW HUGHES

DATE: 02/22/2022

SOLIDWORKS Educational Product. For Instructional Use Only.
### Product Attributes

<table>
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<tr>
<th>TYPE</th>
<th>DESCRIPTION</th>
<th>SELECT</th>
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<td>Category</td>
<td>Prototyping, Fabrication Products</td>
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<tr>
<td></td>
<td>Adapter, Breakout Boards</td>
<td></td>
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<tr>
<td>Mfr</td>
<td>Adafruit Industries LLC</td>
<td></td>
</tr>
<tr>
<td>Series</td>
<td>-</td>
<td></td>
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<tr>
<td>Package</td>
<td>Bulk (①)</td>
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<tr>
<td>Part Status</td>
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<tr>
<td>Proto Board Type</td>
<td>Connector to Plated Through Hole</td>
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<tr>
<td>Package Accepted</td>
<td>USB - micro B</td>
<td></td>
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<tr>
<td>Number of Positions</td>
<td>5</td>
<td></td>
</tr>
<tr>
<td>Pitch</td>
<td>-</td>
<td></td>
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<tr>
<td>Board Thickness</td>
<td>0.040&quot; (1.02mm) 1/25&quot;</td>
<td></td>
</tr>
<tr>
<td>Material</td>
<td>-</td>
<td></td>
</tr>
<tr>
<td>Size / Dimension</td>
<td>0.787&quot; L x 0.394&quot; W (20.00mm x 10.00mm)</td>
<td></td>
</tr>
</tbody>
</table>
SPECIFICATION

- Power Supply: 1.8 Amp (Pin 1, 5), Other Contacts 0.5 Amp
- Voltage: 30V Max.
- Withstanding Voltage: 100V AC
- Insulation Resistance: 100 Megohms Min.
- Contact Resistance: 30 Megohms Max.
- 40 Megohms Max. After 10000 Cycles
- Temperature Range: -30°C~+80°C
- Mating Force: 35N Max.
- Withdrawal Force: 10N Min.
- Durability: 10000 Cycles Min.
- 8~20N After 10000 Cycles
- Insulator: LCP + 30%GF (UL94V-0)
- Contact: Brass
- Gold Flash Over All, Over Nickel
- Shell: SUS301, Nickel Plated Over All
- RoHS Compliant

Recommended P.C.B. Layout (Top View)

(PCB Board Tolerance ± 10.05)

Recommended P.C.B. Layout (Bottom View)

Section A-A

Shell: SUS301, Nickel Plated Over All

RoHS Compliant
For Wire Gauge: 14-16
For Screw Size: 1/4"
NOTES:
1. DEBURR AND BREAK SHARP EDGES, .015 MAX.
2. THIS PART WAS GENERATED USING SOLIDWORKS.
   DRAWING TO BE USED IN CONJUNCTION WITH ELECTRONIC MEDIA.

Φ.620
Φ.5000 +.0010
+.0005

M6 X 1.0 THRU

.325
.100

MATERIAL: DELRIN
SCALE: 2=1
UNLESS OTHERWISE SPECIFIED:
DIMENSIONS ARE IN INCHES
TOLERANCES:
FRACTIONAL: ±1/16
ANGULAR: MACH ±1° BEND ±2°
XXX: ±.01
XXX: ±.005
TOLERANCING PER MMC
M6 THREADED ROD STOCK

MATERIAL: 304SS
SCALE: 2=1
UNLESS OTHERWISE SPECIFIED:
DIMENSIONS ARE IN INCHES
TOLERANCES:
FRACTIONAL: ±1/16
ANGULAR: MACH ±1", BEND ±2°
XXX: ±.01
XXX: ±.005
TOLERANCING PER MMC

TITLE: REAR BUMPER STUD

DRAWN BY: JAROD LYLES
CHECKED BY: SHAW HUGHES

DATE: 02/22/2022

1 OF 1
POLYCARBONATE TUBING, STOCK
Ø 3" OUTER DIAMETER
1/8" WALL THICKNESS
NOTES:
1. DEBURR AND BREAK SHARP EDGES, .015 MAX.
2. FAO
3. THIS PART WAS GENERATED USING SOLIDWORKS. DRAWING TO BE USED IN CONJUNCTION WITH ELECTRONIC MEDIA.

MATERIAL: AL6061
SCALE: 1=1
UNLESS OTHERWISE SPECIFIED: DIMENSIONS ARE IN INCHES
TOLERANCES:
FRACTIONAL: ±1/16
ANGULAR: MACH ±1°, BEND ±2°
XXX: ±.005
TOLERANCING PER MMC

TITLE: TUBE CLAMP

DRAWN BY: JAROD LYLES
CHECKED BY: SHAW HUGHES

DATE: 02/22/2022

SOLIDWORKS Educational Product. For Instructional Use Only.
T10 Drive

5.7mm

1.65mm

10mm

3.0mm

M3 x 0.5mm

18-8 Stainless Steel
Button Head Torx Screws
NOTES:
1. DEBURR AND BREAK SHARP EDGES, .015 MAX.
2. FAO
3. THIS PART WAS GENERATED USING SOLIDWORKS. DRAWING TO BE USED IN CONJUNCTION WITH ELECTRONIC MEDIA.
4. THIS PART WAS MANUFACTURED USING CAM ON A 3-AXIS MILL WITH TRUNION ATTACHMENT. THIS DRAWING INCLUDES CRITICAL FIT DIMENSIONS.
2X R.125
.210
.456

2X R.375

M2 X 0.4 THRU

M3 X 0.5 THRU

\( \phi .320 \) THRU

\( \phi .375 \) \(+0.0005\)

\( \phi .375 \) \(-0.0010\)

\( \phi .002 \) \( M \) A

\( \phi .1250 \) \(+0.0010\)

\( \phi .1250 \) \(-0.0005\)

LIGHT SLIP FIT

NOTES:
1. DEBURR AND BREAK SHARP EDGES, .015 MAX.

63

FAO

3. THIS PART WAS GENERATED USING SOLIDWORKS. DRAWING TO BE USED IN CONJUNCTION WITH ELECTRONIC MEDIA.

MATERIAL: AL6061

SCALE: 1:1

UNLESS OTHERWISE SPECIFIED:
DIMENSIONS ARE IN INCHES

TOLERANCES:
FRACTIONAL: \( \pm \frac{1}{16} \)

ANGULAR: MACH \( \pm 1^\circ \) BEND \( \pm 2^\circ \)

XXX: \( \pm 0.01 \)

TOLERANCING PER MMC

POWER WALKING SENIOR PROJECT

DRAWN BY: JAROD LYLES

CHECKED BY: SHAW HUGHES

TITLE:
BEARING PLATE, LEFT

DWG. NO.
CA-SK-02A

REV
1

DATE: 02/22/2022

1 OF 1
NOTES:
1. DEBURR AND BREAK SHARP EDGES, .015 MAX.
2. FAO
3. THIS PART WAS GENERATED USING SOLIDWORKS. DRAWING TO BE USED IN CONJUNCTION WITH ELECTRONIC MEDIA.

MATERIAL: AL6061
SCALE: 2:1
UNLESS OTHERWISE SPECIFIED: DIMENSIONS ARE IN INCHES
TOLERANCES:
FRACTIONAL: ±1/32
ANGULAR: MACH ±1° BEND ±3°
XXX: ±0.01
XXX: ±0.005
TOLERANCING PER MMC

POWER WALKING SENIOR PROJECT

DRAWN BY: JAROD LYLES
CHECKED BY: SHAW HUGHES

DATE: 02/22/2022

SOLIDWORKS Educational Product. For Instructional Use Only.
18-8 Stainless Steel
Button Head Torx Screws

T10 Drive

M3 x 0.5mm

5.7mm

1.65mm

3.0mm

6mm
NOTES:
1. DEBURR AND BREAK SHARP EDGES, .015 MAX.
2. 63 FAO
3. THIS PART WAS GENERATED USING SOLIDWORKS. DRAWING TO BE USED IN CONJUNCTION WITH ELECTRONIC MEDIA.
NOTES:
1. DEBURR AND BREAK SHARP EDGES, .015 MAX.
2. FAO
3. THIS PART WAS GENERATED USING SOLIDWORKS. DRAWING TO BE USED IN CONJUNCTION WITH ELECTRONIC MEDIA.

MATERIAL: 304SS
SCALE: 3=1
UNLESS OTHERWISE SPECIFIED: DIMENSIONS ARE IN INCHES
TOLERANCES:
FRACTIONAL: ±1/16
ANGULAR: MACH ±10°, BEND ±2°
XXX: ±0.01
XXX: ±0.005
TOLERANCING PER MMC

TITLE: SPRING MOUNT SHAFT

DRAWN BY: JAROD LYLES
CHECKED BY: SHAW HUGHES

DATE: 02/22/2022

SOLIDWORKS Educational Product. For Instructional Use Only.
EC 45 flat ø43.5 mm, brushless, 70 watt

Stock program
Standard program
Special program (on request)

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<tr>
<th>V1 with Hall sensors</th>
<th>V2 with Hall sensors and cables</th>
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<tr>
<td>Motor Data (provisional)</td>
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<table>
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<tr>
<th>Values at nominal voltage</th>
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<tbody>
<tr>
<td>1 Nominal voltage (V)</td>
</tr>
<tr>
<td>2 No load speed (rpm)</td>
</tr>
<tr>
<td>3 No load current (mA)</td>
</tr>
<tr>
<td>4 Nominal speed (rpm)</td>
</tr>
<tr>
<td>5 Nominal torque (max. continuous torque) (mNm)</td>
</tr>
<tr>
<td>6 Nominal current (max. continuous current) (A)</td>
</tr>
<tr>
<td>7 Stall torque (mNm)</td>
</tr>
<tr>
<td>8 Stall current (A)</td>
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<tr>
<td>9 Max. efficiency (%)</td>
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Characteristics

10 Terminal resistance phase to phase (Ω) | 0.573 | 1.560 | 3.070 | 7.370 |
11 Terminal inductance phase to phase (mH) | 0.301 | 0.601 | 1.210 | 4.270 |
12 Torque constant (mNm / A) | 40.4 | 57 | 80.8 | 152 |
13 Speed constant (rpm / V) | 236 | 167 | 118 | 62.8 |
14 Speed / torque gradient (rpm / mNm) | 3.350 | 4.580 | 4.490 | 3.040 |
15 Mechanical time constant (ms) | 6.350 | 8.680 | 8.510 | 5.770 |
16 Rotor inertia (gcm²) | 181 | 181 | 181 | 181 |

Operating Range

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<tr>
<td>8000</td>
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<td>4000</td>
</tr>
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<td>500</td>
</tr>
<tr>
<td>250</td>
</tr>
<tr>
<td>100</td>
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<tr>
<td>50</td>
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Maxon Modular System

Planetary Gearhead

- 20.5 mm (O.D.)
- 0.75 - 6.0 Nm
- Page 394/398

Planetary Gearhead

- 42 mm (O.D.)
- 3.0 - 15.0 Nm
- Page 407

Spar Gearhead

- 45 mm (O.D.)
- 15.0 Nm
- Page 409

Recommended Electronics:

- EPO 36/3/EC
- ESCON Module 50/5
- ESCON 50/5
- ESCON 70/10
- DEC Module 50/5
- EPOS4 Micro 24/5
- EPOS4 Mod./Comp. 50/5
- EPOS4 50/5
- EPOS4 Disk 80/8
- EPOS2 P 24/5

Continuous operation
In observation of above listed thermal resistance (lines 17 and 18) the maximum permissible winding temperature will be reached during continuous operation at 25°C ambient.

Thermal limit.

Short term operation
The motor may be briefly overloaded (recurring).

Assigned power rating

Details on catalog page 46

March 2021 edition / subject to change
FACE 0.2" OF MATERIAL LENGTH FROM SHAFT

.010 x 45° CHAMFER

REMOVE MOLEX ADAPTER. CUT AND SAND CIRCUIT BOARD TO PROFILE.
NOTES:
1. DEBURR AND BREAK SHARP EDGES, .015 MAX.
2. FAO
3. THIS PART WAS GENERATED USING SOLIDWORKS. DRAWING TO BE USED IN CONJUNCTION WITH ELECTRONIC MEDIA.

MATERIAL: AL6061
SCALE: 4=1
UNLESS OTHERWISE SPECIFIED: DIMENSIONS ARE IN INCHES
TOLERANCES:
FRACTIONAL: ±1/16
ANGULAR: MACH ±1°, BEND ±2°
XX: ±.01
XXX: ±.005
TOLERANCING PER MMC

TITLE: IDLER WHEEL

Drawn By: JAROD LYLES
Checked By: SHAW HUGHES

DATE: 02/22/2022

SOLIDWORKS Educational Product. For Instructional Use Only.
### Transmission

**Title:** TRANSMISSION

**Part Numbers and Quantities:**

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<th>PART NUMBER</th>
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<td>3</td>
<td>CA-TM-03A</td>
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<td>CA-TM-04A</td>
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<td>5</td>
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<td>CA-TM-06A</td>
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<td>7</td>
<td>CA-TM-07A</td>
<td>1</td>
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<td>9</td>
<td>CA-TM-09A</td>
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<td>CA-TM-10A</td>
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**Material:** N/A

**Scale:** 2=1

**Dimensions:**
- UNLESS OTHERWISE SPECIFIED:
- TOLERANCES:
  - FRACTIONAL: ±1/16
  - ANGULAR: MACH ±1° BEND ±2°
  - XXX: ±0.005

**Drawn By:** JAROD LYLES

**Checked By:** SHAW HUGHES

**Date:** 02/22/2022

**Revision:** 1

**DWG. NO.:** CA-TM

**REV:** 1

**SCALE:** 1=1

**SOLIDWORKS Educational Product. For Instructional Use Only.**
2X .010 x 45° CHAMFER

NOTES:
1. DEBURR AND BREAK SHARP EDGES, .015 MAX.
2. FAO
3. THIS PART WAS GENERATED USING SOLIDWORKS.
   DRAWING TO BE USED IN CONJUNCTION WITH ELECTRONIC MEDIA.

MATERIAL: AL6061
SCALE: 4:1
UNLESS OTHERWISE SPECIFIED:
DIMENSIONS ARE IN INCHES
TOLERANCES:
FRACTIONAL: ±1/16
ANGULAR: MACH ±1°, BEND ±2°
XXX: ±0.01
XXX: ±0.005
TOLERANCING PER MMC

TITLE:
DRIVE WHEEL

DRAWN BY: JAROD LYLIES
CHECKED BY: SHAW HUGHES

DATE: 02/22/2022

POWER WALKING SENIOR PROJECT

DWG. NO. CA-TM-01A
REV 1

1 OF 1

SOLIDWORKS Educational Product. For Instructional Use Only.
CA-TM-02A

16.6 mm

11.8 mm

2.4 mm

McMASTER-CARR

PART NUMBER 93125K35

Oil-Resistant
Buna-N O-Rings
Pitch: 48 mm
Number of Teeth: 18

0.375" Pitch Dia.
0.286" OD
0.16"
0.08"
0.406"
0.31"
0.4"
BORE THRU HOLE TO Ø4mm

Ø.1575+0.002
+0.004
LIGHT SLIP FIT
Pitch Dia.: 0.375"

Pitch: 48 mm
Number of Teeth: 18

0.08"

0.286"

0.16"

0.31"

0.4"

OD

0.406"

1/8"
NOTE: ADD STEP TO BOTTOM OF MITER GEAR. REMOVE .030 IN LENGTH TO A STEP DIAMETER OF \( \phi .230 \)
Gear Pitch: 48
Number of Teeth: 32

For Shaft Diameter
0.125in

0.7in
0.25in

0.125in
0.375in
0.5in

14-1/2 Degree Pressure
Angle Plastic Gear
NOTE: REDUCE THE GEAR FLANGE TO THE CRITICAL DIMENSIONS SHOWN.
Gear Pitch: 48
Number of Teeth: 18

Gear Pitch Diameter 0.375in

For Shaft Diameter 0.125in
NOTE: REDUCE SPUR GEAR FLANGE TO THE CRITICAL DIMENSIONS SHOWN.


**Notes:**
- Regulator design from TI POWERBENCH Power Designer Tool
- Switch is for switching between a regulated and non-regulated output signal
- Smoothing capacitor (CS1-3) values may change

**Project:** POWER WALKING PCB

**Title:** CA-PB-01B

**Drawn By:** RYAN MCLAUGHLIN

**Date:** 2/21/2022 2:10 PM

**Rev:** Sheet: 1/1
M6 THREADED ROD STOCK

**Title:** PCB SPRING STUD

**Material:** 304SS

**Scale:** 4:1

**Unless Otherwise Specified:** Dimensions are in inches

**Tolerances:**
- Fractional: ±1/16
- Angular: Mach ±1° Bend ±2°
- XXX: ±0.01
- XXXX: ±0.005
- Tolerancing per MMC

**Drawn By:** JAROD LYLES

**Checked By:** SHAW HUGHES

**Date:** 02/22/2022

**Rev:** 1

**No.:** CA-PB-03A

SOLIDWORKS Educational Product. For Instructional Use Only.
M6 x 1 mm Thread

10 mm

5 mm

180% (5
3$57,
QIRUPDWLRQLQWKLVGUDZLQJLVSURYLGHGIRUUHIHUHQFHRQO\$WWSZZZPFPDVWHUFRP\[PP7KUHDG$WDLQOHVV\6WHHO+HXW

CA-PB-04A

McMASTER-CARR® PART NUMBER 91828A251

http://www.mcmaster.com
© 2021 McMaster-Carr Supply Company
18-8 Stainless
Steel Hex Nut

Information in this drawing is provided for reference only.
Thickness Range: 1.4mm - 1.8mm
<table>
<thead>
<tr>
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<tbody>
<tr>
<td>Category</td>
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<td>Mfr</td>
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<td>Wire Termination</td>
<td>Screw - Rising Cage Clamp</td>
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<td>Features</td>
<td>-</td>
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<tr>
<td>Color</td>
<td>Green</td>
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<td>Operating Temperature</td>
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## Capacitor Specifications

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<td>Temperature Coefficient</td>
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<td>Operating Temperature</td>
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<td>Features</td>
<td>-</td>
</tr>
<tr>
<td>Ratings</td>
<td>-</td>
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<td>Applications</td>
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<td>Failure Rate</td>
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<td>Mounting Type</td>
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<tr>
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<td>Thickness (Max)</td>
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</tr>
<tr>
<td>Frequency - Self Resonant</td>
<td>22MHz</td>
</tr>
<tr>
<td>Ratings</td>
<td>-</td>
</tr>
<tr>
<td>Operating Temperature</td>
<td>-40°C ~ 125°C</td>
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<tr>
<td>Inductance Frequency - Test</td>
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</tr>
<tr>
<td>Mounting Type</td>
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</tr>
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<td>Package / Case</td>
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</tr>
<tr>
<td>Supplier Device Package</td>
<td>-</td>
</tr>
<tr>
<td>Size / Dimension</td>
<td>0.512&quot; L x 0.512&quot; W (13.00mm x 13.00mm)</td>
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<tr>
<td>Height - Sealed (Max)</td>
<td>0.287&quot; (7.30mm)</td>
</tr>
<tr>
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<tr>
<td>TYPE</td>
<td>DESCRIPTION</td>
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<tr>
<td>---------------------------</td>
<td>--------------------------------------------------</td>
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<tr>
<td>Category</td>
<td>Resistors</td>
</tr>
<tr>
<td></td>
<td>Chip Resistor - Surface Mount</td>
</tr>
<tr>
<td>Mfr</td>
<td>YAGEO</td>
</tr>
<tr>
<td>Series</td>
<td>RC_L</td>
</tr>
<tr>
<td>Package</td>
<td>Tape &amp; Reel (TR)</td>
</tr>
<tr>
<td></td>
<td>Cut Tape (CT)</td>
</tr>
<tr>
<td></td>
<td>Digi-Reel®</td>
</tr>
<tr>
<td>Part Status</td>
<td>Active</td>
</tr>
<tr>
<td>Resistance</td>
<td>162 kOhms</td>
</tr>
<tr>
<td>Tolerance</td>
<td>±1%</td>
</tr>
<tr>
<td>Power (Watts)</td>
<td>0.25W, 1/4W</td>
</tr>
<tr>
<td>Composition</td>
<td>Thick Film</td>
</tr>
<tr>
<td>Features</td>
<td>Moisture Resistant</td>
</tr>
<tr>
<td>Temperature Coefficient</td>
<td>±100ppm/°C</td>
</tr>
<tr>
<td>Operating Temperature</td>
<td>-55°C ~ 155°C</td>
</tr>
<tr>
<td>Package / Case</td>
<td>1206 (3216 Metric)</td>
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<tr>
<td>Supplier Device Package</td>
<td>1206</td>
</tr>
<tr>
<td>Size / Dimension</td>
<td>0.122&quot; L x 0.063&quot; W (3.10mm x 1.60mm)</td>
</tr>
<tr>
<td>Height - Seated (Max)</td>
<td>0.026&quot; (0.65mm)</td>
</tr>
<tr>
<td>Number of Terminations</td>
<td>2</td>
</tr>
<tr>
<td>Failure Rate</td>
<td>-</td>
</tr>
<tr>
<td>TYPE</td>
<td>DESCRIPTION</td>
</tr>
<tr>
<td>----------------------</td>
<td>--------------------------------------------------</td>
</tr>
<tr>
<td>Category</td>
<td>Resistors</td>
</tr>
<tr>
<td></td>
<td>Chip Resistor - Surface Mount</td>
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<tr>
<td>Mfr</td>
<td>YAGEO</td>
</tr>
<tr>
<td>Series</td>
<td>RC.L</td>
</tr>
<tr>
<td>Package</td>
<td>Tape &amp; Reel (TR)</td>
</tr>
<tr>
<td></td>
<td>Cut Tape (CT)</td>
</tr>
<tr>
<td></td>
<td>Digi-Reel®</td>
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<tr>
<td>Part Status</td>
<td>Active</td>
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<tr>
<td>Resistance</td>
<td>22.1 kOhms</td>
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<td>Tolerance</td>
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<tr>
<td>Power (Watts)</td>
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</tr>
<tr>
<td>Composition</td>
<td>Thick Film</td>
</tr>
<tr>
<td>Features</td>
<td>Moisture Resistant</td>
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<tr>
<td>Temperature Coefficient</td>
<td>±100ppm/°C</td>
</tr>
<tr>
<td>Operating Temperature</td>
<td>-55°C ~ 155°C</td>
</tr>
<tr>
<td>Package / Case</td>
<td>1206 (3216 Metric)</td>
</tr>
<tr>
<td>Supplier Device Package</td>
<td>1206</td>
</tr>
<tr>
<td>Size / Dimension</td>
<td>0.122” L x 0.063” W (3.10mm x 1.60mm)</td>
</tr>
<tr>
<td>Height - Seated (Max)</td>
<td>0.026” (0.65mm)</td>
</tr>
<tr>
<td>Number of Terminations</td>
<td>2</td>
</tr>
<tr>
<td>Failure Rate</td>
<td>-</td>
</tr>
</tbody>
</table>
1 Features

- Functional Safety-Capable
  - Documentation available to aid functional safety system design
- Configured for rugged industrial applications
  - 4.5-V to 36-V input voltage range
  - 2-A continuous output current
  - 60-ns minimum switching on time
  - 500-kHz/1.1-MHz fixed switching frequency options
  - -40°C to 150°C junction temperature range
  - 98% maximum duty cycle
  - Monotonic start-up with pre-biased output
  - Internal short circuit protection with hiccup mode
  - ±1% tolerance voltage reference
  - Precision enable
- Small solution size and ease of use
  - Integrated synchronous rectification
  - Internal compensation for ease of use
  - SO-23 package
- Pin-to-pin compatible with TPS54202 and TPS54302
- PFM and forced PWM (FPWM) options
- Create a custom design using the LMR51420 with the WEBENCH® Power Designer

2 Applications

- Major appliances
- Building automation
- Grid infrastructure
- General purpose wide $V_{\text{IN}}$ power supplies

3 Description

The LMR51420 is a wide-$V_{\text{IN}}$, easy-to-use SIMPLE SWITCHER® synchronous buck converter capable of driving up to 2-A load current. With a wide input range of 4.5 V to 36 V, the device is suitable for a wide range of industrial applications for power conditioning from an unregulated source.

The LMR51420 operates at 500-kHz and 1.1-MHz switching frequency to support use of relatively small inductors for an optimized solution size. It has an PFM version to realize high efficiency at light load and FPWM version to achieve constant frequency, and small output voltage ripple over the full load range. Soft-start and compensation circuits are implemented internally, which allows the device to be used with minimum external components.

The device has built-in protection features, such as cycle-by-cycle current limit, hiccup mode short-circuit protection, and thermal shutdown in case of excessive power dissipation. The LMR51420 is available in a 6-pin SCT-23 package.

Device Information

<table>
<thead>
<tr>
<th>PART NUMBER</th>
<th>PACKAGE(1)</th>
<th>BODY SIZE (NOM)</th>
</tr>
</thead>
<tbody>
<tr>
<td>LMR51420</td>
<td>SOT-23 (6)</td>
<td>2.90 mm x 1.60 mm</td>
</tr>
</tbody>
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(1) For all available packages, see the orderable addendum at the end of the data sheet.
<table>
<thead>
<tr>
<th>TYPE</th>
<th>DESCRIPTION</th>
</tr>
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<tbody>
<tr>
<td>Category</td>
<td>Switches Slide Switches</td>
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<tr>
<td>Mfr</td>
<td>NKK Switches</td>
</tr>
<tr>
<td>Series</td>
<td>AS</td>
</tr>
<tr>
<td>Package</td>
<td>Tray ?</td>
</tr>
<tr>
<td>Part Status</td>
<td>Active</td>
</tr>
<tr>
<td>Circuit</td>
<td>DPDT</td>
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<tr>
<td>Contact Timing</td>
<td>Non-Shorting (BBM)</td>
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<tr>
<td>Switch Function</td>
<td>On-Off</td>
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<tr>
<td>Current Rating (Amps)</td>
<td>0.4VA (AC/DC)</td>
</tr>
<tr>
<td>Voltage Rating - AC</td>
<td>28 V</td>
</tr>
<tr>
<td>Voltage Rating - DC</td>
<td>28 V</td>
</tr>
<tr>
<td>Actuator Type</td>
<td>Standard</td>
</tr>
<tr>
<td>Actuator Length</td>
<td>2.50mm</td>
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<tr>
<td>Contact Material</td>
<td>Phosphor Bronze</td>
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<td>Contact Finish</td>
<td>Gold</td>
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<td>Mounting Type</td>
<td>Through Hole</td>
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<tr>
<td>Termination Style</td>
<td>PC Pin</td>
</tr>
<tr>
<td>Features</td>
<td>Epoxy Sealed Terminals</td>
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<tr>
<td>Operating Temperature</td>
<td>-30°C ~ 85°C</td>
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<tr>
<td>Actuator Material</td>
<td>Polyamide (PA), Nylon, Glass Filled</td>
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<tr>
<td>Switch Travel</td>
<td>2.50mm</td>
</tr>
<tr>
<td>Mechanical Life</td>
<td>50,000 Cycles</td>
</tr>
<tr>
<td>Electrical Life</td>
<td>50,000 Cycles</td>
</tr>
<tr>
<td>Operating Force</td>
<td>260gf</td>
</tr>
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</table>
NOTE: 3D PRINTED PART. DIMENSIONS NOT CRITICAL.
Appendix C: MATLAB® Stud Length Calculator

ME 429, Winter 2022

Author: Shaw Hughes

Date Created: 02/12/2022

Date Modified: 02/20/2022

Description: This script returns the stud and spring lengths for a given spring. Note that it does not account for the possibility of an unmatched set of springs.

The length outputs are defined as follows:

HO-BA-05 spring stud:

HO-BA-06 front bumper stud:

HO-BA-13 rear bumper stud:

Inputs

From the McMaster-Carr spec sheet for HO-SP-01A:

<table>
<thead>
<tr>
<th>solid_length</th>
<th>1.875</th>
<th>[in]</th>
</tr>
</thead>
<tbody>
<tr>
<td>max_extension</td>
<td>4.87</td>
<td>[in]</td>
</tr>
</tbody>
</table>

Define a margin of safety to prevent over-extension or going solid as the bumpers compress

| margin         | 0.05                   | [in] |
Known Dimensions

From the revision A solid model

```
carriage_stud_del = 3.602; %[in]
bumper_surf_front = -.328; %[in] negative because bumper surface protrudes beyond stud
bumper_surf_rear = .456; %[in]
total_base_length = 12.5; %[in]
end_plate_thick = .375; %[in]
```

Calc

Define the distance between the spring studs:

```
l = solid_length + carriage_stud_del + max_extension;
```

Thus, the spring stud lengths are:

```
l_s = (total_base_length - l)/2 %spring stud length, [in]
l_s = 1.0765
```

The bumpers prevent max extension or springs going solid, so

```
b_f = solid_length + bumper_surf_front + margin %front bumper stud, [in]
b_f = 1.5970
```

```
b_r = solid_length + bumper_surf_rear + margin %rear bumper stud, [in]
b_r = 2.3810
```
## Appendix D: Exploration of Springs as Conductors

### ME 429
COR - SPRINGS AS CONDUCTORS ATTACHMENT

<table>
<thead>
<tr>
<th>METAL</th>
<th>CONDUCTIVITY, σ</th>
<th>RIGIDITY MODULUS, G</th>
</tr>
</thead>
<tbody>
<tr>
<td>Stainless Steel</td>
<td>$1.5 \times 10^{-6} , \Omega^{-1} \cdot \text{m}^{-1}$</td>
<td>73.1 GPa</td>
</tr>
<tr>
<td>Beryllium Copper</td>
<td>$5.0 \times 10^{-7} , \Omega^{-1} \cdot \text{m}^{-1}$</td>
<td>48.5 GPa</td>
</tr>
<tr>
<td>Copper</td>
<td>$9.0 \times 10^{-7} , \Omega^{-1} \cdot \text{m}^{-1}$</td>
<td>—</td>
</tr>
<tr>
<td>Aluminum (99.99%)</td>
<td>$1.8 \times 10^{-7} , \Omega^{-1} \cdot \text{m}^{-1}$</td>
<td>—</td>
</tr>
</tbody>
</table>

**Springs Rate for a Coil Spring can be Modeled with** $k = \frac{d^4 G}{8D^3 N}$

For example, HO-SP-DIA (McMaster, 94/35-218)

- $d = 0.016 \, \text{in}$, $D = 0.188 \, \text{in}$, $N = 93.5 \, \text{Turns}$

$$k = \frac{(0.0004 \, \text{in}^3)(73.1 \, \text{Eg N/m}^2)}{8 (0.0048 \, \text{in}^3)(93.5 \, \text{Turns})} = 25 \, \text{N/m}, \text{ close to the rated } 17 \, \text{N/m}$$

**The Electrical Resistance of this Spring is High:**

$$R_w = \frac{1}{\sigma A}$$

where $L = \pi D N$

$$A = \pi \left(\frac{d}{2}\right)^2$$

$$R_w = \frac{1.4 \, \text{m}}{(1.5 \times 10^{-6} \, \Omega^{-1} \cdot \text{m}^{-1})(1.3 \times 10^{-9} \, \text{m}^2)} \rightarrow R_w = 1 \, \Omega$$

**Suppose a Custom B6-CU Spring with Dimensions that Minimize $R_w$ (Minimize number of turns, Maximize $d$)**

If $N = 50$ and $D = 1.5 \, \text{in}$, and we design for the same $k = 25 \, \text{N/m}$

$$d = \left[\frac{8 (25 \, \text{N/m}) (0.03813 \, \text{m}^3) (50)}{73.1 \, \text{Eg N/m}^2}\right]^{1/4} = 0.0016 \, \text{m} \rightarrow d = 0.065 \, \text{in}$$

**The Resistance of this Hypothetical Custom Spring is**

$$R_w = \frac{(3.0 \times 10^{-7} \, \Omega^{-1} \cdot \text{m}^{-1})(50)}{\pi (0.0008 \, \text{m}^2)}$$

$$\rightarrow R_w = 0.1 \, \Omega$$
### Table E.1. Motors considering and their characteristics.

<table>
<thead>
<tr>
<th>Name</th>
<th>Maxon Part No.</th>
<th>B/BL *</th>
<th>Diameter [ mm ]</th>
<th>Mass [ g ]</th>
<th>$K_v$ [ rpm/V ]</th>
<th>Voltage Density† [ g-rpm/V ]</th>
<th>Cost</th>
</tr>
</thead>
<tbody>
<tr>
<td>EC-I 40 HT 100W</td>
<td>488607</td>
<td>BL</td>
<td>40</td>
<td>390</td>
<td>105</td>
<td>40950</td>
<td>$359.25</td>
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<tr>
<td>EC-max 40 120W</td>
<td>283873</td>
<td>BL</td>
<td>40</td>
<td>720</td>
<td>76.1</td>
<td>54792</td>
<td>$608.25</td>
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<tr>
<td>EC 45 flat 50W</td>
<td>651609</td>
<td>BL</td>
<td>42.8</td>
<td>116</td>
<td>121</td>
<td>14036</td>
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<tr>
<td>EC 45 flat 70W</td>
<td>651617</td>
<td>BL</td>
<td>42.8</td>
<td>150</td>
<td>62.8</td>
<td>9420</td>
<td>$185.88</td>
</tr>
<tr>
<td>EC 60 flat 100W</td>
<td>625855</td>
<td>BL</td>
<td>60</td>
<td>355</td>
<td>182</td>
<td>64610</td>
<td>$151.13</td>
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<tr>
<td>RE 35 Ø35 mm 90 W</td>
<td>273756</td>
<td>B</td>
<td>35</td>
<td>340</td>
<td>140</td>
<td>47600</td>
<td>$415.88</td>
</tr>
</tbody>
</table>

*Motor types: (B) brushed, BL (brushless)

†$VD \ [ g - rpm/V ] = m \ [ g ] \cdot K_v \ [ rpm/V ]$, want to minimize this value
## Design Failure Mode and Effects Analysis

**Product:** Rotational Generator  
**Team:** F24

**Prepared by:** The Power Walking Team (F24)  
**Date:** 12/03/2021 (orig)

<table>
<thead>
<tr>
<th>System / Function</th>
<th>Potential Failure Mode</th>
<th>Potential Effects of the Failure Mode</th>
<th>Severity</th>
<th>Potential Causes of the Failure Mode</th>
<th>Current Preventative Activities</th>
<th>Occurrence</th>
<th>Current Detection Activities</th>
<th>Detection RPN</th>
<th>Recommended Action(s)</th>
<th>Responsibility &amp; Target Completion Date</th>
<th>Actions Taken</th>
<th>Severity</th>
<th>Source</th>
<th>Detection</th>
<th>New RPN</th>
</tr>
</thead>
</table>
| Transduction/Convert to Electrical Domain | Energy isn’t converted efficiently | Power output is too low | 4 | a) Generator is inefficient  
b) Generator has too much stiction  
c) Back emf forces are too large | a) Research generators before purchasing | 2 | a) Perform testing with generator before integrating to system to verify performance | 3 | 24 | | | |
| | No energy is converted | No power is generated | 6 | a) Generator fails  
b) Generator overheats | a) Wires break  
b) Wires short  
c) Generator fails  
d) Generator overheats | 3 | a) Test system at voltage/current higher than expected working conditions | 3 | 54 | Design appropriate wiring routing and housing  
Provide wiring in CAD | Ryan  
ECD: 2/12/22 | |
| | Signal isn’t steady | Power output is too low | 6 | a) Rectifier fails  
b) Regulator fails  
c) Power to capacitor exceeds limit | a) Correctly select components rated for high power and high reliability  
a) Round edges near port  
b) Make opening for port larger than common cord footprint  
c) Add cord retention feature | 2 | a) Test system at voltage/current higher than expected working conditions | 2 | 24 | | | |
| | Signal can’t be transferred to an external device | Power is generated, but the user cannot use it | 6 | a) USB interface disconnects from circuit  
b) User cannot easily access the USB port  
c) Cord comes unplugged | a) Round edges near port  
b) Make opening for port larger than common cord footprint  
c) Add cord retention feature | 2 | a) Drop testing  
b) Customer testing (can they easily access the port)  
c) Put device in a backpack and walk/run around | 2 | 24 | | | |
| Circuity/Modify Signal | Circuitry is inefficient | Power output is too low | 4 | a) Capacitors, rectifier, regulator, or other component are inefficient  
b) Electrical components overheat quickly | a) Correctly select components rated for high power and high reliability | 3 | a) Test system at voltage/current higher than expected working conditions | 3 | 36 | | | |
| | Inner structure flexes too much | Power output is low to none | 4 | a) Guide rail has low stiffness  
b) Thermal expansion | a) Correctly select components rated for proper stiffness and thermal operating range  
a) Correctly select components according to stress analysis with long life cycles | 1 | a) Stiffness testing  
b) Temperature test  
c) Visually observe deformations | 2 | 8 | | | |
| Locate Components | Inner structure break | No power is generated | 6 | a) Guide rail snaps (ultimate)  
b) Wear  
c) Rack wears down  
d) Rack is misaligned | a) Stress testing  
b) User Manual for customer | 2 | 24 | | | | | |
<table>
<thead>
<tr>
<th>System / Function</th>
<th>Potential Failure Mode</th>
<th>Potential Effects of the Failure Mode</th>
<th>Severity</th>
<th>Potential Causes of the Failure Mode</th>
<th>Current Preventative Activities</th>
<th>Occurrence</th>
<th>Current Detection Activities</th>
<th>Detection RPN</th>
<th>Recommended Action(s)</th>
<th>Responsibility &amp; Target Completion Date</th>
<th>Action Results</th>
</tr>
</thead>
<tbody>
<tr>
<td>Hold Parts Together</td>
<td>Warping</td>
<td>Power output is low to none</td>
<td>4</td>
<td>a) Deformation of inner structure b) Guide rail has too much friction</td>
<td>a) Correctly select components rated for proper stiffness and thermal operating range b) Lube rail</td>
<td>2</td>
<td>a) Temperature test b) Visually observe deformations after a walk/run with device in backpack c) User Manual for customer to lube rail</td>
<td>2 16</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Joints separate</td>
<td>No power is generated</td>
<td>6</td>
<td>a) Adhesives cannot withstand environmental conditions b) Adhesive delamination</td>
<td>a) Correctly select adhesives rated for all-weather and thermal operating range</td>
<td>3</td>
<td>a) Temperature test b) Peel-adhesion test</td>
<td>2 36</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Joints flex too much</td>
<td>Power output is low to none</td>
<td>4</td>
<td>a) Adhesive joints flex too much b) Adhesives allow for relative motion in joints</td>
<td>a) Correctly select adhesive that keeps flexing to a minimum a) Correctly select components rated for expected load and ensure hole and fastener match</td>
<td>3</td>
<td>a) Peel-adhesion test with higher loads a) Shear test by applying higher load b) Match hole with fastener and observe compatatability</td>
<td>2 24</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Components separate</td>
<td>No power is generated</td>
<td>6</td>
<td>a) Fasteners shear b) Fasteners strip</td>
<td>a) Correctly select components rated for low ductility</td>
<td>1</td>
<td>a) Apply higher loads and observe deflections</td>
<td>2 12</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Gaps between components allow FOD (Foreign Object Debris) inside</td>
<td>Power output is low to none</td>
<td>4</td>
<td>a) Fastened joints flex too much</td>
<td>a) Device not located properly or oriented as to maximize motion capture a) Generator stiction is preventing motion b) Spring breaks c) Spring is too stiff d) Spring is too weak e) Pinion is misaligned g) Gear train stalls h) Gear train flexes too much i) Gear train is misaligned j) Oscillating frame flexes too much k) Oscillating frame breaks</td>
<td>3</td>
<td>a) Study best orientation and backapck location(s) for power generation a) Understand the static frictions in the internal mechanisms b,c,d) Tune and design spring mechanism for appropriate frequency of human motion g,h,i) Design gear train for proper tolerancing and stiffness j,k) Design oscillating frame for proper stiffness and strength conditions</td>
<td>2 42</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Device not oriented properly</td>
<td>Power output is too low</td>
<td>7</td>
<td>a) Device not located properly or oriented as to maximize motion capture a) Generator stiction is preventing motion b) Spring breaks c) Spring is too stiff d) Spring is too weak e) Pinion is misaligned g) Gear train stalls h) Gear train flexes too much i) Gear train is misaligned j) Oscillating frame flexes too much k) Oscillating frame breaks</td>
<td>a) Study best orientation and backapck location(s) for power generation a) Understand the static frictions in the internal mechanisms b,c,d) Tune and design spring mechanism for appropriate frequency of human motion g,h,i) Design gear train for proper tolerancing and stiffness j,k) Design oscillating frame for proper stiffness and strength conditions</td>
<td>3</td>
<td>a) Perform acceleration test on backpacks during hiking a,b,c,d) Model internal power generation mechanism including inefficiencies g,h,i) Optimize gear train design, performing deflection, stiffness, and lifecycle analyses j,k) Optimize oscillating frame design, performing deflection, stiffness, and lifecycle analyses</td>
<td>2 42</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Oscillation/Capture Motion</td>
<td>No power is generated</td>
<td>7</td>
<td>a) Oscillation portion stalls/get stuck</td>
<td>a) Input torque does not overcome the back EMF of rotary generator a) Understand EMF of generator design</td>
<td>2</td>
<td>a) Calculate whether input torque with consen is orkever the back EMF of generator design</td>
<td>2 32</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Note: The table continues with similar entries for each potential failure mode and effect.
### Design Failure Mode and Effects Analysis

**Product:** Rotational Generator  
**Team:** F24  
**Prepared by:** The Power Walking Team (F24)  
**Date:** 12/03/2021 (orig)

<table>
<thead>
<tr>
<th>System / Function</th>
<th>Potential Failure Mode</th>
<th>Potential Effects of the Failure Mode</th>
<th>Severity</th>
<th>Potential Causes of the Failure Mode</th>
<th>Current Preventative Activities</th>
<th>Current Detection Activities</th>
<th>Detection RPN</th>
<th>Recommended Action(s)</th>
<th>Responsibility &amp; Target Completion Date</th>
<th>Action Results</th>
</tr>
</thead>
</table>
| Protect from Environment | Water or foreign material enters housing | No power is generated | 7 | a) Outer housing flex  
b) Outer housing crack  
c) End caps fall off  
d) End-caps break  
e) End-caps flex  
f) Sealant fails | a,b) Design for strength and stiffness with crush and drop load cases  
c,d,e) Design end-caps for strength and stiffness and consider attachment method  
f) Explore sealant methods | a) Design for strength and stiffness with crush and drop load cases  
b) Design end-caps for strength and stiffness and consider attachment method  
f) Explore sealant methods | 2 | Design and testing to come | 4 | 56 | Perform enclosure testing (i.e. water resistance, FOD ingress) | Shaw  
ECD: 3/15/22 |
| USB interface is damaged | No power is generated | 6 | a) Foreign material enters USB port  
b) Cable is damaged by interface with housing | a) Explore methods for protecting USB port from environment  
b) Design strain relief without sharp edges | a) Explore methods for protecting USB port from environment  
b) Design strain relief without sharp edges | 2 | Design and testing to come | 3 | 36 | |
## Appendix G: Design Hazard Checklist

### DESIGN HAZARD CHECKLIST – UPDATED 2/19/22

Team: F24 - Power Walking

<table>
<thead>
<tr>
<th></th>
<th></th>
<th>Y</th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>□</td>
<td>■</td>
<td></td>
</tr>
<tr>
<td>1.</td>
<td>Will any part of the design create hazardous revolving, reciprocating, running, shearing, punching, pressing, squeezing, drawing, cutting, rolling, mixing or similar action, including pinch points and shear points?</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>■</td>
<td>□</td>
<td></td>
</tr>
<tr>
<td>2.</td>
<td>Can any part of the design undergo high accelerations/decelerations?</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>□</td>
<td>■</td>
<td></td>
</tr>
<tr>
<td>3.</td>
<td>Will the system have any large moving masses or large forces?</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>■</td>
<td>□</td>
<td></td>
</tr>
<tr>
<td>4.</td>
<td>Will the system produce a projectile?</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>□</td>
<td>■</td>
<td></td>
</tr>
<tr>
<td>5.</td>
<td>Would it be possible for the system to fall under gravity creating injury?</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>■</td>
<td>□</td>
<td></td>
</tr>
<tr>
<td>6.</td>
<td>Will a user be exposed to overhanging weights as part of the design?</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>□</td>
<td>■</td>
<td></td>
</tr>
<tr>
<td>7.</td>
<td>Will the system have any sharp edges?</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>□</td>
<td>■</td>
<td></td>
</tr>
<tr>
<td>8.</td>
<td>Will you have any non-grounded electrical systems?</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>■</td>
<td>□</td>
<td></td>
</tr>
<tr>
<td>9.</td>
<td>Will there be any large batteries or electrical voltage (above 40 V) in the system?</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>□</td>
<td>■</td>
<td></td>
</tr>
<tr>
<td>10.</td>
<td>Will there be any stored energy in the system such as batteries, flywheels, hanging weights or pressurized fluids?</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>■</td>
<td>□</td>
<td></td>
</tr>
<tr>
<td>11.</td>
<td>Will there be any explosive or flammable liquids, gases, or dust fuel as part of the system?</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>□</td>
<td>■</td>
<td></td>
</tr>
<tr>
<td>12.</td>
<td>Will the user of the design be required to exert any abnormal effort or physical posture during the use of the design?</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>■</td>
<td>□</td>
<td></td>
</tr>
<tr>
<td>13.</td>
<td>Will there be any materials known to be hazardous to humans involved in either the design or the manufacturing of the design?</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>□</td>
<td>■</td>
<td></td>
</tr>
<tr>
<td>14.</td>
<td>Could the system generate high levels of noise?</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>□</td>
<td>■</td>
<td></td>
</tr>
<tr>
<td>15.</td>
<td>Will the device/system be exposed to extreme environmental conditions such as fog, humidity, cold, high temperatures, etc.?</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>□</td>
<td>■</td>
<td></td>
</tr>
<tr>
<td>16.</td>
<td>Is it possible for the system to be used in an unsafe manner?</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>■</td>
<td>□</td>
<td></td>
</tr>
<tr>
<td>17.</td>
<td>Will there be any other potential hazards not listed above? If yes, please explain on reverse.</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

For any “Y” responses, complete a row in your Design Hazard Plan including (a) a description of the hazard, (b) a list of corrective actions to be taken, and (c) the date you plan to complete the actions.

**Figure G.1.** Design Hazard Checklist
<table>
<thead>
<tr>
<th>Description of Hazard</th>
<th>Planned Corrective Action</th>
<th>Planned Date</th>
<th>Actual Date</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ungrounded Electrical Connection</td>
<td>We will ensure that the ground connection for the oscillating element is connected to the housing of the overall device.</td>
<td>2/22/22</td>
<td></td>
</tr>
<tr>
<td>High Accelerating Internal Components</td>
<td>Only testing within standard operating conditions can be performed</td>
<td>4/01/22</td>
<td></td>
</tr>
</tbody>
</table>
## Appendix H: Project Budget

### How the Material is Purchased

<table>
<thead>
<tr>
<th>Account Used</th>
<th>Date Purchased</th>
<th>Purchaser</th>
<th>Description of Item</th>
<th>Vendor</th>
<th>Vendor's Part Number</th>
<th>Team's Part Number</th>
<th>Unit Price</th>
<th>Quantity</th>
<th>Shipping &amp; Handling</th>
<th>Taxes</th>
<th>Total Price</th>
</tr>
</thead>
<tbody>
<tr>
<td>ME Pro-Card</td>
<td>2/3/2022</td>
<td>Bonderson</td>
<td>EC 45 flat ø42.8 mm, brushless, 70W, with Hall sensors</td>
<td>Maxon</td>
<td>651617</td>
<td>CA-MO-01A</td>
<td>$140.20</td>
<td>2</td>
<td>$73.48</td>
<td>$20.33</td>
<td>$300.73</td>
</tr>
<tr>
<td>ME Pro-Card</td>
<td>2/3/2022</td>
<td>Bonderson</td>
<td>Cable with connector - AWG19 500mm</td>
<td>Maxon</td>
<td>339380</td>
<td>-</td>
<td>$25.50</td>
<td>1</td>
<td>-</td>
<td>$1.85</td>
<td>$27.35</td>
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<tr>
<td>ME Pro-Card</td>
<td>2/10/2022</td>
<td>Bonderson</td>
<td>Main Tube - option A</td>
<td>McMaster</td>
<td>8585K38</td>
<td>HO-TU-01A</td>
<td>$21.35</td>
<td>1</td>
<td>$64.64</td>
<td>$1.55</td>
<td>$22.90</td>
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<tr>
<td>ME Pro-Card</td>
<td>2/10/2022</td>
<td>Bonderson</td>
<td>Main Tube - option B</td>
<td>McMaster</td>
<td>8532K23</td>
<td>HO-TU-01A</td>
<td>$56.00</td>
<td>1</td>
<td>-</td>
<td>$4.06</td>
<td>$60.06</td>
</tr>
<tr>
<td>ME Pro-Card</td>
<td>2/10/2022</td>
<td>Bonderson</td>
<td>Aluminum Stock</td>
<td>McMaster</td>
<td>8975K477</td>
<td>Multiple</td>
<td>$47.50</td>
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<td>-</td>
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<td>$50.94</td>
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<td>Bonderson</td>
<td>Skeleton</td>
<td>McMaster</td>
<td>8974K77</td>
<td>CA-SK-01A</td>
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<td>-</td>
<td>$3.81</td>
<td>$56.35</td>
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<tr>
<td>ME Pro-Card</td>
<td>2/10/2022</td>
<td>Bonderson</td>
<td>Idler Shaft .078 in.</td>
<td>McMaster</td>
<td>1263K26</td>
<td>CA-GD-04A</td>
<td>$15.20</td>
<td>1</td>
<td>-</td>
<td>$1.10</td>
<td>$16.30</td>
</tr>
<tr>
<td>ME Pro-Card</td>
<td>2/10/2022</td>
<td>Bonderson</td>
<td>Easy-to-Machine 303 Stainless Steel Rod 3/16&quot;</td>
<td>McMaster</td>
<td>8984K13</td>
<td>Multiple</td>
<td>$6.94</td>
<td>1</td>
<td>-</td>
<td>$0.50</td>
<td>$7.44</td>
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<tr>
<td>ME Pro-Card</td>
<td>2/10/2022</td>
<td>Bonderson</td>
<td>M3x0.5x10 Button Head</td>
<td>McMaster</td>
<td>90991A114</td>
<td>Multiple</td>
<td>$4.48</td>
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<td>-</td>
<td>$0.32</td>
<td>$4.80</td>
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<tr>
<td>ME Pro-Card</td>
<td>2/10/2022</td>
<td>Bonderson</td>
<td>2x8mm Dowel Pin</td>
<td>McMaster</td>
<td>91585A214</td>
<td>CA-SK-04A</td>
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<td>$16.31</td>
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<tr>
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<td>M2x0.4x5 Button Head</td>
<td>McMaster</td>
<td>90910A921</td>
<td>Multiple</td>
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<td>1</td>
<td>-</td>
<td>$1.00</td>
<td>$14.84</td>
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<tr>
<td>ME Pro-Card</td>
<td>2/10/2022</td>
<td>Bonderson</td>
<td>M3x0.5x6 Button Head</td>
<td>McMaster</td>
<td>90991A112</td>
<td>Multiple</td>
<td>$4.36</td>
<td>1</td>
<td>-</td>
<td>$0.32</td>
<td>$4.68</td>
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<tr>
<td>ME Pro-Card</td>
<td>2/10/2022</td>
<td>Bonderson</td>
<td>O-Ring 5.8/9.6mm</td>
<td>McMaster</td>
<td>93125K343</td>
<td>CA-GD-02A</td>
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<td>Bonderson</td>
<td>Bearing .078/.25in, open</td>
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<td>57155K343</td>
<td>CA-GD-03A</td>
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<td>Bonderson</td>
<td>Wave Washer .095/.130in</td>
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<td>99842A103</td>
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<td>Bonderson</td>
<td>Nut M6x1.0</td>
<td>McMaster</td>
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<td>Multiple</td>
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<td>Washer M6x11</td>
<td>McMaster</td>
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<tr>
<td>ME Pro-Card</td>
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<td>Bonderson</td>
<td>.010 Shim, .078/.156in</td>
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<tr>
<td>How the Material is Purchased</td>
<td>Account Used</td>
<td>Date Purchased</td>
<td>Current Material Location</td>
<td>Purchaser</td>
<td>Description of Item</td>
<td>Vendor</td>
<td>Vendor’s Part Number</td>
<td>Team’s Part Number</td>
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<tr>
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<td>Micro USB-B Breakout Board</td>
<td>Ryan</td>
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<td>Digi-Key</td>
<td>282834-5</td>
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<td>STPS130U</td>
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<td>2/16/2022</td>
<td>Capacitor, 10μF</td>
<td>Ryan</td>
<td>Capacitor, 10μF</td>
<td>Digi-Key</td>
<td>CL32B106KBJ2W6E</td>
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</tr>
<tr>
<td>ME Pro-Card</td>
<td>Baker-Koob</td>
<td>2/16/2022</td>
<td>Capacitor, 12pF</td>
<td>Ryan</td>
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<td>C1206C120JSAGACUTO</td>
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<td>Baker-Koob</td>
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<td>Baker-Koob</td>
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<td>Capacitor, 47μF</td>
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<td>CA-PB-14A</td>
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<tr>
<td>ME Pro-Card</td>
<td>Baker-Koob</td>
<td>2/16/2022</td>
<td>Inductor, 10μH</td>
<td>Ryan</td>
<td>Inductor, 10μH</td>
<td>Digi-Key</td>
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<td>-</td>
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<tr>
<td>ME Pro-Card</td>
<td>Baker-Koob</td>
<td>2/16/2022</td>
<td>Resistor, 162kΩ</td>
<td>Ryan</td>
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<td>Digi-Key</td>
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<td>Resistor, 22.1kΩ</td>
<td>Ryan</td>
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<td>Quantity</td>
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<td>2/16/2022</td>
<td>Bonderson</td>
<td>Shaw</td>
<td>18-8 Stainless Steel Threaded Rod</td>
<td>McMaster</td>
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<td>McMaster</td>
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<td>57655K18</td>
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<td>Bonderson</td>
<td>Shaw</td>
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<td>McMaster</td>
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A-95
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<th>Team's Part Number</th>
<th>Unit Price</th>
<th>Quantity</th>
<th>Shipping &amp; Handling</th>
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<td>One Way GARR 320M/16070 TOOLING</td>
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**Budget:** $1,780.00  
**Actual Expenses:** $1,431.22  
**Remaining Balance:** $348.78  
**Total expenses:** $1,431.22
Appendix I: System Dynamics Model Derivation

Title Page for System Dynamics Model Derivation
LINEAR GRAPH & NORMAL TREE

TRANSFORMERS
1 ➔ 2 RACK & PINION
3 ➔ 4 GEAR RATIO
S ➔ G MOTOR

OUTPUTS
\[ y = \begin{bmatrix} V_m & V_{ker} & i_{rl} & J_{2mg} & X_{ker} \end{bmatrix} \]

STATE VARS
\[ x = \begin{bmatrix} V_m & F_{ker} & i_L & V_{in} \end{bmatrix} \]

INPUTS
\[ u = \begin{bmatrix} \frac{dV_{in}}{dt} & V_3 \end{bmatrix} \]

POWER OUTPUT
\[ P_L = V_3 \cdot i_{rl} \]

RELATIVE MOTION OF MASSES TO HOUSING
**Transformers**

**Rack & Pinion**

\[ V_1 = r \cdot \omega_2 \]

\[ F_1 = -\frac{1}{r} \cdot T_2 \]

\[
\begin{bmatrix}
\omega_2 \\
T_2
\end{bmatrix} =
\begin{bmatrix}
r & 0 \\
0 & -\frac{1}{r}
\end{bmatrix}
\begin{bmatrix}
V_1 \\
F_1
\end{bmatrix}
\]

**Gear Train**

**Input Gear 3**

**Gear 4 (Output)**

**For Increasing Speed**, \( N > 1 \)

\[ \omega_4 = -N \cdot \omega_3 \]

\[ T_4 = \frac{1}{N} \cdot T_3 \]

\[
\begin{bmatrix}
\omega_4 \\
T_4
\end{bmatrix} =
\begin{bmatrix}
-N & 0 \\
0 & \frac{1}{N}
\end{bmatrix}
\begin{bmatrix}
\omega_3 \\
T_3
\end{bmatrix}
\]

**Motor**

\[
\begin{bmatrix}
V_6 \\
\omega_6
\end{bmatrix} =
\begin{bmatrix}
k_v & 0 \\
0 & -\frac{1}{k_v}
\end{bmatrix}
\begin{bmatrix}
\frac{\omega_s}{T_3} \\
\frac{V}{S}
\end{bmatrix}
\]

\[ k_v = \text{Back-EMF Constant} \]

\[ k_v = \frac{V_6}{\omega_s} \]

**Units:** \( \frac{V}{\text{rad/s}} \) or \( \frac{V - S}{\text{rad}} \)

\[ F \]
ELEME NTA L & C ONSRAINT EQUATIONS

ELEME NTA L

\[ \frac{dF_{\text{ker}}}{dt} = k_{\text{er}} V_{\text{ker}} \]

\[ \frac{dv_m}{dt} = \frac{1}{m} F_m \]

\[ F_{BL} = B_L V_{BL} \]

\[ F_1 = -\frac{1}{V} T_2 \]

\[ S_2 = \frac{1}{V} V_1 \]

\[ T_{SP} = J_f \frac{dS_2 - S_{SP}}{dt} \]

\[ T_{BP} = B_P S_{BP} \]

\[ T_3 = N T_4 \]

\[ S_4 = -N S_3 \]

\[ T_{SMG} = J_{MG} \frac{dS_2 - S_{MG}}{dt} \]

\[ T_{BM} = B_M S_{BM} \]

\[ T_5 = -k_v i_6 \]

\[ V_6 = k_v S_5 \]

\[ V_R = R i_R \]

\[ \frac{di_L}{dt} = \frac{1}{L} V_L \]

CONSTRAINT

\[ V_{\text{ker}} = V_{IN} - V_m \]

\[ F_m = F_{\text{ker}} + F_{BL} + F_1 \]

\[ V_{BL} = V_{IN} - V_m \]

\[ V_1 = V_{IN} - V_m \]

\[ T_2 = -T_{SP} - T_{BP} - T_3 \]

\[ S_{SP} = S_2 \]

\[ S_{BP} = S_2 \]

\[ S_3 = S_2 \]

\[ T_4 = -T_{SMG} - T_{BM} - T_5 \]

\[ S_{MG} = S_4 \]

\[ S_{BM} = S_4 \]

\[ S_5 = S_4 \]

\[ i_6 = -i_L \]

\[ i_R = i_L \]

\[ V_L = -V_R + V_6 + V_{BO} - V_{RL} \]

\[ i_{RL} = i_L \]
\[
\frac{dV_m}{dt} = \frac{1}{m} F_m
\]
\[
= \frac{1}{m} \left( F_{KeQ} + F_{BL} + F_i \right)
\]
\[
= \frac{1}{m} \left( F_{KeQ} + B_L V_{BL} + \frac{1}{r} T_2 \right)
\]
\[
= \frac{1}{m} \left[ F_{KeQ} + B_L (V_{IN} - V_m) + \frac{1}{r} \left( T_{S_p} + T_{S_m} + T_3 \right) \right]
\]

\[
T_{S_p} = J_p \frac{dS_p}{dt}
\]
\[
= J_p \frac{d}{dt} \left( \frac{1}{r} V_m \right)
\]
\[
= \frac{J_p}{r} \left( \frac{dV_{IN}}{dt} - \frac{dV_m}{dt} \right)
\]
\[
T_{S_m} = B_p \frac{S_m}{B_p}
\]
\[
= B_p \left( \frac{1}{r} V_m \right)
\]
\[
= \frac{B_p}{r} \left( V_{IN} - V_m \right)
\]
\[
T_3 = N T_4
\]
\[
= -N \left( T_{S_m} + T_{S_p} + T_3 \right)
\]

\[
T_{S_m} = J_m \frac{dS_m}{dt}
\]
\[
= J_m \left( \frac{dS_3}{dt} - N \frac{dS_3}{dt} \right)
\]
\[
= J_m (-N) \frac{dS_3}{dt}
\]
\[ T_{\text{mg}} = -N J_{\text{mg}} \frac{d J_{\text{mg}}}{dt} + Vi \]

\[ = -N J_{\text{mg}} \frac{d V_i}{dt} + V_i - V_m \]

\[ = -N \frac{r}{r} J_{\text{mg}} \left( \frac{d V_i}{dt} - \frac{d V_m}{dt} \right) \]

\[ = N \frac{r}{r} J_{\text{mg}} \left( \frac{d V_m}{dt} - \frac{d V_i}{dt} \right) \]

\[ T_{\text{bm}} = B_m \frac{\sigma L_{\text{bm}}}{r} \]

\[ = B_m \frac{\sigma L_{\text{bm}}}{r} - N J_{\text{r}} \]

\[ = -N B_m \frac{\sigma L_{\text{r}}}{2} \]

\[ = -N B_m \frac{\sigma L_{\text{r}}}{2} + V_i \]

\[ = -N \frac{r}{r} B_m V_i + V_i - V_m \]

\[ = \frac{N}{r} B_m \left( V_m - V_i \right) \]

\[ T_5 = -k_v \frac{i_L}{L} \]

\[ = k_v i_L \]

RETURN TO T_3

\[ T_3 = -N \frac{r}{r} J_{\text{mg}} \left( \frac{d V_m}{dt} - \frac{d V_i}{dt} \right) + \frac{N}{r} B_m \left( V_m - V_i \right) + k_v i_L \]

RETURN TO \( \frac{d V_m}{dt} \)
\[ \frac{dv_m}{dt} = \frac{1}{m} \left( F_{ker} + B_L(V_{in} - V_m) \right) \]
\[ + \frac{1}{m} \left( \frac{J_p}{m} \frac{dv_m}{dt} \right) + \frac{B_p}{m} \left( V_{in} - V_m \right) \]
\[ - \frac{N^2}{J_m} \left( \frac{dv_m}{dt} - \frac{dV_{in}}{dt} \right) + \frac{N^2}{J_m} B_m (V_m - V_{in}) \]
\[ + k_v i_L \]

**Multiply out and combine like terms**

\[ \frac{dv_m}{dt} = \frac{1}{m} F_{ker} + \frac{B_L}{m} V_{in} - \frac{B_L}{m} V_m \]
\[ + \frac{J_p}{m r^2} \left( \frac{dv_m}{dt} \right) \quad - \quad \frac{J_p}{m r^2} \left( \frac{dv_m}{dt} \right) \quad + \quad \frac{B_p}{m r^2} V_{in} \]
\[ - \frac{B_p}{m r^2} V_m \quad - \quad \frac{N^2 J_m}{m r^2} \left( \frac{dv_m}{dt} \right) \quad + \quad \frac{N^2 J_m}{m r^2} \left( \frac{dV_{in}}{dt} \right) \]
\[ - \frac{N^2 B_m}{m r^2} V_m \quad + \quad \frac{N^2 B_m}{m r^2} V_{in} \quad + \quad \frac{N^2 k_v}{m r^2} i_L \]

\[ \frac{dv_m}{dt} \left( 1 + \frac{J_p}{m r^2} + \frac{N^2 J_m}{m r^2} \right) = \frac{1}{m} F_{ker} + \frac{N^2 k_v}{m r^2} i_L \]
ALGEBRA (CONT'D)

Aside

\[ C_1 = 1 + \frac{J_p}{mr^2} + \frac{N^2 J_{mg}}{mr^2} \]
\[ = \frac{mr^2 + J_p + N^2 J_{mg}}{mr^2} = \frac{C_2}{mr^2} \]

\[ \frac{dv_m}{dt} = \frac{mr^2}{C_2} \left\{ \frac{r^2}{mr^2} F_{kse} + \frac{N^2 k_v}{mr^2} i_L \right\} \]
\[ + \frac{V_m}{mr^2} \left( -\frac{B_L r^2 - B_p - N^2 B_m}{mr^2} \right) \]
\[ + \frac{V_{in}}{mr^2} \left( \frac{B_L r^2 + B_p + N^2 B_m}{mr^2} \right) \]
\[ + \frac{dV_{in}}{dt} \left( \frac{J_p + N^2 J_{mg}}{mr^2} \right) \]

Finally, recall final form of state eqns

\[ \dot{x} = Ax + Bu \]

Or

\[ \begin{bmatrix} V_m \\ F_{kse} \\ i_L \end{bmatrix} = \begin{bmatrix} A_{11} & A_{12} & A_{13} \\ A_{21} & A_{22} & A_{23} \\ A_{31} & A_{32} & A_{33} \end{bmatrix} \begin{bmatrix} V_m \\ F_{kse} \\ i_L \end{bmatrix} \]
\[ + \begin{bmatrix} B_{11} & B_{12} & B_{13} \\ B_{21} & B_{22} & B_{23} \\ B_{31} & B_{32} & B_{33} \end{bmatrix} \begin{bmatrix} V_{in} \\ V_{in} \\ V_{in} \end{bmatrix} \]
ALGEBRA (CONT'D)

FROM A SINGLE STATE EQN

\[
\frac{d}{dt} V_m = A_{11} \cdot V_m + A_{12} \cdot F_{keq} + A_{13} \cdot \dot{I}_L
\]

\[
+ B_{11} \cdot V_{in} + B_{12} \cdot \dot{V}_{in} + B_{13} \cdot V_0
\]

S0 TERM BY TERM,

\[
A_{11} = -\frac{1}{C_2} \left( B_L \cdot r^2 + B_p + N^2 B_m \right)
\]

\[
A_{12} = \frac{r^2}{C_2}
\]

\[
A_{13} = \frac{N^2 k_v}{C_2}
\]

\[
B_{11} = \frac{1}{C_2} \left( B_L \cdot r^2 + B_p + N^2 B_m \right)
\]

\[
B_{12} = \frac{1}{C_2} \left( J_p + N^2 J_{ag} \right), \quad \text{AND} \quad B_{13} = 0
\]

WHERE

\[
C_2 = \frac{1}{r^2} + J_p + N^2 J_{ag}
\]

NOTE:

BL HAS UNITS OF \( \frac{N - s}{m} \) (LINEAR DAMPER),

WHEREAS \( B_p \) & \( B_m \) HAVE UNITS OF \( N - s - m \)

HENCE, THE UNITS OF \( B_L \cdot r^2 \) AND \( B_p \)

MATCH

\[
\frac{N - s}{m^2} \cdot m^2 = N - s - m = N - s - m \quad \checkmark
\]
NEXT STATE EQN

\[
\frac{dF_{KEQ}}{dt} = k_{eq} \frac{V_{eq}}{V_{eq}} \Rightarrow \quad V_{in} - V_m \\
= k_{eq} (V_{in} - V_m)
\]

A_{21} = -k_{eq}

B_{21} = k_{eq} \quad B_{21} = B_{22} = B_{23} = \phi

A_{22} = A_{23} = B_{22} = B_{23} = \phi

FINAL STATE EQN

\[
\frac{d}{dt} i_L = \frac{1}{L} V_C - V_R + V_C - V_E - V_{RL} \\
= -\frac{1}{L} \left[ V_R - V_C + V_{b3} + V_{RL} \right]
\]

ABIDE

V_R = R_i_L

= R_i_L

V_C = k_v \frac{V_e}{s-4}

= k_v \frac{V_e}{s-4} - N \frac{s-3}{s-2}

= -N k_v \frac{1}{s-3} \frac{s-1}{V_1}

= -N \frac{k_v}{V_1} (V_{in} - V_m)

= -N \frac{k_v}{V_1} (V_{in} - V_m)
\[ V_{RL} = R_L i_t \]
\[ = R_L i_L \]

**Back to** \[ \frac{di_L}{dt} \]

\[ \frac{di_L}{dt} = -\frac{1}{L} \left[ R i_L + \frac{N k v}{r} (V_{IN} - V_m) + V_B + R_L i_L \right] \]

\[ = -\left( \frac{R + R_L}{L} \right) i_L + \frac{N k v}{L r} V_m - \frac{N k v}{L r} V_{IN} - \frac{1}{L} V_B \]

**So,**

\[ A_{31} = \frac{N k v}{L r} \]
\[ A_{32} = 0 \]

\[ A_{33} = -\left( \frac{R + R_L}{L} \right) \]

\[ B_{31} = -\frac{N k v}{L r} \]
\[ B_{32} = 0 \]

\[ B_{33} = -\frac{1}{L} \]

**STATE EQUATIONS COMPLETE, MOVE ON TO OUTPUT EQUATIONS**

\[ Y = \begin{bmatrix} V_m & V_{KER} & i_{RL} & s & S_{MG} & \xi \end{bmatrix} \]
ALGEBRA (CONT'D)

\[ V_m = V_m \quad \checkmark \]
\[ V_{K_{eq}} = V_{in} - V_m \quad \checkmark \]
\[ i_{RL} = i_L \quad \checkmark \]
\[ L_{L_{mg}} = \frac{L}{2} \rightarrow -N R_3 \]
\[ = -N \frac{L}{2} \rightarrow \frac{1}{2} V_i \]
\[ = -N \frac{L}{2} \rightarrow \frac{1}{T} V_i \]
\[ = -\frac{N}{T} \frac{V}{V_i} \rightarrow V_{in} - V_m \]
\[ = -\frac{N}{T} \left( V_{in} - V_m \right) \]
\[ = \frac{N}{T} V_m - \frac{N}{T} V_{in} \quad \checkmark \]

\[ X_{K_{eq}} = \frac{1}{F_{K_{eq}}} \quad \checkmark \]

MATRIX FORM

\[
\begin{bmatrix}
V_m \\
V_{K_{eq}} \\
i_{RL} \\
L_{L_{mg}} \\
X_{K_{eq}}
\end{bmatrix} =
\begin{bmatrix}
1 & 0 & 0 \\
-1 & 0 & 0 \\
0 & 0 & 1 \\
\frac{N}{T} & 0 & 0 \\
0 & 1 & 0
\end{bmatrix}
\begin{bmatrix}
V_m \\
F_{K_{eq}} \\
i_L \\
\frac{N}{T} \\
X_{K_{eq}}
\end{bmatrix} +
\begin{bmatrix}
0 \\
0 \\
0 \\
-N \\
0
\end{bmatrix}
\]

\[ y = Cx + Du \]
AUGMENT THE STATE

Instead of $V_{in}$, $\dot{V}_{in}$ both as inputs, use $\dot{V}_{in}$ as only input and let $V_{in}$ be a state variable.

\[
\frac{d}{dt} \begin{bmatrix} x_1 \\ x_2 \\ \vdots \\ V_{in} \end{bmatrix} = \begin{bmatrix} 1 \\ -1 \\ 0 \\ 0 \end{bmatrix} \begin{bmatrix} V_{m} \\ V_{keq} \\ i_{RL} \\ \delta_{swg} \end{bmatrix} + \begin{bmatrix} 0 \\ 1 \\ 0 \\ 0 \end{bmatrix} V_{in}
\]

So, output eqn's become

\[
\begin{bmatrix} V_{m} \\ V_{keq} \\ i_{RL} \\ \delta_{swg} \end{bmatrix} = \begin{bmatrix} 1 & 0 & 0 & 0 \\ -1 & 0 & 0 & 1 \\ 0 & 0 & 1 & 0 \\ \frac{N}{r} & 0 & 0 & -\frac{N}{r} \end{bmatrix} \begin{bmatrix} V_{m} \\ F_{keq} \\ i_{L} \\ V_{in} \end{bmatrix} + \begin{bmatrix} 0 \\ 0 \\ 0 \\ \delta_{swg} \end{bmatrix}
\]

Added $V_{in}$ here to make sure this works.

Onto state eqn's

\[\text{Next page}\]
AUGMENT THE STATE (CONT'D)

WITH THE STATE EQUATIONS, WE JUST NEED TO REORGANIZE

\[
\frac{d}{dt}\begin{bmatrix}
V_{in} \\
F_{ker} \\
i_L \\
V_{in}
\end{bmatrix} = \begin{bmatrix}
A_{11} & A_{12} & A_{13} & A_{14} \\
A_{21} & A_{22} & A_{23} & A_{24} \\
A_{31} & A_{32} & A_{33} & A_{34} \\
A_{41} & A_{42} & A_{43} & A_{44}
\end{bmatrix} \begin{bmatrix}
V_{in} \\
F_{ker} \\
i_L \\
V_{in}
\end{bmatrix} + \begin{bmatrix}
B_{11} & B_{12} \\
B_{21} & B_{22} \\
B_{31} & B_{32} \\
B_{41} & B_{42}
\end{bmatrix} \begin{bmatrix}
\dot{V}_{in} \\
V_{in}
\end{bmatrix}_{2x1} + \begin{bmatrix}
V_{in} \\
F_{ker} \\
i_L \\
V_{in}
\end{bmatrix} \begin{bmatrix}
V_{in} \\
F_{ker} \\
i_L \\
V_{in}
\end{bmatrix}
\]

\[
\frac{d}{dt}\begin{bmatrix}
V_{in}
\end{bmatrix} = \begin{bmatrix}
\dot{V}_{in}
\end{bmatrix}, \quad \text{SO}
\]

\[
A_{41} = A_{42} = A_{43} = A_{44} = B_{42} = 0
\]

\[
A_{11} \rightarrow A_{33} \text{ ARE UNCHANGED}
\]

\[
B_{11}, B_{21}, \text{ AND } B_{31} \text{ BECOME } A_{14}, A_{24}, \text{ AND } A_{34} \text{ RESPECTIVELY (FROM BEFORE)}
\]

AND FINALLY,

\[
\begin{bmatrix}
B_{12} & B_{13} \\
B_{22} & B_{23} \\
B_{32} & B_{33}
\end{bmatrix} \rightarrow \begin{bmatrix}
B_{11} & B_{12} \\
B_{21} & B_{22} \\
P_{31} & B_{32}
\end{bmatrix}
\]
Rotational Generator: Base Excitation Model

The following is a derivation of the model for the kinematics of the Rotational Generator device, as well as some crossover into the electrical domain to determine final voltage output of the generator.

1 Schematic

A simple schematic of the system is shown below in Figure 1. The parameter of interest is the rotational speed of the motor shaft ($\dot{\theta}_s$), and the input to the system is the motion of the housing ($x_{in}$). The motor carriage (displacement represented by $x_m$) moves along the housing by means of a wheel with radius $r_w$, and the net gear ratio from the wheel to the motor shaft is represented by $N$. Other variables used will be introduced as needed.

![Figure 1: Schematic diagram of the rotational generator system.](image-url)
2 Assumptions

1. Wheel rolls without slip along the housing
2. Motion of human upper body is approximately sinusoidal in the vertical direction
3. $f_n \approx 2$Hz (natural frequency for human walking)
4. No backlash in gearing (no lag in response between components)
5. Linear relation between speed and voltage for the motor

3 Analysis

3.1 Shaft Velocity

To begin, we need to determine the angular displacement of the wheel as it relates to the housing and mass displacement. For this we will write an equation for the relative motion of the carriage (oscillating mass) with respective to the housing.

$$x_{m/h} = x_h - x_m \quad (1)$$

In the case that both the carriage and housing displace by the same amount, the wheel will not rotate. When the relative motion is non-zero, the wheel displacement is

$$\theta_w = \frac{x_{m/h}}{r_w}, \quad (2)$$

where $r_w$ is the radius of the wheel. To relate this rotation to the motor shaft, a net gear ratio, $N$ is introduced such that

$$\theta_s = N\theta_w. \quad (3)$$

Combining equations 1, 2, and 3, we get the angular displacement of the shaft to be

$$\theta_s = \frac{N}{r_w}(x_m - x_h) \quad (4)$$

Since we want shaft velocity not displacement, differentiate both sides, resulting in

$$\dot{\theta}_s = \frac{N}{r_w}(\dot{x}_m - \dot{x}_h) \quad (5)$$

We now need a way to model the velocity of both the carriage and housing. For this, methods from Inman’s Engineering Vibration, 4th Edition[1] will be referenced.

3.2 Base Excitation

From Inman, the most basic base excitation system can be represented with the below system.

Letting $x(t)$ be the carriage displacement, $x_m$, and $y(t)$ be the housing displacement, $x_h$, we first introduce equations for the displacement of each body. The housing is modeled as moving with magnitude $Y$ and frequency $\omega_b$, such that

$$x_h = Y \sin(\omega_b t). \quad (6)$$
From 2.68 in Inman, the displacement of $x_m$ is then

$$x_m = X \cos(\omega_b t - \theta_1 - \theta_2),$$  \hspace{1cm} (7)

where $X$ is the magnitude of displacement for the carriage, and $\theta_1$ and $\theta_2$ are phase shift components defined as:

$$\theta_1 = \tan^{-1}\left(\frac{2\zeta\omega_n\omega_b}{\omega_n^2 - \omega_b^2}\right)$$  \hspace{1cm} (8)

$$\theta_2 = \tan^{-1}\left(\frac{\omega_n}{2\zeta\omega_b}\right)$$  \hspace{1cm} (9)

with damping ratio $\zeta$ and natural frequency $\omega_n$. Again, needing expressions for velocity, we differentiate to obtain the following equations:

$$\dot{x}_h = Y\omega_b \sin(\omega_b t).$$ \hspace{1cm} (10)

$$\dot{x}_m = X\omega_b \cos(\omega_b t - \theta_1 - \theta_2),$$ \hspace{1cm} (11)

Substituting 10 and 11 into 5, we now have the following equation:

$$\dot{\theta}_s = \frac{N}{r_w} [X\omega_b \cos(\omega_b t - \theta_1 - \theta_2) - Y\omega_b \sin(\omega_b t)]$$  \hspace{1cm} (12)

In order to relate displacement magnitudes between the base (housing) and mass (carriage), the term displacement transmissibility can be introduced. Displacement transmissibility represents how much motion is transmitted, and is defined by equation 2.71 in Inman as

$$\frac{X}{Y} = (DT) = \left[\frac{1 + (2\zeta r)^2}{(1 - r^2)^2 + (2\zeta r)^2}\right]^{1/2}$$  \hspace{1cm} (13)

where $r$ is the frequency ratio, $\omega_b/\omega_n$. Thus, resonance is achieved when $r$ is unity. With this definition, we can now factor out a $Y\omega_b$ from both terms inside the brackets, and recognize this leaves $X\omega_b/Y\omega_b$, or $(DT)$ from 13 in front of the cosine term, resulting in the following simplified equation:

$$\dot{\theta}_s = \frac{N}{r_w} (Y\omega_b) [(DT) \cos(\omega_b t - \theta_1 - \theta_2) - \sin(\omega_b t)]$$ \hspace{1cm} (14)
3.3 Incorporating Accelerometer Data

Finally, we need to deal with the $(Y \omega_b)$ term. To do so, we can go back to the equation for housing velocity (10), and differentiate again to get acceleration.

\[ \ddot{x}_h = Y \omega_b^2 \sin(\omega_b t). \]  

(15)

We can then relate the housing velocity amplitude to the input acceleration magnitude and frequency as follows:

\[ Y \omega_b = \frac{Y \omega_b^2}{\omega_b} = \frac{A_{\text{accel}}}{\omega_b} \]  

(16)

where $A_{\text{accel}}$ is the magnitude of the housing acceleration. To estimate values of $A_{\text{accel}}$ and $\omega_b$, data can be collected from an accelerometer. A Fast-Fourier Transform can be applied to the recorded signal to find the base excitation frequency, and the amplitude can be estimated from plotting the data after application of a low-pass filter.

The final equation for shaft speed as a function of values we can either measure for estimation, or perform analysis to estimate is the following:

\[ \dot{\theta}_s = \frac{N}{r_w \omega_b} \left[ (DT) \cos(\omega_b t - \theta_1 - \theta_2) - \sin(\omega_b t) \right] \]  

(17)

Of course, as with any complex electromechanical system, there are many assumptions needed to simplify the problem, and even determining a value such as $\zeta$ for determination of the displacement transmissibility is quite challenging. But, looking at ranges of where we could potentially operate in terms of controllable parameters, the model will hopefully be of use in predicting expected shaft speeds, and hence predicted voltage output from a motor run as a generator.

3.4 Voltage Output

Moving beyond just looking at shaft speeds, we can also think about estimating the voltage a certain system configuration will produce. First, we should consider that the voltage we want from this signal is the root-mean square (rms for short) voltage. This can be found by calculating the rms of a signal produced by Equation 3.4. From there, the rms voltage can be calculated using the following equation:

\[ V_{\text{rms}} = \frac{N_{\text{rms}}}{K_v} \]  

(18)

where $N_{\text{rms}}$ is the root mean square shaft speed (in rpm) and $K_v$ is the motor speed constant (in rpm/V). However, this assumes perfect efficiency and does not account for rectification or voltage regulation effects. Defining the efficiency of the motor and regulator as $K_{\text{eff}}$ and $K_{\text{reg}}$ respectively, as well as a total drop across the diode bridge used for rectification ($V_{\text{rect}}$), the final voltage supplied for charging is

\[ V_{\text{out}} = K_{\text{reg}}(K_{\text{eff}}V_{\text{rms}} - V_{\text{rect}}) \]  

(19)

Using this model and MATLAB code, we can attempt to estimate what gear ratio will be needed at our operating conditions to achieve the desired output voltage. It can also later be used in comparison with the physical system by setting motor speed and determining the voltage output.
4 References

Appendix K: Base Excitation Model Results

Author: Ryan McLaughlin
Date Created: 01/23/22
Last Modified: 02/22/22

Description:

This script has been developed to analyze the kinematics of the proposed design for the Rotational Generator. Methods used for analysis are based on ME 212/326 (Dynamics) methods, as well as being pulled from a base excitation model introduced in ME 318 (Mechanical Vibrations). The goal is to see what kind of shaft speeds we can expect for a given wheel radius, gear ratio, etc. in order to properly select a motor.

1 - Setup Code

```matlab
clear;clc;
set(groot,'defaultTextInterpreter','latex') % set interpreter for all plot text to latex
set(groot,'defaultAxesFontSize',12);
set(groot,'defaultAxesTickLabelInterpreter','latex');
set(groot,'defaultLegendInterpreter','latex');
set(groot,'defaultFigurePosition',[0 0 96*6.5 96*4]); % set default figure size
set(groot,'defaultAxesBox','on')
```

2 - Define System Parameters

2.1 - Mechanical Components

This section will define parameters we can change in our design: gear ratio and wheel radius.

N_0 = 1.5; % [- ] gear ratio, values over 1 equating to an increase in shaft speed
r_w_0 = .0198; % [ m ] wheel radius, how translational energy is converted to rotational

2.2 - Base Excitation Model Parameters

I've used the displacement transmissibility ratio to define the relation between the base motion (our housing) and the oscillating mass (where the motor lives). A visual representation will be used in this section to clearly depict what's going on.

```matlab
syms r zeta
```

Equation 2.71 in Inman, 4th edition (Engineering Vibrations)

\[
DT = \left( \frac{4r^2 \zeta^2 + 1}{4r^2 \zeta^2 + (r^2 - 1)^2} \right)^{0.5}
\]
Here, I'm plotting the figure shown in Inman (Figure 2.14) of DT vs r as a check of what's going on.

```matlab
zeta_vals = [0.05,0.1,.25,.5,.7];
fig1 = figure();
set(gcf,'Position',[0 0 96*6 96*5])
hold on;
for index = 1:length(zeta_vals)
    DT_eqn_i = subs(DT,zeta,zeta_vals(index));
    fplot(DT_eqn_i,[0,2],'DisplayName',sprintf('$\zeta = %.2f$',zeta_vals(index)));
end
legend('Location','best')
xlabel({'transmissibility ratio, $r$ [ - ]'; 'Figure 1. Displacement transmissibility for various $\zeta$ and r values.'});
ylabel('displacement transmissibility, $\frac{X}{Y}$ [ - ]');
warning('off',warning('query','last').identifier);

Plot the specific point related to our system

```
fprintf('For a damping ratio of %.2f and frequency ratio of %.2f, we can expect a value for DT of %.2f',zeta_0,r_0,DT_0);

For a damping ratio of 0.21 and frequency ratio of 1.03, we can expect a value for DT of 2.48

2.3 - Input Parameters from Accelerometer Data

We need to define an input amplitude and frequency

fprintf('base frequency of %.2f Hz',f_b);  % defined earlier

base frequency of 2.07 Hz

A_accel_0 = 5;  % [ m/s^2 ] base acceleration amplitude
syms omega_b A_accel DT t theta_1 theta_2

2.4 - Translational Domain Check

Define the equation for the velocity of the housing

\[
v_h = \left(\frac{A_{\text{accel}}}{\omega_b}\right) \sin(\omega_b t)\]

\[
A_{\text{accel}} \sin(\omega_b t) \quad \omega_b
\]

v_h_sys = subs(v_h,[A_accel,omega_b],[A_accel_0,w_b]);
For the mass/carriage

\[
v_m = \frac{(A_{\text{accel}}/\omega_b)\times(\Delta T)\times\cos(\omega_b t - \theta_1 - \theta_2)}{\omega_b}
\]

\[
A_{\text{accel}} \Delta T \cos(\theta_1 + \theta_2 - \omega_b t)
\]

\[
\text{th}_1 = \arctan\left(\frac{2zeta_0 \times w_n \times w_b}{w_n^2 - w_b^2}\right) \quad \text{[rad]}
\]

\[
\text{th}_2 = \arctan\left(\frac{w_n}{2zeta_0 \times w_b}\right) \quad \text{[rad]}
\]

\[
\text{fprintf('phase shift components of }%.3f\text{ and }%.3f\text{ rad',th_1,th_2)};
\]

phase shift components of -1.408 and 1.161 rad

\[
v_m_{\text{sys}} = \text{subs}(v_m,A_{\text{accel}},\omega_b,\Delta T,\theta_1,\theta_2,A_{\text{accel}}_0,w_b,\Delta T_0,\text{th}_1,\text{th}_2);
\]

% equation specific to our system

Plot the input and output, still in the translational domain

\[
\text{fig2 = figure(); hold on; tspan = [0,2]; % yline(0,'b-'); fplot(v_h_sys,tspan,'k-','DisplayName','Housing'); fplot(v_m_sys,tspan,'k--','DisplayName','Mass'); fplot((v_m_sys-v_h_sys),tspan,'r-','DisplayName','Relative') legend('Location','best') xlabel({'time, $t$ [s]'; 'Figure 2. Translational domain check.'}); ylabel('velocity, $v$ [m/s]');}
\]

![Figure 2. Translational domain check.](image)
3 - Shaft Speed

Finally, define the main equation of motion for the shaft speed

\[
\omega_s = \frac{(N/r_w)(v_m - v_h)}{\omega_b r_w}
\]

\[
\omega_s = \text{simplify}(\omega_s, 2)
\]

\[
\omega_s_{\text{sys}} = \text{subs}(N/r_w(v_m_{\text{sys}} - v_h_{\text{sys}}), [N, r_w], [N_0, r_w_0]);
\]

\[
\omega_{\text{cutoff}} = 500; \quad \% \text{rpm} \quad \text{speed at which we can actually operate}
\]

\[
\text{fig3 = figure();}
\]

\[
\text{fplot(omega_s_{\text{sys}}*30/pi,tspan,'k-');}
\]

\[
\text{ylabel(' shaft speed, } \dot{\theta}_s \text{ rpm');}
\]

Find the maximum speed

\[
\text{w_matrix = double(subs(omega_s_{\text{sys}}, t,[0:.01:1]))*30/pi;}
\]

\[
\text{w_max = max(w_matrix)}
\]

\[
w_max = 803.1629
\]

Find the root mean square (rms) speed

\[
\text{w_rms = rms(w_matrix);}\]

\[
\text{fprintf('Max shaft speed is %.1f rpm, rms speed is %.1f rpm.', w_max, w_rms);}\]

Max shaft speed is 803.2 rpm, rms speed is 567.4 rpm.

\[
\text{axis([0 tspan(2) -w_max*1.1 w_max*1.1]);}
\]

\[
\text{xlabel(' time, } t \text{ s'); ' '};\text{'Figure 3. Shaft speed as a function of time.'});\]
4 - Voltage Output

So, the final question is what kind of voltage will this get us?

\[ K_v = 62; \quad \% \text{ [ rpm/V ] } \quad \text{speed constant of motor} \]

Now, the rms voltage is just the rms speed divided by the speed constant

\[ V_{\text{rms}} = \frac{w_{\text{rms}}}{K_v}; \quad \% \text{ [ V ]} \]

\textit{fprintf}('Estimated rms motor voltage output is %.2f V',V_{\text{rms}});

Estimated rms motor voltage output is 9.15 V

Losses of course will be incurred along the way, so we will need a knockdown factor. Additionally, there is loss in the rectification circuit, so we need to account for this as well

\[ K_{\text{eff}} = 74; \quad \% \text{ percent of estimated voltage achieved} \]
\[ K_{\text{reg}} = 83; \quad \% \text{ percent of voltage at output of regulator} \]
\[ V_{\text{rectification}} = 0.4; \quad \% \text{ [ V ]} \quad 2\text{*single schotky diode forward bias voltage} \]

\[ V_{\text{final}} = \left( \frac{K_{\text{reg}}}{100} \right) \times \left( V_{\text{rms}} \times \frac{K_{\text{eff}}}{100} \right) - V_{\text{rectification}}; \]

\textit{fprintf}(['Assuming:
\n- motor and regulator efficiencies of %.0f and %.0f \%
\n- drop of %.1fV across the rectification circuitry,
\n- expected voltage output is %.2fV'],K_{\text{eff}},K_{\text{reg}},V_{\text{rectification}},V_{\text{final}});

Assuming:

- motor and regulator efficiencies of 74 and 83 percent respectively,
- drop of 0.4V across the rectification circuitry,

expected voltage output is 5.29V
Appendix L: Preliminary Motor Testing

Preliminary motor testing was performed for both motors to get a baseline on motor performance as a generator. In each test, we powered a DC motor with a benchtop voltage supply at 2, 3, 4, and 5V. This motor was coupled to the EC 45, and we then measured the phase voltage coming from two adjacent motor leads. Measured values were signal frequency, which could be used to calculate both shaft speed and predicted voltage, and a measured voltage for comparison to the model prediction.

From the signal frequency, we can calculate shaft speed using the following equation,

\[
    n = f \cdot \frac{2}{N} \cdot 60,  \tag{L.1}
\]

where \( n \) is shaft speed in rpm, \( f \) is the signal frequency in Hz, and \( N \) is the number of pole pairs. Furthermore, predicted peak-to-peak voltage can be calculated based off measured speed and the motor speed constant (in rpm per volts), \( K_v \), as the following,

\[
    V_{\text{pred}} = \frac{2}{\sqrt{3}} \frac{n}{K_v},  \tag{L.2}
\]

where the 2 in the numerator is for conversion to a peak-to-peak value, and the factor of \( \sqrt{3} \) is to convert from phase voltage to line voltage (assuming a wye winding configuration).

The first two data sets were measured with the stock motors as provided by Maxon.

<table>
<thead>
<tr>
<th>Input Voltage</th>
<th>Measured Signal Freq.</th>
<th>Calculated Speed</th>
<th>Measured Phase Voltage</th>
<th>Predicted Phase Voltage</th>
<th>Percent Difference in Voltage</th>
</tr>
</thead>
<tbody>
<tr>
<td>( V_{\text{in}} )</td>
<td>( f )</td>
<td>( n )</td>
<td>( V_{\text{meas}} )</td>
<td>( V_{\text{pred}} )</td>
<td>( % )</td>
</tr>
<tr>
<td>[ ±0.01 V ]</td>
<td>[ ±0.1Hz ]</td>
<td>[ rpm ]</td>
<td>[ ±0.1 V ]</td>
<td>[ V ]</td>
<td></td>
</tr>
<tr>
<td>2.00</td>
<td>22.0</td>
<td>330</td>
<td>6.00</td>
<td>6.07</td>
<td>1.1</td>
</tr>
<tr>
<td>3.00</td>
<td>42.6</td>
<td>639</td>
<td>10.70</td>
<td>11.7</td>
<td>9.8</td>
</tr>
<tr>
<td>4.00</td>
<td>60.0</td>
<td>900</td>
<td>15.40</td>
<td>16.5</td>
<td>7.5</td>
</tr>
<tr>
<td>5.00</td>
<td>80.5</td>
<td>1210</td>
<td>20.20</td>
<td>22.2</td>
<td>10.1</td>
</tr>
</tbody>
</table>

As we can see from Table L.1, measured and predicted voltage matched closely (~10% difference or better for all values) with the first of two stock motors. Reasons for any discrepancy at all could come from the relationship between voltage and shaft speed not being linear at all speeds, measurement error in signal frequency, or error in phase voltage measurements. The data of Table X below for the second of two motors provide further evidence of proper motor performance.
Table L.2. Motor B, factory configuration.

<table>
<thead>
<tr>
<th>Input Voltage</th>
<th>Measured Signal Freq.</th>
<th>Calculated Speed</th>
<th>Measured Phase Voltage</th>
<th>Predicted Phase Voltage</th>
<th>Percent Difference in Voltage</th>
</tr>
</thead>
<tbody>
<tr>
<td>$V_{in}$</td>
<td>$f$</td>
<td>$n$</td>
<td>$V_{meas}$</td>
<td>$V_{pred}$</td>
<td></td>
</tr>
<tr>
<td>[ ±0.01 V ]</td>
<td>[ ±0.1Hz ]</td>
<td>[ rpm ]</td>
<td>[ ±0.1 V ]</td>
<td>[ V ]</td>
<td>[ % ]</td>
</tr>
<tr>
<td>2</td>
<td>23.0</td>
<td>345</td>
<td>6.10</td>
<td>6.34</td>
<td>4.0</td>
</tr>
<tr>
<td>3</td>
<td>41.0</td>
<td>615</td>
<td>10.60</td>
<td>11.3</td>
<td>6.7</td>
</tr>
<tr>
<td>4</td>
<td>59.5</td>
<td>893</td>
<td>15.00</td>
<td>16.4</td>
<td>9.4</td>
</tr>
<tr>
<td>5</td>
<td>77.8</td>
<td>1170</td>
<td>19.80</td>
<td>21.5</td>
<td>8.7</td>
</tr>
</tbody>
</table>

With no significant differences in motor performance between the two motors, we arbitrarily chose Motor A as the motor to be modified for use with the verification prototype. Before moving on to final modifications, we first soldered to a single motor lead trace as shown in Figure L.1.

![Figure L.1. Preliminary test modifications to the EC 45 circuit board, with a 16 gauge, copper wire soldered to one motor lead trace.](image)

We then performed the same test as was conducted before modifications, and the relevant data is shown in Table L.2 below.

Table L.3. Motor A after test modifications.

<table>
<thead>
<tr>
<th>Input Voltage</th>
<th>Measured Signal Freq.</th>
<th>Calculated Speed</th>
<th>Measured Phase Voltage</th>
<th>Predicted Phase Voltage</th>
<th>Percent Difference in Voltage</th>
</tr>
</thead>
<tbody>
<tr>
<td>$V_{in}$</td>
<td>$f$</td>
<td>$n$</td>
<td>$V_{meas}$</td>
<td>$V_{pred}$</td>
<td></td>
</tr>
<tr>
<td>[ ±0.01 V ]</td>
<td>[ ±0.1Hz ]</td>
<td>[ rpm ]</td>
<td>[ ±0.1 V ]</td>
<td>[ V ]</td>
<td>[ % ]</td>
</tr>
<tr>
<td>2</td>
<td>26.0</td>
<td>390</td>
<td>6.50</td>
<td>7.17</td>
<td>10</td>
</tr>
<tr>
<td>3</td>
<td>42.0</td>
<td>630</td>
<td>10.70</td>
<td>11.6</td>
<td>8.3</td>
</tr>
<tr>
<td>4</td>
<td>61.5</td>
<td>923</td>
<td>15.40</td>
<td>17.0</td>
<td>10</td>
</tr>
<tr>
<td>5</td>
<td>82.0</td>
<td>1230</td>
<td>20.80</td>
<td>22.6</td>
<td>8.7</td>
</tr>
</tbody>
</table>

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Although comparison between Tables L.1 and L.3 can be made, it is of more utility to look at percent difference with respect to the predicted output. This is because our motor testing apparatus lacked perfect repeatability, and thus shaft speeds varied slightly for the same input voltage to the DC motor. Therefore, looking at the percent difference in voltage, we can see that the average percent difference increased from 7.1% to 9.4%. Although this is not negligible, it is a promising result that provided engineering evidence to back up our decision to modify the board.

And lastly, Table L.4 provides data collected for two phase leads after final modifications were completed. This involved cutting the board, drilling holes for the wires, sanding the board, and soldering to the exposed traces. For full details regarding motor modifications, see Appendix M.

**Table L.4.** Motor A after final modifications.

<table>
<thead>
<tr>
<th>Input Voltage $V_{in}$ [±0.01 V]</th>
<th>Measured Signal Freq. $f$ [±0.1Hz]</th>
<th>Calculated Speed $n$ [rpm]</th>
<th>Measured Phase Voltage $V_{meas}$ [±0.1 V]</th>
<th>Predicted Phase Voltage $V_{pred}$ [V]</th>
<th>Percent Difference in Voltage [%]</th>
</tr>
</thead>
<tbody>
<tr>
<td>2</td>
<td>20.3</td>
<td>305</td>
<td>5.30</td>
<td>5.60</td>
<td>5.6</td>
</tr>
<tr>
<td>3</td>
<td>38.5</td>
<td>578</td>
<td>9.60</td>
<td>10.6</td>
<td>11</td>
</tr>
<tr>
<td>4</td>
<td>57.3</td>
<td>860</td>
<td>14.40</td>
<td>15.8</td>
<td>9.7</td>
</tr>
<tr>
<td>5</td>
<td>76.2</td>
<td>1140</td>
<td>19.20</td>
<td>21.0</td>
<td>9.2</td>
</tr>
</tbody>
</table>

Again, modifications proved in a small sample size to have limited effects on motor performance (8.8% average percent difference). Moving forward, Motor A will be used for any full system testing, while Motor B will allow for modular testing of the isolated electrical subsystem. This modularity will be paramount to performing as much testing as possible in the coming months.
Appendix M: Motor Modifications Procedure

As mentioned in Section 5.2.3, due to long lead times on a more desirable motor configuration (referred to as V2 by Maxon), we decided to modify the V1 configuration instead. With that being said, for any further development work on this project, a V2 motor could be purchased, thus avoiding the need for modifications in the first place. The below procedure was therefore designed specifically for minimization of risk in performing a one-off modification with little prior history documented online to build on.

For procedural steps followed see Procedure I and II respectively, and for final results of Procedure I see Section 5.2.3. Results of Procedure II will be presented later on once that operation is carried out.

**Procedure I - Wire Configuration Changes**

1. Cut the circuit board to an approximate outline using a band saw. Ensure a proper grip on the board can be maintained throughout the cutting process.
2. Drill a hole through each trace that will get a new wire using a #53 drill bit.
3. Sand the edges of the board that were cut in Step 2 using successively finer grit sandpaper, starting at 600 and ending at 1000 until the board has proper clearance within the skeleton.
4. Next, remove the conformal coating protecting the traces using 600 grit sandpaper. Be sure not to sand more than needed to expose the traces.
5. Wipe the exposed traces and surrounding board areas with isopropyl alcohol to clean the surface.
6. String the casing off of the end of one piece of 16 gauge wire, leaving approximately ¼” of exposed wire.
7. Feed the wire through one of the holes drilled in Step 2.
8. Tin both the wire and trace to be connected. This helps to prep the surface further for the joining process.
9. Using pliers, clamp the wire to the exposed trace. Ensure pressure is maintained during the soldering process.
10. Using a hot, blunted solder iron tip, apply pressure on the wire against the tinned the trace on the board. Allow the solder joint to flow out. When visually confirm that the joint has flowed out, remove heat.
11. Perform Steps 7-10 for the remaining two wires.
12. When finished, clean the solder joints with isopropyl alcohol.

**Procedure II - Shaft Length Reduction**

1. Using soft jaws, place the outrunner of the motor in a lathe chuck.
2. Restrain the stator of the motor to prevent it from spinning. Ensure wiring is routed away from rotating components – namely the chuck – to prevent catching.
3. Face 0.2 inches of material off the shaft and add a new chamfer.
### Appendix N: Manufacturing Plan - Overview

<table>
<thead>
<tr>
<th>Subsystem</th>
<th>Assembly PN</th>
<th>Component</th>
<th>Process</th>
<th>Material</th>
<th>Procurement Status</th>
<th>Equipment and Operations</th>
<th>Key Limitations</th>
</tr>
</thead>
<tbody>
<tr>
<td>Housing</td>
<td>HO-BA-01</td>
<td>Base</td>
<td>Built</td>
<td>Aluminum rect. extrusion, 2x4x12 in</td>
<td>Purchased (McMaster)</td>
<td>Cut stock to length on horizontal bandaw, CNC mill (4 ops, no soft jaws)</td>
<td>CNC mill required</td>
</tr>
<tr>
<td></td>
<td>HO-BA-02</td>
<td>Base End Plates</td>
<td>Built</td>
<td>Aluminum rect. extrusion, 2.5x0.5 in</td>
<td>Purchased (McMaster)</td>
<td>Cut stock to length on horizontal bandaw, CNC mill (2 ops, no soft jaws)</td>
<td>CNC mill required</td>
</tr>
<tr>
<td></td>
<td>HO-BA-03</td>
<td>4x10mm Dowel Pin</td>
<td>Purchased</td>
<td>-</td>
<td>Purchased (McMaster)</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td></td>
<td>HO-BA-04</td>
<td>M5x0.8x12 Button Head</td>
<td>Purchased</td>
<td>-</td>
<td>Purchased (McMaster)</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td></td>
<td>HO-BA-05</td>
<td>Spring Stud</td>
<td>Built</td>
<td>M6 threaded rod, stainless steel</td>
<td>Purchased (McMaster)</td>
<td>Cut to rough length. Face to dimension on lathe. Manual mill lateral hole and flats, sand half-round.</td>
<td>Avoid marring threads with clamping surfaces</td>
</tr>
<tr>
<td></td>
<td>HO-BA-06</td>
<td>Front Bumper Stud</td>
<td>Modified</td>
<td>M6 threaded rod, stainless steel</td>
<td>Purchased (McMaster)</td>
<td>Abrasive cutoff to rough length. Face to dimension on lathe.</td>
<td>Avoid marring threads with clamping surfaces</td>
</tr>
<tr>
<td></td>
<td>HO-BA-07</td>
<td>Bumper OD19mm M6</td>
<td>Purchased</td>
<td>-</td>
<td>Purchased (McMaster)</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td></td>
<td>HO-BA-08</td>
<td>Nut M6x1.0</td>
<td>Purchased</td>
<td>-</td>
<td>Purchased (McMaster)</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td></td>
<td>HO-BA-09</td>
<td>Micro-USB Breakout Board</td>
<td>Purchased</td>
<td>-</td>
<td>Purchased (McMaster)</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td></td>
<td>HO-BA-10</td>
<td>M2x0.4x5 Button Head</td>
<td>Purchased</td>
<td>-</td>
<td>Purchased (McMaster)</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td></td>
<td>HO-BA-11</td>
<td>Ring Terminals 14-16ga</td>
<td>Purchased</td>
<td>-</td>
<td>Purchased (McMaster)</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td></td>
<td>HO-BA-12</td>
<td>Spring Insulator</td>
<td>Built</td>
<td>Delrin</td>
<td>Donated</td>
<td>Manual lathe (1 op). Drill and tap for M6.</td>
<td>Note tolerance on OD</td>
</tr>
<tr>
<td></td>
<td>HO-BA-13</td>
<td>Rear Bumper Stud</td>
<td>Modified</td>
<td>M6 threaded rod, stainless steel</td>
<td>Purchased (McMaster)</td>
<td>Cut to length with miter saw, deburr.</td>
<td>Avoid marring threads with clamping surfaces</td>
</tr>
<tr>
<td></td>
<td>HO-TU-01</td>
<td>Main Tube</td>
<td>Modified</td>
<td>Polycarbonate tubing</td>
<td>Purchased (McMaster)</td>
<td>Cut to length with miter saw, deburr.</td>
<td>Cuts should be perpendicular to axis</td>
</tr>
<tr>
<td></td>
<td>HO-TU-02</td>
<td>Tube Clamp</td>
<td>Built</td>
<td>Aluminum rect. extrusion, 2.5x0.5 in</td>
<td>Purchased (McMaster)</td>
<td>Cut stock to length on horizontal bandaw, CNC mill (2 ops, soft jaws for op 2).</td>
<td>Avoid deforming part in op 2 soft jaws</td>
</tr>
<tr>
<td></td>
<td>HO-TU-03</td>
<td>M3x0.5x10 Button Head</td>
<td>Purchased</td>
<td>-</td>
<td>Purchased (McMaster)</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td></td>
<td>HO-SP-01</td>
<td>Extension Spring 0.17 lb/in</td>
<td>Purchased</td>
<td>-</td>
<td>Purchased (McMaster)</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Carriage (Skeleton)</td>
<td>CA-SK-01</td>
<td>Skeleton</td>
<td>Built</td>
<td>Aluminum round, 2.5x12 in</td>
<td>Purchased (McMaster)</td>
<td>Turn blank on lathe. CNC mill (5 axis, two ops with 4 jaw chuck).</td>
<td>Axis of part concentric and co-linear with trunnion to w/in ±.001&quot;</td>
</tr>
<tr>
<td>---------------------</td>
<td>---------</td>
<td>---------</td>
<td>------</td>
<td>--------------------------</td>
<td>----------------------</td>
<td>------------------------------------------------</td>
<td>------------------------------------------------</td>
</tr>
<tr>
<td>CA-SK-02</td>
<td>Bearing Plate, Left</td>
<td>Built</td>
<td>Aluminum rect. extrusion, 2.5x0.5 in</td>
<td>Purchased (McMaster)</td>
<td>Cut stock to length on horizontal bandaw, CNC mill (2 ops, no soft jaws).</td>
<td>Note tolerance on bearing bores</td>
<td></td>
</tr>
<tr>
<td>CA-SK-03</td>
<td>Bearing Plate, Right</td>
<td>Built</td>
<td>Aluminum rect. extrusion, 2.5x0.5 in</td>
<td>Purchased (McMaster)</td>
<td>Cut stock to length on horizontal bandaw, CNC mill (2 ops, no soft jaws).</td>
<td>Note tolerance on bearing bores</td>
<td></td>
</tr>
<tr>
<td>CA-SK-04</td>
<td>2x8mm Dowel Pin</td>
<td>Purchased</td>
<td>-</td>
<td>Purchased (McMaster)</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>CA-SK-05</td>
<td>M3x0.5x10 Button Head</td>
<td>Purchased</td>
<td>-</td>
<td>Purchased (McMaster)</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>CA-SK-06</td>
<td>M2x0.4x5 Button Head</td>
<td>Purchased</td>
<td>-</td>
<td>Purchased (McMaster)</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>CA-SK-07</td>
<td>M3x0.5x6 Button Head</td>
<td>Purchased</td>
<td>-</td>
<td>Purchased (McMaster)</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>CA-SK-08</td>
<td>Bumper Ring</td>
<td>Built</td>
<td>Aluminum rect. extrusion, 2.5x0.5 in</td>
<td>Purchased (McMaster)</td>
<td>Cut stock to length on horizontal bandaw, CNC mill (2 ops, no soft jaws).</td>
<td>Thin, flexible part is difficult to clamp for op 2</td>
<td></td>
</tr>
<tr>
<td>CA-SK-09</td>
<td>Spring Mount Shaft</td>
<td>Built</td>
<td>303 stainless steel round, 3/16 in</td>
<td>Purchased (McMaster)</td>
<td>Two lathe ops and manual mill.</td>
<td>Slip fit into bearing plates</td>
<td></td>
</tr>
<tr>
<td>Carriage (Motor)</td>
<td>CA-MO-01</td>
<td>EC45 Flat 70W w/ Hall</td>
<td>Modified</td>
<td>N/A</td>
<td>Purchased (Maxon)</td>
<td>Bandsaw PCB to rough shape, hand-sand to final profile. Solder 18ga wires to traces. Face 0.2&quot; from shaft on lathe.</td>
<td>Limited by number and cost of motors. Risk involved in successful modification.</td>
</tr>
<tr>
<td>CA-MO-02</td>
<td>M3x0.5x6 Button Head</td>
<td>Purchased</td>
<td>-</td>
<td>Purchased (McMaster)</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Carriage (Guidance)</td>
<td>CA-GD-01</td>
<td>Idler Body</td>
<td>Built</td>
<td>Aluminum round, 1.0 in</td>
<td>Purchased (McMaster)</td>
<td>One CNC lathe operation.</td>
<td>Small nose radius V-style insert required for finishing</td>
</tr>
<tr>
<td>CA-GD-02</td>
<td>Idler O-Ring 5.8/9.6mm</td>
<td>Purchased</td>
<td>-</td>
<td>Purchased (McMaster)</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>CA-GD-03</td>
<td>Bearing .078/.25in, open</td>
<td>Purchased</td>
<td>-</td>
<td>Purchased (McMaster)</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>CA-GD-04</td>
<td>Idler Shaft .078in</td>
<td>Modified</td>
<td>Ground SS rotary shaft, -.0002&quot; +0&quot;</td>
<td>Purchased (McMaster)</td>
<td>Abrasive cutoff to length, deburr</td>
<td>Length not critical</td>
<td></td>
</tr>
<tr>
<td>CA-GD-05</td>
<td>Wave Washer .095/.130in</td>
<td>Purchased</td>
<td>-</td>
<td>Purchased (McMaster)</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>CA-GD-06</td>
<td>.010 Shim, .078/.156in</td>
<td>Purchased</td>
<td>-</td>
<td>Purchased (McMaster)</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Carriage (Transm)</td>
<td>CA-TM-01</td>
<td>Drive Wheel Body</td>
<td>Built</td>
<td>Aluminum round, 1.0 in</td>
<td>Purchased (McMaster)</td>
<td>One CNC lathe operation.</td>
<td>Small nose radius V-style insert required for finishing</td>
</tr>
<tr>
<td>-------------------</td>
<td>----------</td>
<td>------------------</td>
<td>-------</td>
<td>------------------------</td>
<td>---------------------</td>
<td>-------------------------</td>
<td>-------------------------------------------------</td>
</tr>
<tr>
<td>CA-TM-02</td>
<td>Drive O-Ring, 11.8/16.6mm</td>
<td>Purchased</td>
<td>-</td>
<td>Donated</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>CA-TM-03</td>
<td>Bearing .125/.375in, open</td>
<td>Purchased</td>
<td>-</td>
<td>Purchased (McMaster)</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>CA-TM-04</td>
<td>Drive Shaft</td>
<td>Built</td>
<td>303 stainless steel round, 3/16 in</td>
<td>Purchased (McMaster)</td>
<td>Two lathe operations.</td>
<td>Small nose radius tool to minimize internal fillets</td>
<td></td>
</tr>
<tr>
<td>CA-TM-05</td>
<td>Intermediate Shaft</td>
<td>Built</td>
<td>303 stainless steel round, 3/16 in</td>
<td>Purchased (McMaster)</td>
<td>Two lathe operations.</td>
<td>Small nose radius tool to minimize internal fillets</td>
<td></td>
</tr>
<tr>
<td>CA-TM-06</td>
<td>Output Shaft</td>
<td>Built</td>
<td>303 stainless steel round, 3/16 in</td>
<td>Purchased (McMaster)</td>
<td>Two lathe operations.</td>
<td>Small nose radius tool to minimize internal fillets</td>
<td></td>
</tr>
<tr>
<td>CA-TM-07</td>
<td>Bevel Gear (Motor Shaft)</td>
<td>Modified</td>
<td>Molded Nylon</td>
<td>Purchased (McMaster)</td>
<td>Arbor press onto short section of shaft, turn to drawing profile</td>
<td>Manual mill also possible</td>
<td></td>
</tr>
<tr>
<td>CA-TM-08</td>
<td>Bevel Gear (Output Shaft)</td>
<td>Modified</td>
<td>Molded Nylon</td>
<td>Purchased (McMaster)</td>
<td>Arbor press onto short section of shaft, turn to drawing profile</td>
<td>Manual mill also possible</td>
<td></td>
</tr>
<tr>
<td>CA-TM-09</td>
<td>32T Spur Gear</td>
<td>Modified</td>
<td>Molded Nylon</td>
<td>Purchased (McMaster)</td>
<td>Arbor press onto short section of shaft, turn to drawing profile</td>
<td>Manual mill also possible</td>
<td></td>
</tr>
<tr>
<td>CA-TM-10</td>
<td>18T Spur Gear</td>
<td>Modified</td>
<td>Molded Nylon</td>
<td>Purchased (McMaster)</td>
<td>Arbor press onto short section of shaft, turn to drawing profile</td>
<td>Manual mill also possible</td>
<td></td>
</tr>
<tr>
<td>CA-TM-11</td>
<td>.001 Shims .125/.188in</td>
<td>Purchased</td>
<td>-</td>
<td>Purchased (McMaster)</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>CA-TM-12</td>
<td>Drive Shaft Spacer</td>
<td>Built</td>
<td>Aluminum Round</td>
<td>Donated</td>
<td>Manual lathe (1 op).</td>
<td>Note length tolerance</td>
<td></td>
</tr>
<tr>
<td>Circuit Board</td>
<td>Custom PCB</td>
<td>Modified</td>
<td>N/A</td>
<td>Puchase (JLPCB)</td>
<td>Gerber file to be sent out for production. Use hot plate to reflow surface mount, solder thru-hole by hand.</td>
<td>Verify electrical continuity after assembly</td>
<td></td>
</tr>
<tr>
<td>--------------</td>
<td>--------------------------</td>
<td>----------</td>
<td>-------</td>
<td>-----------------</td>
<td>--------------------------------------------------------------------------------------------------</td>
<td>---------------------------------------------</td>
<td></td>
</tr>
<tr>
<td>CA-PB-02</td>
<td>M2x0.4x5 Button Head</td>
<td>Purchased</td>
<td>-</td>
<td>Purchased (McMaster)</td>
<td></td>
<td>-</td>
<td></td>
</tr>
<tr>
<td>CA-PB-03</td>
<td>PCB Spring Stud M6</td>
<td>Purchased</td>
<td>-</td>
<td>Purchased (McMaster)</td>
<td></td>
<td>-</td>
<td></td>
</tr>
<tr>
<td>CA-PB-04</td>
<td>Nut M6x1.0</td>
<td>Purchased</td>
<td>-</td>
<td>Purchased (McMaster)</td>
<td></td>
<td>-</td>
<td></td>
</tr>
<tr>
<td>CA-PB-05</td>
<td>Washer M6x11</td>
<td>Purchased</td>
<td>-</td>
<td>Purchased (McMaster)</td>
<td></td>
<td>-</td>
<td></td>
</tr>
<tr>
<td>CA-PB-06</td>
<td>Assorted Wires</td>
<td>Modified</td>
<td>N/A</td>
<td>Donated</td>
<td>Use as needed</td>
<td>Thin plastic shielding is best</td>
<td></td>
</tr>
<tr>
<td>CA-PB-07</td>
<td>Screw terminals</td>
<td>Purchased</td>
<td>-</td>
<td>Purchased (Digi-Key)</td>
<td></td>
<td>-</td>
<td></td>
</tr>
<tr>
<td>CA-PB-08</td>
<td>Schottky diode</td>
<td>Purchased</td>
<td>-</td>
<td>Purchased (Digi-Key)</td>
<td></td>
<td>-</td>
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Appendix O: Manufacturing Plan - Detailed Instructions and Assembly

Custom Components

Step-by-step instructions for the manufacture of each “built” component listed in our Manufacturing Plan Overview (see Appendix N) are included below. Please refer to Appendix B for detailed drawings of each part.

Base *HO-BA-01*

1) Machine part features on a 3+ axis CNC milling machine in four operations. All operations can be performed with a standard mill vise.

Base End Plates *HO-BA-02*

1) Cut stock to length on a horizontal bandsaw.
2) Machine part features on a 3+ axis CNC milling machine in two operations. Both operations can be performed with a standard mill vise.

Spring Stud *HO-BA-05*

1) Cut M6 threaded rod stock to rough length on an abrasive cutoff or bandsaw.
2) Gently clamp the part in a lathe and clean up one of the rough-cut faces.
3) Clamp the faced part with soft jaws in a mill vise and mill the flats in two operations. Drill the lateral hole during the second operation.
4) Round the end of the part as shown in the part drawing with a belt sander or equivalent.

Spring Insulator *HO-BA-12*

1) Face and turn the part in a manual lathe as indicated by the part drawing. Drill a 5mm hole through the part and tap for the M6 threaded rod.

Tube Clamp *HO-TU-02*

1) Cut stock to length on a horizontal bandsaw.
2) Machine part features on a 3+ axis CNC milling machine in two operations. The second operation will require soft jaws or an equivalent creative setup. Soft jaws are preferred to minimize part deflection.

Skeleton *CA-SK-01*

1) Cut stock to length on a horizontal bandsaw.
2) Turn the final diameter of the skeleton on a lathe, leaving some extra length. Also turn a 1.25-inch diameter step to hold the part during the first mill operation. The finished results of this operation, and the following two mill operations, are shown in Figure 5.2 in the main body of this report.
3) Machine the first 5 axis CNC mill operation. We used a TR160 trunnion on a Haas VF3SS mill, but any equivalent 5 axis setup will suffice. An adapter plate, as shown in Figure O.1,
was machined in two operations so a 4-jaw lathe chuck could be used to hold the part colinear and concentric with the axis of rotation of the trunnion.

4) Flip the part and re-indicate it in the chuck. Indicate the bottom surface of a lateral pocket to zero the B axis, and machine the second operation. An in-process photo of the second mill operation is shown in Figure O.2. Don’t forget to drill and tap the holes for the PCB mounting like we did…

Figure O.1. 4-Jaw chuck adapter plate.

Figure O.2. In-process photo of the second skeleton mill operation.
Bearing Plate, Left *CA-SK-02*

1) Cut stock to length on a horizontal bandsaw.
2) Machine part features on a 3+ axis CNC milling machine in two operations. Both operations can be performed with a standard mill vise.

Bearing Plate, Right *CA-SK-03*

1) This part is a mirror of CA-SK-02, and the machining operations are identical.

Bumper Ring *CA-SK-08*

1) Cut stock to length on a horizontal bandsaw.
2) Machine part features on a 3+ axis CNC milling machine in two operations. Both operations can be performed with a standard mill vise, as shown in Figure O.3.

![Figure O.3. Bumper ring after the first CNC mill operation.](image)

Spring Mount Shaft *CA-SK-09*

1) Turn the round features of this part in two lathe operation as indicated by the part drawing in Appendix B.
2) Drill the lateral hole with a manual mill.

Idler Body *CA-GD-01*

1) These parts could be machined on a manual lathe with a custom-ground tool profile, but we machined them in one CNC lathe operation. The bores were machined with a small boring bar after struggling with oversized reamed holes due to a bent reamer. The completed parts are shown in Figure O.4.
Figure O.4. Machined idler wheels.

Drive Wheel Body CA-TM-01

1) This drive wheel was machined in a similar fashion to the guide wheels with a single CNC lathe operation.

Transmission Shafts CA-TM-04, CA-TM-05, and CA-TM-06

1) Machine the transmission shafts with two lathe operations; note the tolerances for press and slip fits.

Drive Shaft Spacer CA-TM-12

1) Turn the drive shaft spacer in one or two lathe operations. The only critical tolerance is the length, but the .001” shims (CA-TM-11) can be used to remedy a too-short spacer.

Wire Clamp CA-PB-20

1) 3D print from PLA plastic or equivalent.
2) Post machine as needed; it might be best to print the entire height of the part in the profile as seen from above and remove material afterward.
Modified Components

We are modifying 15 components from McMaster-Carr; it is often easier to modify existing geometry than to make a part from scratch. These parts are listed in the Manufacturing Plan Overview of Appendix N, and detailed modification instruction are included below.

Front and Rear Bumper Studs *CA-BA-06, CA-BA-13*

1) Cut the M6 threaded rod (or part to length with a lathe).
2) Face and chamfer both ends of the part on a lathe.

Main Tube *CA-TU-01*

1) Cut to length on a miter saw or equivalent.
2) Deburr

Motor *CA-MO-01*

For a detailed explanation of the motor modification procedure, please refer to Appendix M.

Idler Shaft *CA-GD-04*

1) Cut to length with an abrasive cutoff saw or equivalent.
2) Deburr with belt sander or lathe if you're feeling fancy.

Bevel Gear (Motor Shaft) *CA-TM-07*

1) Enlarge the 1/8” shaft bore to 4mm on a lathe. Concentricity is critical in this operation.

Bevel Gear (Output Shaft) *CA-TM-08*

1) Shorten the flange and add a heavy chamfer to avoid contact with the adjacent outer bearing race.

32T Spur Gear, 18T Spur Gear *CA-TM-09, CA-TM-10*

1) Temporarily press the gears on to a short section of 1/8” shaft and for convenient lathe work holding.
2) Face the gears to shorten their flanges as indicated by the part drawings in Appendix N.

Custom PCB *CA-PB-01*

1) Apply the supplied stencil over the PCB.
2) Place solder paste on the stencil. Using a flat scraper, distribute the solder paste over the stenciling to apply material to the board. Remove the stencil to reveal apply solder paste locations.
3) With tweezers or a similar tool, carefully locate surface mount components at appropriate locations. Follow the circuit schematic to ensure proper orientation of components.
4) Place the board on the hot plate. Allow the hot plate to reach appropriate temperature for the solder paste mixture (usually on the order of 250°C). Allow the board sufficient time at temperature (about 60 seconds). Visually confirm reflow of components.
5) Remove the PCB from heat and allow to cool to a manageable temperature.
6) Locate through hole components on the board.
7) Using a soldering iron, apply solder joints between the leads of the through hole components and the contact pad of the PCB. Allow to cool. Trim excessive lead material.
8) Inspect the board for complete, wetted solder joints. Rework as necessary using flux as needed.
9) Clean flux residue from the board with isopropyl alcohol and a cotton or foam swab.
Assembly

Each subassembly should be assembled as indicated by the assembly drawings in Appendix B. Critical assembly steps are included in this section.

Housing Assembly

1) Press four dowel pins into the undersize 4mm holes in the base (HO-BA-01A) as shown in Figure O.5.

![Figure O.5. 4mm locating pins pressed into housing base.](image)

2) Press the spring insulators in the base end plates with an arbor press as shown in Figure O.6.

![Figure O.6. Spring insulator pressed into one of the base end plates.](image)

3) Bolt the housing end plates to the base, thread the spring studs into the insulators, and secure the bumper studs the end plates with two pairs of M6 nuts. Thread the bumpers onto the studs.

4) Place the tube in place on the base and secure it in place with the pair of clamps. Apply manual force to ensure the clamps are seated against the base while tightening the bolts.
Carriage Assembly

1) Assemble the transmission and spring stud between the two bearing plates, as shown in Figure O.7.

![Figure O.7. Transmission pre-assembly.](image)

2) Install the motor into the skeleton. Carefully route the wires and install the three M3 bolts to secure the motor.

3) Apply a dot of red thread-locker to the motor shaft and slip the motor shaft bevel gear (CA-TM-07) on to the shaft.

4) Immediately install the transmission pre-assembly. Slide the motor shaft bevel gear into place such that it mates with the output shaft bevel gear. Let the thread-locker cure in this position. If the motor needs to be removed from the skeleton, gently heat the bevel gear to soften the thread-locker and slip it off the shaft.

5) Assemble the idler wheel sub-assemblies, as shown in Figure O.8.

![Figure O.8. Idler wheel sub-assembly.](image)
First, press the idler shaft into the inner race of the bearing with an arbor press. We made a few small tools on a lathe for this step, as shown in Figure O.9.

![Idler wheel assembly detail.](image)

**Figure O.9.** Idler wheel assembly detail.

Assemble the spring washers and .010” shims onto the idler shafts and slide these assemblies into the five slots in the skeleton.

6) Cut the three motor wires, tin the ends, and install them into the terminal block on the PCB.
7) Install the spring stud to the PCB and bolt the PCB to the housing.

**Final Assembly**

Attach the end of each extension spring into the spring studs on the carriage and slide the assembled carriage into the housing tube. Attach the other ends of each spring stud to the spring studs on the housing.
## TEST PLAN

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<th>Test Description</th>
<th>Measurements</th>
<th>Acceptance Criteria</th>
<th>Required Facilities/Equipment</th>
<th>Parts Needed</th>
<th>Responsibility</th>
<th>TIMING</th>
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Appendix Q: Gantt Chart

F24 - Power Walking

Critical Design & Analysis
- Down-Select to Design Focus

Develop Test Platform Design
- Model System Dynamics
- Design Transduction Mechanism
- Design Housing
- Determine Circuitry Path
- Refine CAD
- Present Interim Design Review (IDR)
- Develop BOM
- Order Motor
- Order Remaining Test Platform Parts

Build Test Platform
- Build Mechanical Subsystem
- Build Electrical Subsystem
- Develop Manufacturing Plan
- Make Engineering Drawings

Critical Design Review for Test Platform
- Write CDR Report
- Make CDR Presentation
- Present Critical Design Review (CDR)
- Submit CDR Report to Sponsor

Manufacturing & Testing
- Finalize Budget & Purchase List
- Submit Purchase Order to Sponsor
- Receive Parts
- Build Verification Prototype
- Develop Test Plan
- Approve Verification Prototype
- Perform Testing
- Approve Design Verification Plan & Re...

Project Finale
- Create Expo Poster
- Present at Project Expo
- Write FDR Report
- Submit Final Design Review (FDR) to ...
KINETIC ENERGY HARVESTING DEVICE FOR LONG DISTANCE THRU-HIKERS

FINAL DESIGN REVIEW

PRESENTED BY

David Hernandez
Jarod Lyles
Ryan McLaughlin
Shaw Hawkeye Hughes

Mechanical Engineering Department
California Polytechnic State University
San Luis Obispo
3 June 2022
Final Design Review

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1 Design Updates

After Critical Design Review, we enacted minor design changes to better suit manufacturability and functionality of our prototype. In this section, we detail such design changes.

1.1 End Caps

Considering the on-trail testing application of our device, we designed and manufactured end caps (shown in Figure 1.1 below) for protection against foreign object debris (FOD).

![Figure 1.1. 3D-Printed end cap.](image)

(a) 3-D printed end cap.  (b) End cap assembled on device.

Additionally, the end caps provide clamping force to the base, preventing disassembly of the close-running fit between the tube and the base profile. This part substitutes for the tube clamps, part number HO-TU-02A, which were intended to be a CNC-machined part.

1.2 Wiring Routing

Originally, it was unclear how we would route the final output signal (positive voltage and ground) from the circuit board onboard the carriage to the Micro-USB port. We proposed two solutions: running two wires out of the tube from the PCB, or using the extension springs as positive and negative leads. Due to the resistive losses and functional risk presented by using springs as conductors, we decided against the latter option. Instead, our final design used silicone-insulated, 22-Gauge stranded copper wire. As shown in Figure 1.2, the wires route along the slot on the bottom of device, between the end plate and the base, and through the tube to the PCB on the carriage assembly.
(a) Underside wire routing.

(b) Wire routing to the carriage.

**Figure 1.2.** DC wire routing from carriage to Micro-USB output.

The black and red DC supply leads of Figure 1.2 connect to the Micro-USB output port on the bottom of the device. The flexibility of the wires eliminated any need for additional wire clips or harnesses. Furthermore, during testing we did not encounter any situations where the wire interfered with intended free oscillation of the system.
2 Manufacturing

For details on part procurement, the majority of CNC manufactured parts, and motor modifications, see Section 5 (Manufacturing Plan) of CDR. This chapter will focus on the remaining CNC parts, manual parts, and printed circuit board (PCB) assembly.

2.1 Procurement

Generous funding – $1,500 from the Baker-Koob Endowment and $280 from the Cal Poly Mechanical Engineering Student Fund Allocation Committee (MESFAC) – provided the means to acquire our materials. The final list of expenses can be found in Appendix A.

2.2 Electrical

As discussed in the Manufacturing Plan of CDR Appendices N and O, we assembled our circuit board with a combination of reflow and soldering. First, we used a stainless-steel PCB stencil purchased from OSH Stencils to add solder paste for all the surface mount components. As shown in Figure 2.1, the stencil matches the pads on the board, allowing for rapid application of paste.

Figure 2.1. PCB stencil from Osh Stencils overlaid on top of an unassembled board.

Solder paste was applied using a syringe, and scraped across the stencil to ensure even coverage on all pads. Next, all surface mount components were carefully placed on the board using tweezers. Finally, the board was placed on a hot plate, and the solder was given time to heat up. When the solder paste started to “flow out”, its appearance changed from a dull grey to a shiny silver color. At this point, the board was carefully removed from the hot plate, and allowed to cool.

After performing reflow, through-hole components were manually soldered to the board. This included the screw terminals, DPDT switch, and electrolytic capacitor. Two boards were assembled using this process: one for electrical subsystem testing, and another for the full system
assembly. A final side by side comparison of the board with (right) and without (left) components mounted is shown below in Figure 2.2.

![Figure 2.2. Printed circuit board as ordered (left) and with all components mounted (right).](image)

2.3 Mechanical
The mechanical subsystem consisted of many intricate components that required precision machining techniques.

2.3.1 Manual Parts
Much of our design consisted of manual machined parts. Our BOM and engineering drawings included in Appendices A and B of CDR detail the manufacturing methods chosen for each part. Following these recommendations, the manual parts of our assembly were produced using manual lathes, mills, and cutting machines. Figure 2.3 shows as small subset of the manual parts.

![Figure 2.3. Manually manufactured components.](image)

Figure 2.3(a) depicts the spring mount shaft, which was machined using two lathe and two mill operations respectively. The shoulders on the shaft were turned to diameter and faced to length. The two flats were machined on the manual mill, followed by drilling the spring mount hole with a drill press.
Figure 2.3(b) shows one of three spring studs. First, M6 threaded rod was cut to size. Using a custom fixture block (for thread preservation), we then milled to final length, machined the flats, and drilled the through hole. The round profile of the flat was ground by hand on a bench grinder.

The two spring insulators of Figure 2.3(c) were machined on the lathe in two operations. The through hole was drilled and tapped for M6 thread.

### 2.3.2 Critical Modified Parts

Because we wanted a compact transmission design, the nylon spur gears and steel bevel gears purchased from McMaster-Carr needed size reduction in the width dimension. Thus, we modified the shoulder of each gear (see Figure 2.4 below). To reduce the shoulders, gears were mounted on a scored shaft that was secured on the lathe with a collet block and four-jaw chuck, and turned down to specification. For some of the gears, the holes were bored out to accommodate shaft sizes.

![As-purchased 32 tooth nylon gear.](image)

![Modified gear with reduced shoulder.](image)

**Figure 2.4.** Example of a modified gear.

In addition to cutting the circuit board of the motor (see Section 5.2.3 of CDR), we needed to reduce the shaft length to accommodate the rest of the drive train. The motor in its final modified state with the accompanying pressed bevel gear is shown below in Figure 2.5.

![Modified motor shaft.](image)

**Figure 2.5.** Modified motor shaft.
For this modification, the bulk of material was removed using a Dremel with a cut off wheel. To get to a final length and add a chamfer, the shaft was lapped\textsuperscript{1} by hand using a flat aluminum plate and 800-grit sandpaper.

2.3.3 CNC Machined Parts
In addition to an assortment of manually machined parts, we utilized Haas CNC mills and lathes located in the Cal Poly Mechanical Engineering machine shops to manufacture 14 different parts. For details regarding our most complex CNC part, the skeleton, see Section 5.2.1 of CDR. Following completion of the skeleton, other parts such as the base, end plates, drivetrain shafts, bearing plates, bumper ring, idler bodies, and drive wheel bodies were machined. MasterCAM software was utilized to generate the G-code for running parts on Mustang 60’s Haas MiniMill, TL1, and VF3. Figure 2.6 depicts in-process manufacturing of parts.

\begin{figure}[h]
\centering
\includegraphics[width=\textwidth]{Figure2.6}
\caption{In-process CNC machining images.}
\end{figure}

\textsuperscript{1} Lapping is a machining process in which two surfaces are rubbed together with an abrasive between them, by hand movement or using a machine.
Special thanks to mechanical engineering student Walter Minehart for his support on the CNC mills and lathes. These machines were critical manufacturing technology for our project considering the intricacies and tight tolerances of our parts.

2.4 Assembly

Final assembly consisted of multiple, critical subassemblies. The steps of assembly are outlined in the following sections.

2.4.1 Housing Assembly

The housing assembly started with the CNC-machined base of Figure 2.7.

![Figure 2.7. Base.](image)

Next, spring studs and bumper studs were mounted to the end plates as shown in Figure 2.8. The other end plate was assembled in a similar fashion.

![Figure 2.8. End plate assembly with spring studs and bumper studs.](image)

The end plates were subsequently bolted to the base, as depicted in Figure 2.9 (see next section).
2.4.2 Wiring Assembly

Two leads – ground and 5V high – were soldered to the contacts of the output Micro-USB breakout board, which was then bolted to the underside of the base (see Figure 2.9).

![Figure 2.9. Micro-USB breakout board installed on the underside of the base.](image)

Wiring was routed along the base’s channels to the PCB-side of the housing assembly as shown in Figure 1.2. Extra length on both wires (see Figure 2.10 below) allowed the wiring to be cut to appropriate size.

![Figure 2.10. Wire routing.](image)

2.4.3 PCB

The PCB was installed with a spring stud and accompanying spring as shown in Figure 2.11.

![Figure 2.11. End plate assembly with spring studs and bumper studs.](image)
2.4.4 Idler Wheels

The idler bearing was first pressed into the idler wheel body. An O-ring was stretched by hand to encompass the grooved idler wheel seat. The idler wheel body, with bearing and O-ring, slid onto the idler shaft with a spring washer and flat washer on each side for bearing preload. Figure 2.12 depicts the idler wheel assembly. This was repeated for all five idler wheels.

![Idler wheel assembly](image)

**Figure 2.12.** Idler wheel assembly.

2.4.5 Gear Train

The drive wheel was pressed onto the drive wheel shaft, and the nylon gear was pressed onto the opposite, scored side. Additionally, the drive wheel spacer was placed adjacent to the drive gear. Figure 2.13 depicts the drive wheel shaft assembly.

![Drive wheel shaft assembly components](image)

(a) Drive wheel shaft assembly components.

![Drive wheel shaft assembled](image)

(b) Drive wheel shaft assembled.

**Figure 2.13.** Drive wheel shaft assembly.

For the intermediate transmission shafts and the drivetrain shaft, gears were pressed onto the scored section of the shaft. Loctite® super glue compound was used to prevent slippage of the pressed-on nylon gears. Images of both types of shafts are shown in Figure 2.14 below.
Next, bearings were pressed into the bearing plates (Figure 2.15, left), and the geartrain was assembled by meshing the gearing and shafts (right) in location between the bearing plates.

During assembly of the geartrain, we were careful to ensure all shaft components – the gears, the spacer, the drive wheel – were seated properly on respective shoulder locators to maintain even spacing between the bearing plates.
2.4.6 Carriage

First, the transmission locating pins, shown in Figure 2.16 were pressed into the skeleton assembly.

![Transmission Locating Pins](image)

**Figure 2.16.** Transmission locating pins pressed into skeleton.

Next, the PCB-side idler wheels were pressed into their respective slots, as shown in Figure 2.17.

(a) Idler wheel near respective slot.  
(b) Idler wheel installed.

![PCB-side idler wheel](image)

**Figure 2.17.** PCB-side idler wheel installation on skeleton.

The modified motor was then placed in the hollow compartment of the skeleton and bolted to the skeleton as depicted in Figure 2.18, with wires being routed along the wiring slot.
The transmission was located by the locating pins (shown in Figure 2.16), the transmission shaft bevel gear meshed with the motor bevel gear, and the transmission assembly was bolted to the skeleton arms as depicted in Figure 2.19.

The three motor phase leads were attached to the appropriate header screw terminals on the PCB assembly. Additionally, the leads from the DC outputs to the Micro-USB breakout board were wired into the header of the PCB as seen in Figure 2.20. The PCB was bolted on the back of the skeleton with the DC leads routed away from the carriage assembly.
Figure 2.20. PCB installation on carriage.

Figure 2.21 depicts installation of the bumper ring and slip-fit idler wheels on the drivetrain side of the carriage. The spring was also attached to the spring mount shaft (see Figure 2.3(a)).

Figure 2.21. Final carriage assembly.

The carriage assembly was by far the most intricate subassembly of our prototype, and successful integration was an important milestone for the project.

2.4.7 Final Assembly
The carriage assembly was carefully inserted into the tubular housing, keeping orientation to prevent the drive-end idler wheels from falling out. Figure 2.22 depicts alignment of the guidance wheels with the inner diameter of the tube.
After placing the carriage into the guidance tube, the tube was slid under the bumpers of the end plates and fitted into the profile of the base.

With the carriage displaced to one side of its travel envelope, one spring could be clipped to the end plate stud on the respective side. Spring attachment is shown in Figure 2.24. This process was repeated for the other side.
Once both springs were connected and the tube was centered in the base, assembly of the device was complete. Figure 2.25 shows the final, fully assembled prototype.

Tools critical to assembly include a metric Allen key set and a metric wrench set. Overall, assembly is more complicated and time-intensive than was originally expected. Once assembled, the device is ready for use. Please refer to our risk assessment and user manual, Appendices C and D respectively, for instructions on device operation.
3 Design Verification

Once manufacturing of our Verification Prototype was complete, we moved into an evaluation phase. A thorough evaluation of general physical properties (mass, volume, etc.) and device performance (electrical efficiency, power output, etc.) was critical for determining whether our design proved that harnessing kinetic energy from walking is feasible with such a device and/or what changes could be made for future iterations.

3.1 Specifications

As discussed in Section 2.2 (Rescope of Verification Prototype) of CDR, our prototype was not designed to meet all specifications. The specifications shown below were originally generated for a final, marketable device such as a solar charger; however, our prototype was a test platform built to evaluate feasibility. With that being said, Table 3.1 below lists our engineering specifications table, with final results (if completed) for each test added. For the complete Design Verification Plan and Report see Appendix B.

Table 3.1. Engineering specifications table with results included. Grey text rows indicate specifications that were deemed out of scope.

<table>
<thead>
<tr>
<th>Spec.</th>
<th>Parameter Description</th>
<th>Target</th>
<th>Result</th>
<th>Tolerance</th>
<th>Risk*</th>
<th>Compliance †</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Power Output</td>
<td>5W</td>
<td>-</td>
<td>Min.</td>
<td>H</td>
<td>A, T</td>
</tr>
<tr>
<td>2</td>
<td>Mass</td>
<td>250g</td>
<td>1833g</td>
<td>Max.</td>
<td>M</td>
<td>A, I</td>
</tr>
<tr>
<td>3</td>
<td>Manufacturing Cost</td>
<td>$100</td>
<td>$1264</td>
<td>Max.</td>
<td>M</td>
<td>A</td>
</tr>
<tr>
<td>4</td>
<td>Volume</td>
<td>0.5L</td>
<td>1.80L</td>
<td>Max.</td>
<td>M</td>
<td>A, I</td>
</tr>
<tr>
<td>5</td>
<td>Drop Resilience</td>
<td>Ten drops at 2m</td>
<td>-</td>
<td>Min.</td>
<td>M</td>
<td>T</td>
</tr>
<tr>
<td>6</td>
<td>IP Rating</td>
<td>IP54</td>
<td>-</td>
<td>Min.</td>
<td>L</td>
<td>I, T</td>
</tr>
<tr>
<td>7</td>
<td>Usability</td>
<td>Survey</td>
<td>-</td>
<td>Min.</td>
<td>L</td>
<td>I</td>
</tr>
<tr>
<td>8</td>
<td>Thermal Operating Range</td>
<td>-20 to 50 °C</td>
<td>-</td>
<td>Max.</td>
<td>M</td>
<td>A, T</td>
</tr>
</tbody>
</table>

* Risk of meeting specification: (H) High, (M) Medium, (L) Low
† Compliance Methods: (A) Analysis, (I) Inspection, (S) Similar to Existing, (T) Test

As can be seen from Table 3.1, by the standards set through a Quality Function Deployment (QFD), we failed to meet our specifications. However, this does not signify project failure. In terms of volume, we wanted to create an adjustable test platform as opposed to a final design, which led to the addition of a base (increasing the volume from 1.26 to 1.80L). In addition, the base was the most significant mass of the device. And in terms of system cost, buying individual parts as opposed to bulk is optimal for a prototype, but increases per unit cost significantly.
As for power output, due to a number of issues, we were not able to measure power output from our device. The remaining sections are focused on all testing used to identify potential reasons for low power output.

3.2 Testing

In general, our purpose with testing was to evaluate our device from a development standpoint. As a complex electro-mechanical system, we needed to understand not only if the final output was as expected, but also why we ended up with the results we did and how we could potentially improve the device. For complete test procedures, see Appendix E.

3.2.1 Electrical Testing

To begin, we isolated the electrical subsystem and studied its performance. This included the motor/generator and custom PCB. The purpose of electrical testing was to determine how much power was lost across the generator and circuit board. Although simple in theory, accurately measuring these losses proved to be much more challenging than initially perceived.

For this test, the motor test stand discussed in Section 4.3.2 of CDR was used in conjunction with multiple multimeters and an oscilloscope to gather data. Figure 3.1 below shows the motor test stand (left) and general setup for output measurements. Not pictured are the electrical input to the system provided by an HP 6543A DC Power Supply, and the system load, an Anker PowerCore 20,000 mAh power bank.

![Motor test stand and output measurement setup](image)

**Figure 3.1.** Motor test stand and output measurement setup

In both a regulated and an unregulated mode, we recorded four different measurements at six different input voltage levels, increasing by 0.5V each time. As summarized by Table 3.2, these intermediate measurements were used to calculate input mechanical power and output electrical power.
Table 3.2. Summary of inputs and outputs for electrical testing and how they were measured.

<table>
<thead>
<tr>
<th>Variable</th>
<th>Measured Quantity</th>
<th>Calculated Quantity</th>
<th>Measurement Device</th>
</tr>
</thead>
<tbody>
<tr>
<td>$I_{in}$</td>
<td>Input current</td>
<td>Shaft torque</td>
<td>N/A</td>
</tr>
<tr>
<td>$f_{in}$</td>
<td>EC 45 three-phase lead signal frequency</td>
<td>Shaft speed</td>
<td>TDX2022B Oscilloscope</td>
</tr>
<tr>
<td>$V_{out}$</td>
<td>Output voltage</td>
<td>-</td>
<td>FLUKE 177 True RMS</td>
</tr>
<tr>
<td>$I_{out}$</td>
<td>Output current</td>
<td>-</td>
<td>Multimeter</td>
</tr>
</tbody>
</table>

From these four measurements, efficiency was calculated based on the following equation:

$$
\eta = \frac{V_{out}I_{out}}{2I_{in}K_{T,BDC}f_{in}N},
$$

(3.1)

where $N$ is the number of pole pairs for the EC 45 motor and $K_{T,BDC}$ is the torque constant for the brushed DC motor. For the full derivation of equations used, sample calculations, uncertainty analysis, and completed datasheets, see Appendix F.

Before discussing the results of testing, it is important to note that a constant shaft speed profile was used, as opposed to a sinusoidal shaft speed profile (what would be seen during normal operation). Ideally we could have tested both scenarios, but time constraints limited our scope.

Looking at Figure 3.2 below, we first plotted power output as a function of shaft speed for both modes of operation. Red data points indicate those for which output voltage was too great to achieve successful charging.

![Figure 3.2. Power output as a function of shaft speed for both modes of operation.](image)

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First off, we can clearly see that as input voltage was increased, the unregulated power output increased in a mostly linear fashion. However, most power banks are sensitive to input conditions, thus the higher net power could not be utilized. In a regulated mode, power output peaked at 710 mW, and then decreased with increasing speed. This indicates that an optimum operational range exists when the regulator circuitry is involved. Although these results may have been obtainable from analytical modeling, the complexity and coupling of motor speed curves, regulator performance curves, and many other factors made experimental testing considerably more time efficient.

In addition to looking at power output, we plotted efficiency versus shaft speed, again for both modes of operation. Error bars shown in Figure 3.3 are based on the analysis of Appendix F.

![Figure 3.3. Efficiency as a function of shaft speed for both a regulated and an unregulated mode.](image)

As can be seen from Figure 3.3, efficiency peaked then decreased in both modes (although more noticeably in a regulated mode). This point of peak efficiency is most likely due to the circuitry of the regulator, but since we did not include probing pads on the circuit board for the voltage into the regulator, no conclusive evidence can be provided to verify this hypothesis. However, this does further show the need to operate at very specific conditions.

In conclusion, although data taken during electrical testing was limited, there was a lot to be learned. First, this testing illustrated the need for a robust current and voltage monitor setup. This drove the design of our custom DAQ, and taught us about the challenges of measuring small currents without adding significant load to a circuit. Furthermore, we learned that between running a brushless DC motor as a generator and using simplistic electrical designs such as a full-wave bridge rectifier and Buck voltage regulator, electrical losses are quite significant.
3.2.2 Mechanical Testing

Similarly to the electrical subsystem, we wanted to verify the behavior of the mechanical subsystem (gear train, carriage, etc.) before moving into full-system testing. The first test we conducted was checking the allowed spring envelope (limited by a bumper on each end). The carriage was moved manually and put under heavy oscillation to verify that plastic deformation of the springs would not occur. The setup for this test is shown below in Figure 3.4. Although simple in nature, this test did verify that we were not damaging the springs through normal operation.

![Test setup at no displacement.](image1)

![Test setup at maximum displacement.](image2)

**Figure 3.4.** Spring envelope check test apparatus shown (a) at no displacement and (b) at maximum spring displacement.

The next mechanical test we planned to perform was verifying that the drive wheel was not slipping. Although we did not have time to perform thorough testing, we visually inspected the contact patch (see Figure 3.5 below) between the drive wheel and tube wall for drive wheel sizes from .680” to .710” in increments of .005”. From this method, we found .710” to be optimal: it provided the best traction for the drive wheel, while not adding significant damping effects.

![Contact Patch](image3)

**Figure 3.5.** Contact patch between the .710” drive wheel tire and the inner tube wall.
3.2.3 Full-System Power Output

Unfortunately, during preparation for full system testing in a lab setting, we concluded that for conditions similar to what we were planning to test (5cm amplitude and 2Hz frequency oscillation), we would not achieve a measurable amount of power. In lieu of this testing, we performed detailed troubleshooting to identify possible reasons for low output.

The first contributing factor to low power output was gear train configuration. We designed our geartrain for the three possible gear ratios of the drive wheel rotation to the motor shaft rotation: 2:1, 1:1, and 1:2. With the speed reduction ratio at the motor shaft (2:1 configuration), gear teeth from the larger nylon gears interfered directly with the bevel gear on the motor. In the 2:1 orientation, interference from the larger nylon gear and the motor shaft bevel gear was unintended and unforeseen. Despite this unexpected design flaw, our 2:1 gear ratio was unlikely to drive the generator at sufficient speed. Upon testing the 1:2 gear conversion, the system required significantly greater input torque and thus oscillation was heavily damped. Therefore, we resorted to the 1:1 gear configuration (shown in Figure 3.6 below), as it had no interference issues and the least damping.

![Figure 3.6. Geartrain with 1:1 gear ratio configuration. Note the Loctite super glue joints bonding the nylon gears to their respective shafts.](image)

After determining the best possible gear ratio for the as-built configuration, we ran into O-ring failure issues. Opting for simplicity, we chose not to constrain the carriage from rotating about the tube. In general, this design choice was successful, as the carriage did not display significant rotation. However, any rotation that did occur put the fitted O-rings in torsion. Ultimately, as seen in Figure 3.7 below, the tires failed in fatigue from the torsional shear stress. Though tire failure was not a hinderance to demonstrating the proof of concept, maintenance required to fix each failure (device disassembly and reassembly) slowed down testing efforts considerably.
Lastly, we found that the interference fits between the nylon gears and drive train shafts had significant slip, so much so that rotation of the drive wheel was not transmitted to the motor shaft. We originally intended to use an adhesive bond to secure the nylon gears to the shafts, but during manufacturing found success with scoring the shafts and pressing on the nylon gears. The ridges produced by the scoring process provided a sufficient fit to the nylon gearing, but proved to be only a short-term solution, and the issue was eventually resolved with application of Loctite superglue between gear and shaft, as seen in Figure 3.6.

After resolving individual mechanical issues, we performed integrated testing to determine other potential causes for low power output. First, as shown in Figure 3.8, we connected oscilloscope probes to the phase leads of the motor and manually oscillated the system.

As shown in the oscilloscope capture of Figure 3.9, this setup proved that the generator was successfully producing a voltage signal during oscillation. For more detail regarding the mixed AM-FM signal seen below, see section 4.3.2 of CDR.
After validating basic generator functionality, we monitored voltage and current output with the circuit board connected. Figure 3.10 illustrates the connection of the multimeter for current monitoring and to the oscilloscope for voltage signal monitoring with the PCB connected.

With voltage regulation off (left image of Figure 3.11) we witnessed an inconsistent DC voltage signal with an amplitude of approximately 10V and current of 1mA.
Figure 3.11. Voltage signals of output circuitry with (a) voltage regulation off and (b) voltage regulation on during a period of manual input oscillatory motion.

With voltage regulation on (right), we observed a stable DC voltage signal on the order of 5.2V with a relatively steady current of 0.7mA. Although it is interesting to note the drop in voltage and current with regulation involved, data from these trials cannot be used to extrapolate power data, since they are not time-dependent, one-to-one measurements of current and voltage.

To supplement the basic lab testing described above, we assembled and programmed a data acquisition system (DAQ) for real-time current and voltage measurement. The system consisted of an ESP32 breakout board with a Texas Instruments INA219 current monitor board and voltage monitor board. Measurements from the DAQ were written to a text file on a Micro-SD card. We intended to connect our DAQ to our device and monitor power output during critical operational tests. Figure 3.12 depicts the assembly of our DAQ in its housing minus its lid.

Figure 3.12. Power Walking DAQ.
Unfortunately, after significant preliminary testing of the DAQ, we found the measurement of power to be inaccurate and unreliable. The current monitor provided stable data that agreed with ammeter readings, but the DAQ often recorded random current spike events that were not validated by more reliable means of measurement. Additionally, due to the ESP32 microcontroller lacking a voltage reference pin, our measurements of voltage using the 12-bit analog-to-digital converter (ADC) were with reference to the internal voltage of the ESP32 (a value that fluctuated depending on the power draw of the board and connected peripherals), and thus voltage measurements from the DAQ did not agree with an oscilloscope. However, using a microcontroller with a configurable voltage reference pin would easily remedy this problem.

In addition to the custom DAQ, we designed a backpack testing rig (see Figure 3.13 below) for potential on-trail testing.

![Figure 3.13. Backpack testing rig complete with a GoPro for video analysis, the custom DAQ, the verification prototype, an nPower PEG, and a power bank.](image)

The backpacking testing rig used an external backpacking frame with a sheet metal plate to mount our device along with a few other items to a backpack. Although this would not perfectly match the expected operating conditions (in which the device would be placed freely into a backpack), it would have allowed us to capture video footage, as well as visually examine the behavior of the prototype while walking. Furthermore, it gave us a platform to mount the DAQ and a competitive product from research, the nPower PEG. Unfortunately, like the DAQ, this hardware was not used in meaningful effect. In future iterations of the project, such equipment would be an invaluable resource for capturing data reflective of on-trail hiking conditions.
4 Discussion and Recommendations

After reflecting upon the research, design, and implementation of a prototype, we have summarized our thoughts regarding improvement, iteration, and application of our design and similar mechanical systems.

4.1 Learnings

During manufacturing and testing of our prototype, we found that the system produced minute power output, orders of magnitude lower than the 5 watt design specification baselined from a solar charger. As previously mentioned, the difficulty of measuring power output made us uncomfortable to promote a specific number for power generation. There is a glaring question to be asked: why is our power output so minimal? We theorize the source of underwhelming performance results from the lack of a coherent system-level analysis that considers all losses and inefficiencies driving our design development.

To analyze our concept in design development, we pursued a systems dynamics model, which allowed us to construct a state space model of the system that could be simulated in MATLAB. This system dynamics approach is detailed in our CDR report. Though this model provided a foundation for quantitative analysis of the multi-domain system, we lacked numerical data to appropriately characterize and analyze the system. As such, we could not extrapolate from this analysis a grander system performance – namely operating natural frequency and equivalent damping ratio. Therefore, we decided to take an alternative approach: optimize each subsystem to our best ability, assemble the system, and test performance.

Within our knowledge, time constraints, and available resources, we did our best to optimize all subsystems in an implementable and practical form. Isolated tests of the electrical domain, electromechanical domain, and mechanical domain (respectively, the rectification circuitry, the generator, and the oscillatory carriage/geartrain) showed proficient subsystem design. However, testing of the final assembly demonstrated a lack of practical understanding in subsystem interdependency.

Alternatively to our methods, a process of design-of-experiment tactics and model refinement for both the transduction mechanisms and energy storage elements/dissipators might lead to more effective prediction of inefficiencies and losses in the dynamics, converging on a refined design. We suggest pursuit of a less-refined, experimental test platform that allows for greater data collection and strategies for characterization of the system dynamics.

4.2 Design Changes

After performing troubleshoot testing, we arrived at reasons for unexpected performance of our device and recommendations for improvement. The following is a list of these potential reasons:
1. **Gearing:** Although flexibility was the goal with gear configuration, we hoped to have a two-times speed increase from input to output within the geartrain. However, it quickly became apparent that the torque needed to drive the generator in this configuration was too great. Therefore, our final testing configuration was 1:1, thus leading to lower motor speeds. Additionally, interfacing of gearing to the shafts of the drivetrain is an area to investigate further. It was difficult to monitor for slippage of the interference fit between the gears and the shafts.

2. **Electrical Dynamics:** Although we had initially considered the resistance, capacitance, and inductance that would be introduced to the system by both the motor and the circuit board, our team did not quite understand the magnitude of these effects. For example, the resistance of the motor and/or circuit board act like mechanical friction, the capacitors used to smooth the output signal act as additional equivalent inertia, and the inductor that was part of the regulator circuit acts like a torsional spring. Thus, the natural frequency and damping of the system were significantly different than what was initially expected.

3. **Tire Lifespan:** Although the mechanical subsystem was manufactured to a high standard of execution, there were still some glaring issues once we reached troubleshooting and initial testing. The first issue we noticed was failure from the O-ring tires. Not surprisingly in hindsight, O-rings are designed for pressure loads (normal stress mainly) as opposed to the torsional (shear stress) loads being applied through rotation. Not only that, but without any constraint on the rotation of the carriage about the housing tube, general deformation of the tires occurred as the wheels slid in the direction transverse to the desired direction of rotation. As such, these wheels needed to be replaced quite often, slowing down general testing progress.

4. **Motor:** From a system-level design perspective, there a few items that could improve the implementation of the motor. For one, the large diameter of the motor – 45mm – does not readily accommodate a slimmer, tubular design. A motor of reduced cross-section might provide a basis to design smaller, lighter, and slimmer components. Despite the form factor, our motor was about the best we could find for our application in terms of a maximized back-EMF constant (and subsequently minimized speed constant). However, further exploration could be pursued in generator selection, especially optimization of a motor’s torque-speed relationship for the frequency of oscillation and input force. This would require advanced testing, system dynamics analysis, and iteration. Ultimately, optimization of the generator’s average operating point for lowest input torque requirement, highest rotational speed, and greatest power efficiency is the goal. We were unable to compare our systems operation to that of the torque-speed characteristics of the Maxon EC45 flat motor. Such analysis may lead to enhanced design of a motor for a similar oscillatory power-generation system.
5. **Rectification:** Approaching the rectification of the generator’s three-phase, we entertained a couple paths – passive or active rectification. Ultimately, to not overextend scope, we chose passive circuitry for rectification. However, active rectification has potential to provide greater control over management of voltage rectification resulting in lower losses. Given more time and support from a student or team of students from the electrical or computer engineering department, active rectification could be further considered to improve system efficiency.

4.3 **Manufacturing Changes**

Implementing our design in a manufactured prototype proved to be a tedious and time-intensive process. To improve manufacturing, we suggest simplifying the design to require fewer modified parts and reduce the amount of time and expertise of machining.

The modified parts of focus include the motor and the gears. As documented in CDR and FDR, many hours of research and debate were put into modification procedure of the motor, in addition to the numerous hours of physical modification. Ultimately, we suggest selecting a motor that requires minimal to no modifications. Had a plug-and-play option been available, it would have reduced the risk of motor damage, while also removing the need for a resource-demanding process of researching, manufacturing, and testing. Although less time consuming, gear modifications similarly presented risk and slowed down the build process.

We estimate some 100 hours of time were dedicated to CAM preparation and CNC manufacturing processes to produce the prototype. After fleshing out the process of manufacturing, future iterations are exponentially faster to manufacture. However, for our one-off prototype, the investment in developing the CAM, setting up the machines, and performing machine operations was resource-consuming. Overall, many parts that were CNC machined should be reconsidered from the perspective of designing for manufacturability. Both simplifying the design of CNC manufactured parts and reducing the expertise needed to manufacture such parts would contribute to improved manufacturing time and cost. Though time and cost of production were not critical items in development of this prototype, they are essential to the production of a similar concept device in a mass production setting.

4.4 **Next Steps**

After discussion with our sponsor, Dr. Peter Schuster, and careful consideration of project outcomes, we have formulated recommendations for further investigation of our design concept or other iterations of a kinetic energy harvesting device. There are two main items to pursue: (1) designing a simplified, yet robust test platform for data acquisition and (2) using this platform to quantify the system dynamics.
The complexity and unforeseen flaws of our design led to issues in our testing. Not to mention, the manufacturing lead time reduced our available testing time. Part geometries should be simplified to reduce the dependency on advanced and time-consuming manufacturing methods like CNC programming and machining.

Additionally, we would suggest designing clear and simplified methods of acquiring data from future prototypes that directly influences mechanical and electrical design. Ideally, these methods and designs should be observable in an isolated format to monitor individual energy domains, and capable of guiding system-level integration. Such testing is critical to quantifying the system of equations that dictate multi-domain behaviors.

Ultimately, this proof-of-concept, multi-domain system is only as valuable as the data that is acquired from testing its physical form. Though we executed upon a succinct and elegant design, data acquisition and testing were an afterthought to the complex and manufacturing-intensive design. Design specifications of future test platforms should revolve around clear and sound system characterization goals and test methods, not competition against commercial products.
5 Conclusion

Reflecting on the entirety of the project, we are proud of the work we were able to accomplish over the course of one academic year. Converting kinetic energy of human motion to viable power is a domain with few marketable successes. Although this problem was presented to a team of mechanical engineers, we came to the realization that the scope was much more interdisciplinary than initially perceived. However, we did not let this multidisciplinary nature phase us. Instead, we leveraged our experience with mechanical systems, while utilizing technical research and faculty support to inform decisions in areas of lesser expertise.

In the end, our device did not produce 5 watts (as initially targeted) during normal operation. There were many potential reasons for low power output including, but not limited to, geartrain inefficiencies, limitations on available motors, and unforeseen electrical complications. However, basic functionality of the device showed promise from a feasibility standpoint, and does warrant the potential for further related work.

If we were to embark on this project again, the addition of students outside of the mechanical engineering department would be invaluable. Furthermore, early stage testing and quantification related to mechanical and electrical dynamics could influence a more coherent system design, something our prototype lacked. Lastly, designing for manufacturability by cutting complex part geometries would provide more time for testing and troubleshooting, two areas crucial to system quantification and iteration.
Appendix

A: Final Project Budget ........................................................................................................A-2
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Appendix A: Final Project Budget

Title Page for Final Project Budget
<table>
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<tr>
<th>How the Material is Purchased</th>
<th>Account Used</th>
<th>Date Purchased (Blank if Planned purchase)</th>
<th>Current Material Location</th>
<th>Description of Item</th>
<th>Vendor</th>
<th>Vendor's Part Number</th>
<th>Team's Part Number</th>
<th>Unit Price</th>
<th>Quantity</th>
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<th>Lead Time</th>
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<tr>
<td>Team Reimbursement</td>
<td>Baker-Koob</td>
<td>2/15/2022</td>
<td>EC45 flat #42.8 mm, brushless, 70W, with Hall sensors</td>
<td>1/8 SE Carb Ball EM</td>
<td>Digi-Key</td>
<td>C120G104K471RAC7800</td>
<td>CA-PB-9A6</td>
<td>$8.94</td>
<td>1</td>
<td>$0.50</td>
<td></td>
<td>$9.44</td>
<td>1 Day</td>
</tr>
</tbody>
</table>

| Team Reimbursement            | Baker-Koob  | 2/15/2022                              | 1/16 2F SE Carb Ball EM  | 1/8 SE Carb Ball EM  | Digi-Key | C120G104K471RAC7800  | CA-PB-9A6      | $8.94     | 1       | $0.50             |      | $9.44     | 1 Day    |

| Team Reimbursement            | Baker-Koob  | 2/15/2022                              | 1/8 SE Carb Ball EM .020 Rad | 1/8 SE Carb Ball EM | Digi-Key | C120G104K471RAC7800  | CA-PB-9A6      | $8.94     | 1       | $0.50             |      | $9.44     | 1 Day    |

| Team Reimbursement            | Baker-Koob  | 2/15/2022                              | 1/8 SE Carb Ball EM .020 Rad | 1/8 SE Carb Ball EM | Digi-Key | C120G104K471RAC7800  | CA-PB-9A6      | $8.94     | 1       | $0.50             |      | $9.44     | 1 Day    |

| Team Reimbursement            | Baker-Koob  | 2/15/2022                              | 3/8x1/2x2-1/8 Alumastar  | 3/8x1/2x2-1/8 Alumastar | Digi-Key | C120G104K471RAC7800  | CA-PB-9A6      | $8.94     | 1       | $0.50             |      | $9.44     | 1 Day    |

<p>| Team Reimbursement            | Baker-Koob  | 2/15/2022                              | 1/8 SE Carb Ball EM .020 Rad | 3/8x1/2x2-1/8 Alumastar | Digi-Key | C120G104K471RAC7800  | CA-PB-9A6      | $8.94     | 1       | $0.50             |      | $9.44     | 1 Day    |</p>
<table>
<thead>
<tr>
<th>Date</th>
<th>Reimbursement</th>
<th>Item Description</th>
<th>Supplier</th>
<th>SKU/Part Number</th>
<th>Quantity</th>
<th>Rate</th>
<th>Total</th>
</tr>
</thead>
<tbody>
<tr>
<td>2/16/2022</td>
<td>Bonderson</td>
<td>Resistor, 162kΩ</td>
<td>Digi-Key</td>
<td>RC1206FR-07162KL</td>
<td>10</td>
<td>$0.07</td>
<td>$0.79</td>
</tr>
<tr>
<td>2/16/2022</td>
<td>Bonderson</td>
<td>Resistor, 22.1kΩ</td>
<td>Digi-Key</td>
<td>RC1206FR-0722K1L</td>
<td>10</td>
<td>$0.07</td>
<td>$0.79</td>
</tr>
<tr>
<td>2/16/2022</td>
<td>Bonderson</td>
<td>DPDT Switch</td>
<td>Digi-Key</td>
<td>A522AP</td>
<td>3</td>
<td>$5.06</td>
<td>$15.18</td>
</tr>
<tr>
<td>2/16/2022</td>
<td>Bonderson</td>
<td>18-8 Stainless Steel Threaded Rod</td>
<td>McMaster</td>
<td>90024A228</td>
<td>Multiple</td>
<td>$8.89</td>
<td>$23.48</td>
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<tr>
<td>2/16/2022</td>
<td>Bonderson</td>
<td>4x10mm Dowel Pin</td>
<td>McMaster</td>
<td>9158SA4437</td>
<td>1</td>
<td>$17.58</td>
<td>$18.85</td>
</tr>
<tr>
<td>2/16/2022</td>
<td>Bonderson</td>
<td>M5x0.8x12 Button Head</td>
<td>McMaster</td>
<td>90991A127</td>
<td>1</td>
<td>$11.88</td>
<td>$11.90</td>
</tr>
<tr>
<td>2/16/2022</td>
<td>Bonderson</td>
<td>Bumper OD19mm M6</td>
<td>McMaster</td>
<td>9223K124</td>
<td>2</td>
<td>$8.07</td>
<td>$16.14</td>
</tr>
<tr>
<td>2/16/2022</td>
<td>Bonderson</td>
<td>Extension Spring 0.17 lb/in</td>
<td>McMaster</td>
<td>94135K215</td>
<td>1</td>
<td>$8.93</td>
<td>$8.93</td>
</tr>
<tr>
<td>2/16/2022</td>
<td>Bonderson</td>
<td>Bearing .125/.375in, open</td>
<td>McMaster</td>
<td>57155K349</td>
<td>6</td>
<td>$2.95</td>
<td>$17.70</td>
</tr>
<tr>
<td>2/16/2022</td>
<td>Bonderson</td>
<td>Bevel Gear (M and O Shaft)</td>
<td>McMaster</td>
<td>6529K41</td>
<td>Multiple</td>
<td>$43.94</td>
<td>$94.25</td>
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<tr>
<td>2/16/2022</td>
<td>Bonderson</td>
<td>32T Spur Gear, Molded</td>
<td>McMaster</td>
<td>57655K18</td>
<td>2</td>
<td>$3.14</td>
<td>$6.28</td>
</tr>
<tr>
<td>2/16/2022</td>
<td>Bonderson</td>
<td>0.01 Shims .125/.188in</td>
<td>McMaster</td>
<td>99040A301</td>
<td>1</td>
<td>$1.02</td>
<td>$1.02</td>
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<tr>
<td>3/3/2022</td>
<td>Bonderson</td>
<td>Super Conductive 101 Copper</td>
<td>McMaster</td>
<td>8965K22</td>
<td>1</td>
<td>$2.54</td>
<td>$2.54</td>
</tr>
<tr>
<td>3/3/2022</td>
<td>Bonderson</td>
<td>Corrosion-Resistance Extension Spring w/ Loop Ends</td>
<td>McMaster</td>
<td>7749N31</td>
<td>1</td>
<td>$14.56</td>
<td>$14.56</td>
</tr>
<tr>
<td>3/28/2022</td>
<td>Bonderson</td>
<td>Stainless Steel Stencil</td>
<td>OSH Stencil</td>
<td>Custom</td>
<td>1</td>
<td>$4.07</td>
<td>$4.07</td>
</tr>
<tr>
<td>3/28/2022</td>
<td>Bonderson</td>
<td>PCB - Board</td>
<td>OSH Park</td>
<td>Custom</td>
<td>1</td>
<td>$8.10</td>
<td>$8.10</td>
</tr>
</tbody>
</table>

**Budget:** $1,779.72  
**Actual Expenses:** $1,516.84  
**Remaining Balance:** $262.88
Appendix B: Design Verification Plan and Report

Title Page for Design Verification Plan and Report
### ME 430 DVP&R Sign-Off Scorecard

#### TEAM: F24 Power Walking

<table>
<thead>
<tr>
<th>Category</th>
<th>Percent Complete</th>
<th>Issues</th>
<th>Recovery Plan</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Part Procurement</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Counting by item on your iBOM,</td>
<td>100%</td>
<td></td>
<td></td>
</tr>
<tr>
<td>what percentage of parts have</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>been <strong>RECEIVED</strong>?</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>If less than 100%, fill out</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Issues and Recovery Plan fields</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Manufacturing</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Reviewing Verification</td>
<td>100%</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Prototype, what % of it is fully</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>ASSEMBLED</strong>?</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>If less than 100%, fill out</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Issues and Recovery Plan fields</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Testing</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Reviewing your DVP, what % of</td>
<td>75%</td>
<td></td>
<td></td>
</tr>
<tr>
<td>your tests have been</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>COMPLETED</strong> (including SP &amp;</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>component tests)?</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>If less than 100%, fill out</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Issues and Recovery Plan fields</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Safety</strong></td>
<td></td>
<td></td>
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</tr>
<tr>
<td>Reviewing your FMEA, Hazard</td>
<td>100%</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Checklist, &amp; Risk Assessment,</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>what % of your recommended</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>design actions have you</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>IMPLEMENTED</strong> in your design/</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>build?</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>If less than 100%, fill out</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Issues and Recovery Plan fields</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Reviewing your FMEA, Hazard</td>
<td>100%</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Checklist, &amp; Risk Assessment,</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>what % of your user instructions</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>have you <strong>INCLUDED</strong> in your</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>User Manual?</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>If less than 100%, fill out</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Issues and Recovery Plan fields</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Based on timing presented at</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>CDR</strong>, what is your team's</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>status today?</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Please use the text box to</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>explain your timing status.</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Highlight status:</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>ON TRACK</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>MODERATELY OFF TRACK</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>GREATLY OFF TRACK</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Although we are experiencing testing issues, we have been able to perform intermediate tests and have identified/document many of the apparent problems leading to low/zero power output.

<table>
<thead>
<tr>
<th>Category</th>
<th>Percent Complete</th>
<th>Issues</th>
<th>Recovery Plan</th>
</tr>
</thead>
</table>
## TEST PLAN

<table>
<thead>
<tr>
<th>Test #</th>
<th>Specification</th>
<th>Test Description</th>
<th>Measurement</th>
<th>Acceptance Criteria</th>
<th>Required Facilities/Equipment</th>
<th>Parts Needed</th>
<th>Responsibility</th>
<th>TIMING</th>
<th>Numerical Results</th>
<th>Notes on Testing</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>1, Power Output</td>
<td>Measure power output in a controlled testing environment</td>
<td>Power</td>
<td>&gt; 5W</td>
<td>Controls Lab, Custom DAQ</td>
<td>VP</td>
<td>Ryan McLaughlin</td>
<td>04/21/22</td>
<td>TBD</td>
<td>N/A</td>
</tr>
<tr>
<td>2</td>
<td>1, Power Output</td>
<td>Measure power output in trail conditions</td>
<td>Power</td>
<td>&gt; 5W</td>
<td>Backpack testing rig</td>
<td>VP</td>
<td>Jarod Lyles</td>
<td>05/10/22</td>
<td>05/16/22</td>
<td>N/A</td>
</tr>
<tr>
<td>3</td>
<td>2, Mass</td>
<td>Measure mass using a balance</td>
<td>Mass</td>
<td>&gt; 250g</td>
<td>Balance/Scale</td>
<td>VP</td>
<td>David Hernandez</td>
<td>04/28/22</td>
<td>05/03/22</td>
<td>1833g</td>
</tr>
<tr>
<td>4</td>
<td>3, Manufacturing Cost</td>
<td>Calculated from iBOM</td>
<td>Cost</td>
<td>&lt; $100</td>
<td>None</td>
<td>None</td>
<td>David Hernandez</td>
<td>04/04/22</td>
<td>04/04/22</td>
<td>$1,263.75</td>
</tr>
<tr>
<td>5</td>
<td>4, Volume</td>
<td>Calculated from CAD</td>
<td>Volume</td>
<td>&lt; 0.5 L</td>
<td>None</td>
<td>None</td>
<td>Shaw Hawkeye Hughes</td>
<td>04/04/22</td>
<td>04/04/22</td>
<td>Net: 1.80 L Tube Only: 1.26 L</td>
</tr>
<tr>
<td>6</td>
<td>5, Drop Resilience</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Production</td>
<td>TBD</td>
</tr>
<tr>
<td>7</td>
<td>6, IP Rating</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Production</td>
<td>TBD</td>
</tr>
<tr>
<td>8</td>
<td>7, Usability</td>
<td></td>
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<td></td>
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<td></td>
<td></td>
<td></td>
<td>Production</td>
<td>TBD</td>
</tr>
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<td>9</td>
<td>8, Thermal Operating Range</td>
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<td></td>
<td></td>
<td>Production</td>
<td>TBD</td>
</tr>
<tr>
<td>10</td>
<td>Development</td>
<td>Measure the overall efficiency of the electrical subsystem</td>
<td>Power</td>
<td>&gt; 50% with all circuitry</td>
<td>Motor Testing Apparatus (Custom Built), Mechatronics Lab, Oscilloscope, Multimeter</td>
<td>EC45 Motor, Assembled PCB</td>
<td>Jarod Lyles</td>
<td>04/14/22</td>
<td>04/14/22</td>
<td>17-24% efficiency in a regulated mode, for constant shaft speed</td>
</tr>
<tr>
<td>11</td>
<td>Development</td>
<td>Verify the no-slip condition is met for the drive wheel</td>
<td>Distance traveled</td>
<td>Δx = πD</td>
<td>Cal poly controls lab, ruler</td>
<td>VP</td>
<td>Shaw Hawkeye Hughes</td>
<td>05/02/22</td>
<td>05/12/22</td>
<td>Pass</td>
</tr>
<tr>
<td>12</td>
<td>Development</td>
<td>Verify the spring envelope allowed</td>
<td>Compression distance</td>
<td>No plastic deformation</td>
<td>Ruler</td>
<td>VP</td>
<td>Jarod Lyles</td>
<td>05/02/22</td>
<td>05/12/22</td>
<td>Pass</td>
</tr>
</tbody>
</table>
Appendix C: Risk Assessment

Title Page for Risk Assessment
**designsafe Report**

**Application:** F24 - Rotational Generator  
**Analyst Name(s):** Ryan McLaughlin, David Hernandez, Jarod Lyles, Shaw Hawkeye Hughes  
**Company:** California Polytechnic State University, San Luis Obispo  
**Facility Location:** 1 Grand Ave  
**San Luis Obispo, CA 93407**

**Description:**

**Product Identifier:**

**Assessment Type:** Detailed

**Limits:**

**Sources:**

**Risk Scoring System:** ANSI B11.0 (TR3) Two Factor

Guide sentence: When doing [task], the [user] could be injured by the [hazard] due to the [failure mode].

<table>
<thead>
<tr>
<th>Item Id</th>
<th>User / Task</th>
<th>Hazard / Failure Mode</th>
<th>Initial Assessment Severity</th>
<th>Risk Level</th>
<th>Risk Reduction Methods /Control System</th>
<th>Final Assessment Severity</th>
<th>Risk Level</th>
<th>Status / Responsible /Comments /Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>1-1-1</td>
<td>adult normal use</td>
<td>electrical / electronic : lack of grounding (earthing or neutral) Wire connections are not robust</td>
<td>Serious Unlikely</td>
<td>Medium</td>
<td>Ground to the carriage itself</td>
<td>Serious Remote</td>
<td>Low</td>
<td>Ryan McLaughlin</td>
</tr>
<tr>
<td>1-1-2</td>
<td>adult normal use</td>
<td>electrical / electronic : improper wiring design failure</td>
<td>Moderate Unlikely</td>
<td>Low</td>
<td>Use proper harnessing and double check wiring before final assembly</td>
<td>Moderate Remote</td>
<td>Negligible</td>
<td>Ryan McLaughlin</td>
</tr>
<tr>
<td>1-2-1</td>
<td>adult misuse</td>
<td>mechanical : pinch point If someone were to open up the housing, pinch points could be exposed</td>
<td>Serious Unlikely</td>
<td>Medium</td>
<td>Final product should be glued shut</td>
<td>Serious Remote</td>
<td>Low</td>
<td>David Hernandez</td>
</tr>
<tr>
<td>1-2-2</td>
<td>adult misuse</td>
<td>slips / trips / falls : impact to / with Falling with the device in your backpack</td>
<td>Serious Likely</td>
<td>High</td>
<td>Warn users in the user manual to avoid placing the device directly against their body</td>
<td>Serious Unlikely</td>
<td>Medium</td>
<td>Jarod Lyles</td>
</tr>
<tr>
<td>2-1</td>
<td>passer-by / non-user walk near</td>
<td>&lt;None&gt;</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>3-1-1</td>
<td>Developers first use / test</td>
<td>electrical / electronic : lack of grounding (earthing or neutral) Design failure/bad wiring connections</td>
<td>Serious Unlikely</td>
<td>Medium</td>
<td>Ground to the carriage itself</td>
<td>Serious Remote</td>
<td>Low</td>
<td>Ryan McLaughlin</td>
</tr>
<tr>
<td>Item Id</td>
<td>User / Task</td>
<td>Hazard / Failure Mode</td>
<td>Initial Assessment Severity Probability</td>
<td>Risk Level</td>
<td>Risk Reduction Methods /Control System</td>
<td>Final Assessment Severity Probability</td>
<td>Final Risk Level</td>
<td>Responsible /Comments /Reference</td>
</tr>
<tr>
<td>--------</td>
<td>---------------------------</td>
<td>--------------------------------</td>
<td>-----------------------------------------</td>
<td>------------</td>
<td>----------------------------------------</td>
<td>-------------------------------------</td>
<td>------------------</td>
<td>----------------------------------</td>
</tr>
<tr>
<td>3-1-2</td>
<td>Developers first use / test</td>
<td>electrical / electronic : improper wiring, Design failure</td>
<td>Moderate Unlikely</td>
<td>Low</td>
<td>Use proper harnessing and double check wiring before final assembly</td>
<td>Moderate Remote</td>
<td>Negligible</td>
<td>Ryan McLaughlin</td>
</tr>
<tr>
<td>3-1-3</td>
<td>Developers first use / test</td>
<td>electrical / electronic : overvoltage / overcurrent, Testing at higher speeds than necessary</td>
<td>Moderate Unlikely</td>
<td>Low</td>
<td>Perform calculations prior to any testing</td>
<td>Moderate Remote</td>
<td>Negligible</td>
<td>Jarod Lyles</td>
</tr>
<tr>
<td>3-2-1</td>
<td>Developers Maintenance/repair</td>
<td>mechanical : pinch point, Failure to be careful when assembling/dissassembling the device</td>
<td>Serious Unlikely</td>
<td>Medium</td>
<td>Use caution when working with the device</td>
<td>Serious Unlikely</td>
<td>Medium</td>
<td>Shaw Hawkeye Hughes</td>
</tr>
<tr>
<td>3-3-1</td>
<td>Developers trouble-shooting</td>
<td>mechanical : pinch point, Same as with maintenance/repair</td>
<td>Serious Unlikely</td>
<td>Medium</td>
<td>Use caution when working with the device</td>
<td>Serious Remote</td>
<td>Low</td>
<td>Shaw Hawkeye Hughes</td>
</tr>
</tbody>
</table>
User Instructions

A. Parts List  
B. Harnessing Kinetic Energy  
C. Maintenance and Repairs  
D. Troubleshooting  
E. Safety Tips

Please read all the following before product use. This user’s manual covers all instructions required for product use and pertinent safety information.

Parts List

<table>
<thead>
<tr>
<th>ITEM</th>
<th>QTY</th>
<th>DESCRIPTION</th>
<th>COMMENTS</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>1</td>
<td>Rotational Generator</td>
<td></td>
</tr>
<tr>
<td>2</td>
<td>1</td>
<td>Micro-USB</td>
<td>Type B</td>
</tr>
</tbody>
</table>
**Harnessing Kinetic Energy**

The following instructions cover how to properly operate the Rotational Generator (RG).

Note: There is no extra assembly required.
Note: No personal protective equipment (PPE) is required before operation.

1. Plug the provided Micro-USB cable into the Rotational Generator’s port.
2. Plug the other end of the Micro-USB cable into your portable power bank.¹
3. Place the Rotational Generator in a **vertical position** inside of your backpack.²

The Rotational Generator will continue to charge the portable power bank while you walk, run, or hike. The time for the Rotational Generator to fully charge a portable power bank varies widely on your activity and the type of power bank.

¹Note: It is possible to plug other devices directly from the Rotational Generator; however, this may require adaptors not included.

²Note: The Rotational Generator can harvest kinetic energy in the horizontal position, but for maximum power generation it is recommended to keep it in the vertical position.

---

**Caution:** **Avoid Shaking the Rotational Generator by hand.**

Although it is possible to vigorously shake the device for rapid charging; the Micro-USB must be plugged into the portable power bank, which may lead to product damage or bodily injury.
Maintenance and Repairs
To extend the life of the Rotational Generator please follow these guidelines:

- Never attempt to disassemble or repair the Rotational Generator. This may damage the device and will expose pinch points that may harm you.
- Clean the Rotational Generator with a clean, damp cloth only.
- Do not submerge the Rotational Generator in water to clean.
- Do not use harsh chemicals to clean the Rotational Generator.
- Maintain dust and moisture away from the Micro-USB port on the Rotational Generator.
- Always position the Micro-USB cable correctly when connecting to the Rotational Generator.
- Avoid dropping the Rotational Generator on hard surfaces.
- No repairs are required from the user. If the item is damaged, please return the damaged item to us for repair, replacements, or refund.

Troubleshooting
Follow these guidelines if the Rotational Generator:

Fails to provide power
- Ensure the Micro-USB cable is plugged in correctly on both the Rotational Generator and the portable power bank (or other devices).
- Ensure the portable power bank (or other devices) are working correctly.
- If possible, test the Micro-USB cable with other devices to verify the cable is supplying power.
- Visually inspect the Rotational Generator and check for broken wires, springs, shafts, wheels, bearings, or a damaged tube. If any of these apply, please call, or email the F24-Powerwalking team for repairs.

Provides low power
- Ensure the Rotational Generator is in the vertical position.
- Ensure the Rotational Generator is seated properly inside the backpack to avoid bouncing or external vibrations of the device.
- Ensure the Micro-USB cable is not damaged.
- Verify the portable power bank (or other devices) are not damaged and working correctly.

Safety Tips
Please follow these guidelines to avoid damage to the Rotational Generator or user:

- Do not operate the Rotational Generator in temperatures, below -10°C or above 40°C.
- Do not store the Rotational Generator in temperatures, below -10°C or above 40°C.
- Avoid immersing. The Rotational Generator is not waterproof.
- Do not attempt reverse charging. This could damage the circuitry or generator.
**Warning:**  Never place the device directly on the body.

Slipping, tripping, or falling with the device on the body could lead to severe bodily harm. Always place the device in the backpack.

Have questions?
Please contact us at:
[rmclaug@calpoly.edu](mailto:rmclaug@calpoly.edu)
Appendix E: Test Procedures

The following is the full collection of all test procedures written. Note that not all procedures were carried out due to time constraints and problems found during troubleshooting.

Test procedures have been organized in the following order:

- Net Power Output
- Backpack Testing
- Electrical Subsystem Efficiency
- No-Slip Test
- Spring Travel Envelope
Team: F24 Power Walking

Purpose: The purpose of this test is to verify that power is generated in a controlled testing environment before moving to on-trail testing.

Scope: Verification Prototype

Equipment:

1. Rotational Generator (Verification Prototype)
2. Hydraulic position control system
3. Computer with control programs and National Instruments DAQ card
4. Strap to secure prototype to position system
5. Custom Arduino-based DAQ
6. Wires from the generator (Prototype Motor) to DAQ
7. Micro-USB cable

Hazards:

1. Instructor supervision is required during all testing due to the use of pressurized hydraulic fluid systems
2. Double check before running the hydraulic positioner system that no hands could be crushed, as the system is capable of dangerous forces

PPE Requirements: Eye protection

Facility: Cal Poly Controls Lab 13-102

Test Date(s):

Performed By:

1. 
2. 
3. 
4. 
Procedure:

Part 1: Setup

1. Verify the verification prototype has no loose components or obstructions in the carriage’s path of motion.
2. Verify the hydraulic system has no obstructions in the piston and mass’s path of motion.
3. To move the mass back and forth by hand, please turn off the hydraulic supply (Yellow-Handled Cutoff Valve).
4. Next, unlock the cylinder by opening the needle valve connecting cylinder ports A and B on the cylinder.
5. Now open the green cylinder cut-off valves that are located below the pressure gauges at each port of the cylinder. Now you should be able to move the mass for inspection.
6. In the ME422 Lab Manual follow the initial steps 1-4 to calibrate and run the hydraulic position control system as well as the built-in DAQ.
7. Although two programs were created by following Procedure 4, we will only be using the closed-loop control to tell the computer where to move the mass.
8. Now mount the prototype on the mass and secure it with the strap.
9. Open both bypass valves (counterclockwise) and make sure the green cylinder cut-off valves are closed. Next, open the bench supply valve to allow the flow of hydraulic fluid.
10. **Warning:** Have the instructor turn on the hydraulic pump. Step away from the lab table until the instructor deems it is safe to return to your seats.
11. Connect wires from the rotational generator to the Custom DAQ.

Part 2: Data Collection

12. Run a “Desired Position Reference” with appropriate “PID” values in the Hydraulic Closed Loop PID Controller to simulate hiking conditions, such that a sinusoidal profile with a 5 cm amplitude and 2 Hz frequency is achieved.
13. Turn on the Custom DAQ, and collect data for 30 seconds.
14. Turn off the Custom DAQ and stop the hydraulic positioner from the computer controls.
15. Repeat Steps 12 and 13 for oscillation frequencies of 1.5 Hz and 2.5 Hz.
16. Before disconnecting any hardware, check that the data files have been properly written to the MicroSD card.

Part 3: Testing Wrap Up

17. Disconnect the USB cable from the rotational generator and the DAQ.
18. Close the bypass valves (clockwise) and open the green cylinder cut-off valves. Now closed the bench supply valve.
19. **Warning:** Have the instructor turn off the hydraulic pump.
20. Unstrap the prototype from the mass, remove and secure it.
21. Restart the computer.
Team: F24, Power Walking

Purpose: The purpose of this test is to observe and measure full system functionality and performance in a realistic scenario of hiking on trail with the device mounted in a backpack.\(^1\)

Scope: Verification Prototype

Equipment:

(1) Rotational Generator (Verification Prototype)
(2) nPower PEG
(3) Backpack Testing Rig (including electronics package)

Hazards:

(1) Before collecting data, ensure all devices are properly secured to the backpack rig
(2) During testing, do not run or jump to avoid damaging the rotational generator test platform

PPE Requirements: None

Facility: Local hiking trail(s)

Test Date(s):

Performed By:

(1) Hiker: ____________
(2) Observer: ____________

\(^1\) In this test, the device is fixed to the backpack rigidly, as opposed to being placed in a backpack.
Procedure:

Part 1: Backpack Setup

1. Mount the rotational generator device to the backpack frame using ¼”-20x3/4” bolts and associated hardware. Tighten bolts to wrench tight.
2. Mount the nPower PEG using custom sheet metal clamps, ¼”-20x3/4” bolts, and associated hardware. Tighten bolts to wrench tight.
3. Connect the Micro-USB cable from the measurement unit to the Rotational Generator Micro-USB port.
4. Repeat Step 3 for the nPower PEG.
5. Being careful not to crush any components, the hiker can now lift the backpack onto his/her shoulders and adjust straps as necessary to achieve a desired fit.

Part 2: Data Collection

1. Have the observer press the start button on the measurement unit to begin collecting data.
2. Hike for 5 minutes on relatively flat hiking conditions.
3. After 5 minutes has elapsed, let the observer press the start button again to stop data collection.
4. Repeat Steps 1-3 for the following conditions, with the same 5 minute test interval:
   a. Mainly uphill trail
   b. Mainly downhill trail
   c. Mixed trail conditions
5. After all tests have been completed, disconnect the nPower PEG and Rotational Generator from the measurement unit.
6. Remove the nPower PEG and rotational generator from the backpack testing rig.

Part 3: Analysis

1. Using Excel, MATLAB®, or any other computer program, process the power output data from the measurement unit.
2. Plot power as a function of time for both devices on the same axes (four plots, each with 2 series).
3. For each device, plot results from each test condition on the same axes (two plots, each with 4 series).
4. Note any observed trends in the magnitude of power output, influence of hiking conditions on prototype performance, or other factors.
Team: F24, Power Walking

Purpose: The purpose of this test is to quantify inefficiencies in the motor and custom PCB.

Scope: Unmodified motor and custom PCB

Equipment:

(1) EC 45 BLDC Motor (Motor B, unmodified)
(2) Assembled PCB
(3) Motor test stand
(4) USB-B Cable (Male) with exposed positive and negative leads
(5) Anker PowerCore Power Bank
(6) INA218 Current Monitor
(7) TDX2022B Oscilloscope
(8) BNC cable with attached probe
(9) FLUKE 177 True RMS Multimeter
(10) 6543A 200 Watt Power Supply (35V, 6A)
(11) Breadboard
(12) Alligator clips (10x)
(13) Banana Plug Cables (2x)
(14) Jumper wires
(15) #1 flathead screwdriver

Hazards:

(1) Untangle all wiring. Ensure wires are routed away from the rotating coupling.

PPE Requirements: None

Facility: Mechatronics Lab, 192-116

Test Date(s): 04/14/2022

Performed By¹:

(1) Ryan McLaughlin
(2) Jarod Lyles
(3) ____________
(4) ____________

¹ A minimum of 2 people must be present for this test due to Mechatronics lab regulations.
**Procedure:**

**Part 1: Motor Test Stand Setup**

1. Using banana plug cables and alligator clips, connect the red wire from the DC motor to the positive terminal of the 6543A 200 Watt Voltage Supply, and the black wire to the negative terminal.
2. Setup the motor test stand as pictured below. Ensure the coupling is properly tightened to both shafts. Ensure all parts are snapped into the test stand base.

![Figure 1. Motor test stand.](image1)

3. Turn on the 6543A 200 Watt Power Supply.
4. Set the allowable current to 2 Amps.
5. Set the Voltage Supply voltage to 4V, and verify concentric spinning of the two shafts.
6. Bring the voltage back down to 0V.

**Part 2: PCB and Power Bank Setup**

1. Connect the three BLDC motor leads to the PCB terminals labeled VA, VB, and VC respectively. See Figure 2 below for a detail view of the PCB terminals.

![Figure 2. CAD representation of PCB (left) with a detail view of the terminals (right).](image2)
2. Using jumper wires and a breadboard, connect one wire from the INA218 Current Monitor in series with the V\text{out} terminal to measure the current coming from the PCB.
3. Connect the other wire from the INA218 Current Monitor to the positive wire of the spliced USB-B (Male) cable.
4. Connect the ground terminal of the PCB to the negative wire of the spliced USB-B cable.
5. Plug the USB cable into the charging port of the Anker PowerCore Power Bank.

Part 3: Oscilloscope and Multimeter Setup

1. Turn on the TDX2022B oscilloscope.
2. On the oscilloscope, press “Default Setup”
3. Press the “MEASURE” button from the front-panel buttons, and use the option buttons to select “FREQUENCY” for CH 1.
4. Expose a small amount of wire on two of the three EC45 motor leads, and connect a probe to one lead and the ground clip to the other.
5. Turn on the FLUKE 177 True RMS Multimeter by turning the main knob to the DC voltage setting.
6. During testing, one person will need to manually probe the V\text{out} and GND terminals on the PCB by touching the top of the screw terminals.

Part 4: Initial Verification of Test Setup

1. Set the Power Supply voltage to approximately 5V.
2. To check whether the PCB is in a regulated or un-regulated state, toggle the switch on the PCB
   a. If the shaft speed decreases\(^2\), the PCB is now regulating. No further action is required for this case.
   b. If the shaft speed increases, the PCB has been switched from regulating to non-regulating mode. In this case, return the switch to its original position.
3. Check that the current monitor is reading values to the Arduino serial monitor (values should be in the milliamp range).
4. Manually probing the PCB screw terminals as described in Part 3, Step 6, verify that the output voltage is the range of 4.7-5.3V.
5. Check that the LED light on the Anker PowerCore Power Bank is flashing (indicating that the power bank is accepting charge). If the LED does not flash, try increasing the voltage from the power supply. It has been observed that this model needs at least 10-15 mA of current to accept charge.
6. On the oscilloscope, use the vertical and horizontal adjustments knobs to show at least 2 periods and the full amplitude range of the signal. You will need to adjust these knobs as needed to ensure a full signal is being measured at all times.
7. Once all verification steps are complete, bring the power supply voltage back down to 0V.

Part 5: Data Collection

6. Starting at approximately 2V, increase the supply voltage until the Anker PowerCore Power Bank LED lights are consistently flashing.
7. From the Power Supply, record voltage (in V) and current (in A) in the respective columns of the attached datasheet.
8. From the Oscilloscope, record the signal frequency for the EC45 motor.

\(^2\) This decrease in shaft speed is due to an increase in system capacitance (or equivalent mechanical inertia).
9. From the INA218 Current Monitor readout on a computer, record the output current in mA.
10. Using the FLUKE Multimeter, probe the output screw terminals of the PCB and record the output voltage.
11. Increasing the power supply voltage in increments of approximately 0.5V, repeat steps 7 through 10 until 5-7 data points have been recorded.
12. Once 5-7 data points have been captured for a regulated state, toggle the switch on the PCB to the un-regulated state, and repeat testing for the same set of input voltages.

**Part 6: Wrap Up**

1. Turn off the 6543A 200 Watt Power Supply.
2. Turn off the FLUKE Multimeter.
3. Disconnect the PCB wires from all other hardware.
4. Return all banana plug cables, alligator clips, and the BNC probe to their respective locations in the Mechatronics lab.

**Part 7: Analysis**

1. With all data collected, calculate the following quantities at each data point:
   a. Input Measurements: Input Torque, Shaft Speed, Input Power
   b. Output Measurements: Output Power, Efficiency
2. Plot Efficiency as a function of Shaft Speed, and note any trends.
3. Using uncertainty propagation methods, determine the uncertainty of each measured efficiency data point.
Electrical Subsystem Efficiency Testing

<table>
<thead>
<tr>
<th>Constants</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pittman 14203 Torque Constant, $K_{T,BDC}$</td>
</tr>
<tr>
<td>$0.065$ [ N-m/A ]</td>
</tr>
<tr>
<td>BLDC Pole Pairs</td>
</tr>
<tr>
<td>$8$ [ - ]</td>
</tr>
</tbody>
</table>

### INPUT TESTING

<table>
<thead>
<tr>
<th>Type</th>
<th>Measured</th>
<th>Calculated</th>
</tr>
</thead>
<tbody>
<tr>
<td>Trial No.</td>
<td>Voltage Supply Voltage $V_{in}$ [ V ]</td>
<td>Voltage Supply Current $I_{in}$ [ ±0.0005 A ]</td>
</tr>
<tr>
<td>1</td>
<td></td>
<td></td>
</tr>
<tr>
<td>2</td>
<td></td>
<td></td>
</tr>
<tr>
<td>3</td>
<td></td>
<td></td>
</tr>
<tr>
<td>4</td>
<td></td>
<td></td>
</tr>
<tr>
<td>5</td>
<td></td>
<td></td>
</tr>
<tr>
<td>6</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

### OUTPUT TESTING

<table>
<thead>
<tr>
<th>Type</th>
<th>Measured</th>
<th>Calculated</th>
</tr>
</thead>
<tbody>
<tr>
<td>Trial No.</td>
<td>Voltage Supply Voltage $V_{in}$ [ V ]</td>
<td>Output Voltage $V_{out}$ [ V ]</td>
</tr>
<tr>
<td>1</td>
<td></td>
<td></td>
</tr>
<tr>
<td>2</td>
<td></td>
<td></td>
</tr>
<tr>
<td>3</td>
<td></td>
<td></td>
</tr>
<tr>
<td>4</td>
<td></td>
<td></td>
</tr>
<tr>
<td>5</td>
<td></td>
<td></td>
</tr>
<tr>
<td>6</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
Team: F24, Power Walking

Purpose: This test will ensure that the o-ring of the carriage drive wheel rolls on the housing tube without slip under standard testing conditions.

Scope: The drive wheel, in tandem with the idler wheels, constrains the carriage in the housing tube. Specifically, the drive wheel is connected to the generator shaft via a transmission. Ideally, this fit is just tight enough to prevent drive wheel slip as the generator resists rotation.

Equipment

(1) Rotational Generator (Verification Prototype)
(2) Marking pen
(3) 12 inch ruler
(4) Video camera

Hazards: No significant hazards exist.

PPE Requirements: None

Facility: Cal Poly Controls Lab 13-102

Test Date(s):

Performed By:

(1) 
(2) 
(3) 
(4) 

Procedure

1. Refer to the “Net Power Output” test procedure for instructions regarding use of the hydraulic positioner system in the Controls Lab.
2. Run the positioner system with a sinusoidal profile at an amplitude of 5cm and 2Hz.
3. Place a ruler along the length of the housing tube and make a mark on the perimeter of the drive wheel.
4. Film the oscillating carriage and review the footage.

Note: As the device and tests are iterated (gear ratio, spring rate, oscillation frequency, oscillation amplitude, etc.) this test should be re-run to ensure no slip.

Results

The carriage should traverse $\pi D$ inches per revolution of the drive wheel, where $D$ is the outer diameter of the drive wheel, in inches.
Team: F24, Power Walking

Purpose: The purpose of this test is to verify that the travel of the extension springs does not meet solid compression height (bottom out) or elastic deformation regions within the operating displacement envelope of the oscillating mass.

Scope: The springs provide the return force to constrain the oscillation of the mass within the housing tube. Within the operating displacement envelope of the carriage assembly, the bumpers should provide appropriate limitations to prevent overextension or solid compression of the springs at peak displacement.

Equipment:

(1) Fully-assembled test platform
(2) Ruler
(3) Push stick
(4) 4X Clamps (optional)

Hazards:

- Be aware of pinch points. Use a push stick to displace the carriage.

PPE Requirements: Safety glasses

Facility: Mustang 60 Machine Shop

Test Date(s):

Performed By\(^1\):

1. __________
2. __________
3. __________
4. __________

\(^1\) A minimum of 2 people must be present for this test due to Mustang 60 machine shop regulations.
Procedure:

1. Arrange the test platform to align with Figure 1. Figure 1 identifies the direction of displacement and labels Springs A and B on the transmission and PCB sides of the carriage respectively.

   ![Diagram](image.png)

   **Figure 1.** Test platform coordinate and spring definition.

2. Clamp the test platform to a tabletop at the ends of the housing base. Avoid interference of the clamps with the extension springs.

3. Parallel to the length of the platform, clamp a ruler to provide measurement of the carriage displacement. Align the ruler such that a known zero (home) position of the unaffected carriage is apparent and recorded. Select an appropriate, notable carriage feature (i.e. an end face of the carriage) to zero from. Record the ruler measurement for the zero position.

4. Using the push stick, push the carriage until the carriage meets one of the bumpers. Hold the carriage in this position. Keep light contact between the bumper and the carriage.

5. Record the displacement of the reference carriage feature from its zero position – both as a ruler measurement and as an absolute displacement from zero. Verify the compressed spring does not achieve a solid height (bottomed out) state. Verify the extended spring is operating within elastic deformation limits. Record the displacement in Table 1.
Table 1. Spring extension envelope data.

<table>
<thead>
<tr>
<th>Carriage Reference Feature</th>
<th>Direction of Displacement</th>
<th>Ruler Measurement</th>
<th>Carriage Displacement</th>
<th>Spring Extension/Compression Notes</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>$X_0$ [mm]</td>
<td>$\Delta X_0$ [mm]</td>
<td></td>
</tr>
<tr>
<td>Zero Position 1</td>
<td></td>
<td>0</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Positive (+X)</td>
<td></td>
<td></td>
<td></td>
<td>Spring A:</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Spring B:</td>
</tr>
<tr>
<td>Zero Position 2</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Negative (-X)</td>
<td></td>
<td></td>
<td></td>
<td>Spring A:</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Spring B:</td>
</tr>
<tr>
<td>Zero Position 3</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

6. Allow the carriage to return to its zero position. Verify that the carriage rests at the same zero position. Record the ruler measurement from the reference feature.
7. Repeat Steps 4, 5, and 6 for the opposite direction of displacement.
8. Allow the carriage to return to its zero position. Verify that the carriage rests at the same zero position. Record the ruler measurement from the reference feature.
9. In the case that there is significant difference (on the order of a few millimeters) between the zero positions, there is indication that the springs may be experiencing permanent deformation from the displacement profile.
10. If there is an indication of spring damage, diagnosis the result of deformation. If overextension or solid compression exists at peak displacements, consider modifications to prevent the springs from experiencing these states. Adjust the bumper locations or other interferences to prevent overextension or solid compression of the springs in operation.

Results

Verify that the springs operate elastically – without solid compression or overextension – within the displacement envelope of the carriage. If this is not so, perform root cause analysis to identify why the springs are not operating properly. Identify and perform corrective actions (i.e. adjustment of bumper positions, adjust length of the spring studs, modify for feature interference) to ensure operation of the springs.
Appendix F: Electrical Testing

As detailed in the main body of the report, electrical testing was the only area where we were able to take significant numerical data. Appendix F contains the following documents:

- Derivation of equations
- Sample calculations
- Uncertainty propagation calculations
- Datasheets (unregulated and regulated operating modes)
**Scheme Matic**

**BDC**  
**Brushed DC Motor**  
Model → Pittman 14203 24.0 V  
Torque → \( k_T_{BDC} = 0.065 \text{ Nm/A} \)

**BLDC**  
**Brushless DC Motor**  
Model → EC44S Flat  
Pole Pairs → \( N = 8 \)

**Find:**  
1. The efficiency of the BLDC & PCB for various operating conditions

**Assumptions**

1. Operating at steady state
2. Negligible losses at the coupling
3. Current reading from power supply is current to the BDC
ANALYSIS

FIRST OF ALL, DEFINE EFFICIENCY

\[ \eta = \frac{P_{\text{out}}}{P_{\text{in}}} \]

START ON INPUT SIDE, USING MECHANICAL POWER

\[ P_{\text{in}} = T_{\text{in}} \omega_{\text{in}} \]

CANNOT DIRECTLY MEASURE TORQUE, BUT CAN CALCULATE \( T_{\text{in}} \) BASED ON \( \omega_{\text{in}} \)

\[ T_{\text{in}} = I_{\text{in}} K_T \text{BLDC} \quad \text{[N-m]} \]

FROM POWER SUPPLY

TO GET \( \omega_{\text{in}} \), MEASURE SIGNAL FREQUENCY WITH AN Oscilloscope

\[ \omega_{\text{in}} = \frac{f_{\text{in}}}{60} \quad \text{[RPM]} \]

WHERE \( N = \# \) OF POLE PAIRS FOR THE BLDC

\[ \omega_{\text{in}} = \left( \frac{N \text{ REV}}{\text{MIN}} \right) \left( \frac{2\pi \text{ RAD}}{1 \text{ REV}} \right) \left( \frac{1 \text{ MIN}}{60 \text{ S}} \right) \]

\[ = \frac{\pi}{30} \omega_{\text{in}} \quad \text{[RAD/S]} \]

\[ \therefore \omega_{\text{in}} = \frac{\pi}{30} f_{\text{in}} \left( \frac{2}{2} \right) 60 \]

\[ \omega_{\text{in}} = \frac{4\pi f_{\text{in}}}{N} \]

AND \[ P_{\text{in}} = \left( I_{\text{in}} K_T \text{BLDC} \right) \left( \frac{4\pi f_{\text{in}}}{N} \right) \]
On the output side, we have a simple 5.0 Vdc signal of varying current.

\[ P_{out} = V_{out} I_{out} \]

Both measured using an ESP32.

Thus, our final equation for efficiency is,

\[ \eta = \frac{V_{out} I_{out} N}{2 I_{in} k T, B dc \cdot f_{in}} \]

Where \( V_{out}, I_{out}, I_{in}, f_{in} \) all must be measured at each operating condition.

Make sure to keep track of units; as \( f_{in} \) needs to be in rad/s not Hz to get the correct value.
SAMPLE CALCULATIONS

FOR TRIAL NO. 1 IN A REGULATED MODE

INPUT DATA

\[ T_{in} = I_{in} \cdot k \cdot \cos \theta \]

\[ = (0.25 \text{ A}) \cdot (0.045 \text{ N} \cdot \text{m} / \text{A}) \]

\[ = 0.01125 \text{ N} \cdot \text{m} \]

\[ \omega_{in} = \frac{2\pi \cdot f_{in}}{N} \]

\[ = \left( \frac{2\pi}{8} \right) \left( 51 \text{ Hz} \right) \]

\[ = 80.11 \text{ rad/s} \]

% \( P_{in} = T_{in} \cdot \omega_{in} \)

\[ = (0.01125 \text{ N} \cdot \text{m}) \cdot (80.11 \text{ rad/s}) \]

\[ = 902 \text{ W} \left( \frac{1000 \text{ mW}}{1 \text{ W}} \right) \]

\[ = 1302 \text{ mW} \]

OUTPUT DATA

\( P_{out} = V_{out} \cdot I_{out} \)

\[ = (4.70 \text{ V}) \cdot (50 \text{ mA}) \cdot \left( \frac{1 \text{ A}}{1000 \text{ mA}} \right) \]

\[ = 0.235 \text{ W} \left( \frac{1000 \text{ mW}}{1 \text{ W}} \right) \]

\[ = 235 \text{ mW} \]

EFFICIENCY

\[ \eta = \frac{P_{out}}{P_{in}} \]

\[ = \frac{235 \text{ mW}}{1302 \text{ mW}} = 0.1805 \text{ or } 18.05\% \]
UNCERTAINTY ANALYSIS FOR ELECTRICAL SUBSYSTEM EFFICIENCY TESTING

GOVERNING EQUATION:

\[ \eta = \frac{V_{out} I_{out} N}{2\pi I_{in} k_0 B DC f_{in}} \]

WHERE:

N and k_0 B DC are considered to have zero associated uncertainty.

MEASUREMENT UNCERTAINTIES

\[ \begin{align*}
W_{f_{in}} &= 0.5 Hz \\
W_{I_{in}} &= 0.0005 A \\
W_{V_{out}} &= 0.005 V \\
W_{I_{out}} &= 0.5 mA = 0.0005 A
\end{align*} \]

PROPAGATED UNCERTAINTY

\[ W_{\eta, \text{PROP}} = \sqrt{ \left( \frac{\partial \eta}{\partial f_{in}} W_{f_{in}} \right)^2 + \left( \frac{\partial \eta}{\partial I_{in}} W_{I_{in}} \right)^2 + \left( \frac{\partial \eta}{\partial V_{out}} W_{V_{out}} \right)^2 + \left( \frac{\partial \eta}{\partial I_{out}} W_{I_{out}} \right)^2 } \]

TERM BY TERM

\[ \frac{\partial \eta}{\partial f_{in}} = \frac{2}{f_{in}} \left( \frac{V_{out} I_{out} N}{4\pi I_{in} k_0 B DC f_{in}} \right) \]

\[ = \frac{V_{out} I_{out} N}{2 I_{in} k_0 B DC f_{in}^2} \]

(CONT'D)
UNCERTAINTY (CONT'D)

\[ \frac{\Delta n}{n_{in}} = \frac{-V_{\text{out}} I_{\text{out}} N}{2 I_{\text{in}} k_{\text{B}} T_{\text{finite}}} \]

\[ \frac{\Delta n}{n_{out}} = \frac{I_{\text{out}} N}{2 I_{\text{in}} k_{\text{B}} T_{\text{finite}}} \]

\[ \frac{\Delta n}{n_{\text{in}}} = \frac{V_{\text{out}} N}{2 I_{\text{in}} k_{\text{B}} T_{\text{finite}}} \]

SUB VALUES, SOLVE

\[ u_{\text{prop}} = \sqrt{\left\{ \frac{-\left(4.73\,\text{V}\right)\left(0.05\,\text{A}\right)(8)}{2(0.25\,\text{A})^2\left(0.06\,\text{N} \cdot \text{m}^2 / \text{kg}\right)(50\,\text{Hz})^2} \right\}^2 + \left\{ \frac{-\left(4.73\,\text{V}\right)\left(0.05\,\text{A}\right)(8)}{2(0.25\,\text{A})^2\left(0.06\,\text{N} \cdot \text{m}^2 / \text{kg}\right)(50\,\text{Hz})(2\pi \, \text{rad/s})} \right\}^2 + \left\{ \frac{0.05\,\text{A}}{2(0.25\,\text{A})(0.06\,\text{N} \cdot \text{m}^2 / \text{kg})(50\,\text{Hz})(2\pi \, \text{rad/s})} \right\}^2} \]

\[ = \sqrt{\left\{ \left(8.57 \times 10^{-6}\right) + (1.43 \times 10^{-5}) \right\}^2 + \left\{ (3.992 \times 10^{-8}) + (3.93 \times 10^{-6}) \right\}^2} \]

\[ = \pm 0.0046 \]

CONVERTING TO \( \% \)

\[ u_{\text{prop}} = 0.46 \% \]

FOR TRIAL NO. \( 1 \)

UNREGULATED
## UNREGULATED MODE

### INPUT TESTING

<table>
<thead>
<tr>
<th>Type</th>
<th>Voltage Supply Voltage</th>
<th>Voltage Supply Current</th>
<th>Signal Frequency</th>
<th>Torque Input</th>
<th>Shaft Speed</th>
<th>Input Power</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>( V_{in} )</td>
<td>( I_{in} )</td>
<td>( f_{in} )</td>
<td>( T_{in} )</td>
<td>( \omega_{in} )</td>
<td>( P_{in} )</td>
</tr>
<tr>
<td>1</td>
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<td>0.25</td>
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### OUTPUT TESTING

<table>
<thead>
<tr>
<th>Type</th>
<th>Voltage Supply Voltage</th>
<th>Output Voltage</th>
<th>Output Current</th>
<th>Output Power</th>
<th>Efficiency</th>
<th>Uncertainty</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>( V_{in} )</td>
<td>( V_{out} )</td>
<td>( I_{out} )</td>
<td>( P_{out} )</td>
<td>( \eta )</td>
<td>( u_q )</td>
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\(^1\text{at } V_{in} = 4.5 \text{ V and above, didn't have consistent charging}\)
Electrical Subsystem Efficiency Testing

Test Date: 04/14/2022
Team Members: 1) Ryan McLaughlin
               2) Jarod Lyles

REGULATED MODE

### INPUT TESTING

<table>
<thead>
<tr>
<th>Type</th>
<th>Set</th>
<th>Trial No.</th>
<th>Voltage Supply Voltage $V_{in}$ [V]</th>
<th>Voltage Supply Current $I_{in}$ [±0.0005 A]</th>
<th>Signal Frequency $f_{in}$ [±0.1 Hz]</th>
<th>Torque Input $T_{in}$ [N-m]</th>
<th>Shaft Speed $\omega_{in}$ [rad/s]</th>
<th>Input Power $P_{in}$ [mW]</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>1</td>
<td>3.5</td>
<td>0.25</td>
<td>51</td>
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### OUTPUT TESTING

<table>
<thead>
<tr>
<th>Type</th>
<th>Set</th>
<th>Trial No.</th>
<th>Voltage Supply Voltage $V_{in}$ [V]</th>
<th>Output Voltage $V_{out}$ [V]</th>
<th>Output Current $I_{out}$ [±0.005 mA]</th>
<th>Output Power $P_{out}$ [mW]</th>
<th>Efficiency $\eta$ [%]</th>
<th>Uncertainty $u_{\eta}$ [%]</th>
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</thead>
<tbody>
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### Constants

<table>
<thead>
<tr>
<th>Constant</th>
<th>Value [SI Unit]</th>
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</thead>
<tbody>
<tr>
<td>$K_{T, BLDC}$</td>
<td>0.065 [N-m/A]</td>
</tr>
<tr>
<td>BLDC Pole Pairs</td>
<td>8 [-]</td>
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</table>

Pittman 14203 Torque

**Note:** All measurements are within the specified uncertainties.