Integrated Solar and Piezoelectric Renewable Energy Project

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Abstract— Small photovoltaic energy collection systems are readily available in a wide range of forms, from various do-it-yourself project instructions to plug-and-play demonstrators. Piezoelectric energy collection systems are likewise readily available, though some assembly may be required. Each can capture energy and store that energy in a battery. Various indicators and communications hardware sometimes accompany such photovoltaic systems. This paper describes an undergraduate student project that integrates energy collection by means of a combined photovoltaic and piezoelectric system, communicating the process wirelessly to an LCD display. The students learn and apply basic engineering skills, including the important skill of specifying and combining several subsystems, each of which may already be well known, into a creative end product. The project administration is interdisciplinary. The Mechanical Engineering Department administers the first semester. The Electrical and Computer Engineering Department administers the second semester. This paper addresses technical issues of creating such an integrated photovoltaic / piezoelectric energy collection system with communications and display. There are pedagogical issues in administering a two-department senior design project. An assessment of these issues is presented.

Introduction

This is an interdisciplinary project of an unusual sort. The students enrolled in a Mechanical Engineering design course to learn to create the initial design, up to the point of creating a schematic diagram ready to be built. They then enrolled in an Electrical Engineering design course to complete the circuitry, communication, and display. Due to course offerings and student scholarship deadlines, this interdisciplinary approach was more by necessity than by design. Nonetheless, this project was initiated and became a success. There were many challenges, such as technical advising and administrative necessities. Descriptions, schematics, and performance data support the notion of a successful project, along with an assessment of the feasibility and appropriateness of this project, its interdisciplinary character, and its performance. Perhaps this situation is unique, but maybe it is not. In any case, the following descriptions and assessments document a unique and successful undergraduate design project.

Context and Technical Approach

The application for this energy harvesting system is for transportation, collecting energy available from an ordinary, heavily traveled highway. The system captures energy from the sunshine on the road and from the deformation of the road surface as cars pass by. This project’s deliverable is a small scale prototype having all of the basic functions of such an energy collection system, mounted on a set of circuit boards, sensors with mounts, and displays. No hardened packaging is specified or expected.

Such an energy collection system, as an end product, can become quite complicated. To make the project feasible, we simplify it to its basic elements of photovoltaic energy collection, piezoelectric energy collection, energy processing and storage, wireless communication and control, and information display. Broad specifications are given in Table. 1.

Table 1. Specifications of the project

Item	Specification
Energy sources	A photovoltaic and a piezoelectric source of energy
Storage system	Battery storage of energy collected
Energy stored	5.0 W-hr < storage <40 W-hr; balance between sources not specified, but must be measurable for each.
Energy transfer	Transfers energy from both sources; can be simultaneous or time division multiplexed
Voltage levels	Less than 24 Volts. Safety is the consideration here.
Volume	Less than two liters. One person portable.
Temperature	Commercial temperature range, but feasible for the Saudi Arabian / Kuwaiti desert. Students are Saudi/Kuwaiti.
Piezo force	Typical of feet of one human body. No automobiles for prototype verification.
Photovoltaics	Size and capability typical of a 10W to 20W portable, framed solar panel
Wireless communication	Wirelessly communicate energy data, such as voltage, current, energy, time stamp to a central storage memory element
Data storage	Store data from one hour of operation in a format compatible with archiving in the university's research database
Packaging	Minimal for one-person transportation and system operation on site.
Measurement accuracy	Accuracy specified in technical documentation for instruments in the electrical power lab of the university

Other detailed specifications are given in each section of the discussion that follows.

In either case, photovoltaic or piezoelectric, energy is collected using well known technologies, methods, and hardware. Energy aggregation and storage is in a sealed lead acid battery. The photovoltaic system transfers its collected energy directly to the battery in a continuous fashion common to many solar battery chargers. The piezoelectric system stores its energy in a capacitor for pulsed energy transfer to the battery, interrupting the photovoltaic energy transfer briefly. The difference in energy processing methodology is primarily based on how the energy arrives: photovoltaic energy tends to arrive in a continuous stream whereas the piezoelectric energy arrives in pulses in a pattern characteristic of the arrival of car tires. In the system that was designed for this project, minimizing hardware volume, i.e., capacitor volume, tends to encourage collecting more photovoltaic energy than the piezoelectric energy.

An Arduino microcontroller supervises energy collection and storage. Appropriate voltage and current sensors provide data that enables the Arduino to calculate and to display the amount of energy captured. This information is communicated wirelessly to a simple data collection system and then displayed on an LCD screen.

The result of the project is a prototype that collects energy by both means, stores the energy, and communicates how much energy has been captured. In the following sections of this paper, appropriate design schematics, parts selection, and test results appear.

Photovoltaic Energy Collection

Photovoltaic panel (Luxini Solar Model 1200) specifications are as follows:

- Rated power: 10W
- V_{oc}: 20.6V
- V_{op}: 17.3V
- Short circuit current (I_{sc}): 0.69A
- Working current (I_{op}): 0.58A.
- Temperate coefficient of V_{oc}: - (0.38 +/-0.01)%/ ℃
- Temperate coefficient of I_{sc}: (010+/- 0.01)%/ ℃
- Temperature range: -40℃to +80℃
- Frame: Heavy duty aluminum
- Kind of connection: waterproof junction box, can be customized
- Guarantee of power: >90% within 10 years, >80% within 25 years
- Kind of glass and its thickness: Low Iron, high transparency tempered glass of 3.2mm
- Sealed Lead Acid Battery Voltage: 12V

This is a typical 10W solar panel readily available on line.[1] Figure 1 shows a circuit diagram of the photovoltaic energy collection circuitry and battery charging control.

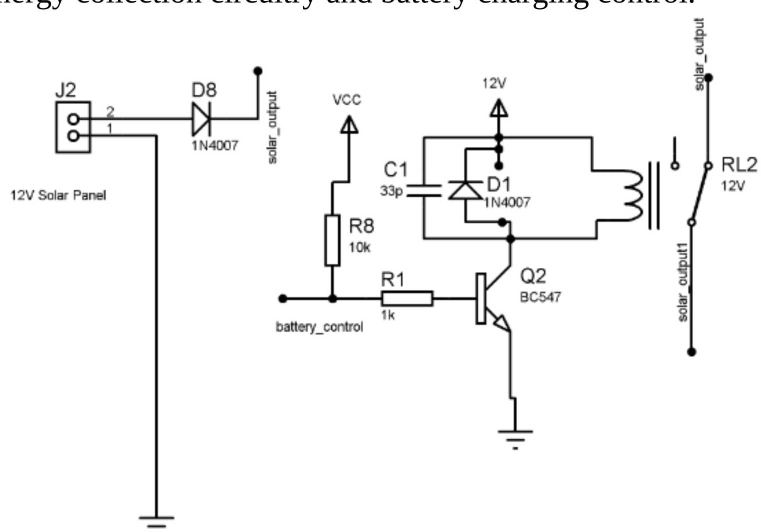

Figure 1. Photovoltaic Energy Collection Circuit Diagram

Photovoltaic energy from the solar panel energy the circuit at J2. A diode D8 prevents current reversal. Energy then flows through a relay RL2 to a voltage regulator / battery charger which places the energy into the battery. The relay is normally closed to enable continuous flow of energy from the solar panel to the battery charger. This automatically provides bias voltage to start the energy collection and the microcontroller. The microcontroller decides when it should close the relay based on the reading of the "solar output" voltage. The microcontroller signal passes through a simple amplifier to drive the relay coil.

Piezoelectric Energy Collection

A piezoelectric transducer comprises a "crystal" sandwiched between two metal plates. When a sound wave strikes one or both of the plates, the plates vibrate. The crystal picks up this vibration, which it translates into a weak AC voltage. Specification for the piezoelectric transducer[2] are as follows:

- Max input voltage 20 Vp-p
- Resonant frequency 4600 Hz
- Resonant impedance 250 Ohm
- Plate material Brass
- Operation temperature -20 ~ +70 C
- Storage temperature -30 ~ +80 C

Figure 1 shows a circuit diagram of the Piezoelectric energy collection circuitry and battery charging control.

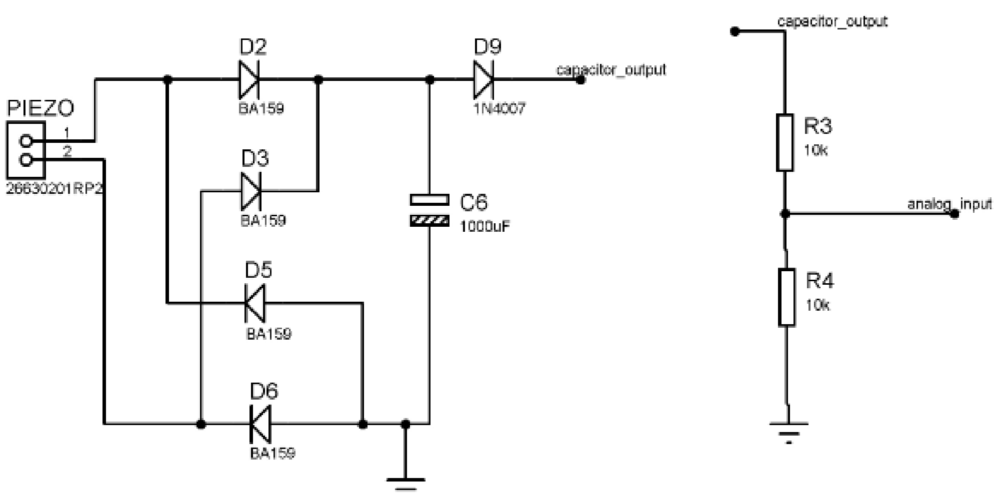

Figure 2. Piezoelectric Energy Collection Circuit Diagram

An alternating piezoelectric voltage from six series piezoelectric cells provides electrical energy to the circuitry at the PIEZO terminal. This voltage is then full wave rectified. Instead of directly connecting to the battery, the rectifier stores its energy in a capacitor C6. The piezoelectric voltage peaks somewhat higher than the nominal 12 Volts of the battery. The capacitor filters these voltage peaks, providing temporary energy storage at a slowly rising voltage level. In this manner, capacitor voltage builds up to a level that is compatible with energy transfer to the battery. Resistor divider R3 and R4 provide voltage information compatible with analog inputs of the microcontroller. Diode D9 prevents backflow of energy when the capacitor is eventually discharged into the battery.

Piezoelectric Pulse Charge Controller

Figure 3 shows the switching system to move energy from the piezoelectric energy collection circuitry of Figure 2 onto the battery.

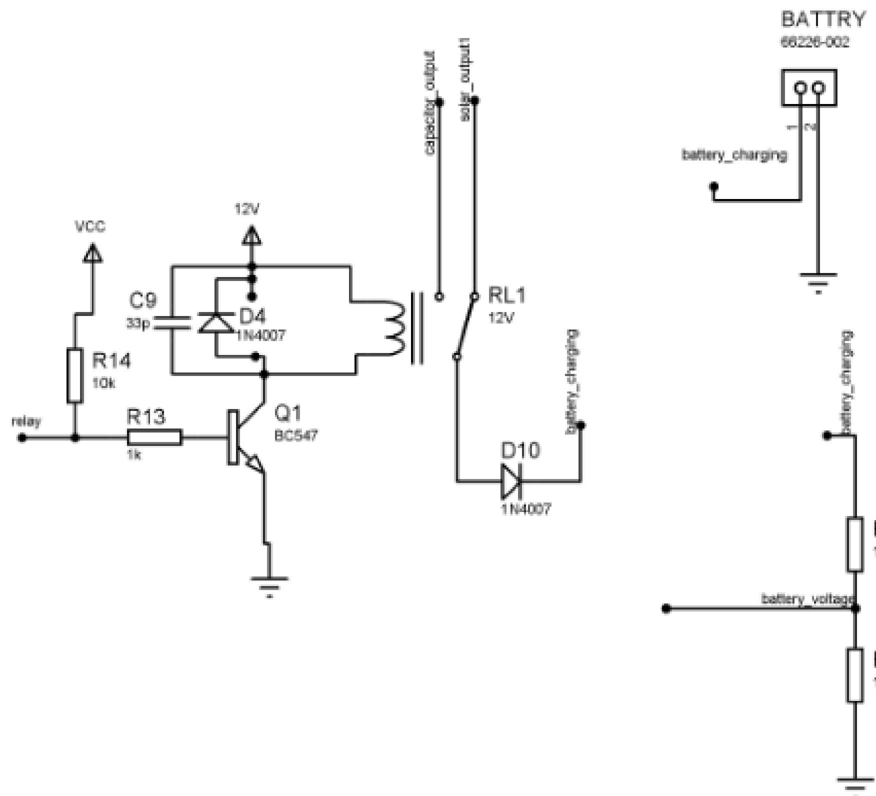

Figure 3. Piezoelectric Pulse Charge Controller

After the capacitor (C6), shown in Figure 2, reaches fifteen Volts (or a desired, programmable voltage level), the microcontroller reads the voltage from the voltage sensor (R3—R4 of Figure 2) and sends the signal to switch relay RL1 to the “capacitor output” connection. Capacitor (c6) discharges when the path is connected to the battery, where it transfers the energy from the capacitor to the battery. Discharge takes approximately two seconds. Relay RL1 returns to its “solar output” connection when the capacitor drops below twelve Volts, completing a transfer of approximately 65% of the capacitor’s stored energy.

Wireless Communication

The project’s specifications require wireless communication of information such as battery voltage and energy collection status in both systems. The basic idea of this part is to have a transmitter and a receiver that are connected wirelessly to transmit data. Each has a Zigbee radio connected to an Atmego 328 microcontroller.

Data collected for transfer includes battery voltage, solar output voltage, and capacitor voltage. A system block diagram is shown in Figure 4.

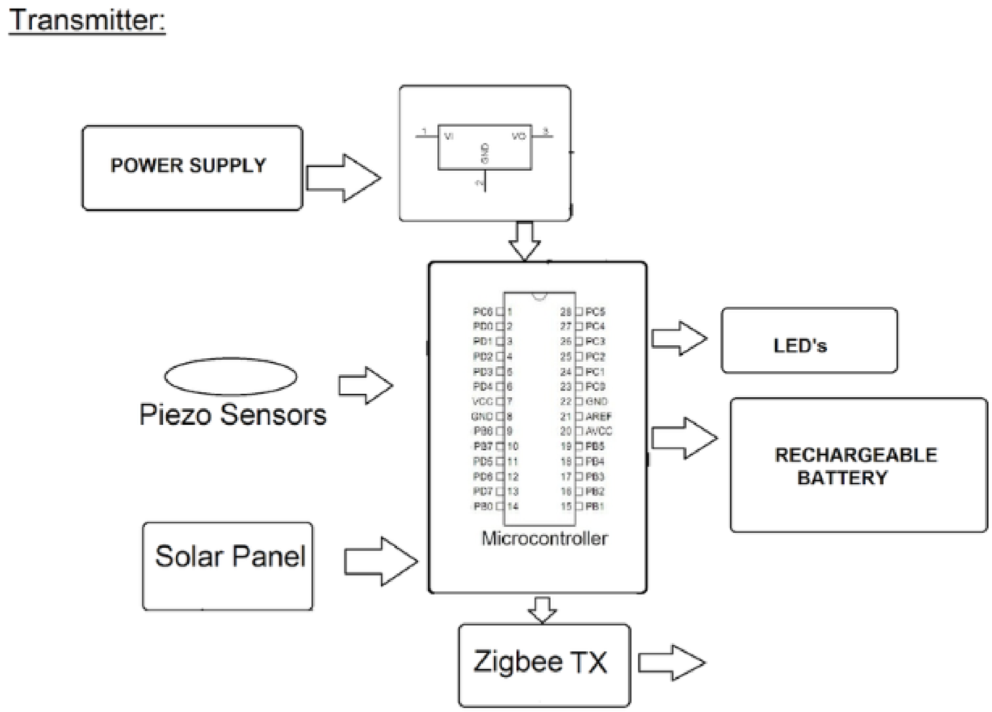

Figure 4. Data Collection and Transmission System

The high-performance Atmel 8-bit AVR RISC-based microcontroller combines 32KB ISP flash memory with read-while-write capabilities, 1KB EEPROM, 2KB SRAM, 23 general purpose I/O lines, 32 general purpose working registers, three flexible timer/counters with compare modes, internal and external interrupts,serial programmable USART, a byte-oriented 2-wire serial interface, SPI serial port, 6-channel 10-bit A/D converter (8-channels in TQFP and QFN/MLF packages), programmable watchdog timer with internal oscillator, and five software selectable power saving modes. The device operates between 1.8—5.5 volts, an attractive feature in a system that may have difficulty in regulating its supply voltage, particularly upon startup.[3]

ZigBee is a wireless technology developed as an open global standard to address the unique needs of low-cost, low-power wireless M2M networks. The ZigBee standard operates on the IEEE 802.15.4 physical radio specification and operates in unlicensed bands including 2.4 GHz, 900 MHz and 868 MHz.[4]

The microcontroller is the same one that regulates energy collection in both the photovoltaic and the piezoelectric energy harvesting circuitry. From its analog inputs, it converts the voltage sensor signals from each analog voltage sensor (as described already) into a digital signal for transmission by the Zigbee Transmitter.

A Zigbee Receiver receives the data and sends the data to another Atmega 328 microcontroller for recording and display.[3,4] A system block diagram is shown in Figure 5.

Receiver:

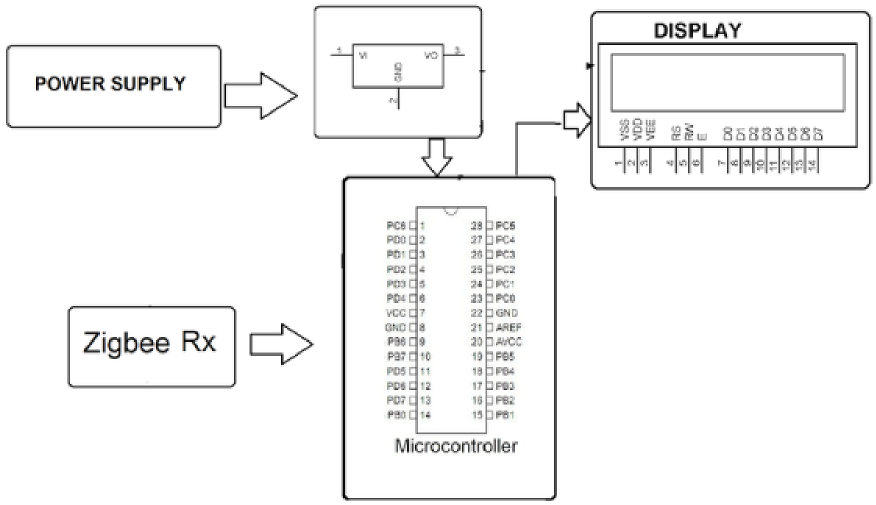

Figure 5. Data Receiver and Display System

The receiver and display are normally kept in a low power mode, activated by a pushbutton switch. Data displayed on an LCD display are the battery voltage solar output voltage, and piezoelectric voltage. Whereas the transmitter side must have tight conservation of energy, the receiver side is assumed to be located where energy for its power supply is abundant.

Lead Acid Storage Battery

Energy is stored in a sealed lead acid battery. A lead acid battery was chosen over a lithium battery because the lead acid is cheaper, safer, and good in high and low temperature. Anticipated environment for this system is the Saudi Arabian desert.

Figure 6. Sealed Lead Acid Storage Battery

Specifications:[5]

- Model: EXP 1270
- Voltage 12V
- Amperage 7A

Testing and Results

Solar: Solar panel performance was measured in three different conditions as shown in Table 2. The solar panel was first exposed to the sunlight. Then half of the solar panel was shaded. Finally, the whole solar panel was shaded. The current shown was transmitted directly to charge the battery.

Table 2. Solar Panel Performance

Conditions	V(DC) Volt	A(Amps)
Max (under sun light)	21.44	0.268
One panel (half shaded)	17.34	0.0074
Under the shade	15.87	0.019

Piezoelectric: The piezoelectric system charged its capacitor to 15 Volts. The microcontroller's main function is to get the voltage to 15V and then switch the relay to the battery to discharge. It performed as expected. The maximum current transferred to the battery was 6mA.

Communication: The communication system accurately measured the battery voltage, solar output voltage, and piezoelectric output voltage. Refresh rate was sufficiently fast enough to show piezoelectric voltage increasing on capacitor C6 until the voltage reached 15 Volts. Thereupon, the relay RL1 switched and the voltage across C6 decreased to 12 Volts. All of this was recorded and displayed on the LCD output display.

Packaging

Figure 7 shows minimal packaging of the prototype. Clockwise from upper left are the piezoelectric cell hardware, receiver, solar panel, battery, and transmitter. Not shown are the two microcontroller boards.

Six piezoelectric sensors are placed in series under squared hard plastic. Each sensor has foam placed underneath so it gives it more protection from breaking and it also gives more deflection. This way of assembly is to generate more voltage. The Printed Circuit Boards are more efficient as they require no wires. An LED has been placed on the transmitter and receiver boards to give a sign of whether or not the board is functioning.

The students learned and applied basic engineering skills, including the important skill of specifying and combining several subsystems, each of which may already be well known, into a creative end product.


Figure 7. Energy Harvesting System Hardware

Interdisciplinary Senior Design Program: History

This paper addresses issues of creating such an integrated photovoltaic / piezoelectric energy collection system with communications and display. The preceding discussion has addressed technical issues. There are pedagogical and administrative issues in a two-department senior design project.

The university hosts a strong interdisciplinary senior design program within its College of Engineering. The program dates back to 1999 when two Mechanical Engineering professors and one Electrical Engineering professor combined their efforts in teaching a two-semester senior design course sequence. Initially, there were only a few interdisciplinary projects. Emphasis was on creating a unified curriculum that spanned the disciplines. Common elements were identified and a common pedagogy developed. As industry and government sponsors were recruited with greater success over the following years, interdisciplinary projects began to appear in greater frequency. Biological and Agricultural Engineering joined the program in 2004 and Computer Science joined in 2009. Chemical and Materials Engineering plans to join the program in Fall 2017. The current program and an archive of projects appears at the joint course website[6] http://www.webpages.uidaho.edu/mindworks/capstone_design.htm .

Throughout its nearly two decades, the program has balanced department control while pooling assets for administration and teaching. A majority of the projects are now interdisciplinary.[7,8,9,10] Mechanical Engineering has always provided overall program leadership. Each department provides instructors in its disciplines for both administration and technical advising. The committee formed by all of these instructors, administrative and technical, decides project offerings and assigns students to projects. Each respective department's administrative instructors award grades to students. Grading is by carefully defined rubrics contained on the course administrative webpage, readily available to students. On interdisciplinary projects, there is always a technical advisor from each interested discipline assigned to the project. The technical advisor provides disciplinary guidance and input on grades. . Departments assign the equivalent of one course to each administrative instructor's teaching load. Departments assign

5% of instructor time as credit for serving as technical advisor for a project. Multiple projects under a single instructor earn 5% credit each.

Interdisciplinary Senior Design Program: Specific Assessment

The project at hand is primarily an Electrical Engineering project with important aspects of Mechanical Engineering in the design, modeling, and construction. This project's first semester was administered by Mechanical Engineering. Electrical Engineering does not offer senior design in the summer term. A technical advisor from Electrical Engineering served, but administration, classes, and even the course number was Mechanical Engineering. Both Mechanical and Electrical instructors attended weekly project meetings. They coordinated course requirements, student presentations and reports, and grades by in-person meetings. The students had to petition to get this first semester to count toward their Electrical Engineering degree.

Electrical Engineering administered the project's second semester as the latter half of its spring-fall two-course sequence. Again, the same technical advisor from Electrical Engineering served and the course director was also Electrical Engineering. Formal instruction was under supervision of Mechanical Engineering, as it has been since 1999. For all this complicated structure, the project's administration was quite smooth. Some of that may be due to both the Mechanical Engineering lead instructor, also the overall senior design course lead, and the Electrical Engineering technical advisor were two of the original three professors who created the program in 1999.[10,11]

ABET requirements were addressed by each department separately. Each department writes its own amplification of the (a) through (k) outcomes to this capstone design. The instructor in each respective department completes his own department's ABET reports in the context of his own department's requirements, outcomes, and formats. Student work records are maintained by the Mechanical Engineering department as the lead department in the interdisciplinary structure. These are shared as requested to support ABET visits. Since 1999, there have been three ABET visits to each program (2001, 2007, and 2013) without a single adverse comment. On the contrary, the program has won national awards for its effectiveness and the thoroughness of its centralized documentation at the Mechanical Engineering Department.

Student performance in this interdisciplinary design project had a slow start. The summer session is only eight weeks. The first five weeks showed little progress, including their presentation on the project definition that they did. A bad grade seemed to motivate them. Their end-of-course design review was quite strong. They finished their first semester with most of the design work completed. Only construction and validation remained. In their second semester, the project was essentially complete by mid-semester. Their design simulations were successful. They built the prototype and completed testing and validation. They met specifications and received an "A" grade for their successful work. Their technical success is the subject of the first part of this paper. All students graduated at the end of the second semester. There was some variation in contributions to the project's success, with two of the students exhibiting somewhat greater knowledge and performance than the other two. The project's results form a basis for writing a grant proposal for advancing the work. Two of the students wrote that proposal under the supervision of the lead Electrical Engineering instructor.

This project exhibits an important application of teaching engineering design skill. For a long time, engineering design involved integrating and applying basic elements to create a product or process that performed to specifications. More recently, the basic skill of the engineer has become an ability to take packages or modules and combine them into a productive system. It is important to be able to integrate existing hardware and software as a basic skill of today's engineer. This project is an illustration of the latter. Many engineering functions already exist in commercially available hardware and software packages. Engineers now may combine these packages into desired systems. All of the elements of this project are packages or modules of some sort or other. There is little design from scratch elements. The result is a system that performs to system specifications. This is an important design concept that this project teaches.

Conclusions

This paper documents a senior engineering design project of an unusual sort. The project itself, from a technical perspective, integrates a photovoltaic energy harvesting system with piezoelectric energy capture circuitry. Specifications were met with a system that provides continuous photovoltaic energy to charge a battery. Piezoelectric energy is stored in a capacitor and then pulsed into the battery in an organized fashion. Data from voltage sensors is gathered and wirelessly transmitted to a place where it is stored and displayed. Technically, the project performed to specifications. As an interdisciplinary project, this combined the resources of Mechanical Engineering with Electrical Engineering under the umbrella of a senior design course sequence and system that has produced successful interdisciplinary project for nearly twenty years. Administrative hurdles were successfully navigated while maintaining the integrity of the senior design program. An assessment reveals that the documented senior design system that has proven successful since 1999 again provided these students with a smooth and meaningful experience despite the unique circumstances. Students learned appropriate engineering skills through a challenging and unique project.

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