Capstone Project – Harvesting Vehicular Kinetic Energy Using Piezoelectric Sensors

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Abstract

Road pavements sustain numerous times of vehicle passage each day. The kinetic energy of vehicle motion can be captured, harvested, and converted into electricity for decentralized roadway lighting and operation of traffic lights. Application of piezoelectric technology is a promising method to harvest mechanical energy of vehicles which otherwise is dissipated as heat. The primary objective of this Capstone project was to design an energy harvester using a network of piezoelectric sensors to capture the kinetic energy of vehicles and generate electricity to charge a battery. The team was formed by engineering students with different majors. They were tasked to compare alternative designs considering the overall shape and size of the harvester and the arrangement of internal components. The present contribution outlines the design process based on a feasibility and merit analysis. Discussion includes social, technical, and economic challenges of using piezoelectric technology and its integration with transportation infrastructure.

Keywords

Capstone project; Energy harvesting; Vehicle motion; Piezoelectric sensors.

Introduction

An important aspect of Capstone Design projects for engineering students is to prepare them for challenges of emerging technologies. Working on open-ended and multidisciplinary projects that address real-world problems will instill confidence and increase excitement in students in the formative year of their education. Harvesting of ambient energy is a process during which energy is extracted from external sources and transformed into electricity. The is an emerging field of study for engineers as the demand for energy surges. Finding creative methods to harvest energy and increasing the efficiency of harvesters are ideal subjects for engineering Capstones.[1]

Harvesting the kinetic energy of vehicles and converting it to electricity is a promising way for renewable supply of power to roadway and traffic lights. The electricity can be generated from pavement deformation or vibration caused by the vehicles motion. This energy can be harvested by sensors embedded in the pavement. Piezoelectric materials are a class of ceramic materials with non-centrosymmetric point groups in their internal structure.[2] As a result, these materials create a finite electric voltage after a net distortion from equilibrium positions. Among all energy harvesting materials, piezoelectric materials cover the largest range of power densities at a given voltage. The created voltage is generally large enough to be used directly without need of up-converting.[3] The piezoelectric transducers can be integrated in mechanical structures in a variety of different ways. The structures receive the force applied by the vehicles and transfer it to the piezoelectric materials. The transducers generate a finite amount of electric potential after each deformation cycle. The generated voltage can be harvested and used for powering the signalized intersection or roadway lighting. This contribution represents the results of a Capstone Design project for a group of engineering students at Mercer University, majoring in Mechanical and Electrical Engineering. The group was tasked with designing a decentralized energy harvester using piezoelectric sensors. The overall goal was to have a proof of concept for which piezoelectric sensors can charge a battery if placed on a roadway in a protective casing.

Technical and Economic Challenges

At the first step, students were asked to identify the challenges facing the use of piezoelectric harvesters to supply power for roadway lighting. The results are listed as follows: (1) Durability and construction issues: The safe design of piezoelectric structures subjected to dynamic and random traffic loadings is a challenging task. Other factors, such as temperature, under pavement humidity, and corrosive agents may limit the lifetime and performance of transducers. Additionally, insertion of an energy harvester into the pavement may compromise the performance of the pavement and/or interfere with the regular pavement maintenance. (2) Conversion and storage efficiency: AC voltage generated by piezoelectric transducers must first be converted into digital signal using AC-DC converters and a diode rectifier. Studies show that the efficiency of energy harvesting by these circuits is not high.[4] (3) Lack of guiding business models: although piezoelectric technology can be used for generation of green and sustainable energy in transportation, there is no standardized project management tools to implement the technology.[5,6] (4) Need of economic impact analysis: efficiency of piezoelectric transducers in conversion of kinetic energy relies on multiple factors such as zoning ordinance, flow of traffic, geographic site, vehicle weight, and vehicle speed in addition to the characteristic features of the transducer. The variability of influential parameters needs to be considered to determine whether the use of power pavement and piezoelectric technology along roadways is a viable choice. (5) Lack of technical awareness and regulatory clarity: the lack of regulatory clarity makes it difficult to encourage state and federal agencies to adopt pump-priming strategies for widespread use of piezoelectric technology for energy harvesting.[5,6]

Project Overview

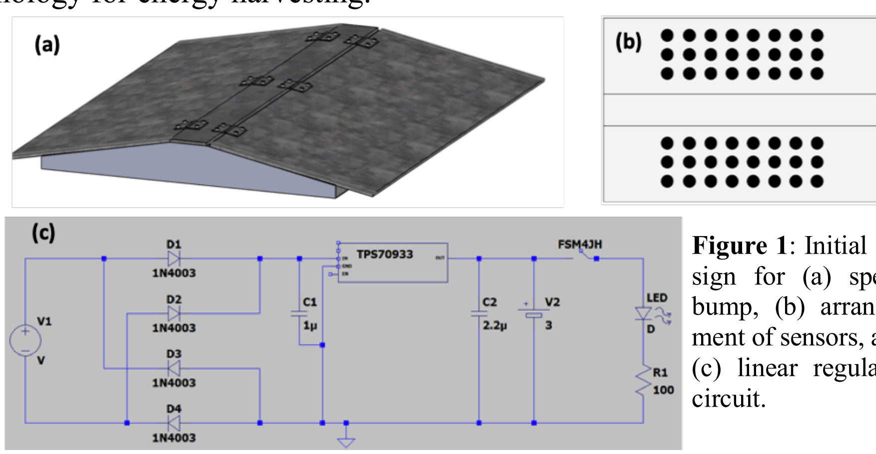

Figure 1: Initial design for (a) speed bump, (b) arrangement of sensors, and (c) linear regulator circuit.

Conceptual Design

The selected design consisted of a speed-bump to be placed on a roadway with electric circuitry inside. Initially, the speed bump, shown in Figure 1(a), was selected. The circuitry consists of 50 piezoelectric sensors (Figure 2(b)) wired in parallel to each other and then connected to a full-bridge rectifier and a linear regulator (Figure 1(c)). 50 piezoelectric sensors were necessary to have a high enough current output to activate the power electronic components. The circuitry components were to charge a 3 V, 1 mAh coin cell battery where the charge can be indicated with a 160 mW LED light activated through a push-button switch.

Ramp Construction

To construct the outer casing, two types of steel sheets and 5/8 in diameter plain carbon steel rods were used. All parts were combined using MIG welding and hinges to construct the full frame. Figure 2(a) represents the basic frame outline. A support triangle was welded on every corner of the frame. Before welding, each 12 in rod was milled at a 14° angle to fit between the 3 in center rod and the edge. After the base was welded together, two triangular shaped supports on the 24 in sides were welded to the frame. To create the support triangle, plain carbon sheets were cut into 9 in^2 (6 x 3 x 1/8 in) pieces to create a total of four supports. The team decided two additional inner supports needed to be constructed approximately 12 in from the original edge supports. This would enhance the mechanical performance of the casing. By adding two additional inner supports, the inner structure of the casing separated into three compartments. This allowed for one of the outer compartments to hold the electrical equipment to be connected to the sensors, located in the middle compartment of the frame. There was also room made for two wires to be placed through one of the inner supports to connect the two compartments to power the battery. Figure 2(b) shows the inner frame. The base was welded by welding two 1/16 in thick plain carbon steel sheets and bolting the bottom sheet to 6 in^2 triangles using screws and washers. Six panels were constructed the doors of the outer casing, shown in Figure 2(c). The completed casing, shown in in Figure 2(c), weighed approximately 80 lbs.

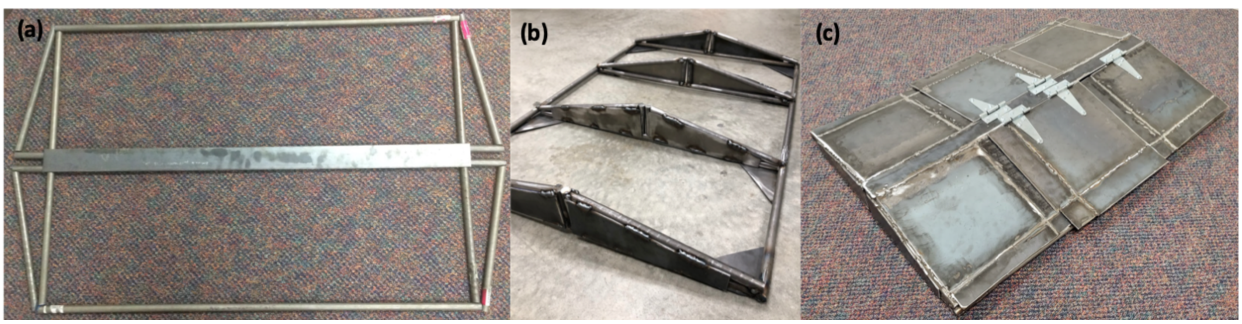

Figure 2: (a) Frame outline with center plate, (b) constructed steel frame, and (c) completed outer casting.

Silicone Molding

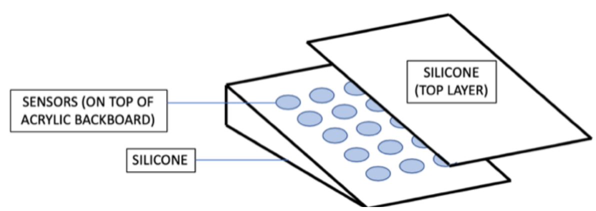

Figure 3: Silicon layering diagram.

To protect the sensors from vehicular loads, a mold was built to cast a silicone pad. The original mold, built to hold two gallons of silicone, consisted of an 11 x 12 x 3.5 in cardboard box lined with wax paper. The mold was filled with a silicone rubber material, and then the dried silicone wads cut diagonally. This created a triangular silicone pad that would be located beneath where the sensors are placed, as shown in Figure 3. Two 11 x 11 x ¼ in acrylic plates were cut as backboard for the sensors. There would be one backboard for each side of the ramp and the backboard would be located between the sensors and the diagonally cut silicone. When pressure is applied to the sensors through the silicone molding, they are pressed against a solid backboard.

Piezoelectric Network Construction

The specific piezoelectric sensors used were Goedrum 35-mm ceramic disk piezoelectric sensors. After successfully checking that each sensor would output at least 5 V, all 50 sensors were placed on a breadboard, wired in parallel, and tested for their overall voltage and current output. Since the ultimate goal for this project was to charge a battery using piezoelectric sensors, a high current in the milliamp range was necessary to charge the battery. To raise the output current for the piezoelectric sensors, they needed to be placed in parallel to add all output sensor currents at a constant voltage. To prevent the sensors from overlap and to have a more uniform sensor surface for preliminary checks, the 50 piezoelectric sensors were divided into two groups of 25 sensors and were taped down on two flat cardboard sheets, as shown in Figure 4. In preliminary checks, the maximum DC voltage output from multiple sensors being pressed was found to be approximately 30 V, while the current reached a maximum of 94 µA, close to the original 100 µA generation goal.

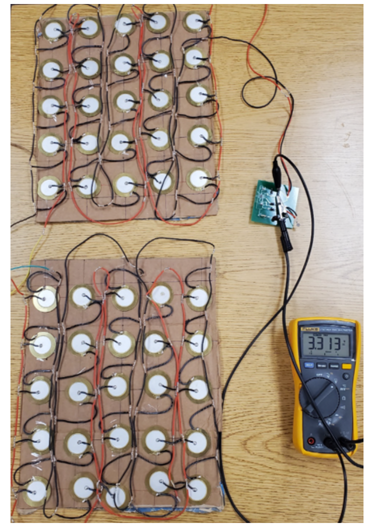

Figure 4: Testing setup for piezoelectric sensors connected to charging circuit.

Charging Circuitry Construction

The original circuitry design called for using a TPS70933 linear regulator, as shown in Figure 1(c). The maximum efficiency for this design would have been 66%, which would have resulted in high losses from the input power to the battery charge. Therefore, the team switched to a buck converter since all parts were readily available and the design provided a higher maximum efficiency of 83%. The schematic of buck converter is shown by Figure 5. The buck converter chip used was Texas Instruments LMZM23601SIL, which allows for a very low input current of 24 µA. The minimum input voltage for this converter is 4 V, and when the 1.4 V voltage drop from the full-bridge rectifier is applied, the theoretical minimum input voltage from the piezoelectric network to charge the battery would be 5.4 V. The capacitor values were found using the buck converter specification sheet. The full bridge regulator portion of the design is to convert the AC input from the piezoelectric network to DC. The selected battery to be charged was a 3 V, 1 mAh coin-cell battery. This low storage power battery was selected to decrease the amount of time needed to fully charge the battery for testing purposes. All electrical components were soldered to the PCB, as shown in Figure 6. Once the ramp design and the electrical circuitry were completed, they were combined to determine if the circuitry could fit properly inside the ramp (Figure 7). The ramp design was completed with three access panels attached by hinges. The total cost of the project was $695.46 divided into the electrical and mechanical costs, as is shown in Table 1.

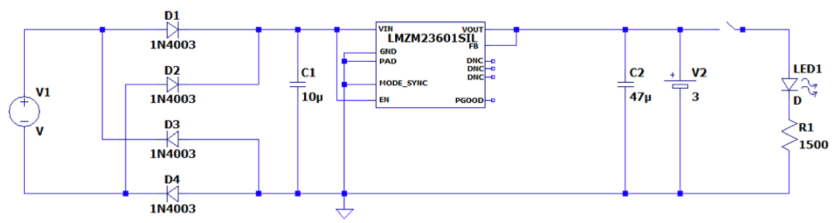

Figure 5: Buck converter design.

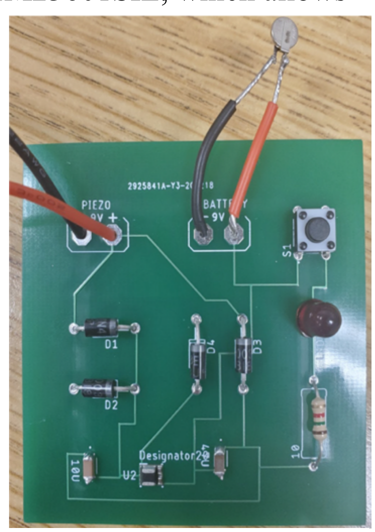

Figure 6: Final assembled charging circuit.

Testing Results and Discussion

Table 1: Cost of the project.

Electrical Cost	Mechanical Cost	**Total Cost**
$230.34	$465.12	**$695.46**

After checking that all the sensors operated properly, the piezoelectric network was built with all sensors in parallel and connected to a breadboard. The full-bridge rectifier to convert the AC output from the sensors to DC was also attached to the breadboard at the output. First, the DC battery voltage of the coin-cell battery was monitored. Figure 8(a) shows the rise in battery voltage over time, indicating the coin-cell battery will charge over time when an input voltage is present, as originally designed. This is a significant result, since one of the specific aims to this project was to demonstrate that the piezoelectric network can act as an AC power source to charge a battery. For this test, during an approximate 80-minute timespan, the charge was increased up to nearly 2.51 V from the original 2.446 V using the function generator. This increase was a voltage of 0.064 V over the 80 minutes. In addition to the battery charging, the overall discharge rate was monitored by removing the function generator input and then pressing FSM4JH switch to turn on the testing LED to drain the battery, as shown in Figure 8(b).

Figure 7: Final casing with piezoelectric network installed with charging circuitry.

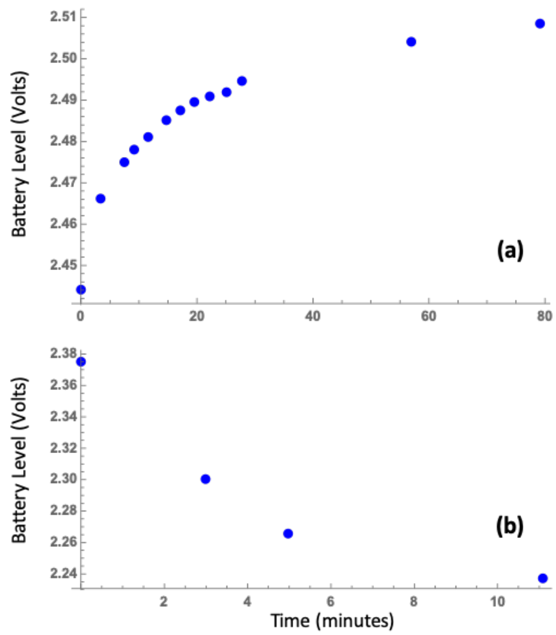

Figure 8: Variation of battery charge with time during (a) charging and (b) discharging.

The proposed tests to ensure the outer casing meets the project requirements were a durability test and waterproof test. The durability test consisted of gradually increasing the weight applied to the steel casing. The casing withstood an applied load of 100 lbs with no significant deformation and no sign of fracture. The team had originally planned to continually increase the applied load until the required load of 700 lbs. In addition, waterproof testing was to be performed to ensure water does not leak into the harvester and damage the electrical compartments. Due to time constraints, however, these tasks were not fully completed.

Economic Feasibility

The students were encouraged to consider the economic feasibility of using energy harvesters and identify important elements in cost-benefit analysis of energy pavement technology.[5,6] The initial capital cost includes the cost components for manufacturing and installation. In addition, yearly operation cost, maintenance, and financing need to be considered. All of these cost components are subjected to great uncertainty considering the size of the project, implemented technology, hardware design, location, and maintenance needs. The benefit of harnessing kinetic energy of vehicles and converting it to electricity can be evaluated by (1) the electricity production to power roadway and traffic lights at signalized intersections during grid power failure and (2) the reduction of CO_2 emission and other pollutants. The following factors can be used to quantify the monetary value of user and non-user benefits:[5,6]

- Travel time saving and delay reduction: upon power outage, the signalized intersection turns to all-way stop that adds to the travel time. Highway Capacity Manual provided microscopic simulation models that can be used to quantify the time delay and the cost associated with it.[7]
- Improving safety: power outage increases the possibility of accidents at signalized intersections that can be prevented by energy saved by piezoelectric technology. In California, for example, each grid powered traffic light experiences eight outage per year on average. The cost associated with accidents caused by power outage at signalized intersection can be estimated using simulation models such as Surrogate Safety Assessment Model.[8]
- Fuel saving: traffic jam at signalized intersections during power outage increases the cost of fuel consumed by vehicles. Following Zhao and Sharma the value of fuel saving can be estimated using the approximate methods mentioned in AASHTO Red Book.[5,9]
- Reduction of emission: traffic lights powered by renewable source of energy eliminate the gas emission caused by delayed vehicles at intersections during grid power failure. The mass of pollutants generated by emission can be estimated using the empirical equations introduced in AASHTO Red Book.[9] The cost associated with cleaning the pollutant can be considered as the monetary value of the emission. The U.S. Department of Transportation, for example, used the value of \$2/ton for CO_2 as the Social Cost of Carbon.[10]

Conclusion

This Capstone Design was an example of a project-centered and team-oriented approach to teaching and learning focusesd on harvesting vehicular kinetic energy using piezoelectric sensors. Derick *et al*.[1] considered the inclusion of energy harvesting projects into Capstone Design courses. Following their approach, this project provided a collaborative opportunity for mechanical and electrical engineering students to design a low-cost energy harvester to generate electricity for roadway and traffic lights. The learning objectives included understanding the technical and economic challenges of using piezoelectric harvesters to supply power for roadway lighting, conceptual and detailed design and analysis, prototyping, mechanical and electrical testing, and identifying the key elements for the future feasibility studies (Figure 9). Prior to the conceptual design stage, a primary source of reference materials was provided for the students to learn about piezoelectricity and its application in energy harvesting. The students were left free to create their own conceptual design. Their design was improved after several rounds of meetings with technical advisors. The project started in the fall of 2019 but the time for completion of some tasks ran out in spring of 2020, including the mechanical testing of the protective casing.

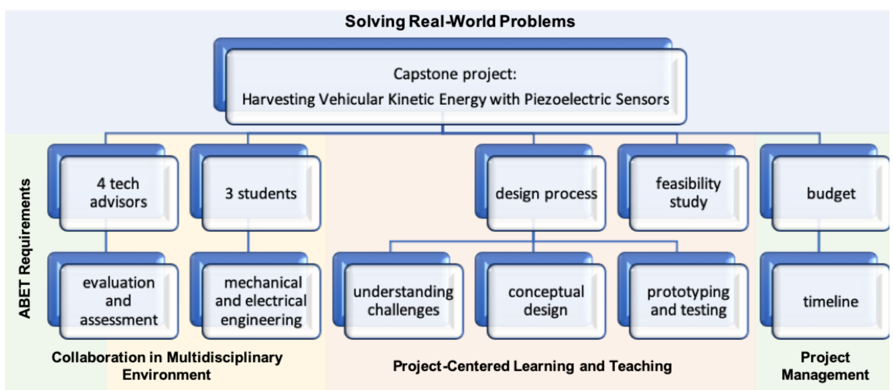

Figure 9. Capstone project overview.

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