

Team 11

Design of a Vibration Energy Harvester

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Goal:

The purpose of this project is to design and build a compact system that can yield electrical energy from mechanical-kinetic energy. This energy converter is to be able to supply power to help recharge batteries installed on the converter, and also extend the measurement unit's own battery life up to 3 months or greater. The mentioned unit is Instrumented Sensor Technology's (IST) "VTP-3Dv2", mechanical shock measurement unit.

The expected outcome after this product undergoes design and analysis is that it will be able to power and recharge 3.7 volt batteries, at any oscillation frequency within the expected range. The target market for this product is public and commercial transportation vehicles, where a lot of untapped, and nearly endless amounts of vibrational energy exists. The current power usage of various vehicular devices can be reduced by energy converters such as our own.

Facilitator:

Xiaobo Tan

Sponsor:

Instrumented Sensor Technology (IST)

Technical section

Customer needs / requirements

Portable sensor networks are being implemented into a variety of pre-existing systems to improve the functionality of the system as a whole. These sensor networks are highly diverse and can be implemented almost anywhere. Instrumented Sensor Technology (IST) has developed a chain of products that are able to sense and record mechanical vibrations in transit vehicles. These devices have a low power requirement which is often supplied by a battery. But despite tremendous efforts in the development of battery technology we can not keep up with the growing power demands for these portable devices.

Batteries are heavy, expensive and require constant maintenance as they must be changed every time they run out. Our project is to develop a device that can harvest vibrational energy present in the ambient environment, and convert it into electrical power so that it can be stored into a rechargeable cell for later or immediate use. Vibration energy is wasted energy present in all motorized vehicles, and by converting this energy we can utilize the low powered sensor networks installed on these vehicles and extend the battery life of these sensor devices thus lowering our needs for batteries.

The vibration harvesting device that we are developing must be able to function with a pre-existing device developed by IST, the VTP-3Dv2. The VTP-3Dv2 is built to operate in the bed of a shipping truck where it can collect and record vibration data for later analysis. Our harvesting device must be optimized for this same type of environment. Low frequency vibrations (less than 10 Hz) are most prominent in shipping trucks, therefore we will need to tune our device to be most effective at these low frequencies to ensure maximum generation. The device must also be durable enough to survive being in the bed of a truck, and small enough to prevent obstruction to other things within the bed.

Our goal is to extend the battery life of the VTP-3Dv2 beyond 3 months to indefinitely by replacing the battery supply in the VTP-3Dv2 with a Vibrational Energy Harvesting device. At the moment the VTP-3Dv2 is powered by four non-rechargeable AA 3.6V lithium batteries, with a carrying capacity of 2600 mAh, and an estimated lifespan of about 3 months. We will need to find a rechargeable cell that can meet the same requirements of this pre-existing battery supply and design our device to output power at a similar rated voltage of 3.6V. The VTP-3Dv2 draws approximately 5 mA of current while operating. In order to perpetuate the life of the device we will need to supply approximately 5 mA of current or more.

Background

Vibration harvesting is the idea of taking vibrational energy and converting that energy into usable electrical energy. Piezoelectric technology, touch capacitive technology, and electromagnetic coils are a few popular methods of converting mechanical energy into electrical energy. For this project we are concerned with generating as much power as possible at varying frequencies using one of these methods. Our goal is to design a compact detachable device that can be fastened to a truck bed and convert the mechanical vibrations inside the truck bed's environment while in transit into useful electricity that can be used to recharge or drive a small electronic unit, the VTP-3Dv2 developed by IST.

Vibrations present in the truck bed are low frequency (less than 10 Hz). Much has been invested into the development of piezoelectric materials, however piezoelectric materials are often optimized for higher frequencies and do not work very efficiently at low frequencies. The method of using piezoelectric material is not a feasible solution. Our solution is to design an apparatus that generates electrical power from a magnet oscillating back and forth through a coil. This allows alternating current to be produced due to magnetic inductance that is being produced by the magnet and coil. The alternating current will be rectified using a regulating powertrain circuit, a rechargeable battery will be attached to the circuit, and the receiving electronic load is attached as well. The goal with this simple electronic system is to help recharge the battery that operates the VTP-3Dv2 vibration measuring device, and also to extend battery longevity. The electrical system will not output a constant voltage or current. Most of the energy harvesting will occur at a sporadic rate. The electromagnetic apparatus, will be able to harvest electricity at irregular frequencies when the truck suspension is hitting bumps in the road. The goal at the end of this project is to be able to harvest enough electricity to be able to extend battery life, using this design.

Design Specifications

- Device should be able to supply power to the VTP-3Dv2 device:
The vibration harvester that we develop should be able to function with IST's VTP-3Dv2. This requires the device to be portable and applicable to motorized vehicles.

- Device should provide a rated output voltage of 3.6v:

The VTP-3Dv2 is powered by a 3.6 v battery supply, with an approximate capacity of 2600mAh. We must adjust the power output of the vibration harvester to suit the requirements of the VTP-3Dv2.

- Output a current of 5 mA:

The VTP-3Dv2 draws approximately 5 mA of current while operating. To perpetuate the life of the VTP-3Dv2 our vibration harvester will have to be able to supply approximately 5 mA of current (or 18 mW of power). If the average current output is lower than 5mA then operation life is only extended.

- Operate at low frequencies (under 10 Hz):

We must design our vibration harvester to collect as much power from the vibrations in the environment around it. This means designing our project for the qualities of these vibrations. The vibrational content inside of a truck bed while in transit are predominantly low frequency oscillations typically under 10Hz.

- Recharging device (vibration harvester) should be able to assist in recharging VTP-3Dv2 and help extend the time of use beyond 3 months, or even reduce the need of batteries in the VTP-3Dv2.
- Re-charging generator is attachable/detachable. The device needs to be able to operate anywhere the VTP-3Dv2 goes, which could be anywhere from a truck bed to inside a shipping container.
- The automotive environment can be very harsh, as well as diverse. Our device needs to be able to operate under a wide range of temperatures, from -40C to 125C. Our device will also need to be able to operate under a wide range of humidities.

Set of Conceptual Designs

In order to harness vibration energy we must devise an apparatus to convert physical movements into a voltage swing. There are a few possible solutions which can produce this result: electromagnet coils which induce a current in a coil when a magnet passes by it, piezoelectric materials which produce a voltage when the material is physically warped, and capacitive-sensitive materials which produce slight voltage swings when touched. From there an

irregular signal is produced. We can convert this signal into a regulated output compatible with the VTP-3Dv2 via a power conversion circuit.

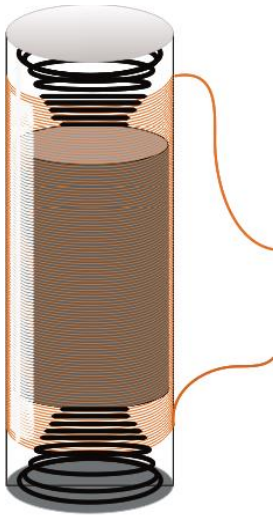
	Importance	Electromagnet	Piezoelectric Material	Capacitive-Sensitive Material	Buck-Boost Regulator	IC Voltage Regulator
Low Frequency	5	9	1	1	1	3
Generate Power	5	9	9	3	3	3
Easily attachable	2	3	9	9	3	3
Meet voltage/current specifications	4	9	3	3	3	9
Low weight and size	1	1	9	9	9	9
Compatible with STP-3Dv2	3	3	3	3	9	9
Extend battery life	5	9	3	3	3	3
Applicable to other devices	1	3	1	3	9	9
Total		190	114	86	98	132

Based off the results from our selection matrix we decided that it would be most feasible to design our vibration harvester using an electromagnetic coil with an IC voltage regulator power train. The electromagnetic method is the best solution for operating with low frequency vibrations ($f < 10\text{Hz}$), while piezoelectrics are more effective when oscillating at a high frequency. The vehicle is most likely to bounce and oscillate at low frequency, especially if in motion at a constant speed. Piezoelectric technology would suffice if the vehicle was bouncing constantly at high frequency, which realistically in this case, would be undesirable. The amount of piezoelectric material needed to harvest energy at high frequency, would be a fair amount, and it would have a substantially high production cost, while only one or two electromagnetic apparatus units are needed for energy harvesting at low frequencies.

The electricity from the electromagnet apparatus goes through an IC voltage regulator power; we decided to use this method due to its simplicity and intended outcome. We originally were going to use a buck-boost (DC-DC) converter, but the intended use was not appropriate for

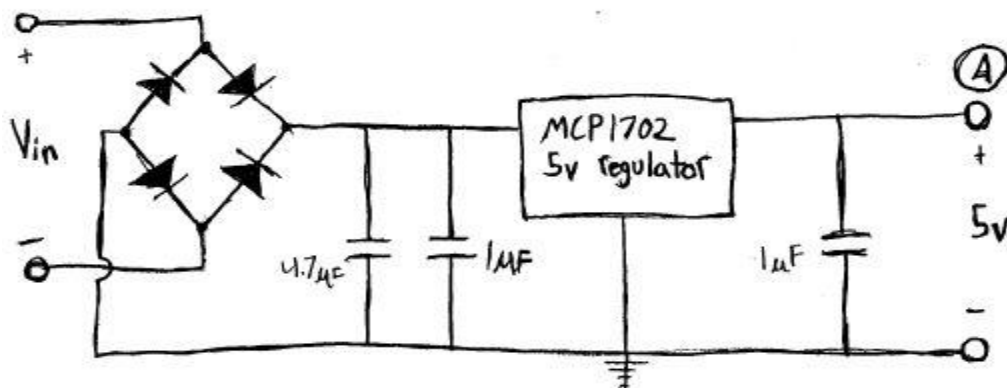
using a buck-boost converter. A buck-boost converter requires a controlled pulse width modulation (PWM) signal, and more analog circuit components. The voltage can easily be controlled or regulated by using a voltage regulator, that outputs the desired voltage. If the circuit needed to be turned off due to overvoltage, or the battery charge is at the limit, a microcontroller can be implemented and a transistor can switch the circuit on or off.

Proposed design solution

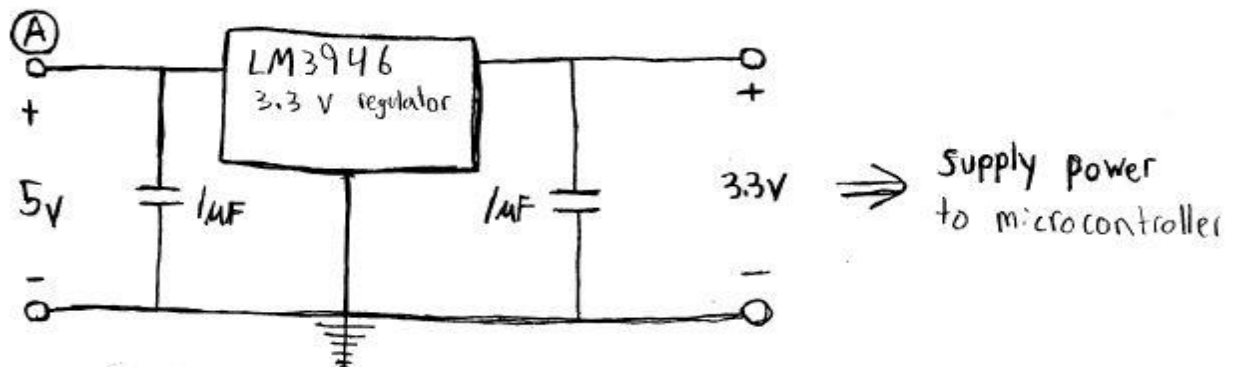


Our design is broken up into several different parts which must all operate together as one. The first part is the vibration harvesting apparatus, which is designed to produce electrical charge when oscillating. This apparatus is made of a magnet attached to 2 springs, which is housed inside of a PVC pipe that is wrapped in magnet wire. According to Faraday's Law, when a vibration stimulus is introduced to our apparatus, the magnet will oscillate and create an alternating current inside of the coil. The resonant frequency of our springs will match the average vibrational frequency of the truck bed, in order to maximize the voltage output of our apparatus.

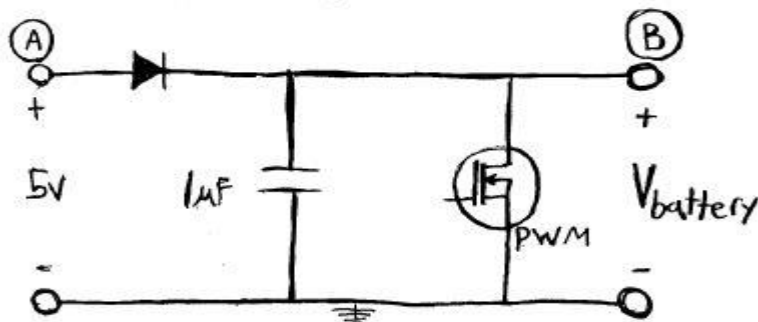
The next part of our design is the powertrain circuit, which converts the irregular alternating current generated by the harvesting apparatus into a consistent 3.6V DC supply. A full wave rectifier will convert the AC current into a DC voltage which we can then regulate with simple IC voltage regulators. We will implement three separate stages in the regulating circuit (see topology below).



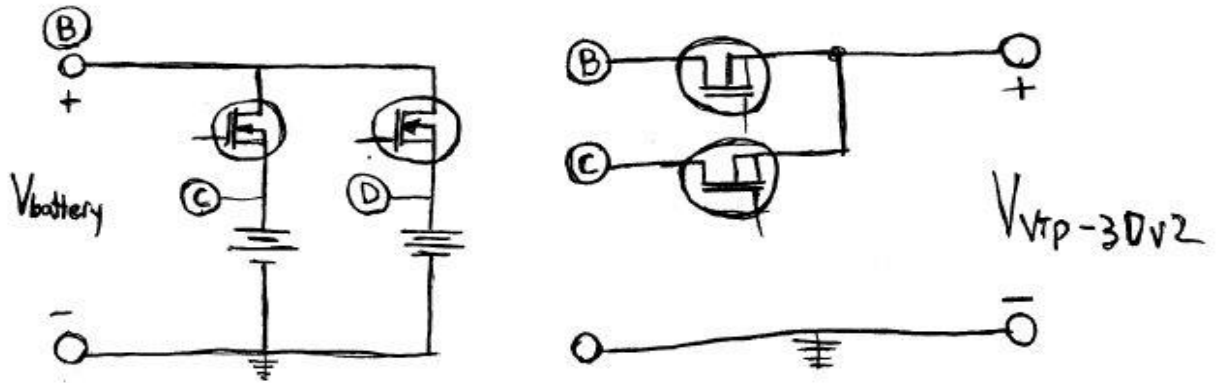
First we rectify our irregular power input and then run the DC power into a 5v regulator, the MCP1702. The MCP1702 is able to accept a variety of inputs and outputs a consistent 5 volts. We then use this regulated power to supply the VTP-3Dv2 and a microcontroller. The microcontroller requires a lower voltage so we step down the 5v using a 3.3v regulator (see below).



The LM3946 can take in 5v and convert it to 3.3v. This will provide the power necessary for our microcontroller to operate. We also need to supply the VTP-3Dv2. We will be charging one of two battery cells at any one time, while the other provides power to the VTP-3Dv2. This requires us to vary the supply voltage from our power train circuit to the battery pack. Using the regulated 5v output from the MCP1702 we will implement a simple buck converter that uses a PWM signal in order to adjust the DC voltage level as appropriate (see circuit below).



The microcontroller will output a PWM signal using one of its timer outputs to the FET. We then run this adjustable DC voltage level into the dual cell battery pack. One battery cell will be recharged as the other battery cell supplies power to the VTP-3Dv2. The microcontroller will monitor the storage levels of these two cells simultaneously and switch between them as appropriate.



This circuit will be enclosed in a compact case, detachable from the VTP-3Dv2 unit.

As stated earlier, the microcontroller will be working in conjunction with the rectifying circuit to control the current supplied by the harvesting apparatus. The microcontroller used will be a TI MSP430FR6989 16 MHz ultra-low-power microcontroller with a 12-bit analog-to-digital converter (ADC). The microcontroller will monitor the available output current of the vibration harvester using the ADC by measuring the voltage drop across a small sense resistance placed in series at the output of the rectifier. When the current output is low, the microcontroller will stop charging the battery cells and allow both batteries to power the device directly in order to prepare for a situation where the harvester is not generating any power.

This entire apparatus needs to be able to attach wherever the VTP-3Dv2 is being used. The most extreme case of this being the mechanical suspension system of a vehicle. In the event of vehicular maintenance, our device should be easy to detach off of the suspension rod of the vehicle, creating easy access to the vehicle's suspension. After maintenance, the vibration energy harvesting apparatus can be easily attached again. With this kind of design, this should help recharge and extend battery life of the vibration measuring unit.

Using this simple electromagnetic apparatus design will work best for the end goal of this project. The reason why this method is feasible is, it is able to harvest power at any low frequency; given that the frequency is sporadic. The big disadvantage with piezoelectric material is, it depends on almost-constant shear, stress and strain in order to harvest electricity efficiently. For the most part, the vehicle's physical suspension systems did not resonate at a very high frequency while in transit. At low frequency, the truck will pick up some bumps, and the electromagnetic apparatus will be able to pick up the amplitudes of each of the bumps, and harvest power. The right optimization and tuning of this apparatus will improve the efficiency of

energy harvesting. The only disadvantage of this apparatus is that if the truck suspension were to oscillate at a high frequency, the apparatus efficiency would decrease.

Product and Functionality Risk Analysis

A functional and lasting design will be challenging. Converting mechanical energy into electrical involves equipping our device with mechanical components connected to precise circuit systems that requires a certain level of precision that can be difficult to produce without proper equipment. The energy converter has several systems, those being the mechanical harvesting apparatus, the powertrain, the battery, and the VTP-3Dv2 device. We have estimated several risks that could hinder the functionality of our product.

1. Cost
 - a. The analyzed risk is that providing more efficient power and battery usage will not outweigh the value of producing this product.
2. Structural Failure
 - a. Unpredictable events such as a vehicle crash or mishandling of the product could rattle the magnet apparatus aggressively. Fixtures that keep the springs and magnets in place have a chance to fracture and compromise the structural integrity. If for any reason the integrity of the apparatus was compromised, the functionality of the product would also be.
3. Circuit Failure
 - a. Aggressive rattling of the product also can break circuit connections anywhere throughout the device. Properly functionality would likely cease no matter where the broken connection was made.
 - b. Depending on the size of the entire device there is a possibility that the movement of the neodymium magnet will induce current in other parts of the device. If undesired currents are to be induced inside of the microcontroller or the VTP-3Dv2 both would likely fail to operate properly. Undesired currents could also be induced in any part of the powertrain which could have adverse effects as well.
4. Battery Failure
 - a. Depending on the power supplied to the batteries there is a risk of overcharging and destruction during the operation of the rechargeable batteries. Even with surge control and microcontroller control through monitoring, it could still not be enough protection. If the structural integrity of the a battery was to fail, there

would also be a risk of toxic exposure, or even a risk of explosion from the battery.

Personnel

Stephen Pliska:

Steven is the manager of the project and will be delegating the group to achieve results by an appropriate deadline. He will also be involved with the designing of the powertrain circuitry that connects the harvesting apparatus to a rechargeable battery. This circuit will include three major parts: a full-wave rectifier, an adjustable voltage regulator, and an electronic switch.

The full-wave rectifier will convert the irregular AC signal produced by the harvesting apparatus into DC. The voltage regulator will produce a constant DC supply compatible with the VTP-3Dv2's requirements. The electronic switch will be a safety mechanism located at the final stage in the powertrain to switch off connection to the battery pack from the power train circuit. Steve will work with Tom and Andrew to improve the connectability of the powertrain to other major parts of the device.

Technical Task Timeline

Design powertrain circuit	(Feb 15 - Feb 19)
Compile/Order parts	(Feb 22 - Feb 26)
Build/Test first prototype	(Feb 29 - Mar 4)
Build/Test final prototype	(Apr 4 - Apr 8)
Implement into final design	(Apr 18 - Apr 22)

Tom Dochoda:

Tom is the laboratory coordinator/worker. His role will be establishing tests of the prototype, and interpreting test result. Tom will be involved with designing the electromagnetic apparatus portion of the energy harvester, which attaches to the analog circuit portion. Electromagnetic portion of the circuit will involve the use of a neodymium magnet and a coil of wire. The oscillation between the magnet and the coil will harvest alternating current.

Technical Task Timeline

Design electromagnetic apparatus	(Jan 22 - Feb 4)
Review and discuss design with group	(Feb 5 - Feb 15)
Order specific parts	(Feb 16 - Feb 21)
Complete design/ Assemble Apparatus	(Feb 22 - Feb 28)
Test first prototype	(Feb 29 - Mar 3)

Improve design with powertrain circuit	(Apr 4 - Apr 17)
Implement all improvements into final design	(Apr 18 - Apr 22)
Implement and assemble final design	(Apr 23 - Apr 29)

Andrew Schroeder:

Andrew is in charge of presentation of the material. He will be in charge of creating the presentations and charts/diagrams that help explain our project. Andrew will also be selecting the parts for the vibration harvesting apparatus, along with the microcontroller and rechargeable battery. He will also be working with Tom and Steven to build the harvesting apparatus, and also designing the power-point tracking circuit to link the microcontroller to the harvesting apparatus, regulating circuit, and rechargeable battery.

Technical Task Timeline

Research microcontroller solutions	(Jan 11 - Feb 17)
Finalize microcontroller circuit design	(Feb 17 - Feb 25)
Implement power-point tracking	(Feb 25 - Mar 2)
Construct the harvesting apparatus	(Feb 29 - Mar 4)
Test and record the recharging data/scenarios	(Mar 2 - Apr 4)
Make improvements and calibrations	(Apr 4 - Apr 28)
Implement final design	(Apr 29)

Daniel Fresneda-Rojas:

Daniel is in charge of the team's website and online presence. He will be coordinating with the rest of the team to make sure that all of the team's documents are available and that the website is accurate. He will also be working with Andrew on choosing an appropriate microcontroller to use for the control system. Lastly, he will be designing the software responsible for monitoring and controlling the battery charging circuit.

Technical Task Timeline

Choose microcontroller	(Feb 22 – Feb 26)
Design and program monitoring/charging code	(Feb 29 – Mar 4)
Test charging code in standalone configuration	(Mar 14 – Mar 18)
Test monitoring code with vibration harvester	(Mar 14 – Mar 18)
Improve code and refine with standalone testing	(Mar 21 – Apr 8)
Test code in final configuration	(Apr 11 – Apr 15)
Finalize code	(Apr 11 – Apr 29)

Jovanni Ivanaj:

Jovanni is the documentation coordinator. He will be working with the team to ensure that proper documentation throughout the design project is made. The goal is to identify the requirements and purpose of every document and assure that they are met. In order to develop a functional power storage system Jovanni will be working with Steven and Daniel so that power input/output specifications and requirements are met, as well as efficient operation. The batteries used will to be able to store charge and are to be controlled in such a way that allows one to charge while the other supplies the VTP-3Dv2.

Technical Task Timeline

Establish power needs data	(Feb 15 - Feb 19)
Compile/Order parts	(Feb 22 - Feb 26)
Build/Test prototype	(Feb 29 - Mar 4)
Build/Test final design	(Apr 4 - Apr 8)
Implement into final design	(Apr 18 - Apr 22)

Resources / Facilities

Michigan State University (MSU) senior lab will be provided along with tools and utilities, also provided by MSU faculty.

Instrumented Sensor Technology (IST) will provide necessary devices or measurement equipment to this project.

Project Schedule

Conceptualize	1/11/16 - 02/05/16
-Meet as a group	
-Assign group roles and tasks	
-Brainstorm ideas about possible solutions to project	
-Meet with sponsor and facilitator to obtain specifics about project	
Logistics	02/05/16 - 02/10/16
-Finalize decision on harvesting method	
-Pitch harvesting method to IST	

Design 02/10/16 - 02/24/16

- Design the harvesting apparatus
- Design the regulating circuit
- Research possible microcontrollers
- Research rechargeable batteries
- Order parts for harvesting apparatus
- Order parts for regulating circuit
- Order microcontroller
- Order rechargeable battery

Assemble Prototype 02/24/16 - 03/04/16

Testing Prototype 03/04/16 - 03/16/16

- Build Prototype
- Test Prototype

Review/Improve 03/17/16 - 04/11/16

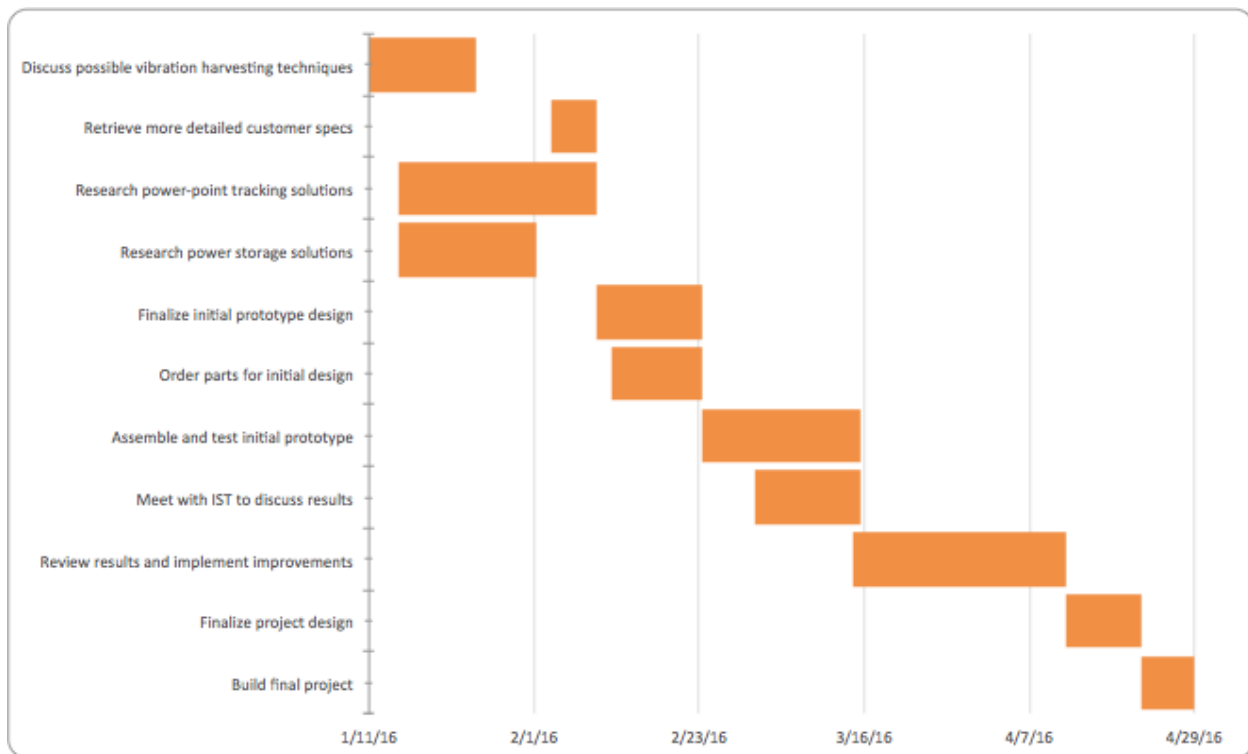
- Extrapolate our short-term results
- Do a long-term cost analysis
- Improve our energy consumption and storage methods

Production 04/12/16 - 04/29/16

- Finalize design
- Build final prototype
- Run short-term test with IST truck drivers

Task	Start Date	Duration	End Date
Discuss vibration harvesting techniques	01/11/2016	14	01/25/2016
Retrieve more customer specs	02/04/2016	6	02/10/2016
Research power-point tracking solutions	01/15/2016	26	02/12/2016
Research power storage solutions	01/15/2016	18	02/02/2016
Finalize initial prototype design	02/10/2016	14	02/24/2016
Order parts for initial	02/12/2016	12	02/24/2016

design			
Assemble and test initial prototype	02/24/2016	21	03/16/2016
Meet with IST to discuss results	03/02/2016	14	03/16/2016
Review results and implement improvements	03/15/2016	28	04/11/2016
Finalize project design	04/12/2016	10	04/22/2016
Build final project	04/22/2016	7	04/29/2016



Cost section (These costs are subject to change relating to shipping/handling fees)

Budget

\$27.55	(1) 20 AWG Gauge Magnet Wire
\$2.66	(1) 1" PVC Pipe
\$4.64	(1) Rubber Cement
\$14.60	(20) PVC Caps
\$33.95	(3) 1" x 1" Neodymium magnets

\$59.01	(15) Compression Springs
\$1.66	(1) LM3940IT, 3.3v regulator
\$0.83	(1) LP2950ACZ, 5v regulator
\$0.36	(1) LM78L05ACZ, 5v regulator
\$0.48	(1) MCP1702, 5v regulator
\$1.73	(1) BA00BC0Wt, adjustable regulator
\$3.17	(1) LT3080, Adjustable regulator
\$1.04	(8) 1N4007, Diode
\$2.72	(8) 2N7000TA, MOSFET
\$6.64	(8) IRF630, MOSFET
\$1.30	(5) Aluminum Capacitor, 1 uF
\$0.72	(3) Aluminum Capacitor, 4.7 uF
\$1.50	(5) Aluminum Capacitor, 10 uF
\$0.69	(3) Aluminum Capacitor, 47 uF
\$1.50	(5) Aluminum Capacitor, 100 uF
\$17.99	(1) TI MSP-EXP430FR6989 Launchpad
 \$220.38	 Total Spent

References

“Introduction to Vibration Energy Harvesting”

by. Francesco Cottone

<http://www.nipslab.org/files/file/nips%20summer%20school%202011/Cottone%20Introduction%20to%20vibration%20harvesting.pdf>

<https://www.boundless.com/physics/textbooks/boundless-physics-textbook/induction-ac-circuits-and-electrical-technologies-22/magnetic-flux-induction-and-faraday-s-law-161/faraday-s-law-of-induction-and-lenz-law-569-6693/>

<http://hyperphysics.phy-astr.gsu.edu/hbase/electric/farlaw.html>

<http://web.mit.edu/viz/EM/visualizations/coursenotes/modules/guide10.pdf>

Nise, Norman. *Control Systems Engineering, Sixth Edition*. Hoboken NJ: John Wiley & Sons, 2011.