ARL-TR-8560 ● OCT 2018

US Army Research Laboratory

Micro-Power Energy Harvester and Sensor Architecture using Low Illumination Light (LIL) Energy Harvesting and Radioisotope Power Sources

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NOTICES

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REPORT DOCUMENTATION PAGE

Form Approved
OMB No. 0704-0188

1. REPORT DATE *(DD-MM-YYYY)* October 2018	**2. REPORT TYPE** Technical Report	**3. DATES COVERED (From - To)** June 2018–August 2018

4. TITLE AND SUBTITLE

Micro-Power Energy Harvester and Sensor Architecture using Low Illumination Light (LIL) Energy Harvesting and Radioisotope Power Sources

5a. CONTRACT NUMBER

5b. GRANT NUMBER

5c. PROGRAM ELEMENT NUMBER

6. AUTHOR(S)

Hakan Berk, Tian Ying Lee, Madeline Ford, Johnny Russo, Marc Litz, and David Bigio

5d. PROJECT NUMBER

5e. TASK NUMBER

5f. WORK UNIT NUMBER

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)

US Army Research Laboratory
Sensors and Electron Devices Directorate (ATTN: RDRL-SED-E)
2800 Powder Mill Road
Adelphi, MD 20783-1138

8. PERFORMING ORGANIZATION REPORT NUMBER

ARL-TR-8560

9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)

10. SPONSOR/MONITOR'S ACRONYM(S)

11. SPONSOR/MONITOR'S REPORT NUMBER(S)

12. DISTRIBUTION/AVAILABILITY STATEMENT

Approved for public release; distribution is unlimited.

13. SUPPLEMENTARY NOTES

14. ABSTRACT

An energy harvesting system (EHS) that can power unattended sensors for more than a decade without having to replace an energy source is of great interest to the US Army for use in communication nodes operating in remote locations as well as health monitoring sensors for all types of personnel. Most of our EHS is fabricated from commercial off-the-shelf (COTS) materials such as the energy harvesting evaluation board, thin-film batteries, a low-power microcontroller, and various sensor loads. The indium gallium phosphate or gallium arsenide photovoltaic cells and radioisotope power sources that will serve as input within the microwatt power range into the EHS are from previous US Army COTS projects. The overall design of the EHS offers the user the ability to conduct input and output power calculations, which will identify the quantity of EHS components needed. Future capabilities include a self-sustaining, cost-effective solution that involve a motion-activated camera to take a picture and transmit it back to the nearest receiver when there is enough power to do so within the EHS.

15. SUBJECT TERMS

energy harvesting, radioisotope power sources, thin-film batteries, sensor suite, low-power microcontroller

16. SECURITY CLASSIFICATION OF:			**17. LIMITATION OF ABSTRACT**	**18. NUMBER OF PAGES**	**19a. NAME OF RESPONSIBLE PERSON**
					Johnny Russo
a. REPORT	**b. ABSTRACT**	**c. THIS PAGE**	UU	59	**19b. TELEPHONE NUMBER (Include area code)**
Unclassified	Unclassified	Unclassified			(301) 394-5530

Standard Form 298 (Rev. 8/98)
Prescribed by ANSI Std. Z39.18

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1. Introduction/Motivation

The objective of this project is to design an energy harvester system (EHS) that accepts photovoltaic (PV) cells and/or radioisotope power sources (RPSs) as an input energy source, stores excess energy in lithium (Li) thin-film batteries (secondary energy storage), and powers sensors requiring between 100 µW to 25 mW of power. A benefit of this circuit would be to have a low-power architecture where a user can power a sensor requiring milliwatts through the EHS with a constant microwatt energy source and secondary energy storage that lasts the lifetime of the sensor and energy sources. By calculating the input and output power needed for a specific application in a specific environment (time-dependent energy profile), the EHS component combination (thin-films, indium gallium phosphate or gallium arsenide PV cells, RPS cells, and sensor run time per day) and quantity of each component can be identified. Examples of future applications would be remote/unattended ground or orbital sensors and health monitoring sensors for all types of personnel.

2. Background

There is a great demand for an EHS that can power unattended sensors and embedded devices for more than a decade without having to replace an energy source. For example, power solutions for pipe systems buried deep in the ground are being widely investigated.[1] Sensors that monitor the performance of pipe infrastructure must be powered for decades at a time due to their inaccessibility. An EHS powered by an RPS offers a no-maintenance solution to this problem. There is not a commercially available system, mainly since energy harvesting for low-power applications has only received interest over the past few years. Its capability to power sensors at the milliwatt range makes our system a first of its kind. Our solution allows for a self-sustaining, cost-effective, no-maintenance system. Figure 1 shows the basic building blocks of an EHS.

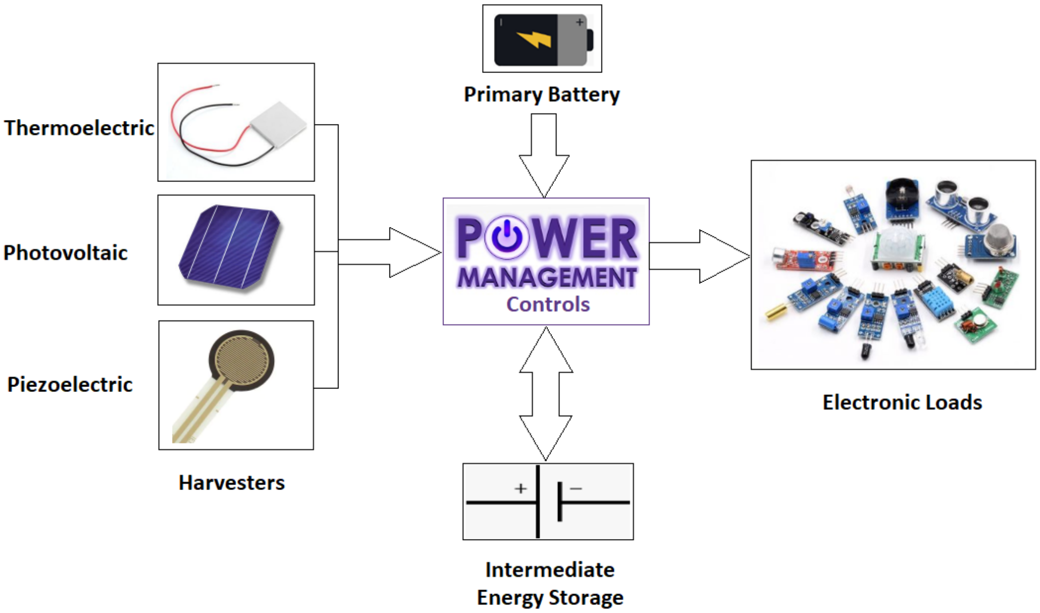


Fig. 1 Proposed EHS[2]

The major objective of the EHS is to find a low-power (100 µW–10 mW) sensor to activate and turn on a black-and-white camera, which then transmits out to a receiver using two transceivers. The purpose of the EHS would be to support a remotely located motion detector, which then triggers the microcontroller followed by a camera and transceiver for situational awareness. Raspberry Pi seems like an appropriate candidate but its slow boot-up would limit operating time when using an RPS. Transmitting images poses another problem because commonly used radios like the Zigbee take over 200 mW when in active mode. In this report, we discuss the major components of the EHS, both successful and unsuccessful experiments, and the next steps that should be taken to progress the development of the EHS.

3. Hardware

3.1 Energy Harvester Circuit Board

The energy harvester circuit board is the main component of the EHS, and we needed a board where the input current was in the microamps range since that is the current that can be provided by RPS and PV cells. In 2013, Linear Technologies harvesters were attempted. We avoided these circuit boards because of the high input current and voltage (~12 V) needed to turn on these circuits. In 2014, the Texas Instruments CC3200 LaunchPad, C3200 Camera Booster Pack, and the MT9D111 Camera Module[3] seemed to be the ideal system, but due to unknown reasons, the official camera booster was never released nor successfully constructed.

Fast forward to 2018: based on a research search and literature review, there have been no new releases of energy harvester circuit boards that use PV cells nor has anyone developed an EHS. After further research, we identified the SPV1050 energy harvester from STMicroelectronics, which is nearly identical to an Analog Devices energy harvester evaluation board released in 2013. The SPV1050 is a chip that is integrated within a STEVAL-ISV020V1 evaluation board. The datasheet states that the evaluation board can accept PV cells as input, charge Li batteries, has battery overcharge (4.2 V threshold) and over discharge (3.7 V threshold) protection, has a buck-boost circuit, and can turn on with an input current as low as 10 µA.[4] It also has two fully independent low-dropout (LDO) regulators with 1.8- and 3.3-V output. Some of its applications include wireless sensor node, access control, and surveillance. The technical specifications of this board fits perfectly with our EHS, and the LDO output is enough voltage to power some of the selected sensors. Figure 2 is an image of the STEVAL-ISV020V1 and relevant pins.

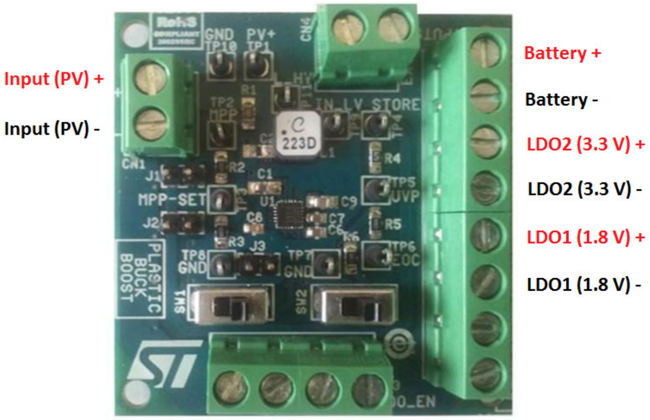


Fig. 2 STEVAL-ISV020V1 evaluation board[4]

3.2 Secondary Energy Storage

EnFilm rechargeable, solid-state, Li thin-film batteries (secondary energy storage) have many advantages over supercapacitors and conventional Li-based rechargeable batteries. These devices offer a high energy density, high discharge rate, and low leakage current (<1 µA).[5] Our purpose for using thin films is to provide onboard backup and energy storage for the RPS or PV cells to directly power various sensors during high-power active modes. The RPS trickle charges the battery array. Unfortunately, most thin films are obsolete or have a low energy density per package volume, such as Cymbet EnerChip Smart solid-state batteries, which are only available as bare die batteries, so we decided to buy the remaining stock of the STMicroelectronics EFL700A39-RL from Mouser Electronics. The EFL700A39-RL has a 0.7-mAh energy storage.[6] The operating voltage is between 3.0 and 4.2 V with a maximum pulsed discharge and charge current of 10 mA. It takes approximately 40 min to fully charge one thin film. The dimensions are 25.7 × 25.7 × 0.22 mm. The cathode, electrolyte, and anode are lithium cobalt oxide, lithium phosphorous oxy-nitride ceramic, and Li, respectively. Figure 3 is an image of the EFL700A39-RL.

Fig. 3 EFL700A39-RL thin film

3.3 Arduino Uno

The Arduino Uno is a microcontroller board that uses the ATmega328P. It has 14 digital input/output pins (6 of which can be used as pulse width modulation [PWM] outputs) and 6 analog inputs.[7] The board can be connected to the computer with a USB cable and programmed with Arduino Software. The software is similar to the C programming language, has a user-friendly interface, and has tons of open-source code as well as a large community. The Arduino's operating voltage is 5 V DC current per input/output pin is 20 mA, and the DC current for the 3.3 V pin is 50 mA.[7] If something goes wrong with the Arduino, the chip can be easily replaced for under $5. The length, width, and weight are 68.6 mm, 53.4 mm, and 25 g, respectively. Figure 4 is an image of the Arduino.

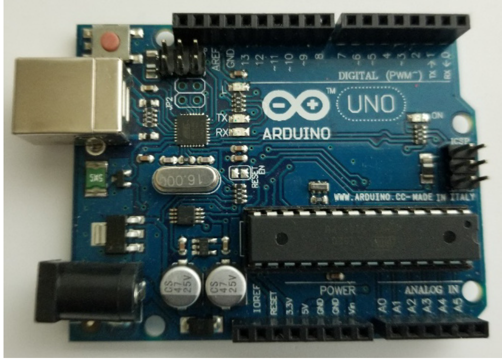


Fig. 4 Arduino Uno

3.4 Photovoltaic Cells

For demonstration purposes only, we are using three PV cells. Figure 5 shows images of the PV cells: two Emcore ZTJ PV cells and one PowerFilm PV cell. Table 1 indicates the output voltage and current of the PV cells. Please note that whenever we refer to PV cells throughout this report, it is some combination of these three PVs. These measurements are taken under artificial room lighting or low illumination light (LIL).

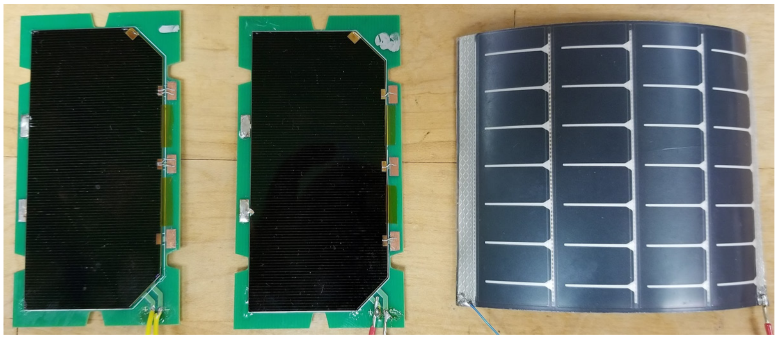


Fig. 5 PV cells

Table 1 Voltages and currents of PV cells

Name of PV	Voltage (V)	Current (μA)
Emcore ZTJ PV cell #1	1.46	493
Emcore ZTJ PV cell #6	1.72	423
PowerFilm PV cell	2.51	245

4. Experiments

4.1 Running the VC0706 Camera with Arduino Uno

4.1.1 Purpose

A camera circuit using the VC0706 camera and Arduino Uno is constructed. The power requirement is 242 mW during active mode, which is too much power for our EHS to output. The final goal is to reduce its power consumption.

4.1.2 Materials

The following materials were used:

- VC0706 camera
- Arduino Uno
- Two 10-kΩ resistors
- MicroSD card breakout board
- MicroSD card
- Breadboard and jumper wires

Figure 6 shows a picture of the VC0706 camera and its circuit diagram.

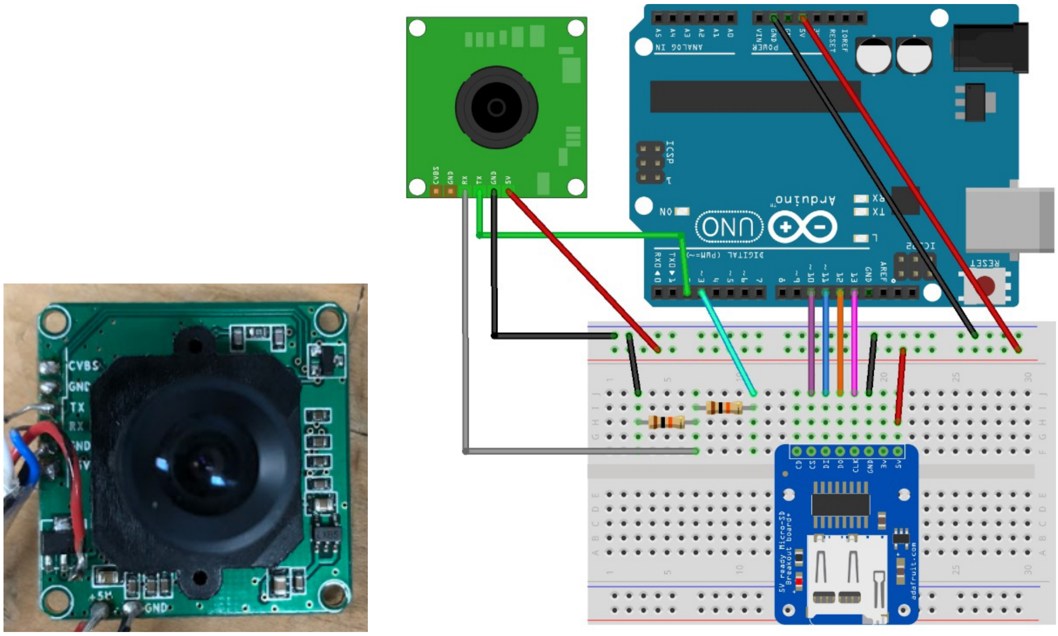


Fig. 6 **VC0706 camera (left) and breadboard configuration (right)**

4.1.3 Procedure

We connected the VC0706 camera and MicroSD card breakout board as shown in Fig. 6. The red wire is connected to 5 V, the black wire is connected to ground, gray is the receiver (RX), and green is the transmitter (TX). Next, we download the Arduino code needed to run the camera and store the image in the MicroSD breakout board.[8] To see the image, the MicroSD card needs to be removed from the breakout board and plugged into the computer.

4.1.4 Results

Although we know this camera will likely require more power than the EHS can handle, it is wise to record the power consumption of each pin from the camera and the MicroSD breakout board when they are turned on. Table 2 shows the calculations for the Arduino power draw. As seen in the table, most of the power draw comes from the Power pin for both the Camera and the SD card. The other pins have a negligible amount of current which makes their power draw almost negligible as well. The total of 540mW needed to run this system is far too much for the end goal EHS system as the radioisotope and PVs cannot power this camera. The next steps would be to find a camera with a smaller power draw and find a way to reduce the power of the Arduino.

Table 2 Calculations for the Arduino Uno power draw

In use table	Voltage (V)	Current (mA)	Power (mW)	Time (s)	Energy (mJ)
Camera VC0706					
Power pin	3.385	69.520	235.325	…	…
Tx pin	3.180	0.030	0.095	…	…
Rx pin	3.770	1.525	5.749	…	…
Camera total	…	…	241.170	1.000	241.170
SD card					
Power pin	3.376	14.210	47.973	…	…
CS pin	4.277	0.005	0.021	…	…
DI pin	4.285	0.027	0.116	…	…
DO pin	3.374	0.309	1.043	…	…
CLK pin	0.020	0.473	0.009	…	…
SD card total	…	…	49.162	1.800	88.492
Sum of circuit components	…	290.332	…	…	…
Arduino approximate (mW)	…	250	Arduino gets 5 V from USB and 50 mA draw, so 250 mA	…	…
Total mW needed	…	540.332	…	…	…

4.2 Running the OV7670 Camera with Arduino Uno

4.2.1 Purpose

Since the VC0706 camera consumed too much power for the EHS to handle, we decided to use the OV7670, a black-and-white camera that is rated for 60 mW when in active mode[9], as shown in Fig. 7. The OV7670 has a resolution of 640 × 480 pixels. The pinout connections and descriptions are shown in Fig. 8.

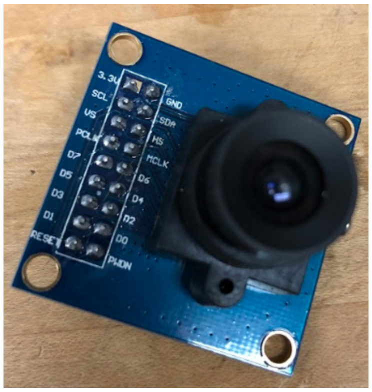
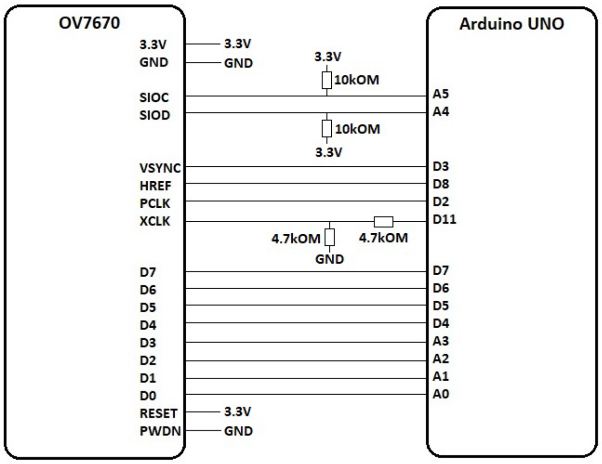


Fig. 7 OV7670 camera



Pin	Type	Description
VDD	Supply	Power supply
GND	Supply	Ground level
SDIOC	Input	SCCB clock
SDIOD	Input/Output	SCCB data
VSYNC	Output	Vertical synchronization
HREF	Output	Horizontal synchronization
PCLK	Output	Pixel clock
XCLK	Input	System clock
D0-D7	Output	Video parallel output
RESET	Input	Reset (Active low)
PWDN	Input	Power down (Active high)

Fig. 8 OV7670 pinout connections (left) and descriptions (right)[10]

4.2.2 Materials

The following materials were used:

- OV7670 camera
- Arduino Uno
- Two 10-kΩ resistors
- Two 4.7-kΩ resistors
- Breadboard and jumper wires

4.2.3 Procedure

We followed the wiring diagram in Fig. 8 to connect the OV7670 camera to the Arduino Uno. Please note that if the 3.3-V pin from the Arduino is used, then the voltage divider with the 4.7-kΩ resistors should be removed. Using both Java and Arduino code from an Instructables tutorial, we ran a java program on the command prompt that would take a picture and store it on the computer's C: drive.[10] The Java code was used to interpret the bits from the Arduino and convert them into a .bmp file output. The program that ran on the command prompt would continue to take pictures every couple of seconds until the program was stopped.

4.2.4 Results

From attempting to take many pictures, it was determined that the camera is very difficult to focus. As a result, most pictures were blurry. The camera was able to focus from around 4–6 inches away. If the camera was placed too far away, the pictures would appear as all white. It took a couple of seconds for each image to be saved. Since the energy harvester can barely handle a 25-mW load, the 60-mW camera will not work with the energy harvester unless there is a way to get more output power from the energy harvester or lower the power requirement for this camera to function in active mode. In Fig. 9, the picture to the left is of the computer's keyboard, while the picture to the right is a picture of the TI-1975 calculator.

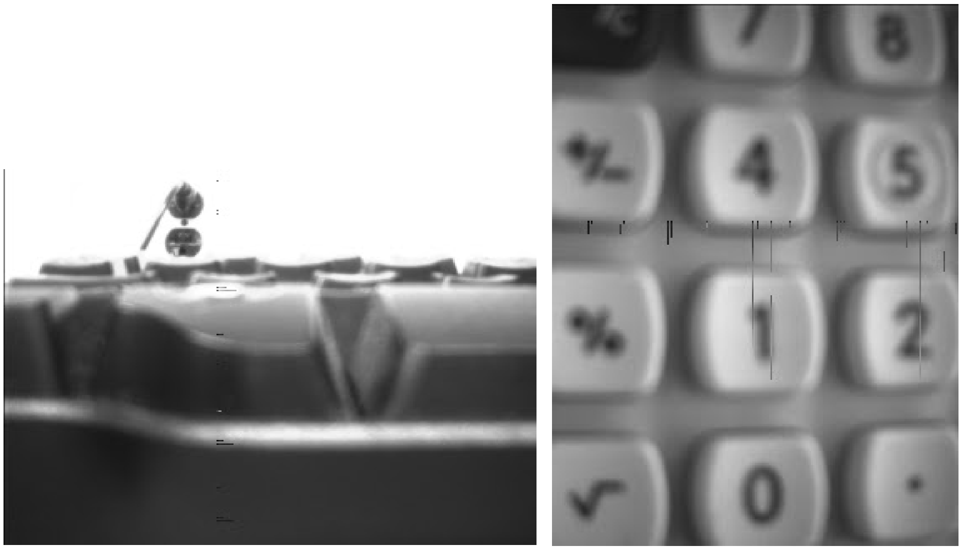


Fig. 9 Pictures taken by the OV7670

4.2.5 Next Steps

We would like to run the OV7670 with a low-power Arduino, and ultimately run the low-power Arduino through the EHS.

4.3 Charging/Discharging Thin-film Batteries

4.3.1 Purpose

The energy harvester circuit board and its interactions with the thin-film batteries are an unknown; therefore, it was desirable to figure out how the charging and discharging mechanisms work. We designed two simple experiments: one to charge and one to discharge the thin-film batteries. If the experiments behaved as predicted, then we can confirm qualitatively how the energy harvester works and quantitatively by measuring the change in voltage over time.

4.3.2 Materials

The following materials were used:

- Power supply
- Energy harvester circuit board
- Five thin-film batteries
- Multimeter
- TI-1795 calculator

4.3.3 Circuit Diagrams

The first circuit diagram is designed to charge the thin-film batteries (Fig. 10). It has the power supply at 3.5 V and a small amount of current going into the input of the energy harvester. Then, there is no output from the energy harvester, since only the thin films are attached. The hope is that the board will realize there is nothing to power and automatically start charging the thin films.

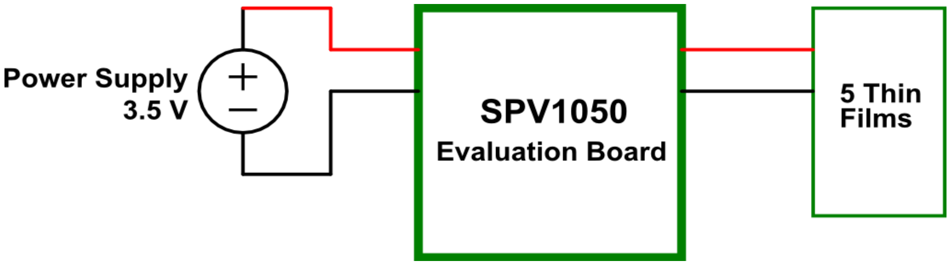


Fig. 10 Charging thin films schematic

The second diagram is used to hypothetically discharge the thin films (Fig. 11). There is no power supply going into the energy harvester, but instead the thin films are the only source of power. The TI-1795 four-function calculator was used as a load. Since the load was so small, it barely discharged at a rate of 0.1 V per minute.

One must make sure that the calculator is connected to the output pin that has 3.3 V. The team made the mistake of plugging it into the 1.8 V pin, and the thin films fell to 1.8 V and soon 0 V, which meant the battery had died.

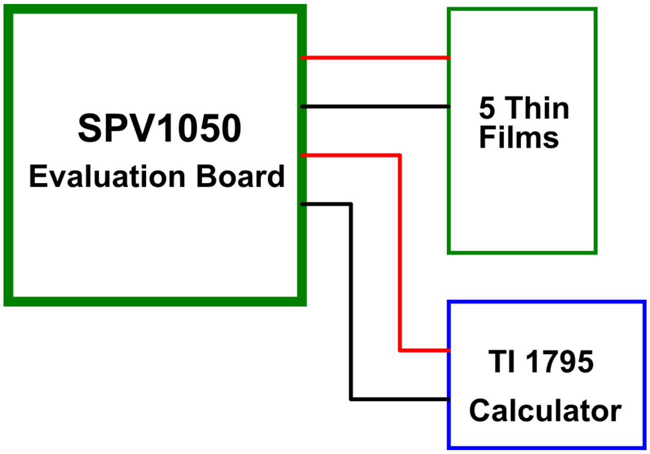


Fig. 11 Discharging thin films schematic

4.3.4 Procedure

As seen in the circuit diagrams in Section 4.3.3, we charged five thin films by plugging them into the output battery pins of the SPV1050 evaluation board and supplied 3.5 V plus a bit of current as input. When discharging the five thin films, we took away the power supply and added the TI-1795 calculator as a load in the 3.3-V pins. A multimeter was used to monitor the voltage of the thin films every few seconds.

4.3.5 Results

We managed to successfully charge and discharge the thin films using the harvester. Figures 12 and 13 illustrate the change in voltage over time.

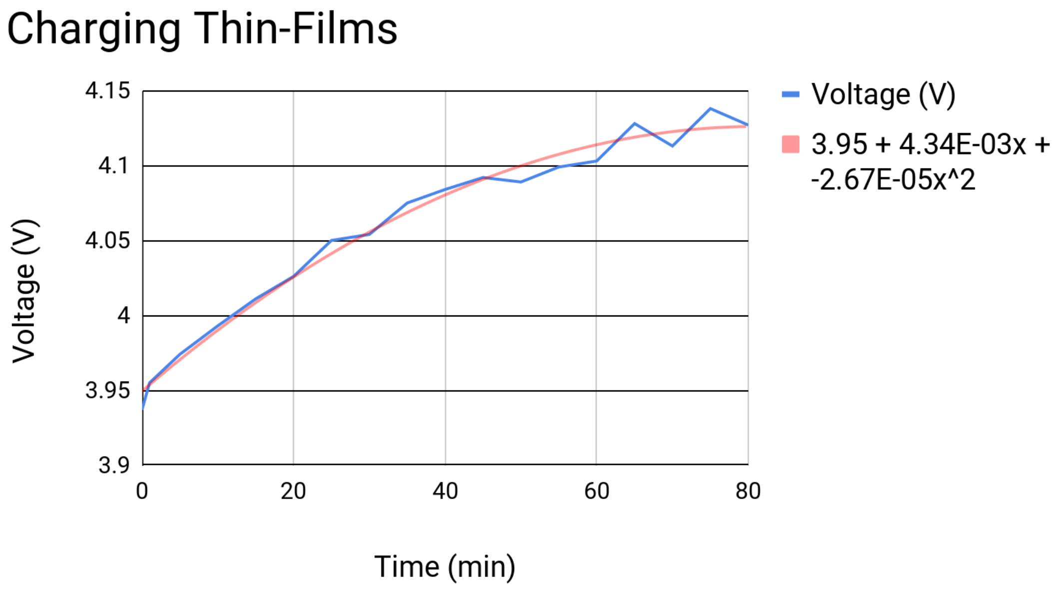


Fig. 12 Charging thin films experimental data

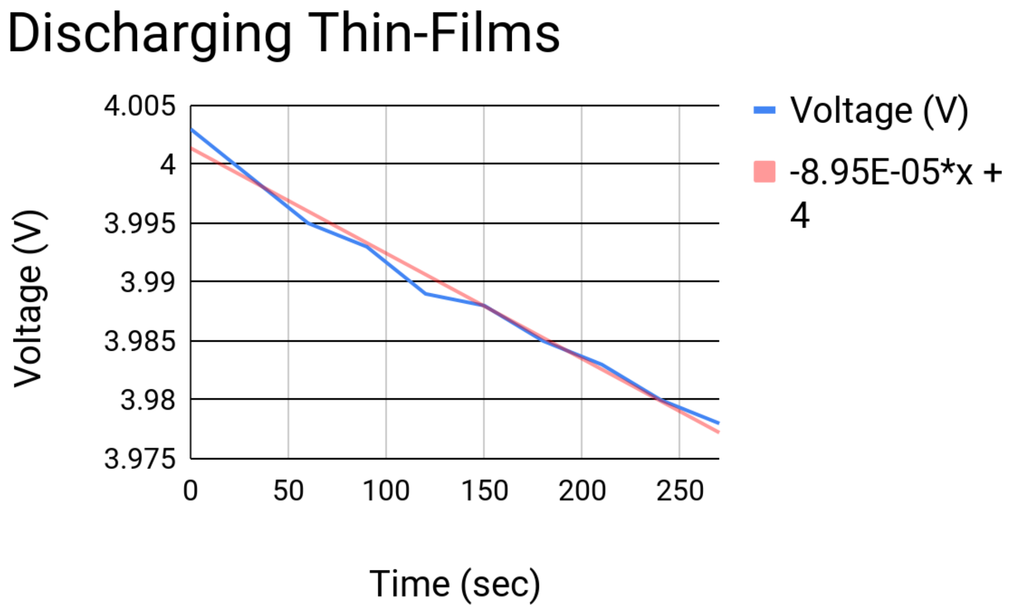


Fig. 13 Discharging thin films experimental data

4.3.6 Next Steps

This experiment was a success, since the function of each circuit was predicted correctly. There are several avenues of follow-up experiments that can be taken. First, it would be beneficial to repeat this experiment but discharge for a longer period of time to see if the graph continues to be linear. Second, various loads can be tested when discharging to see how that affects the discharge graph.

Theoretically, the thin films should charge faster and being able to quantify that is important for predicting the functionality of the EHS. Finally, the thin films have a datasheet that shows their charging/discharging rate. Comparing this graph with the added component of the energy harvester board is important to see what effect the energy harvester board has on the charging/discharging mechanism of the thin-film batteries.

4.4 Powering the TI-1795 Calculator with the Energy Harvesting System

4.4.1 Purpose

The purpose of this experiment is to test if the energy harvester connected to a power supply and thin films can power a four-function calculator. We also wanted to see if the calculator would turn on once we swap out the power supply for PV cells.

4.4.2 Materials

The following materials were used:

- Power supply
- PV cells
- Energy harvester circuit board
- Five thin-film batteries
- TI-1795 calculator
- Two 1-kΩ resistors
- Breadboard and jumper wires

4.4.3 Procedure

We connected the power supply through a 1-kΩ resistor and into the input pins of the energy harvester. The thin films were connected to the battery pins, and the calculator was connected through a 1-kΩ resistor and into the 3.3-V output pins of the harvester. We then repeated this procedure but with PV cells as input.

4.4.4 Results

The calculator successfully turned on using the harvester. Figure 14 shows the calculator working when the power supply was used as input, but it also worked with PV cells. The power supply was at 2.2 V and 4.9 mA when the calculator turned on. After the power supply was turned off, the calculator lasted 8.7 min. The PV cells were at 2.25 V and 0.24 mA when the calculator turned on. After the PVs were disconnected, the calculator lasted 3 min.

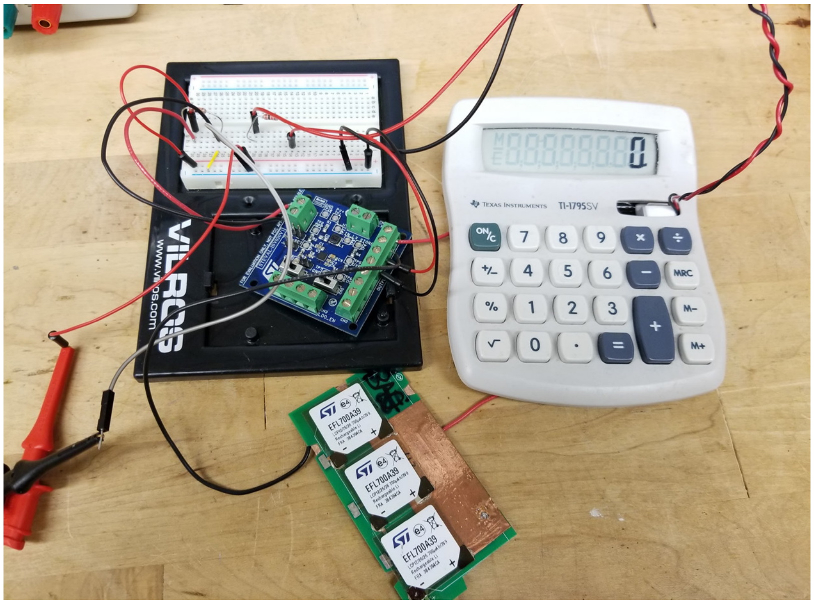


Fig. 14 Powering the calculator with the energy harvester

4.5 Building the TritiLED 3.0

4.5.1 Purpose

Ted Yapo on Hackster.io designed a long-lasting, low-powered light sensor, and it would be an appropriate demo to use with our EHS.[11]

4.5.2 Materials

The following materials were used:

- PIC12LF1571 8-pin small-outline integrated circuit (SOIC)
- 74LVC1G123 monostable SM8
- 10-µF 25-V 1206 X7R multilayer ceramic chip capacitor (MLCC) capacitor
- 1-µF, 25-V 0805 X7R MLCC capacitor
- 100-Ω 1206 resistor
- IRLML6244 N-channel SOT23 metal-oxide-semiconductor field-effect transistor (MOSFET)
- DMG2305UX P-channel SOT23 MOSFET

- CR2032 battery retainer
- 100-pF C0G 0603 capacitor
- CR2032 coin cell battery
- Oslon Signal Verde (505-nm) LED
- Bourns SRR6028-102Y 1-mH inductor
- 51-kΩ 0603 1% resistor
- TritiLED printed circuit board (PCB)
- PICkit 3
- Breadboard and jumper wires

Figures 15 and 16 show the hardware diagrams.

Fig. 15 TritiLED part placement

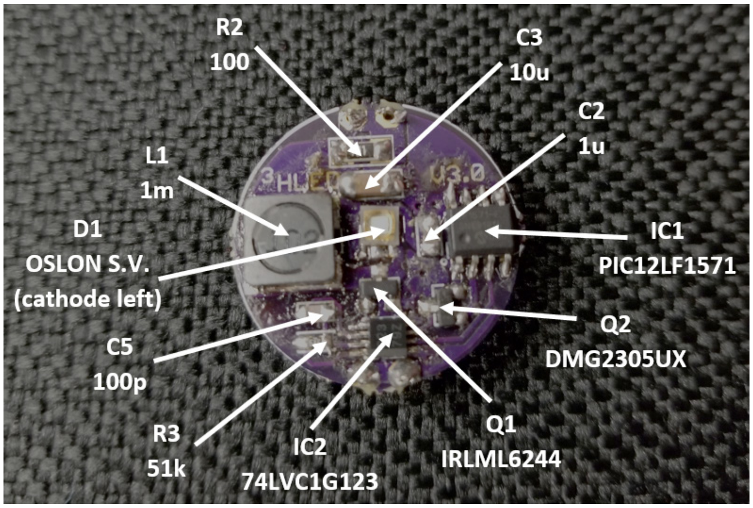


Fig. 16 TritiLED part placement

4.5.3 Procedure

We first soldered the OSLON LED in the center and then soldered the next convenient component until all the parts were secure on the PCB. Then, we soldered wires onto the PIC12LF1571, which connects to one end of the PICkit 3 and into the computer via a USB cable on the other end. Yapo's C-code was successfully compiled on the MPLAB X integrated development environment (IDE). The resulting hex file was then uploaded onto the PIC12LF1571 using the MPLAB X integrated programming environment (IPE).

4.5.4 Results

We finished soldering the components on the PCB, and there was voltage running through each component when the 3-V coin cell battery was inserted. Note that when measuring the voltage of a MOSFET, gate is power and drain is ground. Table 3 shows the voltage measurements of each component. We attempted to program it using a PICkit 3 and the MPLAB X IDE. Although it seemed like the code was successfully uploaded onto the board, the LED did not turn on. Since the components are not intended to be hand-soldered, this is by far the biggest variable we are facing. In the future, the soldering technique of reflowing the board should be used.

Table 3 Voltages of various components on TritiLED

Component	IC1	C3	C2	L1	IC2	Q2	Q1	D1	C5	R3	R2
Voltage (V)	2.95	2.86	1.30	1.30	1.98	2.86	2.87	1.67	1.62	1.69	2.44

4.6 Maximum Output Power of the Energy Harvester Board

4.6.1 Purpose

The purpose of this experiment is to further gain an understanding of what the energy harvester board is able to do with the thin-film batteries, and then what we might be able to power. This is achieved by having a set power requirement, finding the resistor needed, and checking to see that we see the expected current. If the system cannot handle the load, then the current will be close to zero.

4.6.2 Materials

The following materials were used:

- Energy harvester board
- Power supply

- Five thin-film batteries
- Various resistors
- Multimeter
- Breadboard and jumper wires

4.6.3 Sample Calculation

The following is the calculation we used:

- Desired power = 15 mW and output voltage = 3.3 V
- Using power = $(\text{voltage})^2$ / resistance, we have 15 mW = 3.3^2 / R.
- Solving for R, we get R = 726 Ω.
- Expected current: V = I × R, 3.3 = I × 726, I = 4.5 mA

4.6.4 Procedure

The first thing that we did was calculate the resistor values for 50, 35, 30, 25, 15, and 10 mW. We did not know how much we could power before we started, so we just started at 50 mW and worked our way down if the circuit did not work.

For each circuit that was implemented, we simply checked that the output pin was still at 3.3 V and that the current was what we expected for that resistor. If voltage or current readings were significantly lower than expected, we understood that the energy harvester could not power that specific load. The thin-film batteries were attached to the battery pins of the energy harvester board (not shown in Fig. 17). Figure 17 shows a block diagram of the circuit that we used a power supply, but we also repeated the experiment with PVs as well.

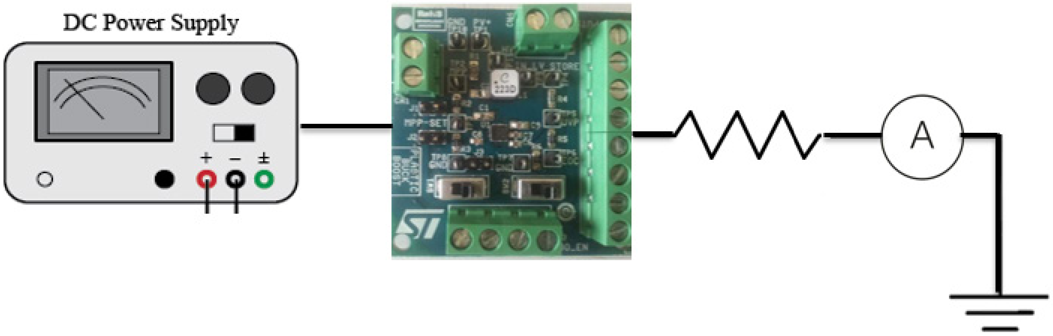


Fig. 17 Diagram to determine maximum output power and current of the energy harvester

4.6.5 Results

For this experiment, 10, 15, 25, 30, 35, and 50 mW were all tested. Only 10, 15, and 25 mW were able to be powered. When the power supply was replaced by various PV cells, the maximum output power dropped to around 15 mW. This is very likely to happen with the fact that the PV cells provided were not able to give as much current as the power supply since they had comparable amounts of voltage. The final system will have PV cells and not a power supply, so it is important to try to create a system that will take less than 15 mW to function.

4.7 Minimum Current to Turn On the Energy Harvester Board

4.7.1 Purpose

The purpose of this experiment is to verify the manufacturer's datasheet that the minimum current to turn on the energy harvester board is 10 μA. This is important to verify because if the current is actually lower than what the manufacturer said, then it is possible to make the circuit even lower powered than anticipated. It is also a sanity check that the component that was shipped to us is working properly.

4.7.2 Materials

The following materials were used:

- Energy harvester board
- Power supply
- Five thin-film batteries
- Various resistors
- Multimeter
- Breadboard and jumper wires

4.7.3 Procedure

Because the power supply in the laboratory did not have fine tuning in the range of microamps, we had to design several simple circuits to lower the output current of the power supply (Fig. 18). To determine whether or not the energy harvester board actually turned on, the voltage of the output load pins was monitored to see if they were actually 3.3 and 1.8 V, respectively. If they read anything significantly lower, it was determined that the board did not turn on.

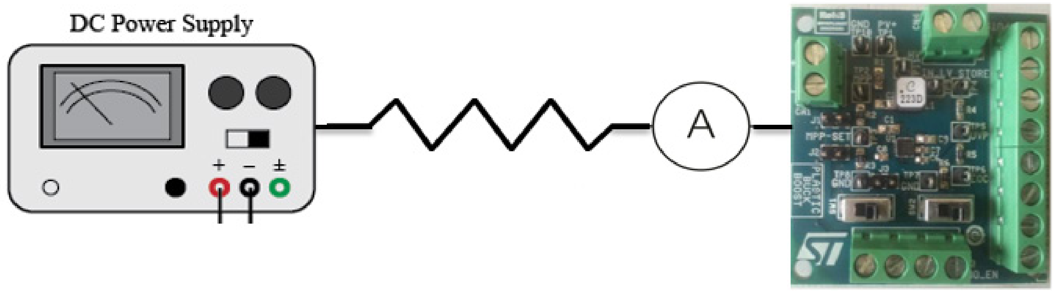


Fig. 18 Simple diagram of the circuit used to find the minimum current

As seen in Fig. 18, we simply continued to replace the resistor with higher and higher values to lower the input current from the DC power supply until the energy harvester was no longer able to turn on and therefore we had a minimum input current.

4.7.4 Results

The experiment was conducted four different times. The currents measured were 27, 20, 10, and 7 µA. For each experiment where the current was at or above 10 µA, the energy harvester board turned on as expected. It is important to note that the energy harvester board took a little longer to turn on the closer the current was to the minimum. As soon as the current went below 10 µA, the voltage on the output pins dropped significantly. Therefore, we simply confirmed the datasheet's values of the minimum current to turn on the energy harvester board and that the input power for the system cannot be lowered any more.

4.8 Low-Power Arduino Circuit

4.8.1 Purpose

Being able to use an Arduino opens up tons of possibilities of what our low-powered system is able to do since the sensors can be programmed and the data can be analyzed as well. Therefore, we were looking for a way to use an Arduino in our system. The problem was that the Arduino took a lot of power compared to what was able to be provided by the system. Marco Schwartz created a website where he took the Arduino's microprocessor chip, ATmega328, and made it work on a breadboard with significantly less power.[12]The purpose of this experiment was to be able to replicate what Schwartz did so we would be able to build off of it.

4.8.2 Materials

The following materials were used:

- Atmel ATmega328

- 10-µF capacitor
- Two 22-pF capacitors
- 10-kΩ resistor
- 5-kΩ resistor
    - Note: This resistor can be higher or lower depending on how much current we want to go into the load. Schwartz's value was 220 Ω.
- Red LED
- 4-MHz crystal clock
    - Note: We changed the 16-MHz clock to a 4-MHz clock.
- Power supply
- Breadboard and jumper wires

Figure 19 shows the circuit diagram, and Fig. 20 shows the hardware configuration.

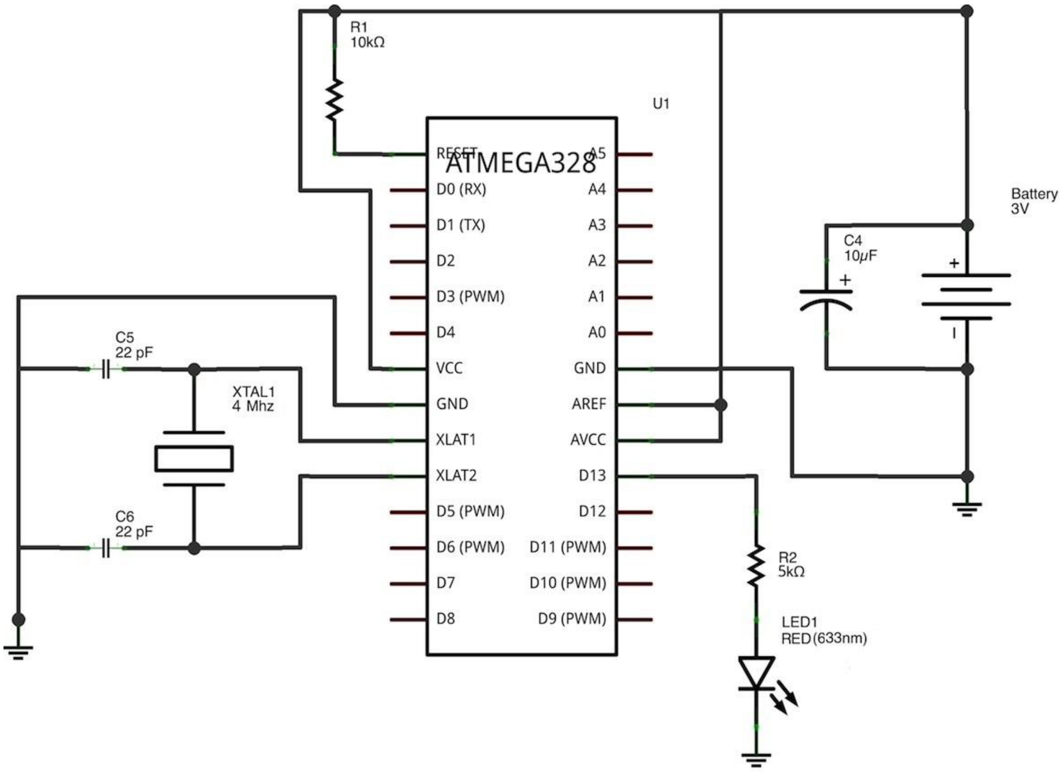


Fig. 19 Low-power Arduino circuit diagram[12]

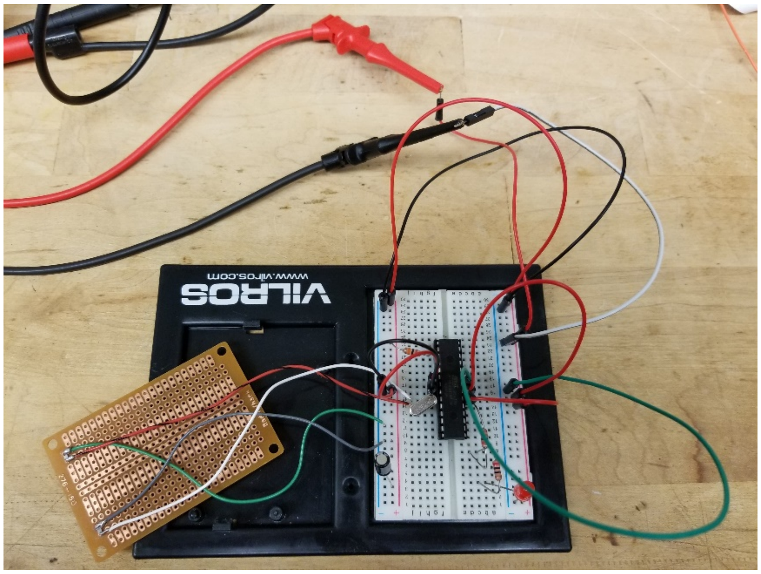


Fig. 20 Low-power Arduino hardware configuration

4.8.3 Procedure

We built an Arduino system with the minimal components possible. The main component is the Atmel ATmega328 microcontroller that will run our code. To power the Arduino, we supplied 3 V from the power supply. The components needed around the chip was one 10-µF capacitor, two 22-pF capacitors, one 10-kΩ resistor, one 22-Ω resistor, one red LED, and one 4-MHz crystal clock. To program the ATmega328, we removed the ATmega328 from the real Arduino Uno and transplanted our chip onto the board. Then, we uploaded the default blink sketch onto our chip. We also installed the JeeLib library, a header file meant to lower power consumption, and included it on our sketch. Finally, we placed the ATmega328 back into the circuit and the red LED should blink on and off with 5-s intervals.

4.8.4 Results

We successfully replicated Schwartz's low-power Arduino. Using a 16-MHz crystal clock and the JeeLib library on the Arduino software, he states that the low-power Arduino takes 2.2 mA when the LED is on and 43 µA when the LED is off. Our circuit did not turn on with the 16-MHz clock through the energy harvester. Only when switching to a 4-MHz clock did the Arduino turn on. The datasheet for the ATmega328 says that the 4-MHz takes lower power, but we have yet to figure out the current consumption calculation when a lower clock rate is used. Next steps for this circuit would be to try a 2-MHz or even 1-MHz crystal clock and see if that would reduce even more power. We would also have to make sure that all of the components are still functional with the lower clock frequency.

4.9 Minimum Current for Energy Harvester and Low-Power Arduino Circuit

4.9.1 Purpose

To understand if our system can power the low-power Arduino, we need to understand the power requirements. Part of this is finding the minimum current needed for the energy harvester to still be able to turn on the Arduino.

4.9.2 Materials

The following materials were used:

- Low-power Arduino
- Power supply
- Energy harvester board
- Five thin-film batteries
- Various resistors
- Multimeter
- Breadboard and jumper wires

4.9.3 Procedure

Because the power supply in the laboratory did not have fine tuning in the range of microamps, we had to design several simple circuits to lower the output current of the power supply. The circuit setup was that we had the power supply in series with a resistor in series with the ammeter, and then to the energy harvester board. We tried various resistances, and with each circuit, we wanted to see what the current was before any load was attached and after the harvester turned on (Table 4). To determine whether or not the energy harvester board and the low-power Arduino circuit actually turned on, the voltage of the output load pins was monitored to see if they were actually 3.3 V. If they read anything significantly lower, it was determined that the board cannot handle the circuit. If the output load pins did read 3.3 V, we would then proceed to measure the current with the ammeter.

Table 4 Finding minimum current for low-power Arduino

Resistor (Ω)	1k	3.3k	5.1k	7.5k	20k	39k	100k	120k	130k[a]	180k[a]
No load (A)	1 mA	340 µA	213 µA	330 µA	88 µA	50 µA	30 µA	25 µA	23 µA	17 µA
Energy harvester on	0.7 mA	220 µA	150 µA	110 µA	45 µA	26 µA	15 µA	18 µA	17 µA	12 µA

[a] The harvester could not turn on the low-power Arduino.

4.9.4 Results

This experiment took a while to run because we had to make sure that there was no residual power left on the harvester. Thus, we had to make sure the input and output voltages were zero before plugging the thin films in. We learned that a circuit that provides 25 µA of current, or 18 µA when the load is plugged in, is barely enough to turn on the circuit. A 20-µW RPS, at least, can be used as the power source based on the load's requirements.

4.10 Running Multiple Loads off of the Energy Harvester

4.10.1 Purpose

We wanted the energy harvester to run the low-power Arduino which then runs an LED, a calculator, and a passive infrared (PIR) sensor at the same time.

4.10.2 Materials

The following materials were used:

- Red LED
- TI-1795 calculator
- Low-power Arduino
- Energy harvester board
- Five thin-film batteries
- Power supply
- 5-kΩ resistor
- Breadboard and jumper wires

4.10.3 Procedure

We edited the low-power Arduino code to make pin 13 always high so that the calculator would always be on. The power supply, five thin films, and the low-power Arduino are connected to the energy harvester. One of the steps to make this circuit more successful was to lower the resistance of the resistor in series with the LED. If the resistance is low, it caused problems because the power output would be high (V^2/R). We chose to put a 5-kΩ resistor with the LED so that it would not take up much power but it was still bright enough that we could tell that it was on. After the experiment was successful in running the LED and the calculator, we decided that we wanted to add the PIR sensor to see if we can handle running all three at the same time.

4.10.4 Results

Figure 21 shows the circuit when all three items are connected to the output of the Arduino. The PIR sensor has an LED attached as well so we can check if it is working. From testing, we learned that the PIR sensor was in fact very sensitive to movement. It was also sensitive based on the amount of current that was going through it. The less current going through it, the better it would behave. This was beneficial to us because we again wanted to use a large resistance in series with the LED to limit the total power usage. Once it is on, it will stay on for a long period of time since our loads do not take up much power at all. For this reason, we usually disconnect the output power and ground from the load to turn off the circuit. To get the Arduino working again, we have to physically lift the ATmega328 off the breadboard and insert it again. This always does the trick, and we have no idea why. In summary, this experiment proved that the harvester is capable of running a low-power Arduino, a LED, a calculator, and PIR sensor at the same time.

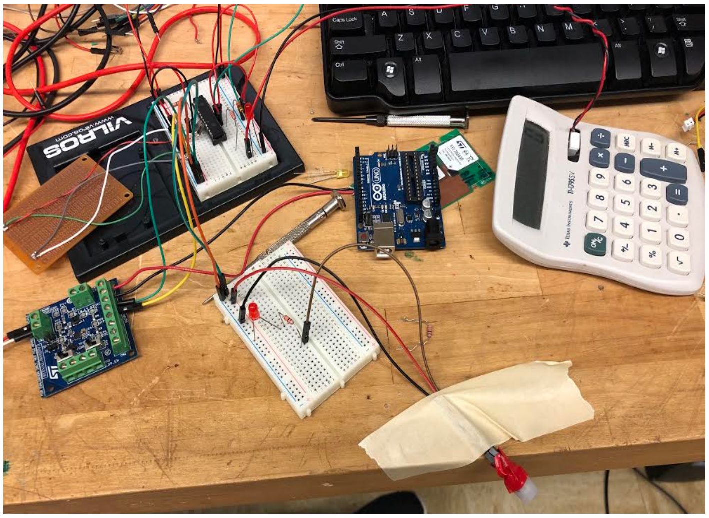


Fig. 21 Running a low-power Arduino, calculator, LED, and PIR sensor off of the harvester

4.11 Testing the 1.8-V Output Pin of the Energy Harvester Board

4.11.1 Purpose

The purpose of this experiment is to learn more about the harvester's 1.8-V output pin so that we know its capabilities when we encounter a load that requires this pin. We know for a fact that the low-power cameras from the other universities will utilize the 1.8-V pin.

4.11.2 Materials

The following materials were used:

- Energy harvester board
- Power supply
- Five thin-film batteries
- Various resistors
- Red LED
- TI-1795 calculator
- Breadboard and jumper wires

4.11.3 Procedure

First, we tried powering a 10-mW circuit by using a resistor. The calculation is as follows $P = V^2/R \rightarrow 10 \times 10^{-3} = 1.8^2 / R \rightarrow R = 324\ \Omega$. We checked to see that the output voltage without any load is 1.8 V when the harvester is powered. Then, we want to connect a 324-Ω resistor and see if it can handle that load. If the voltage on the output pin is still 1.8 V, then the experiment is successful. We repeated this procedure, but for a 15-, 16-, 17.5-, and 20-mW circuit.

Next, we tried two different setups in relation to the thin-film batteries when powering the LED. The first was to still include the thin films like we had been doing all along, and then unplugging the thin films. The final test was to use the calculator as a load.

4.11.4 Results

The 1.8-V output pin was able to handle a 10-mW circuit. Since we knew that the 1.8-V pin could power this circuit, we wanted to use it again to see the change, if any, in input current from attaching a load. When the load was not attached, the input current into the harvester was 3.4 mA, but when the load was attached, the input current into the harvester went up to 8–10 mA. After testing a few more circuits, we concluded that the harvester can power at most a 15-mW circuit with the 1.8-V pin.

When the thin films were included, the LED circuit lit up with a 1-kΩ resistor but was very dim when compared to the 3.3-V circuits. After unplugging the thin films, the LED still turned on. The main difference between the two circuits was the input current to the energy harvester. With the thin films, it was about 5 mA. Without the thin films, it was about 0.2 mA. We do not understand why the thin films cause the input current to go up. Theoretically, it should only be boosting the output current to help power tougher loads that the energy harvester itself cannot handle. Finally, we tested the calculator without a resistor to see if we could power a small load like that as well and we can. The input current was around 0.5 mA. The output current going through the calculator was 0.3 mA.

4.11.5 Next Steps

Since there were several parts of the experiment we did not understand, we should investigate further to figure out how the energy harvester works. First, we must figure out why the input current to the harvester went up when a load was attached. The input current should be seemingly independent to the output current. Also, it seemed strange that the input current to the harvester changed when the thin films were attached versus unattached. It was thought that this should only change the output current. This should also be investigated but is not particularly urgent since the thin films will always be plugged into the energy harvester board in the final circuit.

4.12 Power Consumption of the Energy Harvester Board

4.12.1 Purpose

Now that we know the minimum power to turn on the energy harvester, it is important to identify out how much power the harvester takes to stay on.

4.12.2 Materials

The following materials were used:

- Energy harvester board
- Power supply
- Multimeter

- Various resistors
- Five thin-film batteries
- Breadboard and jumper wires

4.12.3 Procedure

We connected the power supply through an input resistor, and then into the energy harvester board. From there, we measured the input current into the energy harvester board and compared it to the expected current if it was just that one resistor. The reason for doing this is to see what the impedance of the energy harvester is for this configuration and if it changes depending on the setup. Table 5 shows the data collected during the experiment.

Table 5 Data from experiment 4.12

Input resistance (Ω)	Input voltage (V) power supply	Input voltage (V) EH	Expected current (mA)	Current with EH (mA)	Resistance of EH (Ω)	Current with EH and Arduino	Power draw (mW)
1k	3.385	2.8	3.385	0.6 but saw values over 1	4.64k	0.6–0.7	1.68
3.3k	3.445	2.8	1.04	0.17–0.2	16.6k	0.17–0.2	0.47
5.1k	3.448	2.855	0.676	0.117–0.134	23.8k	0.117–0.134	0.329

Note: EH=energy harvester.

4.12.4 Results

Looking at the first circuit with an input resistance of 1k, the expected current is 3.385 mA, but we saw values of 0.6 mA when measuring the current. That meant that the measured resistance of the entire circuit was actually 5.6 kΩ and that the energy harvester board was acting as a 4.64-kΩ load. In addition, it is important to note that the voltage drop due to the energy harvester was constant for each experiment, dropping the input voltage from around 3.4 V to approximately 2.8 V. It is also interesting to note that the value of the resistance measured for the energy harvester changed for every circuit. This also meant that the power draw was different for each circuit as well. This was particularly intriguing because we had thought that the power draw for the energy harvester would be constant and not depend on the input to the energy harvester.

Another observation that we liked to see is that the output current is not affected by the input load. The current whether there was or was not a load attached was exactly the same. This kind of proved to us that the thin films were doing the heavy lifting in terms of powering the output loads. This was good because we want the RPSs and PVs in the future to simply turn on the energy harvester and have the thin films power the higher-power loads attached to the outputs.

4.12.5 Next Steps

As it turns out, this experiment taught us that we do not know a lot about how the energy harvester really functions. The two main questions to try to learn from are, “Why does the apparent resistance of the energy harvester change?” and “Based on this data, is it possible to tell when the energy harvester is charging or discharging and does that make it consume more power?”

Essentially, we need more data points in order to make any conclusive statements about the energy harvester board and how it behaves. First, we would want to continue putting various input loads and making the table from this experiment larger. This will make it easier for us to determine if there actually is a trend happening. Based on the power draw, we can also determine how low the power draw gets to the theoretical minimum of 26 µW based on 10 µA and 2.6 V.

4.13 SparkFun Transceiver Circuit

4.13.1 Purpose

Once we can get the harvester to run a low-power camera, the next step would be to transmit the image to a receiver. The main reason we chose the SparkFun transceiver was because it was Arduino compatible, and we are going to try to run the transceiver through our low-power Arduino.

4.13.2 Materials

The following materials were used:

- Low-power Arduino
- Arduino Uno
- Power supply
- Energy harvester board
- Five thin-film batteries
- Two SparkFun transceivers
- Breadboard and jumper wires

Figure 22 shows the circuit diagrams. Note: The SparkFun RedBoard is just their version of an Arduino.

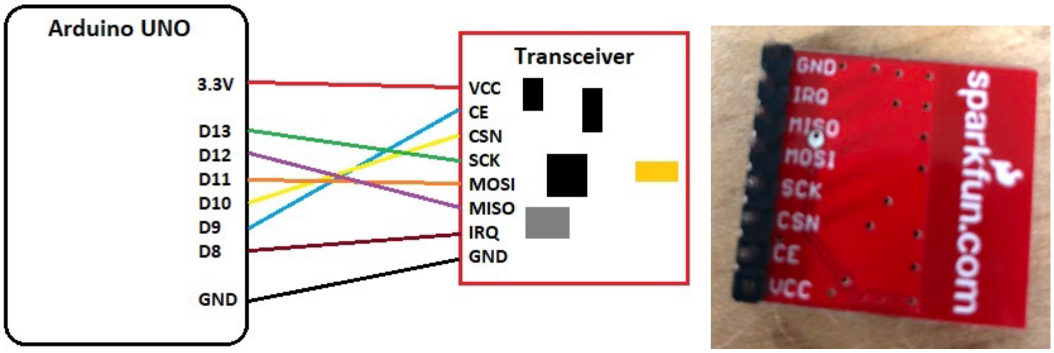


Fig. 22 SparkFun transceiver circuit (left) and pin configuration (right)

4.13.3 Procedure

First, we soldered male headers pins onto both transceivers. By following the circuit diagram in Fig. 22, we hooked up the transceiver to the Arduino Uno as follows: VCC to 3.3 V, GND to GND, IRQ to D8, CE to D9, CSN to D10, MOSI to D11, MISO to D12, and SCK to D13. We then duplicated the connections between our low-power Arduino and another transceiver. Next, we downloaded the given RF24 library and uploaded the code onto each ATmega328.[13] The Arduino Uno will stay connected to the computer and act as a receiver. The low-power Arduino will be connected to the 3.3-V output pin of the energy harvester, five thin films will be connected to the battery pins, and the power supply connected to the input pins.

4.13.4 Results

The transceiver was definitely able to be powered from the regular Arduino. We were struggling to get it powered through the low-power Arduino. So, then we tried using the power supply as well instead of going through the energy harvester. The transceiver received the 13 mA that it needed to turn on, but this did not occur each time. The transceiver is a large load for the EHS and Arduino to handle, and therefore, it will be a challenge to incorporate it. Because of its necessity, it is something that we must answer.

4.14 Multiple Energy Harvesters in Parallel (Thin Films)

4.14.1 Purpose

Since one energy harvester only outputs enough current to run at most a 25-mW circuit, we theorize that we can double the output current with the output of two harvesters placed in parallel or triple the output current with three harvesters. Before we purchased two more harvesters, we tested this theory by placing the output of one harvester in parallel to a second power supply. With just the harvester, the output current was 0.3 mA. With just the second power supply, the output current was 87 mA. We plugged the two sources in the breadboard in parallel, had an ammeter in series, and the resulting current was 87.3 mA. As a result, it was deemed sufficient proof that we could place multiple harvesters in parallel to sum up the output currents and thus increase the output power.

4.14.2 Materials

The following materials were used:

- Multiple energy harvester boards
- Multimeter
- Two power supplies
- Two packs of five thin films
- Various resistors
- Breadboard and jumper wires

Figure 23 shows the circuit diagram.

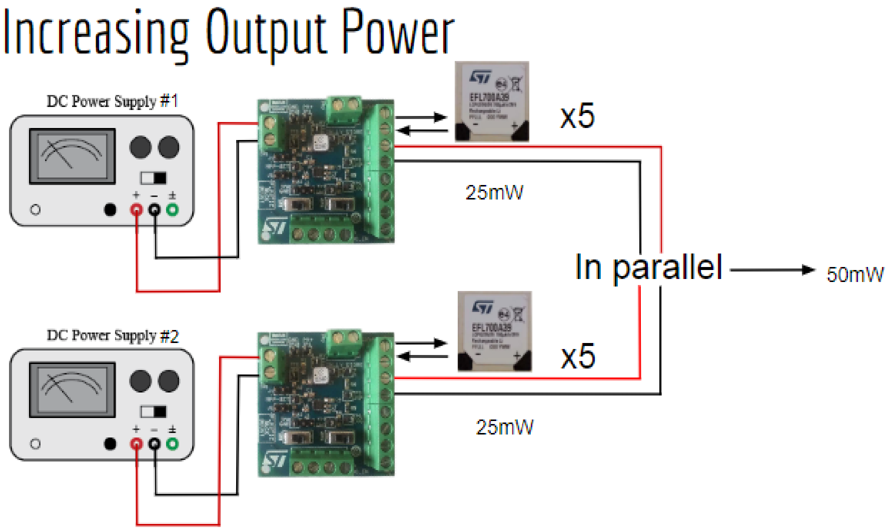


Fig. 23 Output of two harvesters in parallel

4.14.3 Procedure

As seen in Fig. 23, power supply #1 is connected to the input of the first energy harvester, five thin films connected to the battery pins, and the 3.3-V output pins goes into the breadboard. Similarly, power supply #2 is connected to the input of the second energy harvester, five thin films connected to the battery pins, and the

3.3-V output pins goes into the breadboard but parallel to the 3.3-V output pins of the first harvester.

4.14.4 Results

We learned is that each new thin film could power a 30-mW load on its own. The problem is that when we put the output of the energy harvester boards in parallel using the new thin films as the secondary power source, the power did not add like we expected. We were unable to power a 40- or 50-mW load when we would expect to power 60 mW. This was pretty concerning for us as the experiment results did not match with theory and we did not have a good explanation for why.

4.14.5 Next Steps

We must figure out why this circuit did not work as anticipated. Therefore, we will try to use a different type of secondary power source, a cell phone battery, and see if we can combine the output power of multiple energy harvesters. If it works for a different type of battery, then we can point to the thin films as the problem and figure out how to proceed from there.

4.15 Multiple Energy Harvesters (Li-ion Battery/Typical "Cell Phone" Battery)

4.15.1 Purpose

The purpose of this experiment is to see if the thin films were the issue in combining output power from multiple energy harvester boards. Therefore, we conduct the same experiment and just switch out the thin films for the cell phone batteries. It is important to note that the cell phone batteries are much stronger.

4.15.2 Materials

The following materials were used:

- Two energy harvesters
- Breadboard
- Cell phone batteries
- Various resistors for loads

4.15.3 Procedure

Because the cell phone batteries have a higher energy storage capacity than the thin-film batteries, we first must figure out how much power each individual cell phone battery can output. From there, we can put the output of each energy harvester in parallel to then see if we can power a larger load.

4.15.4 Sample Calculations

We did the following calculations:

- Theoretical power output: $P = V^2/R = 3.3^2 / 43 = 252$ mW
- Measured power calculation: $P = IV = 63 \text{ mA} \times 3.3 = 200$ mW
- Efficiency = 1 - (Theory - Measured) / Theory = (250-200)/200 = 75%

Table 6 shows the power data for this experiment.

Table 6 Multiple energy harvester using cell phone battery power data

Resistor used (Ω)	Theoretical power output (mW)	Measured current (mA)	Measured voltage (V)	Measured power (mW)	Harvesters used
43	250	63	3.3	200	1
36	300	78	3.3	250	2
27	403	96	3.3	307	2
22	465	110	3.3	352	2
18[a]	568	120	3.3	396	2
20	512	125	3.3	406	2

[a] The circuit with 18 Ω used as the load could not be powered with two energy harvester boards. The readings were very spotty, and we could not get the right current reading.

4.15.5 Results

The first circuit could be powered by just one energy harvester board. When we increased the output power required, the circuit could no longer be powered with just one board. We, then, added the second energy harvester in parallel to see if we could power the newer, higher-power circuits. We discovered is that, in fact, having a second cell phone battery through the energy harvester in parallel boosted the maximum output power. The fact that the maximum power output was doubled was a good sign that there was not any significant losses in power from adding the second energy harvester in parallel.

This is an important discovery because doing this experiment with the thin-film batteries did not work. Therefore, we know there must be something with the thin films that prevents them from combining currents as well as the cell phone battery.

4.15.6 Next Steps

There are two next steps relevant to this experiment. First, we want to add the third energy harvester to this circuit to see if we can power a 75-mW circuit with three thin films. Theoretically, this should work, but we had some initial problems while trying to get the third cell phone battery as a part of the circuit. Second, we should revisit the thin-film batteries to figure out how and if it is possible to make the thin film and energy harvester in parallel combination work.

4.16 Low-Power Arduino Maximum Output Power (Power Supply)

4.16.1 Purpose

To see if we can power a low-power camera, we want to see what the maximum power the Arduino can output. If it cannot power the 60-mW camera, then we want to identify the maximum power output of the Arduino.

4.16.2 Materials

The following materials were used:

- Arduino
- Energy harvester board
- Various resistors to get maximum output power

4.16.3 Procedure

We programmed the Arduino with a short Arduino program to just turn on one of the output pins. We, then, took the ATMEGA328 out of the Arduino and plugged it back into the breadboard and the low-power Arduino circuit. We then connected the ammeter in series with output resistor to see if we get the right current for the resistor. If so, then we consider the load “powered”. We continuously changed the resistor until we found the maximum output power of the Arduino. Therefore, we could measure the output voltage of the Arduino pin as well as the output current to see what we could power. Table 7 shows the measured output for this experiment.

Table 7 Measured output power of low-power Arduino

Goal power output (mW)	Calculated resistance	Measured current (mA)	Measured voltage (V)	Actual power output (mW)
10	1000	3.3	3.3	10.89
20	550	6	3.3	19.8
30	390	8.4	3.276	27.5184
40	270	11.7	3.159	36.9603
50	217	13.5	2.9295	39.54825
60	180	15.3	2.754	42.1362
70	150	18	2.7	48.6
80	133	19.4	2.5802	50.05588
90	120	21.26	2.5512	54.238512
100	110	22.59	2.4849	56.133891
110	99	24	2.376	57.024
120	90	25.03	2.2527	56.385081
130	84	25.98	2.18232	56.6966736
140	75	28.72	2.154	61.86288
150	71	29	2.059	59.711

4.16.4 Results

Important things to note is that it seems we are barely able to get up to a 60-mW output load. Even as we continued to push the theoretical power up, the Arduino output did not increase much at all. This can be seen from around 70 to 150 mW, where the measured output only increased from 12 mW (from 48 to 60 mW). Therefore, there is not a linear relationship of the expected and measured power output for this system. The problem is that as we became closer to that value, the voltage drops from 3.3 V, basically showing the system was struggling to support it.

4.16.5 Next Steps

This experiment makes us skeptical that the OV7670 will be able to be powered by the low-power Arduino. The problem is that the camera needs 3.3 V and the microcontroller output pin was unable to support that as the output power that was needed increased. Technically, the camera needs 5 V, but we were able to make it work with the 3.3 V using the Arduino Uno. Because of this, we doubt that the camera will work with anything less than the 3.3 V. The next step is to incorporate the camera with the low-power Arduino circuit and see if it has the right amount of voltage and current going through it.

4.17 Powering the OV7670 Camera with the Low-Power Arduino

4.17.1 Purpose

Despite the fact that it did not seem optimistic that the low-power Arduino would be able to power the OV7670 based on Experiment 4.16, we still wanted to see if we could power the OV7670.

4.17.2 Materials

The following materials were used:

- Arduino
- Energy harvester board
- OV7670 camera

4.17.3 Procedure

We set up the circuit to power the OV7670 from Experiment 4.2. We wanted to see if the camera was getting the right voltage and current through it to determine it was on. So instead of plugging the power pin into the breadboard, we incorporated the ammeter in series to determine if the camera was getting enough current. We also were able to use a voltmeter on the camera's power and ground to make sure that it was getting enough voltage.

4.17.4 Results

The voltage reading from the camera read 3.3 V as expected. The problem was that the current readings were only 1.7 mA. For a 60-mW camera operating at 3.3 V, we should expect 18 mA, which is nowhere near the value we saw.

4.17.5 Next Steps

The conducted experiment only had the power and ground wires plugged in. We then uploaded the program and plugged in the rest of the wires. The current reading then went to 0 mA, which essentially told us that there was not much hope that we would be able to power this circuit. We either need to figure out a way to lower the power needed for the camera, find a lower-powered camera, or identify a different microcontroller than the Arduino that will work with a low-powered camera.

4.18 Powering the Transceiver with the Low-Power Arduino

4.18.1 Purpose

We want to be able to power the transceiver with the Arduino because that is how we imagine the circuit in the field. The TX would be used to send data to a RX to us to then interpret. Being able to power the transceiver would then be an important aspect of the EHS.

4.18.2 Materials

The following materials were used:

- Power supply
- SparkFun transceiver
- Cell phone battery
- Low-power Arduino circuit
- Energy harvester
- Thin films

4.18.3 Procedure

We used the circuit for the transceiver from Experiment 4.13 with the low-power Arduino this time instead of the normal Arduino. The hope is that the low-power Arduino would also be able to make the transceiver turn on.

This experiment was conducted three times. The first time was with one thin-film battery. The second was with a cell phone battery. The last was with three thin-film batteries in parallel.

4.18.4 Results

For the first attempt, we conducted the experiment with just the one thin-film battery. There were 3 mA going into the Arduino, but only 0.9 mA was going into the transceiver. According to the datasheet, the transceiver should be using around 11.3 mA for TX and 13.3 mA for RX.[14] Therefore, we determined that one thin-film battery pack was not enough to power the transceiver.

The second time we conducted the experiment was with the cell phone battery. There, we saw a reading of 14 mA, which means that the circuit had turned on.

The last time we ran the experiment was with three thin-film packs in parallel to see if that would be enough current to turn on the circuit. Since the final circuit implementation will use thin films, this was especially important to try since the transceiver is not worth much to us if it cannot turn on with just the thin films. The problem is that the transceiver did not turn on with the three thin films in parallel.

4.18.5 Next Steps

The major next steps associated with this experiment are to figure out how many thin films are required to turn on this transceiver since it is an essential component to the EHS. This should be done both theoretically since we know the capacity of each thin film as well as experimentally to confirm the calculations.

If the number of thin films is unreasonable, then we should look into other alternatives for a transceiver. If the number of thin films needed is reasonable, then we should build that circuit to see if the transceiver can be powered. Also, this circuit has to be powered with PVs and not the power supply, so that also has to be considered.

4.19 Power Calculations for the TI-1795 Calculator

4.19.1 Purpose

The purpose of this experiment was to get the power requirements for the TI-1975 because we could not find a datasheet with this information online. Having the power requirements for the calculator is useful so we can quantify one of the objects that we have powered.

4.19.2 Materials

The following materials were used:

- TI-1795
- Power supply

4.19.3 Procedure

We turned the power supply to the least amount of current and voltage as possible and still have the calculator be turned on. Since the readings from the power supply are not exact, we also took measurements from the multimeter to get the voltage and current. Once we have the voltage and current, we can then easily calculate the power because P = IV.

4.19.4 Results

The minimum current that we were able to get with the power supply was 100 μA. The minimum voltage were able to get with the power supply and still have the calculator turn on was 1.68 V. This gives us a power of 168 μW.

4.19.5 Next Steps

Since the power supply is inaccurate in the amount of voltage and current it provides, we can use resistors in the future to lower the current and voltage even more before it hits the calculator. This way we can see what the true minimum power requirements for the calculator are. This is not an urgent experiment to follow-up on, and the results we obtained are likely good enough for our purposes.

4.20 Minimum Current to Turn on the Low-Power Arduino (Minimum Load)

4.20.1 Purpose

The purpose of this experiment is to see the minimum current to turn on the low-power Arduino, without the energy harvester board. This experiment is to simply learn more about the low-power Arduino and what its requirements are to turn on and function.

4.20.2 Materials

The following materials were used:

- Low-power Arduino circuit
- Power supply
- Various resistors as load
- 5-kΩ resistor
- Red LED

4.20.3 Procedure

We used resistors to bring down the current from the power supply before trying to turn on the low-power Arduino circuit. We saw that the low-power Arduino circuit was on with a red LED that was attached to the output of pin 13. We, also, had a 5-kΩ resistor in series with the red LED to reduce the power on the output load. We could not use a resistor that was too much higher than 5 kΩ because we could already barely see that the LED was on. We recorded the current measurement for each circuit to try to see the true minimum.

4.20.4 Results

We learned that the Arduino turns on when it has 2.1 mA. We saw it turn on when there was 2.0 and 1.9 mA but the LED was dimmer and struggled to stay on. Knowing this minimum input current is an important part in building the EHS and understanding the power requirements of what we are building.

4.20.5 Next Steps

One thing that we could try is to not use an LED at all and just use a voltmeter to measure the voltage coming out of pin 13. It is possible that 2.0 and 1.9 mA will work better without any load attached to the low-power Arduino. The lower we can have the input current be the better because we are trying to minimize the power for the EHS.

5. Energy Harvester System (EHS)

The EHS system (Fig. 24) shows both the progress that we have made as well as our future plans. Currently, we have conducted most of our tests with a power supply first, and then PVs to make sure it will work in this final configuration. We did not have access to the final RPSs, so tests were not done with that component of the diagram. The calculator, low-power Arduino, motion sensor, and LEDs were all successful loads that were able to be powered by this system. The TritiLED was unsuccessful at even being powered by a normal battery source, as shown in Experiment 4.5. We are awaiting cameras from various universities since the commercially available cameras are too high power (<60 mW). We are likely going to take more time to figure out how to incorporate the light sensor into the circuit. Finally, the transceiver's power requirement is too high for the low-power Arduino, so circuit adjustment may need to be made in order for it to power the transceiver and camera.

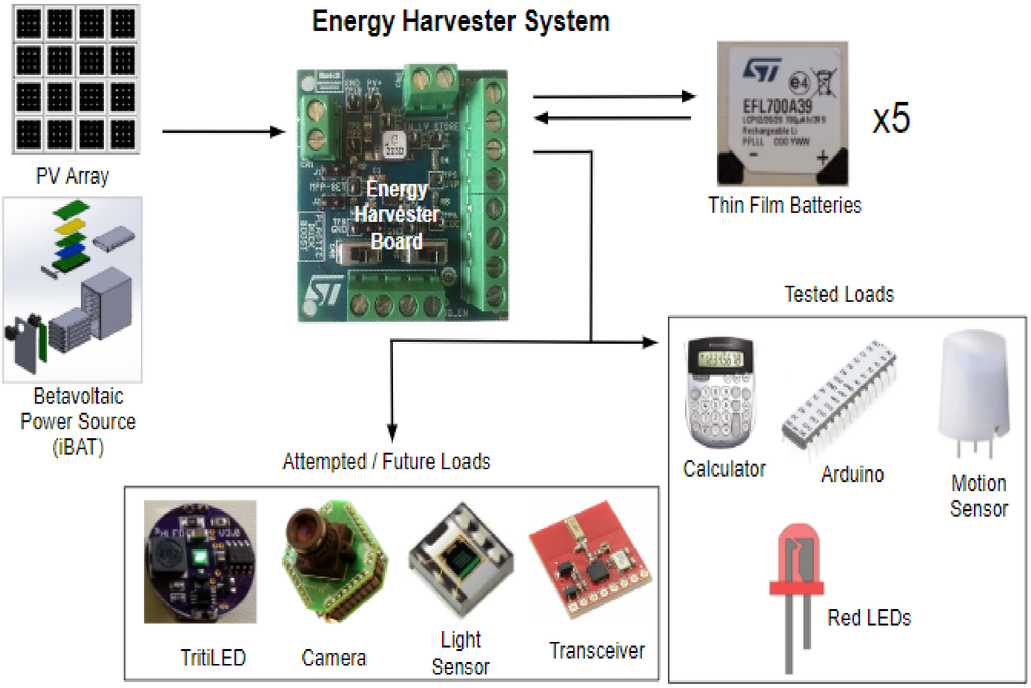


Fig. 24 EHS overview

Table 8 shows the power consumption of the various devices and also how much energy they will take up if used for 24 h. This chart allows us to gauge the energy that is needed from the thin films since the sole function of the RPS will be to turn on the energy harvester. The thin films will be doing most of the heavy lifting in terms of powering the devices.

Table 8 Power consumption of EHS devices

Device	Power consumption	Energy per day
TritiLED	3.80 µW	328 mJ
Camera	2.36 mW	204 J
Light sensor	3.24 µW	280 mJ
Motion sensor	561 µW	48.5 J
Arduino	7.26 mW	627 J
Transceiver	37.29 mW	3221 J
Calculator	168 µW	14.5 J
Red LEDs	2.18 mW	188 J

Table 9 goes through each device in the EHS system that we are imagining, takes the time that they need to work, and multiplies by its power consumption to find the energy needed to function one time per day. The calculation revealed that we only need 250 mJ to run the entire system once. This is great news since one thin-film pack will provide us with 37.5 J, meaning we could potentially run the system 150 times on just one pack.

Table 9 Power calculations to turn on devices once

Component	Time needed to run once (s)	Power consumption	Energy needed (mJ)
Low-power Arduino	10	7.26 mW	72.6
Very-low-power camera	5	2.36 mW	10
Motion sensor	30	561 µW	16
Transceiver	5	37.28 mW	150
Total			~250

Table 10 shows the bill of materials for the EHS; Table 11 shows the bill of materials for the TritiLED.

Table 10 Bill of materials for EHS[a]

Vendor	Part no.	Description	Quantity	Unit price	Cost
Digi-Key	497-15985-ND	SPV1050 evaluation board	3	$40.00	$120.00
Digi-Key	1568-1295-ND	SparkFun transceiver breakout	2	$19.95	$39.90
Amazon	B00TKXAGZM	OV7670 camera module	1	$10.99	$10.99
Amazon	B00NAY2NAI	Adafruit MicroSD card breakout board	1	$9.36	$9.36
Mouser	511-EFL700A39-RL	STMicroelectronics EFL700A39-RL	10	$10.50	$105.00
Amazon	B018ZR3F7O	3pcs ATMEGA328-PU chip and dip IC sockets	1	$13.99	$13.99
Digi-Key	296-44201-ND	Texas Instruments LAUNCHXL-CC1310	1	$30.11	$30.11
Mouser	769-EKMC1601111	PIR sensor (EKMC1601111)	1	$12.32	$12.32
Mouser	595-OPT3002DNPR	Light sensor (OPT3002DNPR)	1	$1.56	$1.56
				TOTAL:	$343.23

[a] We did not include parts that were already in the lab, such as the Arduino Uno, a breadboard, various resistors, various capacitors, the VC0706 camera, TI-1795 calculator, red LEDs, jumper wires, and so on.

Table 11 Bill of materials for TritiLED[12]

Vendor	Part no.	Description	Quantity	Unit price	Cost
Digi-Key	PIC12LF1571-I/SN-ND	IC MCU 8-bit 1.75-KB flash 8SOIC	3	\$0.57	\$1.71
Digi-Key	296-18758-1-ND	IC SNGL mono multivibtor SM8	3	\$0.70	\$2.10
Digi-Key	587-3486-1-ND	10-µF, 25-V 1206 X7R MLCC capacitor	3	\$0.38	\$1.14
Digi-Key	587-1281-1-ND	1-µF, 25-V 0805 X7R MLCC capacitor	3	\$0.17	\$0.51
Digi-Key	311-100FRCT-ND	RES SMD 100-Ω, 1% ¼-W 1206	3	\$0.10	\$0.30
Digi-Key	IRLML6244TRPBFCT-ND	IRLML6244 N-channel SOT23 MOSFET	3	\$0.59	\$1.77
Digi-Key	DMG2305UX-13DICT-ND	DMG2305UX P-channel SOT23 MOSFET	3	\$0.46	\$1.38
Digi-Key	BAT-HLD-001-THM-ND	CR2032 battery retainer	3	\$0.28	\$0.84
Digi-Key	587-2303-1-ND	100-pF C0G 0603 capacitor	3	\$0.11	\$0.33
Digi-Key	P189-ND	Battery Li 3-V COIN 20 mm	3	\$0.29	\$0.87
Digi-Key	475-3450-1-ND	LED Oslon signal GRN 505-nm 2 SMD	3	\$3.49	\$10.47
Digi-Key	SRR6028-102YCT-ND	Fixed IND 1-mH 150-mA 4.5-Ω SMD	3	\$0.79	\$2.37
Digi-Key	311-51.0KHRCT-ND	RES SMD 51-k Ω, 1% 1/10-W 0603	3	\$0.10	\$0.30
OSH Park	N/A	TritiLED V3.0 Oslon signal edition - pack of 3	1	\$4.10	\$4.10
				TOTAL:	\$28.19

6. Conclusion

Overall, the project was a major success. We are able to power sensors in the milliwatt range with microwatts of input power. The EHS takes in microwatts to milliwatts of input DC power from PV, RPS, thermophotovoltaic, and/or thermoelectric generator, stores the input power in thin-film batteries, and outputs milliwatts of DC power for application-specific energy profiles. This allows us to create an EHS system that will last longer than the RPS/PV or a thin-film battery would on their own. The goal is to create an unattended system, maximizing the run time and minimizing the power lost in energy conversion. An EHS like this is the first of its kind to operate at the lower energy harvester levels and consume approximately 20 µW when in active mode, and we hope to improve on it in the future as well as gaining a deeper understanding of how to further reduce losses as specific applications and energy profiles are identified.

7. Next Steps

We are currently awaiting the collaboration with the University of Washington, University of Idaho, and University of Bologna so we can use our energy harvester to power their low-power cameras. We have provided the details of each camera in Table 12. We are looking for a camera to take a picture, so frame rate is not of great importance. For this reason, the cameras from the University of Idaho or University of Bologna will be better fits for our system.

Table 12 Research group low-power cameras[15–17]

	University of Washington	University of Idaho	University of Bologna
Power consumption	2.36 mW	6.53 µW	193–277µW
Frame rate (FPS)	13	5	10
Maximum operating distance (ft)	150	Unknown	Unknown
Image size (pixels)	112 × 112	96 × 96	128 × 64

We also need to understand more about how the energy harvester circuit board operates. Part of what is needed to be understood is its interactions with the thin-film batteries. Since the energy harvester and thin films are going to be a part of the final circuit, it is essential to understand the charging/discharging relationship between the two. Therefore, we need to conduct more experiments in order to plot the graphs and find equations of charging and discharging with the energy harvester and thin film combination. We need to also repeat this test with different types of loads as that affects the rate of discharge. It will be interesting to see if this matches up with the graphs on the thin film's datasheet.

Also, we need to understand why using an energy harvester in parallel with thin films as a secondary energy source does not work as well as the energy harvester in parallel with the cell phone battery as the secondary energy source. For the circuit to be optimized and able to power useful sensors, we want to be able to put the energy harvester in parallel.

The final steps of this project would be to condense and redesign the EHS to optimize with ARL PV arrays and RPS. Figure 25 illustrates our future plans.

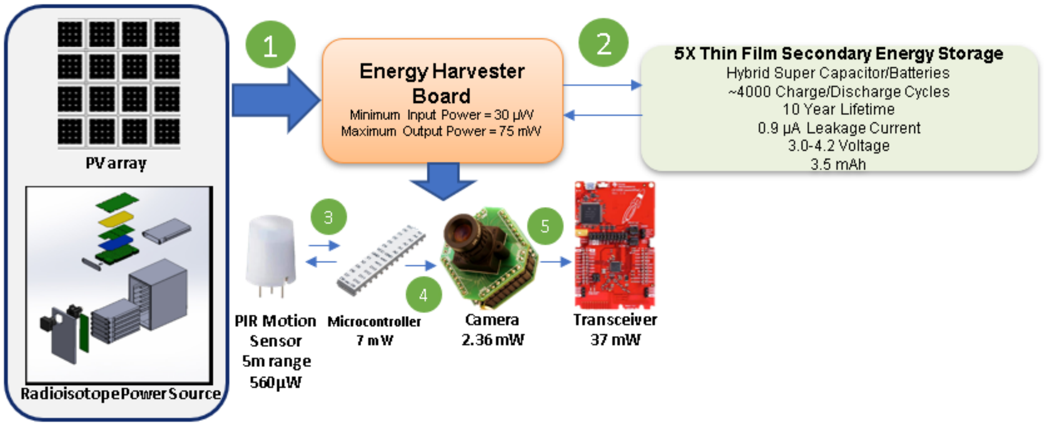


Fig. 25 Future plans

The PV array and RPS would be connected to the input of the energy harvester circuit board. Microamps of current are needed to turn on the energy harvester board, and once it is turned on, the thin-film secondary energy storage will provide the rest of the power needed to turn on the devices. The setup in the diagram in Fig. 25 will have the PIR motion sensor on 24 h a day. The motion sensor will turn on the low-power Arduino microcontroller when it detects a moving object in its detection proximity. The Arduino will then turn on the camera to take a picture. Finally, the Arduino will turn on the transceiver to then transmit the image back to the nearest receiver. The devices will all turn off to minimize power usage until the PIR detects movement again.

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List of Symbols, Abbreviations, and Acronyms

ARL	US Army Research Laboratory
DC	direct current
EH	energy harvester
EHS	energy harvester system
IDE	Integrated Development Environment
LED	light-emitting diode
LDO	low-dropout
Li	lithium
LIL	low illumination light
MOSFET	metal-oxide-semiconductor
PCB	printed circuit board
PV	photovoltaic
PWM	pulse width modulation
RPS	radioisotope power sources
USB	universal serial bus

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