

# A systems engineering Persistence Of Vision teaching module integrating coordinated sensing, actuation, multithreaded computation, custom PCB design, and inductive power transfer

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**We present a new electro-mechanical educational platform to educate students in interdisciplinary engineering design principles. We focus specifically on the design and use of an extensible Persistence Of Vision (POV) educational robotics kit. The prototype of this kit, presented here, is designed to introduce embedded systems to students, motivating the learning of printed circuit board (PCB) design and the integration of inductive power transfer, coordinated sensing, Bluetooth communication, computational features, and multithreading. Each of these components is not particularly difficult by itself, but it is sometimes daunting for the student to combine such subsystems effectively to develop larger systems capable of complex functionality. Educational platforms such as the one proposed in this effort should be quite useful to help students develop confidence in the design and construction of efficient robotic systems capable of complex behavior.**

## I. Introduction

This paper presents a robotic subsystem prototype — specifically, a Persistence Of Vision (POV) module — designed at the UCSD Coordinated Robotics Lab. The teaching module incorporates principles from ME, EE, and CS in order to support interdisciplinary education in robotics at the high school, college, and professional levels. This work builds upon an educational robotics kit, dubbed EduMIP, for building a Mobile Inverted Pendulum (MIP) around a credit-card-sized Linux computer, as discussed in [1]. The new POV module mounts a spinning custom-made Printed Circuit Board (PCB) atop the EduMIP, and programs it to synchronized LEDs to display images as it rotates. The presented module is valuable to motivate and teach students to design and program PCBs by utilizing open source software supported by TI, using their real-time operating system TI-RTOS, microchip specification sheets, and an Electronic Design Automation (EDA) package for PCB design, Autodesk Eagle, which is available for free download. The project exposes students to a plethora of engineering principles that must be successfully integrated, creating a motivating design challenge. This prototype presents the solution to two main challenges of the POV module: generating the POV image and orientation, and wirelessly transmitting power and signal to the spinning POV module.

Common standards for video frame rates are between 24Hz and 60Hz, depending upon the speed of the action; generally humans perceive videos at such frame rates as continuous in time. POV is a related natural phenomenon that occurs when the brain interprets an object spinning quickly as a single image. This occurs because the effects of, e.g., bright lights on a spinning object persist on the retina for a fraction of a second, allowing the brain to "blur together" flashes of light (e.g., from a row of LEDs distributed radially) that are actually slightly separated in time, and thus distributed over the circle that the lights spin through, in order to form a single 2D image over this circle [9].

Established methods of powering POV LED displays are either through slip-rings, or by attaching a separate battery to the spinning part [8]. Slip rings use carbon brushes that are in constant contact with traces to transfer power to the rotating part. Disadvantages of slip rings include wear over time and friction on the rotating object; further, if the system gets even slightly misaligned, this friction can get quite large and generate unacceptable vibrations.

Wireless power transfer has the potential to solve the issues that arise from using slip rings and on-board battery supplies. Inductive charging, also known as inductive coupling, is a technique used to transfer energy through a magnetic

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field over coils of wire that are in close proximity, and approximately aligned. Inductive charging is increasingly common in many small consumer products today, including cellphones and electric toothbrushes, due to its inherently safe and durable nature, with no exposed conductors that can corrode or be shorted. High-power inductive charging systems for the consumer market, such as for the charging of electric vehicles, are also being considered [3].

With the POV module, the power must be transferred through a rotating coil, which adds additional challenges to the problem. Passing power to rotating objects wirelessly has already been studied. In 2016, two coils were used with a resonant converter circuit to generate 20W with the coils mounted on L-shaped ferrite cores with a 1mm air gap to generate a 87.7% efficiency [8]. While research on efficient power transmission and wireless communication through inductive coupling exists, this technology is largely underutilized in modern electro-mechanical systems.

## II. Robot Design

The POV-MIP robot is made of two subsystems: the eduMIP robot and the POV-PCB, as shown in Fig 1. The eduMIP handles the inverted pendulum balancing, robot controls, and controls the brushed DC motor which spins the POV-PCB. On its top, the POV system handles the LED and is powered via inductive charging from the main battery on the eduMIP. The subsystems communicate with one another via Bluetooth. The POV-PCB detects its absolute spin angle with respect to the eduMIP via a Hall effect sensor spinning above a magnet that is mounted to the shoulder of the eduMIP. The current design of the POV MIP robot meets the functional requirements of the Tier 1 subsystem as laid out in Table 1.

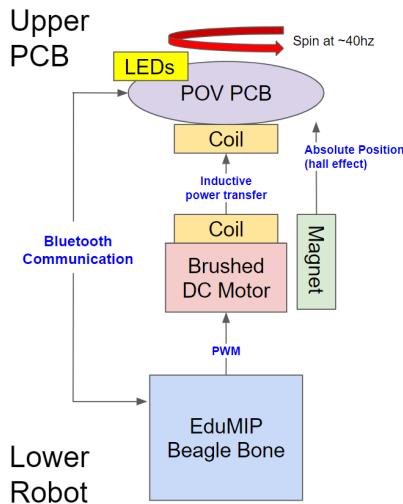


Fig. 1 POV-MIP system design overview.

Table 1 Functional Requirements of Deliverable System

| Tier 1                       | Tier 2                           |
|------------------------------|----------------------------------|
| Minimal Vibration            | Minimal Form factor changes      |
| Spin at 40Hz+                | Low Cost                         |
| RGB LED Display              | Control LED Remotely             |
| Power Transferred Wirelessly | Extensive Software Documentation |

### A. Power Transmission

The battery of the robot is carried by the MIP robot, creating a fundamental problem of transmitting power from the MIP robot to the spinning POV-PCB. The previous POV-MIP design, which was also made by our research group, utilized a slip-ring and a carbon brush to transmit power to the POV-PCB. The Pov-PCB was attached directly to motor instead of motor shaft and the motor shaft also acted as the electrical ground. Power transmission through a slip-ring and carbon brush is simple to implement, but the friction between the brush and the PCB creates a significant amount of vibration and the brush itself can degrade over time.

The current design utilizes coils for inductive power transfer to power up the PCB which eliminates the vibration due to friction from the previous design. The coils located on the MIP robot are supplied with AC current through the AC signal generator circuit, which creates an alternating magnetic field that the coils attached to the PCB converts back into AC electrical current. This AC electrical current is then transformed into DC voltage by using a full-bridge rectifier which then passes through a voltage regulator [6]. The power transfer diagram can be seen in Fig 2.

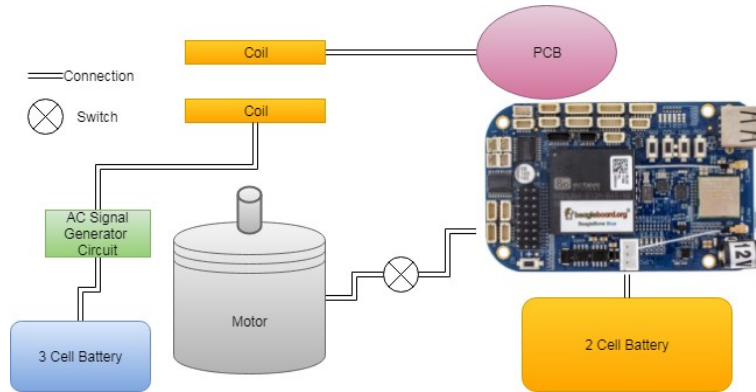


Fig. 2 Power diagram of the system

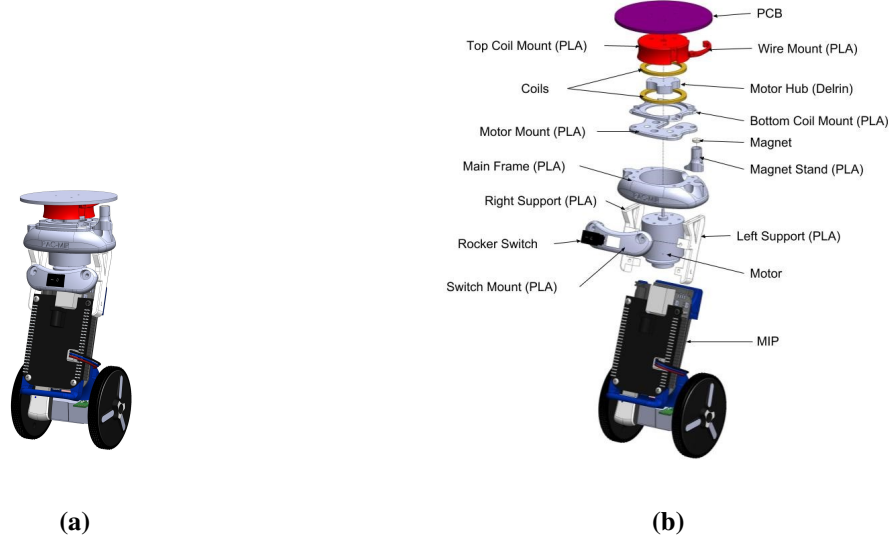
### B. Mechanical Design

The POV system, which consists of the 3D printed mounts (made of PLA), brushed DC motor, coils and the POV-PCB, is attached on top of the MIP robot as shown in Fig. 3. Therefore, the mechanical design of this robot focuses primarily on the mount CAD design, component selection and placement with the goal of spinning the POV-PCB at a sufficiently high speed.

The components are aligned such that the combined center of mass of the whole robot is not shifted too far away from the MIP robot's original vertical axis. However, the POV-PCB subsystem adds more components above the MIP robot, which alters the mass distribution and affects the MIP balancing, necessitating a simple re-tuning of the balancing controller. The present subsystem needs to spin the POV-PCB at 40Hz or more. We selected a gearmotor from Pololu (37D mm metal gearmotor), which has a no load speed of 11000 rpm at 12V. The MIP robot uses a 2-cell battery pack (rated 7.4V), so we have a no load speed of 6800 rpm (110Hz) which is more than sufficient. The motor is controlled through the Pulse Width Modulation (PWM), which is handled by the Beaglebone micro-controller, in order to maintain a constant rotational speed required for POV.

The 3D printed PLA mounts were designed with rigidity and feasibility of assembly in mind. The Top Coil Mount was designed to lift the PCB 12mm from the Coil so that the impact of the magnetic field is reduced. The Coils are adhered to their corresponding mounts with silicon. Since the Motor Hub is permanently fitted onto the motor shaft, the Bottom Coil Mount can be inserted from above the Hub and the Motor Mount can be slide in from the side. Additionally, the Motor Hub was shaped to allow for the screwing of the motor even after the Hub has been press-fitted. The Magnet Mount is placed so that the center of the magnet is 65.6mm from the center of the PCB, directly below the Hall effect sensors.

A rocker switch to cut off the power to the motor is added for safety, considering that the thin PCB can spin at 40Hz or faster. The Switch Mount shown in Fig 3 is designed so that it curves around the motor to prevent the switch's wires from coming into contact with the motor. For this reason this is the only part that will require supports when 3D printed.



**Fig. 3 (a) Final POV-MIP Design. (b) Exploded view of POV-MIP parts.**

### C. Electrical Design

There are five main components to the electrical design: the microcontroller which controls the display and wireless communication, the LED and LED drivers, the wireless power circuit that transfers and regulates the power to the PCB, the Hall effect position sensor, and finally the PCB itself.

A TI Bluetooth chip (CC2650MODA) serves as both a microcontroller and wireless communication module. This microchip contains a powerful ARM Cortex microcontroller with two cores (M3 and M0) with up to 48MHz clock speed and 15 programmable GPIO pins. By programming the ARM microcontroller of the Bluetooth chip, we are able to save space on the PCB as well as reduce the cost of the project. The Bluetooth chip allows the POV board to communicate to the MIP robot or a cell phone which can update the LED display.

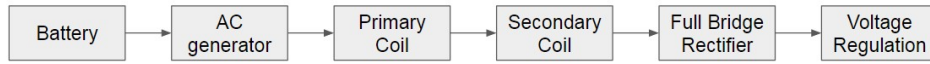
The PCB contains a row of 16 RGB LEDs (LTST-C19HE1WT) creating a total of 48 individually controlled LED's. Since there are 48 LEDs and only 15 GPIO pins, LED drivers (MAX6969) are used to provide power and control the LEDs. The CC2650MODA communicates with three LED drivers (MAX6969) over a serial peripheral interface (SPI), which reduces the amount of GPIO pins to six. In addition the led driver can regulate the current of all the connected LEDs with a single resistor, reducing the number of resistors needed to three, as opposed to 48, thereby minimizing the traces in the PCB Design.

To receive wireless power, the PCB is connected to a coil that generates an AC voltage. This is converted to DC Voltage through the use of a Schottky full bridge rectifier (750-CDBHD240-G). Next, a step down regulator (TPS560200DBVR) was used to generate a 6.12V signal by using the following resistors:  $R_1 = 133k\Omega$  and  $R_2 = 20k\Omega$  in equation from data sheet which can shown below:

$$R_2 = \frac{R_1 0.8V}{V_{out} - 0.8V} \quad (1)$$

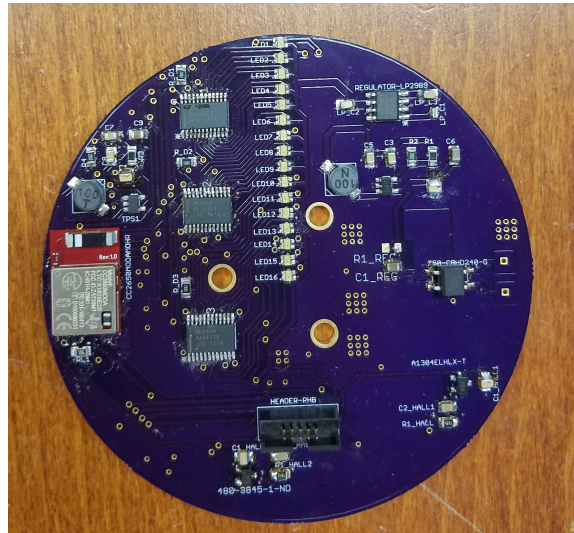
A LP2989AIM-5.0/NOPB low drop-out regulator (LDO) further reduces the voltage to 5v to power the LEDs. Another step down regulator is used to regulate the voltage down to 3.3V ( $R_1 = 61.9k\Omega$  and  $R_2 = 20k\Omega$ ) to power the CC2650MODA microchip. The power transmission of our system can be seen in Fig. 4.

In order properly display the POV image, the PCB must sense the speed and orientation of the PCB relative to the robot below. A hall effect sensor is used measure the magnetic field of a fixed magnet mounted below. As the sensor passes over the fixed magnet, we can obtain a speed and position estimate of the PCB. While design shows two hall effect sensors, only one sensor is necessary. Two sensors were used as a performance experiment. In practice we found both sensors to be adequate. The first Hall Sensor is an Allegro MicroSystems, LLC linear analog sensor (A1304ELHLX-T) with  $\pm 375$  and a typical sensitivity of  $4mV/G$ . The second hall sensor is a Honeywell analog sensor (SS39ET) with a  $\pm 1000$  Gauss range and a typical  $1.4mV/Gauss$  sensitivity.



**Fig. 4 Flowchart of the power transmission through inductive charging.**

When designating the component placement on the PCB, many precautions were taken to protect the accuracy of communicating signals from the noise of the AC power generation. Extra layers of GND and 3.3v serve as signal shielding from the magnetic field created by the coils. The finalized PCB design was fabricated through Oshpark, an online rapid PCB prototype company. The finalized PCB is shown in Fig. 5. The components of the PCB was surface mounted by applying a soldering paste (SMDLTFP-ND) using a stencil, placing the components on the board, and then baking it on a hot plate.



**Fig. 5 The PCB for the POV LED display.**

#### **D. Software Development**

When coding the CC2650, TI-RTOS was utilized with the IDE Code Composer Studio v7.1 and the XSD110 USB Debug Probe and Compiler 5.2.6. One of the benefits of TI-RTOS is the useful APIs that come with it. For controlling the PCB, there are multiple APIs used included but not limited to PWM, ADC and PIN. The RTOS handles scheduling, interrupts, memory management and more. The CC2650MODA has two ARM Cortex-MX processors: The M3 which is the main processor, and the M0, which takes care of Bluetooth functions.

##### *1. Debugging*

To communicate with the PCB, the JTAG standard is used with signals TDI, TDO, TCK, TMS, GND, 3.3V, 5V and NRESET. In order to code the CC2650, only the 3.3V logic signal is necessary, but since the LEDs require 5V, the extra signal was added. The MSP432P401R microcontroller's XSD110 USB Debug Probe was disconnected and reconnected to Adafruit Cable Breakout Board (Product 2743) according to the PCB's JTAG signals. The JTAG ribbon cable can be used to communicate with the PCB (it comes with the MSP432P401R).

## 2. TI-RTOS Integration

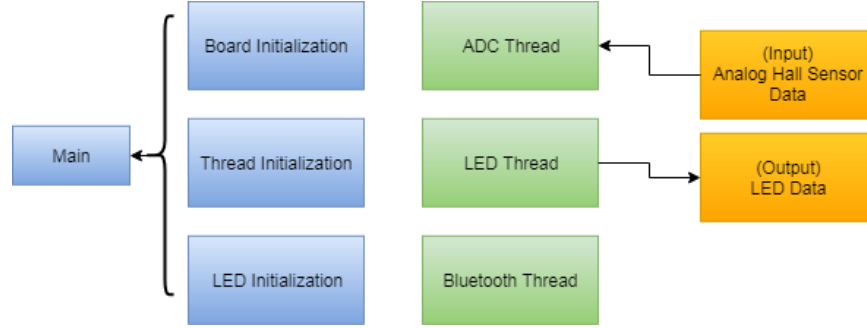
The multitasking real-time kernel is utilized by running multiple threads, or tasks as they are called in this RTOS. In the following sections the use of important APIs is explained.

## 3. Pin API

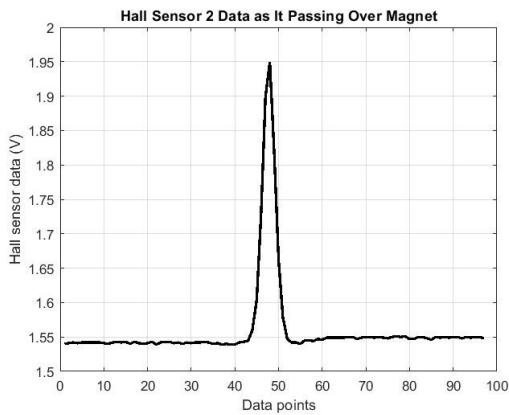
By using the PIN API, the LED'S can be controlled according to the LED display desired. MOSI (data in), CLK (clock), LE (Latch Enable) ,and OE (Output Enable) are declared, enabled and set to OFF mode in a pin configuration table. This table is referred to in main function and allocated to a handle function which will allow LED control.

## 4. ADC Thread

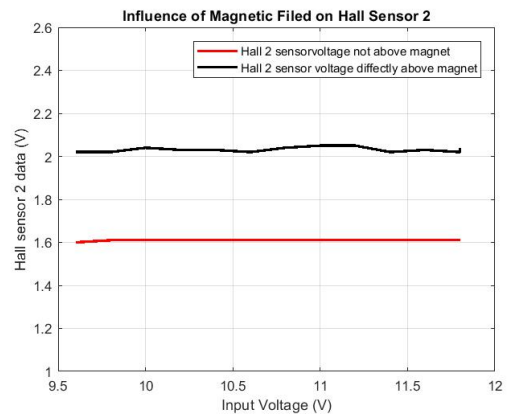
Software logic is presented in Fig. 6 to show how the multi-threaded system works. One of the threads being operated monitors the voltage generated by Hall Sensor 2. The ADC TI-RTOS API has two functions: it samples and then converts the analog reading. Fig. 7 (a) shows the analog data received from the hall sensor as it passed over the magnet mounted directly below it during one revolution. The magnet creates a distinct peak so each revolution will be counted when the signal is above 1.8V. The code is formatted so that every time this threshold is reached the LEDS will be turned off for a certain time depending on how wide the POV-MIP should be. This can be accomplished because the Max6969 drivers have an OE switch signal, when High, the 16-bit shift register information is not latched into the output, thereby turning off the LED's. In Fig. 7 (a) the peak that was explained earlier in this paragraph can be observed.



**Fig. 6 Software Logic**



**(a)**



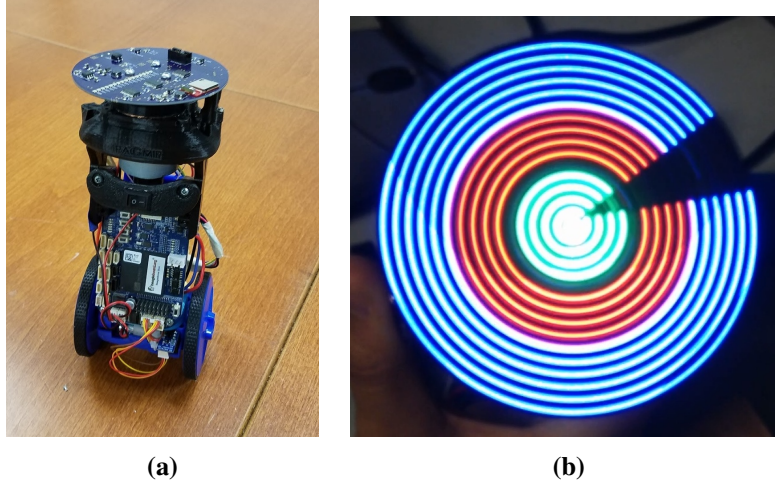
**(b)**

**Fig. 7 (a) Hall Sensor 2 analog voltage reading as it passes over the magnet mounted below. (b) This graph shows how the magnetic field generated by the coils at different voltage levels affects Hall Sensor 2 analog output in the final mechanical design.**



### III. Results

A working prototype of the POV-MIP has been built and tested, as seen in Fig. 8a. The POV-MIP display successfully created a simple multi-color image, as shown in Fig. 8b, by spinning the motor at 40.3 Hz while powering the PCB via inductive coupling with a 2mm gap between the coils. Fig. 9b shows the average output voltage after rectification and filtering, created by different voltage inputs into the Adafruit circuitry. The power transfer system exhibits an interesting and repeatable hysteretic behavior, as seen on Fig. 8. This behavior is due to the well-studied magnetic hysteresis phenomenon. The PCB had 3 voltage buses (6.12V, 5V, and 3.3V); as seen in Table 2, the inductive power delivery system and voltage regulators were able to meet these targets accurately.



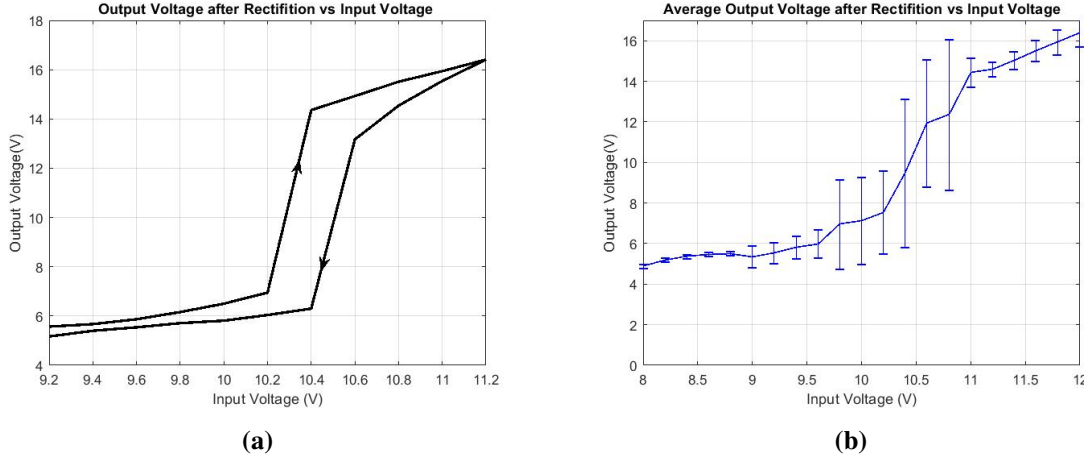
**Fig. 8** (a) The POV-MIP robot prototype. (b) The image shown by the RGB LEDs on the PCB while spinning at 40.3Hz.

**Table 2** Voltage Target Results

| Voltage Level (V) | Actual (V) | Error (%) |
|-------------------|------------|-----------|
| 6.12              | 6.11       | 2         |
| 5                 | 4.91       | 1.8       |
| 3.3               | 3.26       | 1.2       |

The magnetic field can affect the performance of the PCB, for example in Fig. 7a the average Hall Sensor 2 reading when passing over the PCB is  $1.541 \pm 0.001V$  but when the PCB is powered through inductance the voltage rises to  $1.61 \pm 0.01V$  as seen in Fig. 7b. It can be observed that the voltage in the ADC reading rises due to the added magnetic field of the coils. However, once the magnetic field of the coils is added to the system, increasing the voltage in the input range of operation did not affect the Hall sensor readings, as can be seen in Fig. 7b. Note that even though the voltage is being increased the sensor still reads  $1.61 \pm 0.01V$  and  $2.02 \pm .02V$  when above and not above the magnet (readings being influenced by the magnetic field). The increase in voltage due to the magnetic field of the coils is 4.5% when not placed above the magnet.

The main objective of this project was to create a POV platform powered through inductive coupling to display a POV-MIP and accomplish Tier 1 fundamental requirements (see Table 1), all of which were met and most of which were confirmed empirically. The only requirement which was confirmed only qualitatively (but was, evidently, substantial) was the reduction of vibration. Some secondary goals that were also accomplished in this project included cost reduction. The current cost for a single unit of this subsystem (not including the EduMIP) is \$110; substantial cost reductions will be further explored in the next iteration. The infrastructure for remote control of the LED display, via Bluetooth communication to the main board of the eduMIP (and, potentially, wifi communication from there to the cloud) is implemented in this design, though that feature has not yet been thoroughly tested. Extensive software documentation is under development.



**Fig. 9 (a) Increasing and decreasing input DC voltage applied on adafruit DC-AC circuit board vs output voltage obtained after rectification in the PCB circuitry. (b) Input DC voltage applied on adafruit DC-AS circuitry vs output voltage obtained after rectification in the PCB circuitry.**

All SolidWorks files, Eagle board and schematic files, code, and other documentation associated with this project are available at [https://github.com/Janelle-Duenas/POV\\_MIP](https://github.com/Janelle-Duenas/POV_MIP).

#### IV. Conclusion

In this paper we introduced a prototype POV subsystem kit that can serve as an educational design platform to educate students about interdisciplinary systems engineering in robotics. In understanding (and, ultimately, extending) this prototype, students learn the following:

- 1) Printed Circuit Board design and fabrication, using Eagle, to produce a circuit board from schematic,
- 2) Rapid prototyping using SolidWorks and 3D printing,
- 3) Wireless power transmission through inductive charging,
- 4) Integrating coordinated sensing, and
- 5) Implementation of TI-RTOS, including multi-threaded computations.

#### V. Future Work

The POV design uses a system of power transfer that can be improved. Currently, the system has enough wattage to create a display, but not enough to power 48 LEDs simultaneously. To be able to turn all 48 LEDs, the system needs 1A. There are multiple methods to solve this. For example, a different set up of the coils specifically designed to meet this power requirement can be investigated. Another way to transfer more power to the POV subsystem is by using isolated flyback converter that transfers maximum current of 2A. For the flyback converter, a small circuit needs to be designed and attached to the coils. Additionally, the system can be configured to use a single 2-cell battery, to power both the BeagleBone Blue and the PCB.

#### VI. Educational Impact

Leveraging the robotics kit prototyped in this paper, we are planning to develop an online class to educate and motivate students towards STEM fields, and inspire them to learn and get involved in the systematic design of engineering systems. This class will be at an entry level, and integrate valuable core concepts in robotics, including important aspects of CS, EE, and ME. A low-cost educational kit will be provided along with this course in order to provide an accessible and motivational experiential learning experience.



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