New York City College of Technology

Final Design Report
Project RainCar

IND4850 Senior Project

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gutta cavat lapidem [non vi sed saepe cadendo]

A water drop hollows a stone [not by force, but by falling often]

1 – Introduction

1.1 Introduction

Love it or hate it, rainfall is all around us. We have all encountered rain but what many of us do not realize is that each drop has within it a certain amount of potential energy. If we can somehow harness the multiple mechanical impacts from a single rainfall, we can capitalize on a readily available source of energy. Based on some estimates, the potential energy of an inch of rainfall on the average single-story house is approximately 120KJ of energy. With the average monthly precipitation in New York City ranging from 3.25 inches to 4.25 inches, the amount of energy that could be potentially captured is staggering.

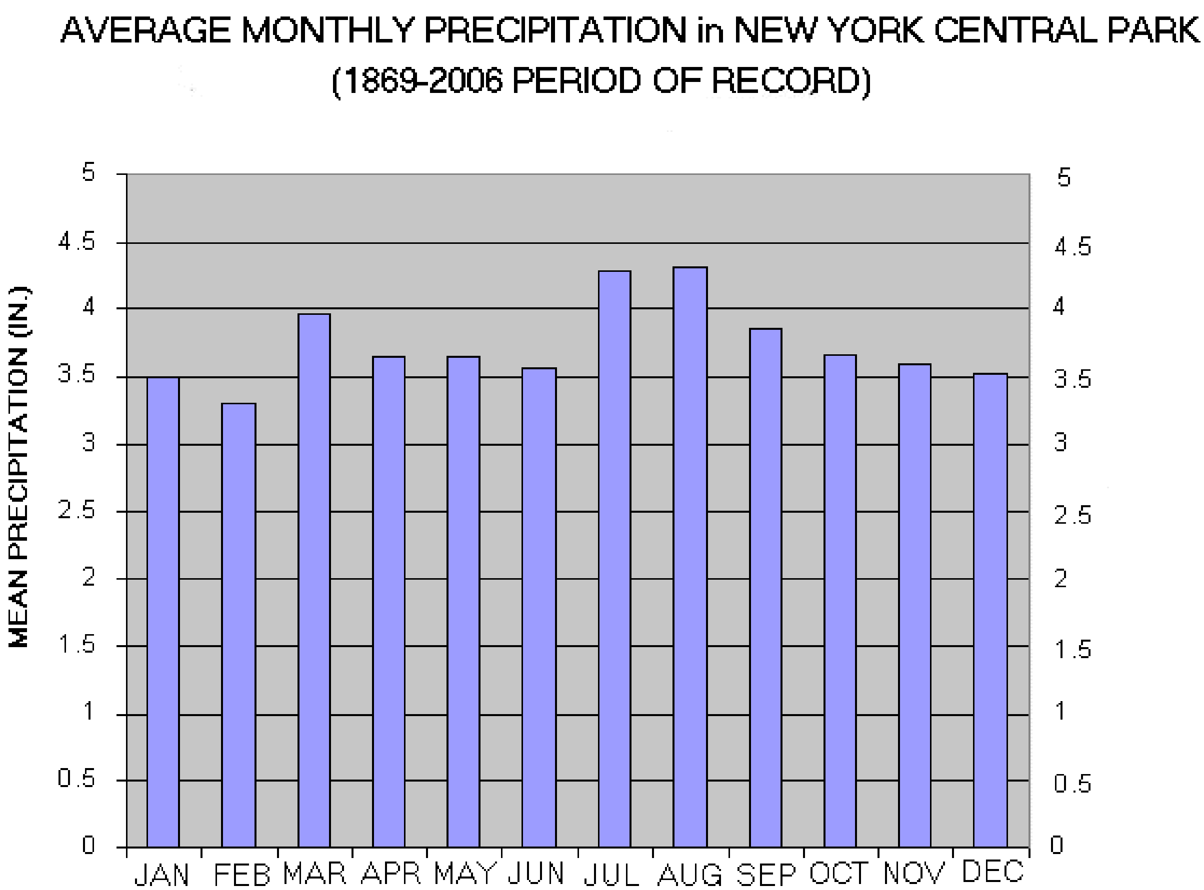


Figure 1.1.1 – Average Monthly Precipitation in New York Central Park (1869-2006). This graph shows average monthly rainfall in inches. Retrieved from: http://www.climatestations.com/images/stories/new-york/nyprcp4.gif

The amount of energy that can be potentially extracted from a drop of falling water is equivalent to its kinetic energy at the moment of impact which is given by the following equation:

$$KE = 1/2mv^2 \qquad \text{(eq.1)}$$

Where KE is the kinetic energy, m is the mass, and v is the velocity of the drop of water. The following table shows the size of typical raindrops, their terminal velocities, and their corresponding amount of kinetic energy.

Table 1.1.1 Kinetic Energy of Various Sizes of Rain Drops					
	Drop Size		Terminal Velocity		Kinetic Energy
Rain Type	mm	in	m/sec	miles/hr	Joules
Light Stratiform Rain (0.04” per hr)	-	-	-	-	-
Small Drop	.5	.02	2.06	4.6	1.4×10^{-7}
Large Drop	2.0	.08	6.49	14.4	8.8×10^{-5}
Moderate Stratiform Rain (.25” per hr)	-	-	-	-	-
Small Drop	1.0	.04	4.03	8.9	4.3×10^{-6}
Large Drop	2.6	.10	7.57	16.1	2.6×10^{-4}
Heavy Thunderstorm (1.0” per hr)	-	-	-	-	-
Small Drop	1.2	.50	4.64	10.3	9.7×10^{-6}
Large Drop	4.0	.16	8.83	19.6	1.3×10^{-3}
Largest Possible Drop	5.0	.20	9.09	20.2	2.7×10^{-3}
Hailstone	10	.40	10.0	22.2	2.6×10^{-2}
Hailstone	40	1.6	20.0	44.4	6.7

Table 1.1.1 – Kinetic Energy of Various Sizes of Rain Drops. This table outlines the type and size of rain drops and shows their corresponding terminal velocity and kinetic energy. Retrieved from: shortsmeyer.com/wxfaqs/float/rdtable.html

To harness the power of falling rain, several methods will be proposed in the following sections. Each idea may differ in its methodology, yet they strive to achieve the same goal. The following report will outline the design of the rain powered vehicle from concept to fabrication. The first section will run through the preliminary design phase of the project and cover the customer requirements, market analysis summary, design concepts and the process through which we decided which concept to pursue. The nest section is the design proposal in which we develop the idea chosen in the previous section. It covers many project management aspects and includes design specifications, scheduling, tasks, barriers, and risks associated with the project. The section following the design proposal covers the detailed product design and deals with the assembly model and drawings as well as the circuit design for our product. The next section will be the manufacturing section that deals with the fabrication of the product. Following the manufacturing section, a section on product safety and improvement is presented. Finally, the report ends with a conclusion, appendix, and reference section.

2 – Preliminary Design

2.1 Customer Requirements

In recent years, the major engineering trend has to design vehicles that capitalize on renewable and sustainable energy sources. These "green energy" sources are usually in the form of hydroelectric, wind, or solar, but this project will utilize a new form of renewable energy. The goal of this project is to design and fabricate a proof of concept vehicle that captures the potential energy within rain and converts it into useful energy. Our design constraints are as follows:

- The energy source will be a one liter bottle of water at one meter high
- All water must be contained within the device and no water should be spilled
- The car will travel as far as it can go in a straight line

2.2 Market Analysis Summary

Gas prices are pushing the sales of hybrid cars to a new level. Since April 2012, consumers are choosing to buy hybrid vehicles like the Toyota Camry hybrid and the Prius. The Camry hybrid had over a 1000 percent increase in sales since August 2011 until late summer 2012. However the Prius continues to be the top choice for consumers looking to get into the hybrid market with over 13,000 units sold over the past year. Electric cars have become more appealing to consumers. The Chevy Volt is the most popular electric car selling almost 3,000 units within August 2012. Other successors include the Prius PHV and the Nisan Leaf. The number of electric cars that have been sold amount to over 4,700 units in August 2012. From this data, including the table below, the market for alternative energy in cars is climbing.

2.3 August 2012 Hybrid Car Sales Numbers

Hybrids sold in the U.S. (August 2012): **38,369**
Hybrid Take-Rate: **3.0%**

***Note: Vehicles who sold less than 1,000 units have been omitted**

Model	Units	vs. last month	vs. August 2011	CYTD	vs. CYTD 2011
Toyota Prius Liftback	13,311	40.3%	40.2%	106,461	26.9%
Toyota Camry	3,840	20.1%	1,107.5%	30.587	397.2%

Model	Units	vs. last month	vs. August 2011	CYTD	vs. CYTD 2011
Prius c	3,428	11.1%	n/a	22,744	n/a
Prius v	3,325	-1.7%	n/a	29,130	n/a
Chevy Malibu Hybrid	2,414	24.6%	n/a	11,320	47,066.7%
Hyundai Sonata	1,766	-6.5%	-57.3%	14,221	18.1%
Lexus CT 200h	1,472	-1.8%	-29.5%	12,415	67.6%
Lexus RX400/450h	1,170	-0.1%	39.1%	7,917	12.3%
Ford Fusion	1,071	-3.4%	395.8%	7,168	-10.4%
Buick LaCrosse	1,024	18.1%	n/a	8,649	n/a
All hybrids	**38,369**	**21.4%**	**81.2%**	**278,680**	**65.0%**
All vehicles	**1,280,360**	**11.3%**	**19.8%**	**9,678,702**	**14.7%**

2.4 August 2012 Plug-in Electric Car Sales Numbers

Plug-in cars sold in the U.S. (August 2012): **4,715**
Plug-in Take-Rate: **0.37%**

Model	Units	vs. last month	vs. August 2011	CYTD	vs. CYTD 2011
Chevrolet Volt	2,831	53.1%	837.4%	13,497	325.5%
Prius PHV	1,047	52.2%	n/a	6,068	n/a
Nissan Leaf	685	73.4%	-49.7%	4,228	-31.5%
Tesla Model S	71 (est.)	144.8%	n/a	100 (est.)	n/a
Mitsubishi i-MiEV	37	12.1%	n/a	403	n/a
Ford Focus Electric	34	-10.5%	n/a	169	n/a
Honda Fit EV	9	28.6%	n/a	16	n/a

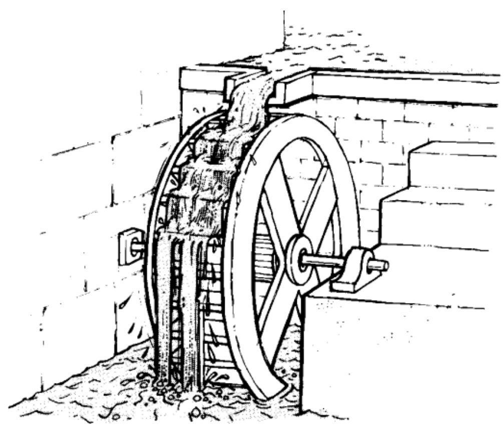
Model	Units	vs. last month	vs. August 2011	CYTD	vs. CYTD 2011
Smart forTwo EV	1	-85.3%	n/a	136	54.5%
BMW Active E	0	100.0%	n/a	673	n/a
All plug-in cars	**4,715**	**54.8%**	**183.4%**	**25,290**	**168.2%**
All vehicles	**1,280,360**	**11.3%**	**19.8%**	**9,678,702**	**14.7%**

Data provided by hybridcars.com

2.5 Design Concepts

In order to convert the mechanical impact of rain fall into useful energy, we have several concepts from which to choose from. These concepts range from high tech solutions to simple water wheels. The following sections will briefly detail each concept, its pros and cons, and if it is a viable method for our rain car vehicle.

Water Wheel (Low-Tech Solution)



Water wheels have been in use since Greco-Roman times with the first literary reference to a water wheel appearing circa 280-220 BC. The water wheels where simple wooden wheels with a central axle. The wheel contained paddles which would be pushed by the force of moving water to produce useful work. In terms of uses, the water wheel was used for milling and irrigation. However, the advent of other more reliable means of production have phased out the water wheel as a viable source of energy.

In terms of mechanical design, a water wheel is a time-tested and proven technology. The fact that it has been used for millennia is a testament to its mechanical design. In terms of mechanical efficiency, the water wheel's axle robs a majority of the energy from the system. While this solution may provide a quick and simple solution, it will not be the best in terms of efficiency and mechanical design.

In addition, water wheels spin relatively slow and in order to fully convert the cyclic motion of the water wheel into useful electricity, the use of a step-up gearbox is vital. The purpose of the gearbox will be to increase the speed of the rotational speed into the generator. Electromagnetic generators are similar to motors in that a non-negligible torque is needed to start rotation and a certain RPM is needed to produce voltage. The voltage, V, generated by a permanent magnet generator at rotational speed is given by the equation:

$$V = K\Phi n\Omega \qquad \text{(eq. 2)}$$

Where K is the electromagnetic constant, Φ is the electromagnetic flux, n is the number of pairs of permanent magnets and windings, and Ω is the rotational speed of the generator. Being that K, Φ, and n is inherent in the design of the generator and cannot be changed, the rotational speed of the generator is the only variable that can be directly affected by outside forces. Equation 2 also shows us that the voltage generated is proportional to the speed of the rotation and thus the faster we can spin the generator, the more voltage we can potentially capture.

Piezoelectric Materials (High-Tech Solution)

A piezoelectric material is one that produces an electrical potential when subjected to mechanical deformation, stress, or vibration. The word piezoelectric is derived from the Greek word *piezien* meaning to squeeze or press. The piezoelectric affect was first discovered in the middle of the 18th century with its first practical application appearing during World War I. Since then, piezoelectric materials have been used as sensors, actuators, motors and have had various military applications.

For use as an energy collector, piezoelectric materials have shown some promise. When embedded in roadways and sidewalks, the impact of a person's foot would generate electricity. For our purpose, drops of water would be used to generate the electrical charge. The effectiveness of a rain energy collector would depend on the effectiveness of the piezoelectric material used. There exist many piezoelectric materials readily available and some can even be created at home.

The difficulty with using piezoelectric materials is their relatively small wattage output as compared to other energy devices. This problem can, however, be overcome in several ways. By increasing the piezoelectric material's surface area, either by using a large sheet of material or by using several smaller sheets, one can alleviate this problem.

The voltage generated from a piezoelectric element is given by the following equation:

$$V = gXt \qquad \text{(eq. 3)}$$

Where g is equal to the piezoelectric coefficient of the material, X is the applied stress in the relevant direction, and t is the thickness of the material.

In order to design a piezoelectric circuit for use in this project, selecting the proper piezoelectric material is crucial. Keeping in mind equation 3, the piezoelectric material we require is one with a relatively high piezoelectric constant. Another consideration is the thickness of the material. While the thickness of the material is directly proportional to the voltage induced, increasing the thickness increases the minimum amount of force needed to induce a voltage. Therefore, we require a piezoelectric material with a relatively low young's modulus and a relatively high piezoelectric constant.

After a thorough search and consultation from outside sources, we have reached the conclusion that a PVDF (Polyvinylidene Fluoride) material would be the best choice for our application.

Water Wheel with Piezoelectric Materials (Hybrid Solution)

One of the major drawbacks to the water wheel design is the large amount of torque needed to initiate movement. If coupled with a gearbox, frictional losses within the gearbox reduce efficiency. In order to circumvent these characteristic problems of a waterwheel, we propose the use of a hybrid solution utilizing both the waterwheel and piezoelectric elements.

Rather than using the waterwheel to drive a generator, the purpose of the waterwheel will be to deform, disturb, and vibrate the piezoelectric elements in such a way as to induce a voltage response. This concept will also solve the problem of synchronizing the impact of rain drops across numerous piezoelectric elements. By hitting each piezoelectric element at the same time, we believe that the voltages generated will be greater and depending on the way the elements are wired together, we can create higher amperages as well.

The hybrid water wheel will consist of two separate pieces; the rotary water wheel itself and a stationary fixture for the piezoelectric elements. The water wheel itself will be designed with pegs or protrusions that will disturb the piezoelectric elements as they rotate past. The downside to this is that the more piezoelectric elements we add to the stator, the more torque will be required from the rotor. Eventually, these negative effects will outweigh the positive effects of using the piezoelectric elements.

2.6 Decision Matrix

In order to predict which idea we will pursue for this project, we compiled all ideas into a decision matrix. Design goals are given scores of out ten as well as a design weight factors. The weight factors indicate which design goals are more important to our design. Each idea only slightly differs from the others. For this reason, several design goals are given the same score. The total score for each idea was tabulated by first multiplying the design score with the weight factor and then summing up each score.

Table 2.6.1 Decision Matrix for the Rain Powered Vehicle								
Ideas & concepts	Design Goals						Total Score by idea	Percent difference from leader
	Sturdiness & strength	Innovation	Electricity generation	Motors & motion	Holding water	Cost		
	Weight Factors							
	80	100	100	80	80	90		
	Score: out of ten							
Piezoelectric only	8	10	10	8	8	6	***4460***	0
Waterwheel only	8	7	7	8	8	8	4040	9.88%
Hybrid solution	8	8	8	8	8	8	4240	5.06%

Table 2.6.1 – Decision Matrix for the Rain Powered Vehicle. This table outlines the major design goals and their associated weighted scores that must be met in order to develop the Rain Powered vehicle.

For this project, we placed an emphasis on innovation and electric generation above all else. In order to power a motor, generation of electric power is vital. As such, the design goal of electricity generation was given a weight factor of 100. The second highest consideration for this project would be cost. We understand that piezoelectric materials can be quite expensive. Without careful consideration as to the type and amount of piezoelectric material we use, the cost of this project could potentially grow out of hand.

From this decision matrix, we can see that the concept of using only a piezoelectricity fulfills all our design goals better than the others. This is closely followed by the hybrid of waterwheels and piezoelectric elements and then by the solution using only a waterwheel. In accordance with this matrix, we will pursue the development of piezoelectricity first and foremost. It should be noted that if after testing, we discover that the piezo-only solution does not fully meet our design requirements, we will fall back onto the other ideas.

3 – Design Proposal

3.1 Description

The Rain Car will utilize the water from a 1 liter bottle and use it to propel a vehicle forward. The water will flow from the bottle passing through an intravenous (IV) drip similar to those used in hospitals. The IV drip will be adjusted so that a steady and constant drip will strike the piezoelectric crystal. Striking the piezoelectric crystal will cause the crystal to generate a small amount of alternating current. The electric current from the crystal will then be used to power a small electric motor. In turn, the motor will propel the vehicle forward.

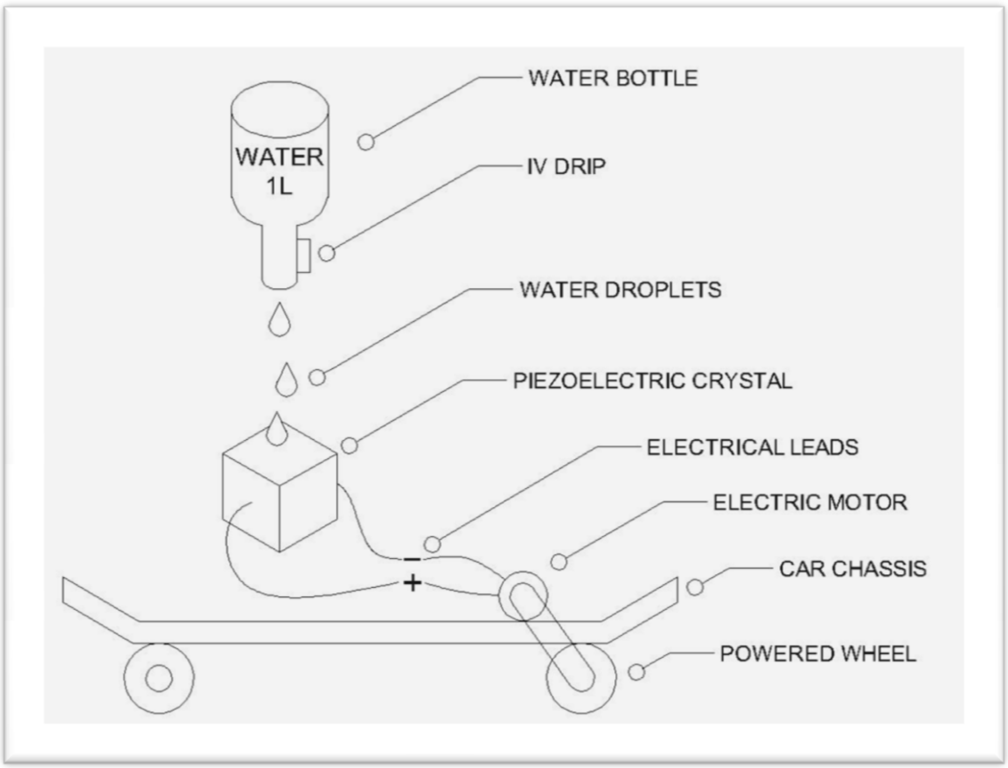


Figure 3.1.1 – Initial concept sketch of the Rain Car Vehicle

3.2 Specifications

The specifications of the Rain Car are as follows:

- 1 liter of distilled water at 1 meter from the floor
- Model car

    - Preliminary design of the car will be a four wheel, rear wheel drive vehicle. Model car will be subject to change.
- Piezoelectric crystals (Rochelle Salt)
    - Piezoelectric material will need to be tested. Other viable materials will also be prepared and tested only if necessary.
- Electric motor and gearbox
- Electrical wiring and circuitry
    - Additional battery may be used to store the electricity generated

3.3 Design Tasks

In order to capture the potential energy in a drop of falling water, we need to develop a device that can convert that potential energy into useful energy. The simplest way will be to use a water wheel to spin a generator. However, this idea has been used many times before and is no longer innovative. For our project, we would need to develop a unique and innovative way to capture the potential energy; that is through the use of piezoelectric crystals. For the rain car prototype to work sufficiently a number of tasks have to be completed:

1) The testing of the piezoelectric crystals. The crystals should be tested to see the output of a certain voltage and to keep that voltage at a continuous rate.
2) The circuitry of the electromechanical system. The feasible circuit board is needed to make sure the right amount of voltage is used to power the mechanical system to drive the car.
3) Flow rate of the water. A continuous flow would be needed to make sure the car is self-sufficient.
4) The design of the system to fit onto the car.

3.4 Barriers

Several barriers stand in the way of our completion of the Rain Car. These barriers are shown below:

1) Picking the right piezoelectric materials to make sure they have the right shape and have the correct chemical makeup.
   Solution: Conduct tests and seek advice from chemists

2) Making the water flow continuous.
   Solution: Look into designing a siphoning system

3) Making sure the weight to size ration is compatible with the car.
   Solution: Design the electromechanical system around the specifications of the car.

The development of the piezoelectric crystal is a major barrier to overcome. Originally, we planned to create the crystals ourselves using over the counter and readily available ingredients. However, due to questions about the purity and size of the crystals, piezoelectric crystals were abandoned for a more reliable material.

The piezoelectric material which we will be using is known as poled PVDF (Poly-vinyl Di-fluoride) polymer film. The PVDF is currently used as transducers and is reported to be 10 times more viable as a piezoelectric material than the Rochelle salts. Additionally, by being a poled material (having a north and a south), the PVDF will allow current to flow through it. The various properties of poled PVDF are outlined in table 3.4.1 and include the mechanical, electrical, and piezoelectric properties of the material.

Table 3.4.1 Properties of PVDF Material		
Description	Semi-crystalline polymer consisting of crystallites embedded within amorphous polymer chains	
Mechanical Properties	-	- - -
Density	ρ	1780 kg/m^3
Melting Temperature	T_m	175 – 180 deg C
Glass Transition Temperature	T_g	-42 deg C
Young’s Modulus	E	8.3 GPa
Bulk Modulus	K	4.3 GPa
Shear Modulus	U	3.5 GPa
Poisson’s Ratio	v	0.18
Piezoelectric Properties	-	- - -
Piezoelectric coefficient	d	6 – 7 pC/n
Maximum Usable Temp.		75 – 110 deg C
Electrical Properties	-	- - -
Dielectric constant	ε_r	10 - 12

Table 3.4.1 – Properties of PVDF Material. Mechanical, electrical, and piezoelectric properties of the material are shown.

3.5 Cost Analysis Summary

When designing the Rain Car, one of the design considerations was to keep costs to a minimum. In order to achieve this, many of the parts and raw materials were taken from things currently available from around the shop. The machining processes and equipment needed are also provided and readily available in the shop. This keeps the cost of producing our prototype to a minimum. The only area which would incur expenses is the purchase of the PVDF piezoelectric material. The price at which we purchased our PVDF material was $40 for 10 PVDF transducers. In total, the proof of concept Rain Car can be assembled for less than $100 excluding equipment costs and labor.

Material cost – Prototype Car Only

Table 3.5.1 Cost Analysis Summary				
Description	Responsible	Cost	Deliverables	Pick-up
PVDF Piezoelectric	Shaul	$40	10 PVDF elements	Shaul
Electrical Components	Fritz	$20	Assorted electrical components	Fritz
Raw Building materials	Ethan	$40 (est.)	Aluminum sheets, PVC Tubing, asstd. hardware	Ethan
Other materials	Roy	$20 (est.)	Design Notebook, electrical wires, breadboard, etc.	Roy

Table 3.5.1 – Cost Analysis Summary. The cost of various items associated with the design of the rain powered vehicle. (est) denotes the estimated cost the item.

3.6 Risk Assessment Matrix

As with all projects, a certain level of risk is inherent and cannot be avoided. Identifying risks early in the product life cycle, though, can help mitigate the consequences of these risks. To aid in identifying project risks early on, a risk assessment matrix is often used. A risk assessment matrix classifies each risk and ranks them in terms of their likelihood, degree of impact, action trigger, and response plan. Table 3.5.1 shows a risk assessment matrix for our Rain Car project.

Table 3.6.1 Risk Assessment Matrix					
Project Assumption	Risk	Likelihood of occurrence	Degree of impact	Action Trigger	Response Plan
Using Lab	Unable to make the product	Low	Low	Staff doesn't not trust the students	Make the product at home or go with plan B
Plan A Piezoelectric materials	Deformation and the crystals is small (the bigger the better)	High	Middle	Cooling	Remake the Piezoelectric materials
Plan A Piezoelectric materials	Piezoelectric materials generate lower than expected	High	High	Testing indicate low voltage and amperages	Increase the number of piezoelectric elements

	power				
Plan B Waterwheel	Time	High	High	Starting it late	Put more time into it.
Plan C Hybrid	Too many piezo retard movement of the rotor	Moderate	Moderate	Water wheel does not rotate	Redesign rotor and/or stator
Electrical Circuit	Electrical circuitry becomes too complex	High	Moderate	Difficulties in understanding or making the circuit	Design a simpler circuit. Enlist outside help

Table 3.6.1 – Risk Assessment Matrix. The risks associated with this project are outlined in this table. Low, moderate, and high represent the severity of likelihood and degree of impact.

3.7 Task Schedule

Scheduling is a part of every design project and this particular project is no exception. To ensure the project stays on track, several important dates are listed in table 3.7.1. A Gantt chart that illustrates the project schedule is also shown in figure 3.7.2.

Table 3.7.1 Key Dates and Events

Activity	Respond	Estimation Duration	Date	Description
Meeting	All	3 hours	August 27,2012	Choosing the project
Meeting	All	3 hours	September 3, 2012	Finalize the agree to choices of our project and coming up with back up plan
Meeting	All	3 hours	September 10, 2012	Assigning task to the group members
Meeting	All	3 hours	September 17, 2012	Talking to staff about using the Equipment
Meeting	Shaul/Fritz	1 hours	September 24, 2012	Finalize talking to Chemistry Chairman on using the lab
Design Proposal	All	N/A	September 10, 2012	Assignment 1: Design Proposal Due
Preliminary Report	All	N/A	September 24, 2012	Preliminary Design Report due
Intermediate Report	All	N/A	October 29, 2012	Intermediate Design Report due
Comprehensive Report	All	N/A	December 3, 2012	Comprehensive design report due
Final Report	All	N/A	December 21,	Final Design Report

			2012	due
Final Presentation	All	3 hours	December 21, 2012	Final Presentation. Project completion

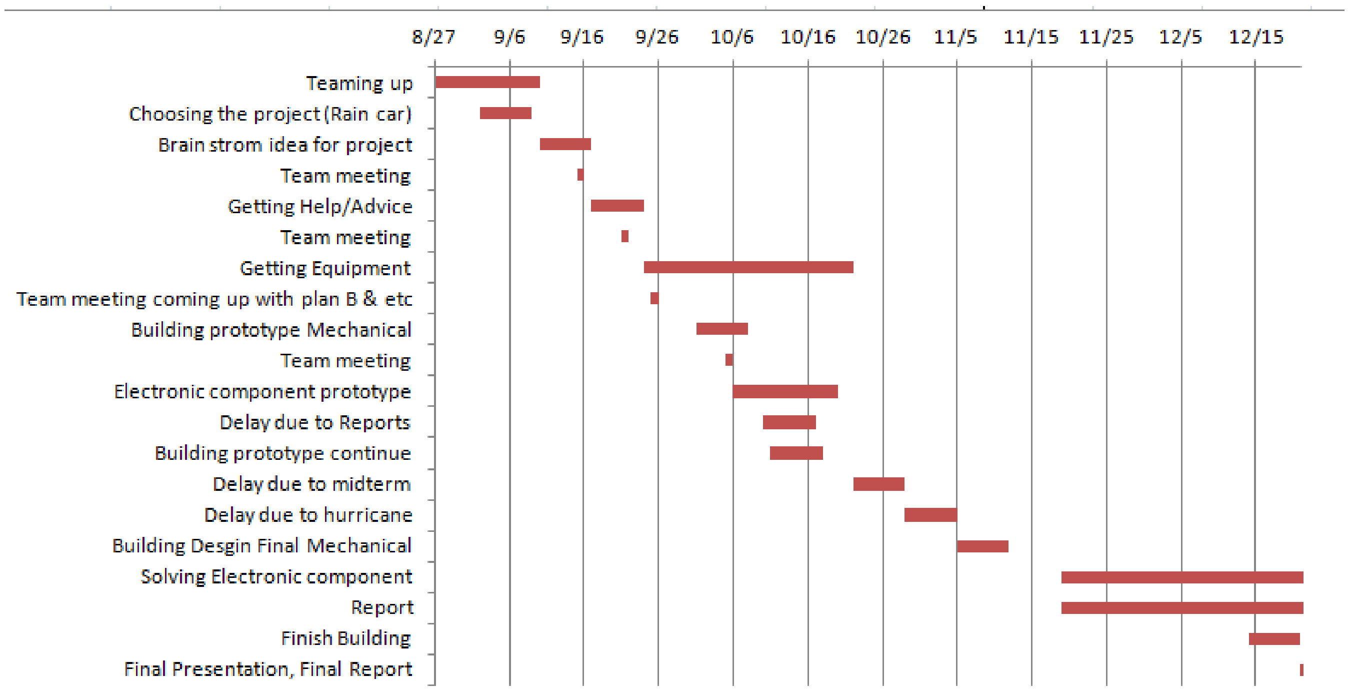


Figure 3.7.2 – Gantt Chart for the Rain Powered Vehicle Project showcasing the events, dates, and duration of each activity.

4 – Detailed Product Design

4.1 Assembly Model and Drawing

As previously stated, our rain car will utilize piezoelectric materials to gather the energy from falling water to generate electricity. The intention of the rain powered vehicle to drive forward in a straight line for as far as it can go. The only source of power allowed is a one liter bottle to water held at one meter above the vehicle. Incorporating these ideas into a single design, we arrived at the design shown in the figure 4.1.1 below:

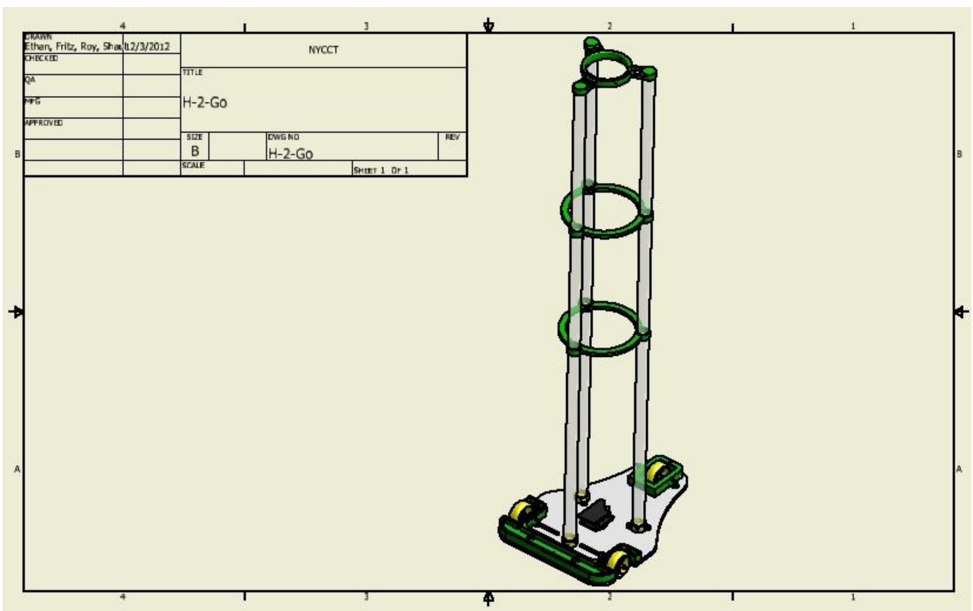


Figure 4.1.1 – H2GO Rain Powered Vehicle (Tentative Name) Final Product Design

The piezoelectric materials we will be using for this product will be PVDF (Polyvinylidene fluoride) which comes in the form of PVDF transducers. These transducers and appropriate dimensions can be seen in the figure below:

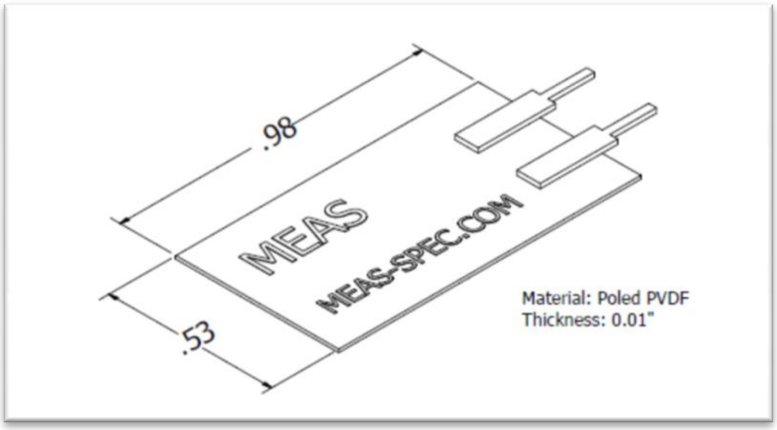


Figure 4.1.2 – Part Drawing of PVDF Transducer

In order to hold the PVDF transducers, a fixture must be created. The fixture must hold each transducer secure while also arranging each in a circular pattern. The holder can be seen in the figure below:

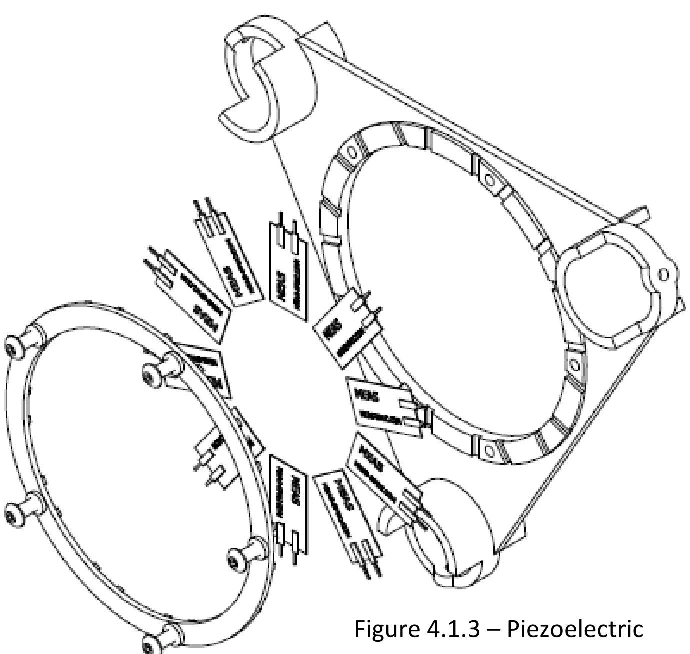


Figure 4.1.3 – Piezoelectric Holder Exploded View

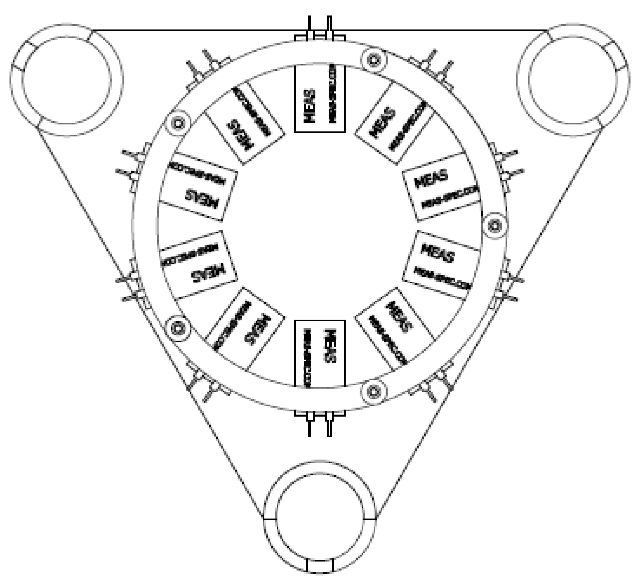


Figure 4.1.4 – Piezoelectric Holder Front View

The rest of the vehicle is to be made out of parts that must be cut on a water jet machine or printed on a 3D printer. The drawing files for these parts are shown in the various figures below.

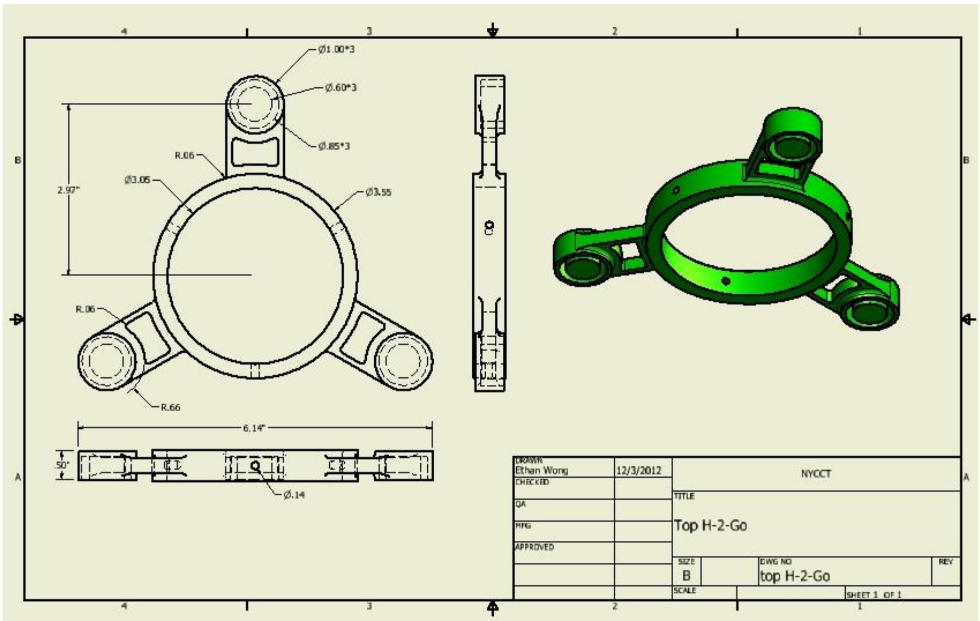


Figure 4.1.5 – Vehicle Chassis Layout. Chassis will be the base for the entire car.

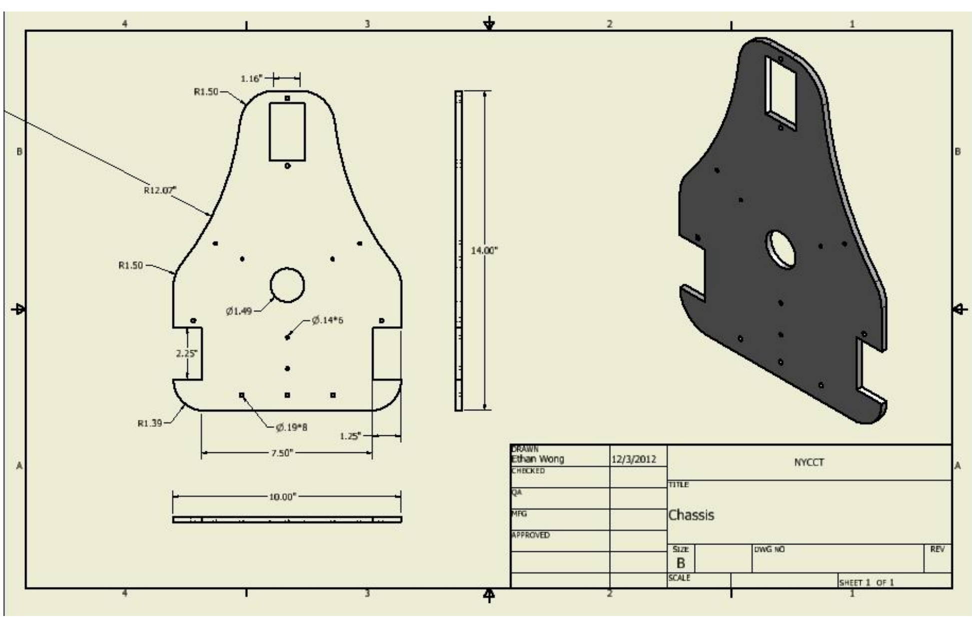


Figure 4.1.6 – Water Bottle Holder located at top of vehicle.

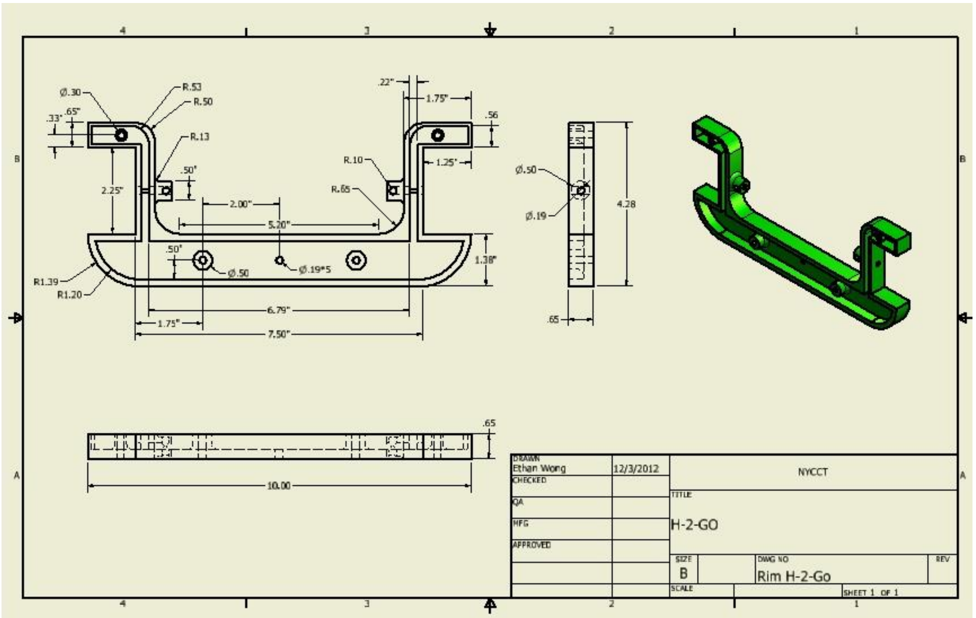


Figure 4.1.7 – Vehicle Wheelbase. Part used to attach wheels onto chassis.

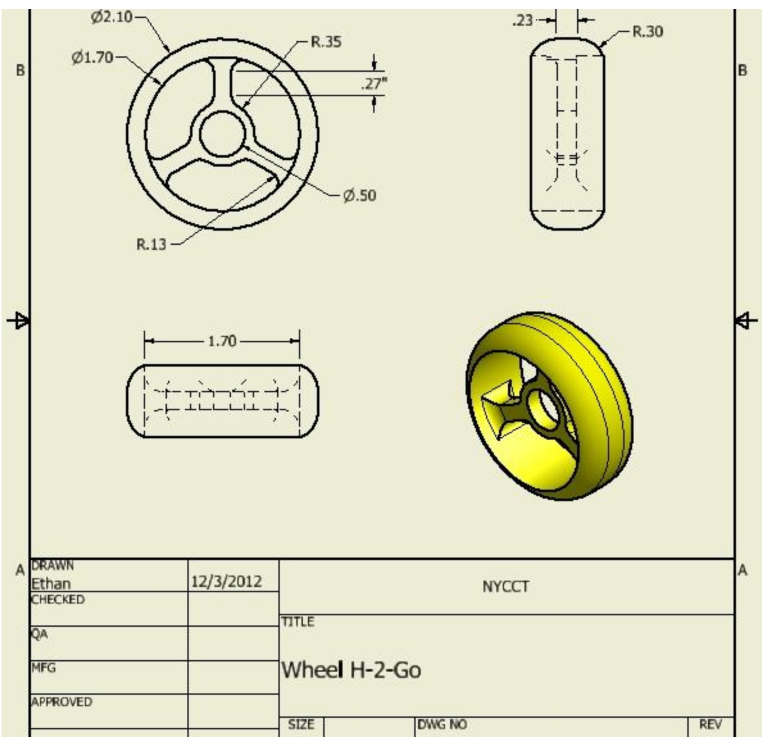


Figure 4.1.8 – Wheel and rim printed as one part. Ball bearing to be added to reduce friction.

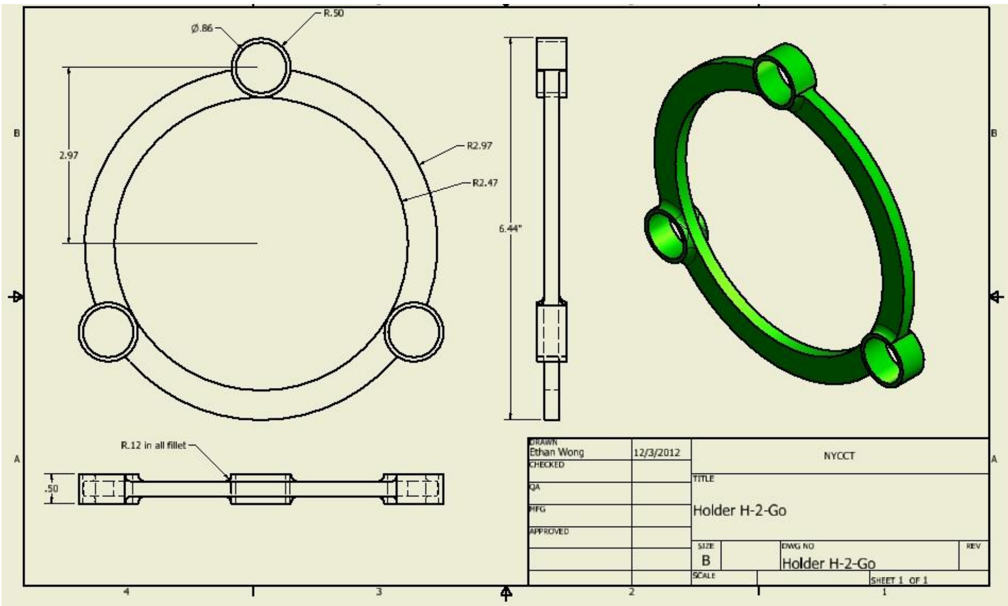


Figure 4.1.9 – Structural Bracing for PVC columns. Used to prevent buckling.

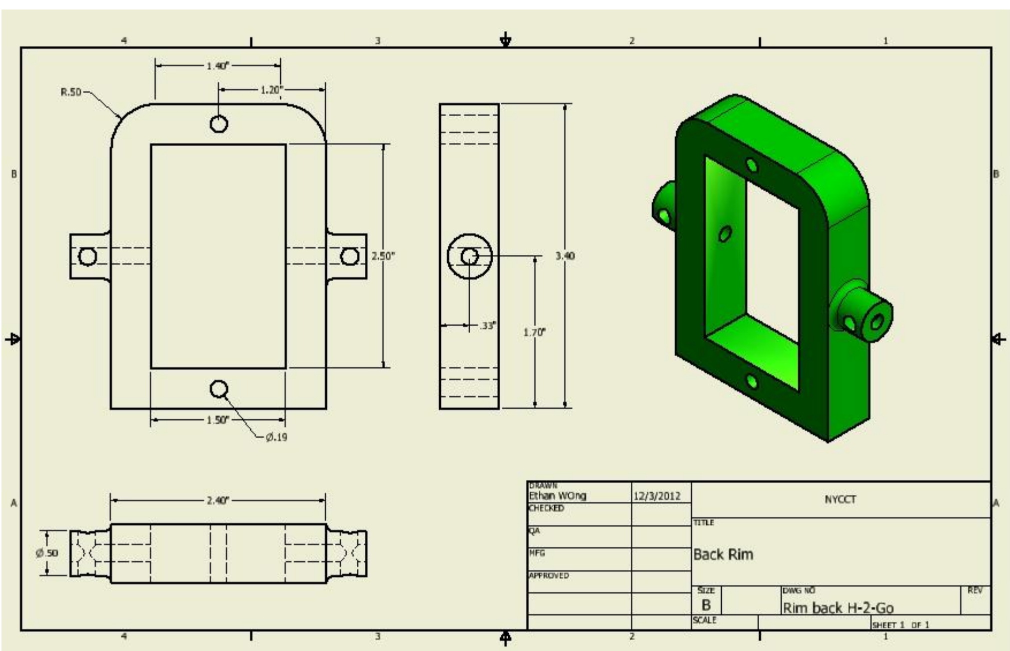


Figure 4.1.10 – Front wheel holder.

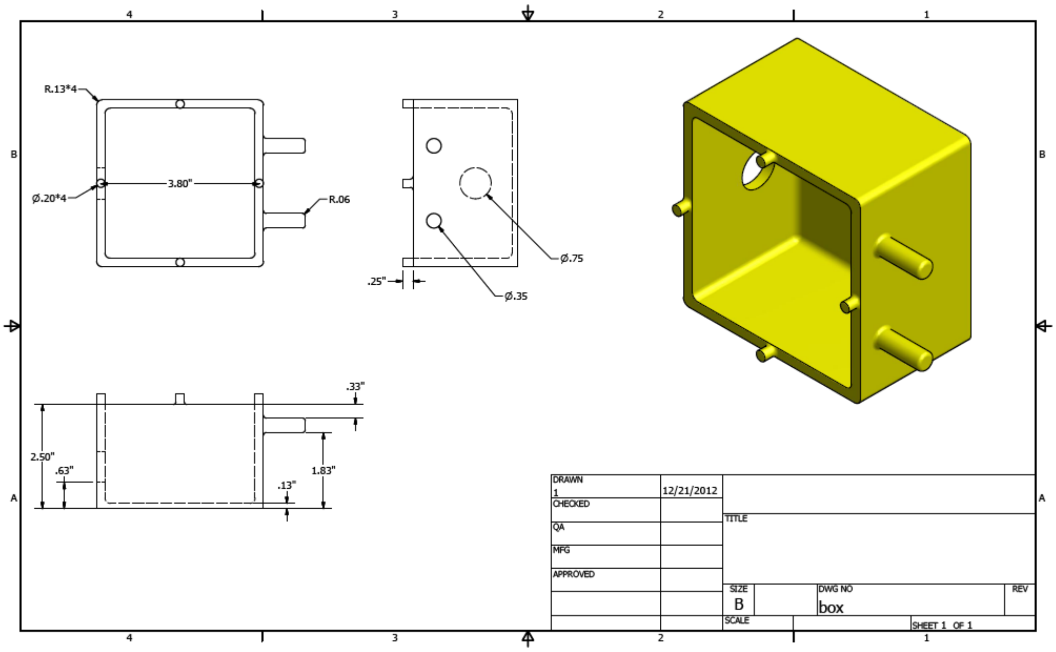


Figure 4.1.11 – Sealed box for circuitry

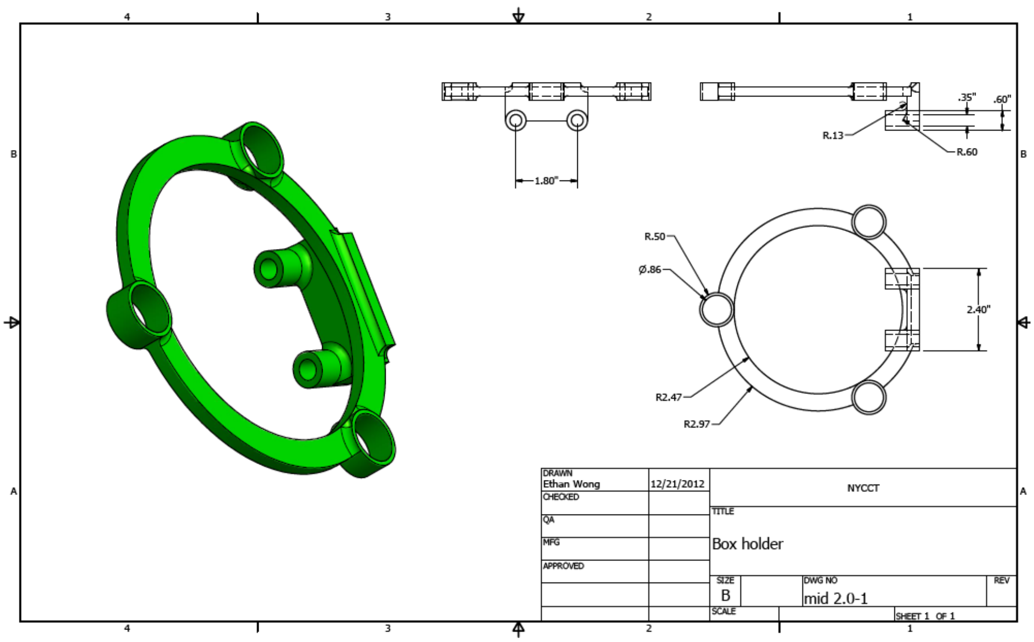


Figure 4.1.12 – Fixture for attaching box to the chassis

4.2 Circuit Design

As stated previously, a circuit must be created in order to maximize power output of the piezoelectric material and also to capture, store, and release the electricity generated. Before we begin designing the circuit, we need to know the electrical behavior of the PVDF piezoelectric. To do so, we bench tested the PVDF films using an oscilloscope and a testing rig. The setup is shown in the figure below:

Figure 4.2.1 Piezoelectric testing setup. Shown on left is the oscilloscope used to measure the voltage and current from the piezoelectric. Shown on right is the piezoelectric array with 5 PVDF transducers.

The testing data of the PVDF films is shown in figure 4.2.2. The piezoelectric film in figure 4.2.2 was attached directly to the oscilloscope. From this initial test, we can see that the max voltage generated was 11.1volts with a RMS (Root Mean Square) of 1.06volts. We can also see that the voltage response of the PVDF film resembled a damped AC sine wave.

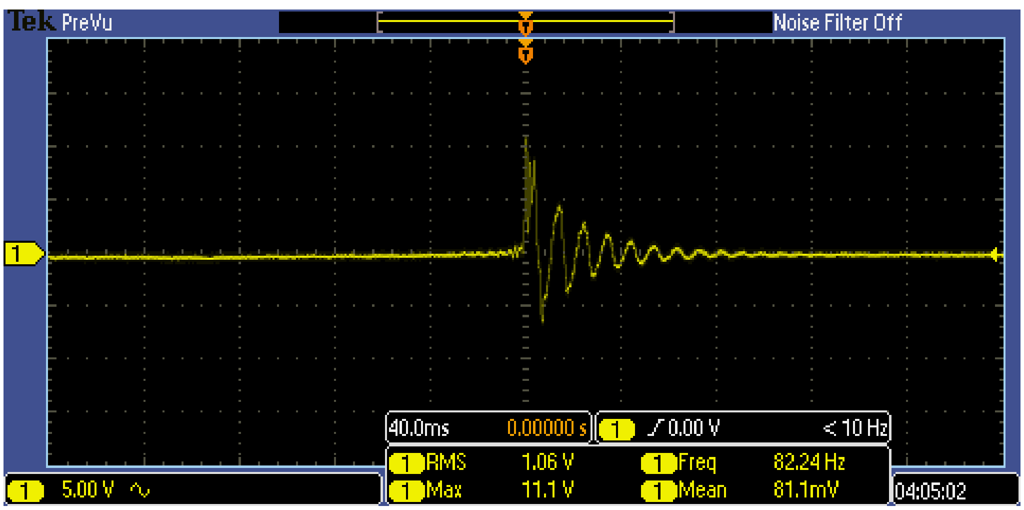


Figure 4.2.2 – AC response of piezoelectric film

The AC wave from figure 4.2.2 presents a slight drawback in that the AC current must first be rectified before it can be used. In order to utilize this current to run a motor, we need to rectify the AC current first. In order to accomplish this, we plan to use a circuit known as a diode bridge or full-wave rectifier. A simplified diagram of the diode bridge is shown in figure 4.2.3. Alongside an image of the circuit we made in figure 4.2.3. The screen capture of the diode bridge on the oscilloscope is shown is figure 4.2.4.

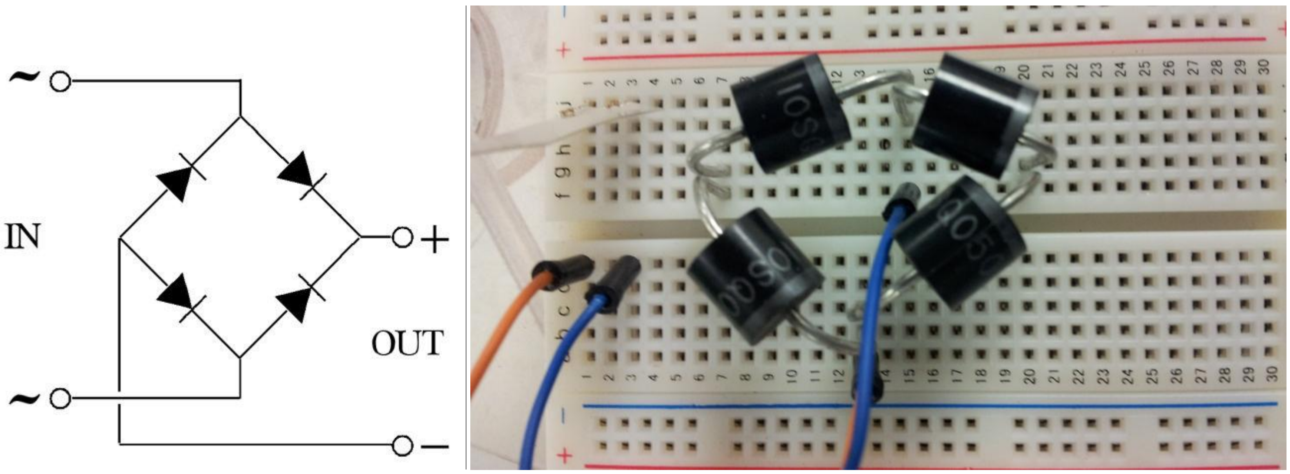


Figure 4.2.3 – Shown on left is the wiring diagram for a diode bridge. Shown on right is the actual circuit on a solder-less breadboard

The screen capture of the diode bridge on the oscilloscope is shown is figure 4.2.4. We can see that the voltage has been rectified meaning that the output is only positive voltage. We can also see that both the max and RMS voltage has been reduced significantly due to passing through the diode bridge. This is an inherent property of all diodes known as forward voltage and cannot be neglected.

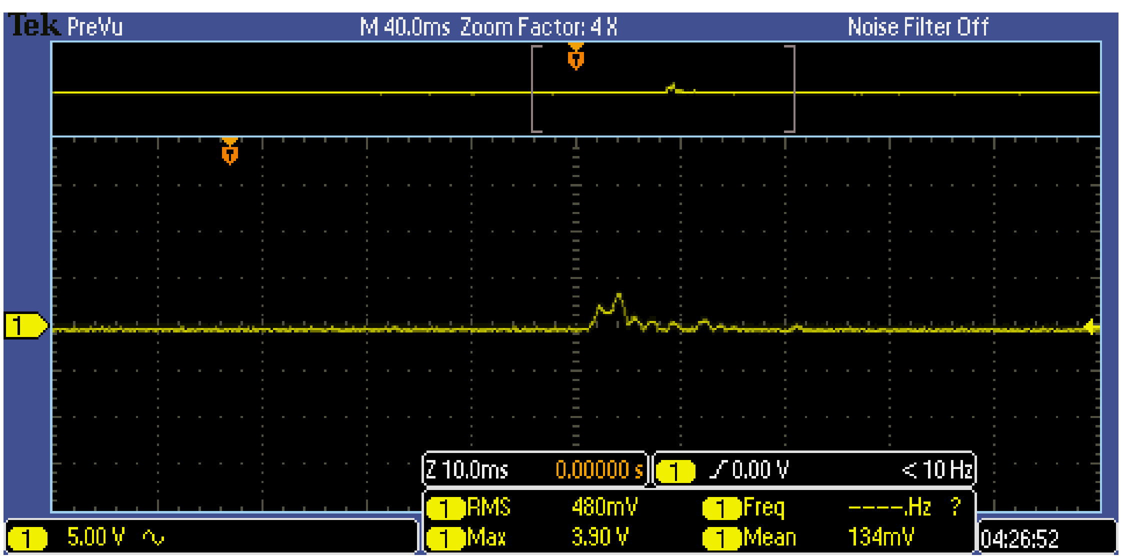


Figure 4.2.4 – Screen capture of voltage response through a diode bridge.

The test was run again on the same circuit, this time testing for current. We can see in figure 4.2.5 that the maximum amperage reached was 3.3A with an RMS of 434mA.

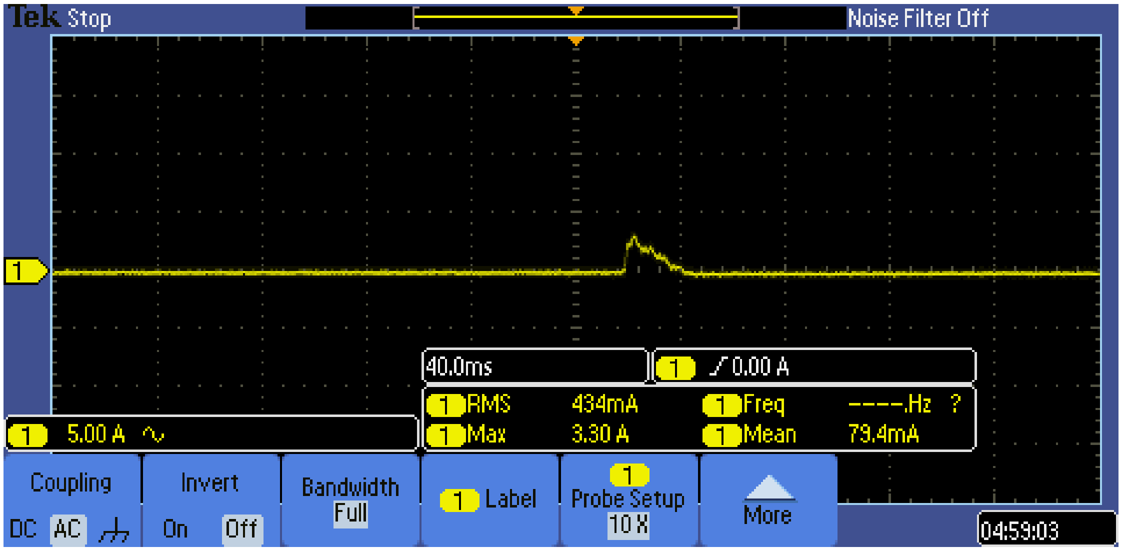


Figure 4.2.5 – Screen capture of current response through a diode bridge

From these initial tests and using the RMS values we received, we can calculate the power generated by a single piezoelectric element. From equation 4 below, the power can be calculated as:

$$P = I \cdot V \qquad \text{(eq. 4)}$$

Where P is the power in watts, I is the current, and V is the voltage. From this equation 4, we get that the power generated by a single PVDF element is 0.21W.

In order to capture and store the electricity created from the piezoelectric element, capacitors that store charge will be added into the circuit. The capacitors also prolong the pulse generated by the piezoelectric element. A circuit diagram shown in figure 4.2.6 is an optimized version of a piezoelectric charging circuit. A diode bridge is represented by the four diodes in the circuit. The circuit in figure 4.2.6 also contains a transistor and an inductor to maximize the power output of the piezoelectric. For our purposes, a simplified version of the circuit in figure 4.2.6 will need to be developed.

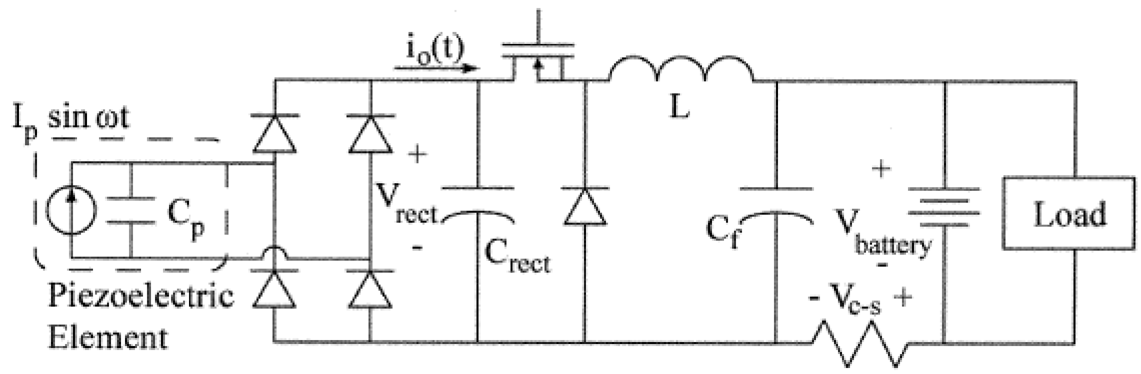


Figure 4.2.6 – Optimized piezoelectric energy harvesting circuit

The elements in the circuit which we would like to preserve are the diode bridges and the capacitance storage. While many capacitance storage circuits utilize super-capacitors, capacitors with large values of capacitance in the order of tens to hundreds of farads, we will be using multiple smaller capacitors in parallel. By placing several smaller capacitors in parallel, we can increase the capacitance of the entire circuit. The circuit is shown in figure 4.2.7. A switch is also added into the circuit to allow for charging and discharging of the capacitors. When the switch is open, the capacitors store the charge from the piezoelectric array. When the switch is closed, all the charge that has been accumulated will be released at once. A close-up of the piezoelectric array is also shown in figure 4.2.8.

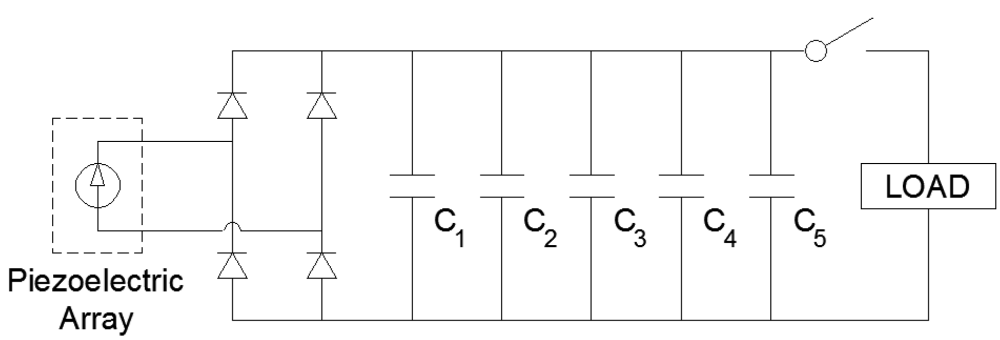


Figure 4.2.7 – Simplified piezoelectric energy harvesting circuit with storage capacitors

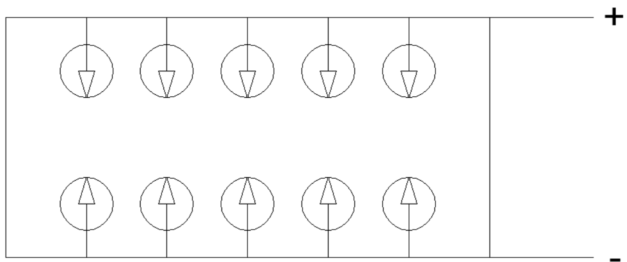


Figure 4.2.8 – Close up view of piezoelectric array

Being that we are using capacitors, the charging and discharging times become an important factor. We wish to maximize the discharge time while minimizing the charging time. In addition, the current and voltage from charging and discharging a capacitor are functions of time and follow the equations shown below:

$$i_c = \frac{E}{R}e^{-t/\tau} \quad \text{charging} \qquad \text{(eq. 5)}$$

$$v_r = E(1 - e^{-t/\tau}) \quad \text{charging} \qquad \text{(eq. 7)}$$

$$i_c = \frac{E}{R}e^{-t/\tau} \quad \text{discharging} \qquad \text{(eq. 8)}$$

$$v_r = Ee^{-t/\tau} \quad \text{discharging} \qquad \text{(eq. 9)}$$

Where E is the voltage, R is the resistance, τ is the time constant, and t is the time.

The time it takes to charge and discharge the capacitance circuit is given by equation 10.

$$T = RC$$

Where T is the time in seconds, R is the resistance, and C is the capacitance.

5 – Manufacturing Plan

5.1 Facility

The Voorhess building of Citytech proves to be the most cost-efficient and readily available space for manufacturing this product. In the past it has proven capable in the development of robotics, prototyping, machining, testing, designing, and other engineering activities. The fifth floor of the building contains resources that match other manufacturing centers throughout the country. The facility also contains professionals with expertise in various backgrounds such as manufacturing, mechanical engineering, electrical engineering, and more. Recognition has come from a number of organizations and institutes some of which include Accreditation Board for Engineering and Technology (ABET), The National Aeronautics and Space Administration (NASA), the American Society of Mechanical Engineers (ASME), and the National Science Foundation (NSF).

5.2 Staffing

There will be a four man team working on the production of the rain car. At least two of the staff members will be available at the facility to work on the car. One person will be responsible for directing the work and aiding with the production. Documentation and scheduling will fall under the responsibility of at least two people. Consultation will be provided by a professional in mechanical engineering.

5.3 Materials

The following list of materials will be used:
1 liter container
Drip chamber
4’ by 3’ Plexiglas
1+ meter PVC pipe
Chassis (1’x 6”)
Motor (12V)
Bearings
Piezoelectric microphone transducers
Wires

5.4 Manufacturing Process

<u>Model Car</u>

Chassis

A) The chassis is designed using a 3D design software (Autodesk Inventor). The overall dimensions of the chassis have 10 inch by 14 inch boundary with various slots. Also a 1.49 inch hole is provided to house the motor (figure 6).
B) The aluminum stock was placed in the water-jet machine (OMAX). The file is converted into a dxf. file for the machine’s computer to read. After zeroing the machine to the end of the

stock, the program will pick up the information from the file and begin to cut and shape the chassis.

C) When the water-jet is finished cutting, the piece has to be deburred.

Container

A) The 1 liter container was connected to the IV drip; also a small cloth was put over the drip to control the volume of drops.

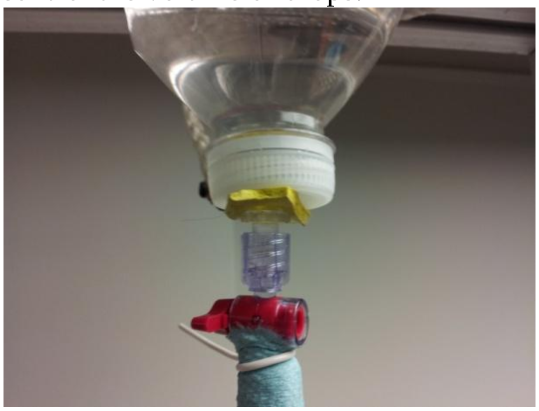


Figure 5.4.1– Container with IV drip and cloth to control droplet volume

Container holder

A) Using the same 3D software, the holder is designed using specified dimensions (figure 7).

B) The file is then converted to stl. file format for the 3D printer (Dimension).

C) The printer is checked to make sure enough polymer material is available for the piece. Then the machine is zeroed for the program to pick up the information from the file.

Circuitry

Breadboard

A) The circuit was put together according to the schematic in figure 4.2.7. The capacitors were put together in parallel. The four diodes were put together in series to form a rectifier bridge.

6 – Product Safety Analysis and Improvement

6.1 FMEA

The FMEA (Failure Modes and Effects Analysis) is a step-by-step procedure to identify all possible failures and their effects in a particular design or product. The Failure Mode portion of the FMEA looks for the ways in which the part may fail. Failures include errors in the parts that may lead to catastrophic breakdown, malfunction, or possible injury. The Effects Analysis is more focused on the consequences of the product failing. The effects are broken up into three sections; severity, occurrence, and detection. Each section is given a number value ranging from one to ten that indicate the extent to which the effect is harmful. A rating of 10 would indicate catastrophic failure while a rating of 1 would indicate little to no hazard. A final RPN (Risk Priority Number) is then calculated. The FMEA conducted for the rain car is shown in the table below:

Table 6.1.1 Failure Mode and Effect Analysis									
Failure Mode		Severity		Occurrence		Detection			
Function	Potential Failure	Effect	Rating	Causes	Rating	Tests	Rating	RPN	Recommended Action
Hold Water	Water Bottle may leak	Water Spillage, short circuits	7	Poor Material	8	Leak test before every start	1	56	Check bottle for leaks
Stable Chassis	Vehicle may tip over	Damage to all parts	7	Center of gravity no in center	5	CAD analysis of chassis	1	35	Wheelbase to be enlarged
Circuitry	Voltage overload	Damage to all circuits	5	Poor circuit design	2	Testing of prototype circuit	5	50	Create circuit protection device
Electronics	Electrical Shortage	Damage to all electronics	5	Electronics not protected	3	Check for water leaks	3	45	Protect electronics
Columns to support water	Buckling of Column due to weight of water	Damage to vehicle, water spillage	3	Poor material	3	Buckling test to be performed	3	27	PVC to be replaced with composite

Table 6.1.1 – Failure Mode and Effect Analysis. FMEA of Rain powered vehicle project.

From the FMEA above, the RPN indicates that the leaking of the water bottle poses the greatest risk to our project. Leaking water is also the root cause of many of the other problems listed in the FMEA. However, since the vehicle is designed to simulate rain fall, leaking of the water cannot be prevented. Special precautions must thus be taken to prevent the effects of falling water on other components. To do so is a simple task as many of the other components can be insulated easily.

6.2 Areas of Improvement

As with all design products, areas of improvement will become apparent throughout the course of the design process. This project is yet again no exceptions and various areas of improvement exist. These improvements direct result from limitations encountered throughout the course of the project.

In terms of the design of the vehicle, all steps were taken to minimize weight without sacrificing the strength of the entire product. The limitation faced when designing chassis of the rain powered vehicle was the equipment and material available to us. While we did make use of lightweight aluminum and polymer materials, we would have liked to have used composite materials with higher strength-to-weight ratios that aluminum or plastics. The use of composites would have required tools and equipment not currently available to us. If in the future, however, we were given access to composite fabrication, we could lower the weight of the chassis without sacrificing the performance. We believe that a lighter vehicle would reduce the torque required to initiate and sustain motion.

The next area of improvement would be the PVDF film used in the project. We purchase ten PVDF transducers with a total combined surface area of 5.2 in^2. By purchasing a single sheet of piezoelectric material, the effective surface area of the energy collector can be maximized and thus result in greater power recovered from the falling rain. The major downside is of course the cost of a sheet of piezoelectric material. This is further hindered by the greatest limitation of the entire project; that is the relatively small budget allocated for our project. It is the belief of this design team that if we were given a much larger budget, we could have purchased additional piezoelectric materials that would have helped us out tremendously.

Another area of improvement is in the circuitry we developed for this project. While the members of this design team are familiar with electronic components and circuits, we eventually reached a point when our understanding of electrical engineering has reached its limits. Team members did elicit help from knowledgeable individuals with electrical engineering backgrounds. Our understanding of advanced electrical circuits was enhanced thanks to these individuals but we still, unfortunately, lacked many of the electrical components needed to develop the more advanced circuits. For future improvement of the rain powered vehicle, we wish to purchase these electrical components from various vendors online. With these components in our possession, we would have been able to develop optimized circuits for our product.

7 – Conclusions

7.1 Conclusions

The design of the Rain Car was both a challenging and rewarding project for those involved. Through our struggles, mistakes, and successes, we were able to attain greater know in the field of piezoelectricity.

The design of the chassis for the rain powered vehicle completed its design objectives. The chassis is lightweight yet robust and small yet sturdy. The height of the vehicle does not impede its performance and due to the wide wheel-base, the vehicle will not easily tip over. The chassis was also designed to be as frictionless as possible to facilitate its movement along the ground. The smooth bearings and small plastic wheels incorporated into the design results in the rain powered vehicle to move effortlessly across a smooth surface.

The motor chosen to propel the vehicle was a small 1.5V toy motor with a reduction gearbox. While the output torque of the motor is very low, 0.5mN*m without the gearbox, due to the low rolling friction of the wheels, it is sufficient enough to move the vehicle forward. Even with the vehicle fully loaded and carrying the weight of the 1-Liter bottle, the vehicle would still inch forward.

The piezoelectric elements used in the rain car project work admirably to generate electrical charge per drop of water. The piezoelectric elements alone cannot power the motor. With that being said, by utilizing the piezoelectric elements to generate charge, the motor can be powered by way of the piezoelectric materials. The downfall of the piezoelectric harvesting system, in our case, was the circuitry involved with storing the charge. We had initially believed that capacitance storage would have powered our vehicle. Within the electrical engineering community, capacitance will soon replace batteries as portable sources of energy. Our system sought to capitalize on this new movement and while we were able to capture and discharge enough current to move the motor, it would not be for prolonged periods of time.

Throughout the course of this design project, team members were constantly challenged to go above and beyond current designs. Team members also pushed the limits of their engineering abilities to see the innovative rain car project to completion. In doing so, members built upon previous research of the past and recommendations made here will be able to help further the knowledge in this field.

7.2 Acknowledgement

Our project would not have been successful without the help of the following people. Our team would like to sincerely thank:

- Aidan Murphy, CET/EMT Student, NYCCT
- Ali Harb, CET/EMT Student, NYCCT
- Peter Spellane, Chairman of the Chemistry Department, NYCCT
- Angran Xiao, Professor of Mechanical Engineering, NYCCT
- Bijan Bayat-Mokhtari, MET Student, NYCCT

Appendix A – Glossary of Terms

Series Circuit

Components in a series circuit are connected in a single path. Different components of a circuit behave in a certain when connected in series. For example resistors connected in series are added together to form a greater resistance. Also voltage sources are added to make a greater voltage when connected in series.

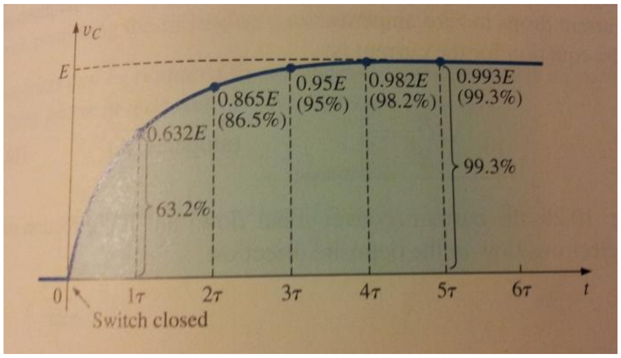
Parallel Circuit

Components connected in parallel when "two elements, branches, or circuits are in parallel if they have two points in common." Some components that are in parallel are added together to form a greater sum (Is= I1 + I2 + I3 + ...). Other components are summed up with their reciprocals (RT = R1 + R2 + R3 + ...)

Capacitor

A capacitor holds the charge of the supplied voltage so that it can be returned to system. The unit for capacitance is farads. When a capacitor is charging this formula is considered:

$$v_C = E(1 - e^{-t/\tau}) \text{ (volts, V)}$$



where E = supplied voltage

τ is the time constant, which is the amount of time it takes the capacitor to charge to a certain percentage. The formula for the time constant is:

$$\tau = RC \text{ (time, s)}$$

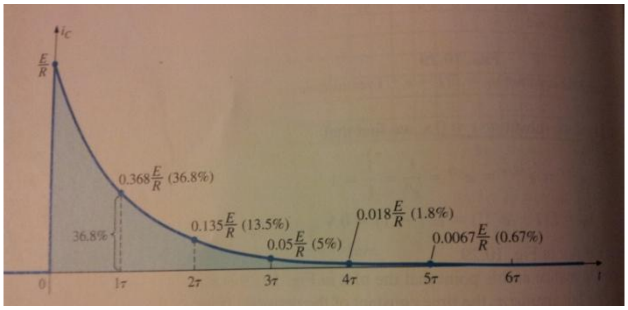
where R = resistance; C = capacitance

After five time constants the capacitor has the same voltage as the voltage source.

The current going to a capacitor while it is charging has the formula:

$iC = E/R\ e^{-t/\tau}$ (amperes, A)

When the current is flowing toward the capacitor while its charging the current goes to zero amperes.

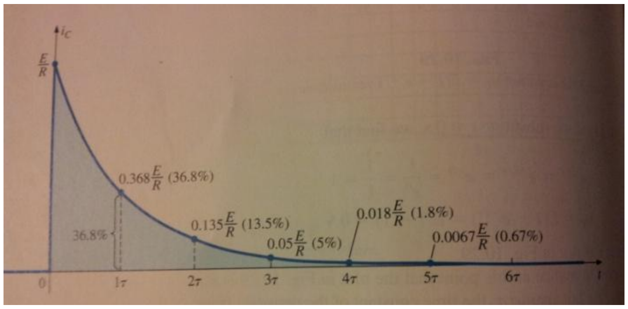


The following formulas are used when the capacitor is discharging:

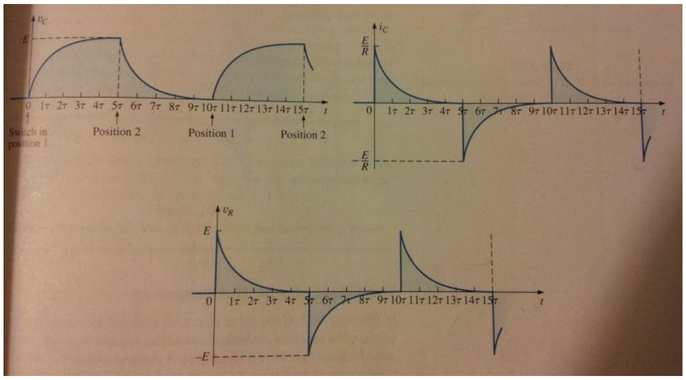
$vC = Ee^{-t/\tau}$

$\tau = RC$

$iC = E/R\ e^{-t/\tau}$



The opposite happens to the voltage and current during the discharge phase.



<u>Diode</u>

A diode is a two terminal semiconductor that has the ability to allow current flow in one direction and block it from flowing in the opposite direction.

3D printer

A 3D printer is manufacturing device that goes through an 'additive' manufacturing process. This process builds a model layer by layer saving a lot of time and material. As oppose to a traditional 'subtracting' manufacturing (cnc machining, lathe, milling, etc.), which waste a lot of material to get to the finished component.

Water jet

A machining method that uses a jet of pressurized water containing abrasive powder for cutting steel and other dense materials.

IV drip

An intravenous drip is used as a short-term method to rehydrate a patient or give them medicine or nutrients to revitalize them. It's a very efficient process to quickly supply the entire body with prescribed medicine. IV drips are routinely used in hospitals as well as in clinics and doctor’s offices that prepare patients for admittance to hospitals.

Oscilloscope

A device for viewing oscillations, as of electrical voltage or current, by a display on the screen of a cathode-ray tube.

Multimeter

An instrument designed to measure electric current, voltage, and usually resistance, typically over several ranges of value.

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