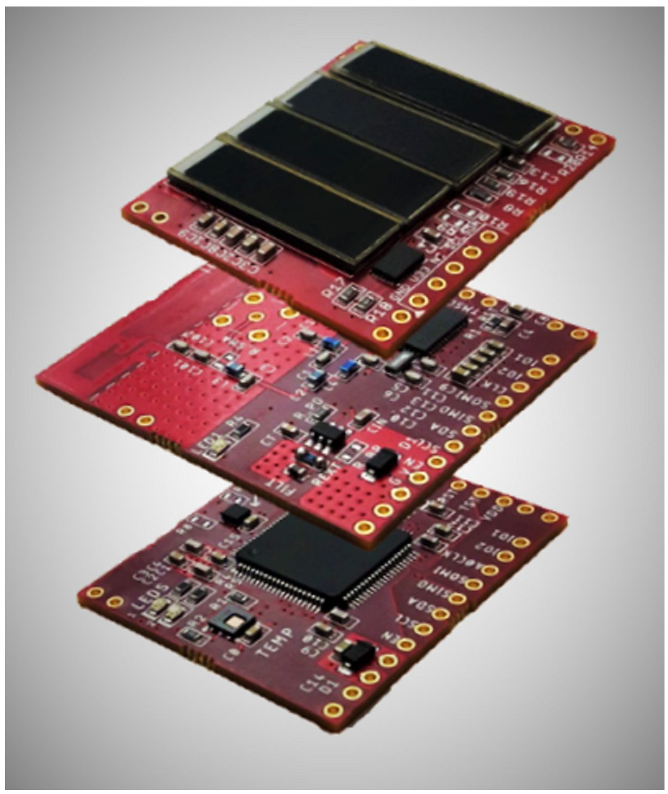
CHARIoT Final Report

Senior Design Aug. 20, 2018—Apr. 26, 2019



Robert Flechas | Jennifer Hellar | Nathaniel Morris

Rachel Nguyen | Brady Taylor | Robyn Torregrosa

TABLE OF CONTENTS

EXECUTIVE SUMMARY

Sensing and acquiring data from the nearby environment is becoming increasingly vital in many industries which depend on real-time information to optimize their business. Internet of Things (IoT) devices, electronic products that can wirelessly communicate with a larger network of devices, are poised to fit these needs. Current IoT device development operates on the principle of designing from scratch for a specific application, a process which cannot keep up with the growing demand for these devices. Our vision is to create a sensor node platform allowing easy redesign to suit a variety of applications. The design would be small for easy placement, self-powered for independent deployment in any environment, and wireless for integration into a larger network.

Our current design CHARIoT, or CHip ARrangement for the Internet of Things, is a self-powered wireless sensor node, architecturally versatile and modular to enable rapid redesign and deployment for a variety of applications. For the purposes of easy redesign, the CHARIoT node is broken into three physical layers which each serve a distinct function: an energy harvesting layer, a communications layer, and a sensor layer. Any of these layers can be disconnected and replaced to suit a given application. In addition, the distinct subsystems make the ultimate goal of scaling down to a System-in-Package (SiP) design, which encapsulates the entire node in a package as small as a coin, more feasible for the future.

The CHARIoT energy harvesting layer supports solar energy harvesting, since that currently is the most efficient harvesting technique. Wireless connectivity is established over a Bluetooth Low Energy link, a common protocol supported by many smart devices already. Our software design only supports node to aggregator links, but the component could support a mesh network with only software modification. The microcontroller, chosen for its low power consumption, collects raw sensor data and transmits it to the aggregator for processing.

We selected the essential components (processor, communications, and energy harvesting chip) based on small size and low power usage. The initial prototype was laid out on a breadboard and tested for functionality and low power performance. Once we confirmed that the design met our baseline criteria, we moved to designing a second prototype manufactured on a printed circuit board (PCB). In this second iteration, we focused on form factor (the ability to slot the three layers together), encapsulating the systems in their respective layers and making each individual layer easy to test. In our third (and final) prototype, we shrunk each layer to a smaller footprint while still maintaining the ability to stack and change-out the layers.

The final CHARIoT design is fully functional in generating and storing solar energy; collecting sensor data for temperature, humidity, and acceleration; and powering on and transmitting that data to an aggregator (proof of concept was done using an Android app we developed for this purpose).

In the future, we'd like to further decrease the size of our product to a SiP, or System-in-Package, which would be a small system in one package about the size of a quarter. We plan to hand off our work to our sponsors and their future design teams, who are likely to work with Octavo, a company specializing in fabricating SiP technology.

INTRODUCTION & LITERATURE REVIEW

In 2017, $235 billion was spent on hardware, software and system integration of IoT devices [1]. In 2018, there were an estimate 7 billion IoT devices, with an expected growth to 20 billion devices by 2020 [2]. The market for IoT devices, however, is currently focused on developing purpose-built IoT devices, rather than on making generic hardware base that can be redesigned for different applications. There is a market for electronic prototyping platforms (ie Arduino, Raspberry Pi, TI Launchpads, BeagleBone, etc), but the challenge with these platforms is that it can be difficult to move from prototype to a smaller form-factor, and require the user to add separate communication hardware modules to extend to IoT applications.

IoT networks are well-suited for providing solutions to environmental and industrial monitoring, applications that require outdoor, long-term use. For these reasons, there is a need for IoT solutions capable of energy-harvesting at a level that allows nodes to remain in the field indefinitely. Improvements in solar energy technology are enabling systems to receive substantial power from individual solar cells rather than solar panels [3].

New System-in-Package (SiP) technology makes it possible to shrink generic hardware platforms with multiple ICs into smaller footprints. Octavo Systems specializes in making these SiP devices that abstract system complexity, allow designs to reuse subsystems in a variety of designs, and eases the process of scaling from concept to manufacture [4]. These aspects make SiP technology an appropriate avenue for developing a generic platform for ultra-small IoT device development.

Research being done in the development of small-scale IoT devices has so far omitted energy-harvesting components, choosing to instead rely on solid-state batteries without re-charging capability. A group at King Abdullah University of Science and Technology (KAUST) developed a IoT environmental sensing device with a small form-factor [5].Their manufacturing process utilized SiP enclosure of the sensors (humidity, temperature, and H2S gas level) and antenna, but requires the inclusion of a high-capacity battery rather than sustaining itself using energy-harvesting techniques. Without the ability to recharge the batteries, this system is disposable by design.

Another group from the Chinese Academy of Sciences (CAS) focused on high-density packaging of an IoT sensing node using SiP technology [6]. The project focused mainly on 3-D packaging design for thermal management, rather than on component selection for application versatility. This design integrated sensors (sound and vibration), digital signal processing (DSP)

IC, and relied on a purpose-built ASIC rather than on a general-purpose microcontroller. The SiP did not feature energy-harvesting capability, thus requiring an external source of power.

Both of these research projects have been limited in scope by lack of energy-harvesting capability, and neither was intended to be used as a generic IoT platform. Both projects exist in the prototype stage, and have not progressed to commercial manufacturing level.

All of the production-scale solutions we have found in this area focus on a single aspect of the IoT device, there are no commercially available platforms that integrates sensing, energy harvesting and IoT communication capability. For example, Cymbet specializes in developing Enerchips, an energy-harvesting hardware module suitable for needs of IoT devices [3] while Renesas has developed ultra-low-power sensors [7]. We have not found any companies that make integrated platforms suitable for developing IoT devices with a variety of applications. A comparison of these solutions is summarized in **Table 1** below.

Table 1: Previous work and current products feature comparison

	KAUST Research Group	CAS Research Group	Renesas Low Power Sensor	Cymbet Enerchips	CHARIoT Node
Generalizable Architecture	✔	✔			✔
SiP (System in Package) Compatible	✔	✔			✔
Energy Harvesting				✔	✔
Sensing	✔	✔	✔		✔
Integrated IoT Communication	✔	✔			✔

SYSTEMS ENGINEERING

Our system had 3 main subsystems for power, communications, and sensing. Although we had 3 separate subsystems, these subsystems are not completely partitioned; some components belong to multiple subsystems. The full system diagram can be seen in **Figure 1** below.

The power system consisted of the BQ25570 Energy Harvester from TI, a collection of solar cells in parallel, a battery, and fuel gauge (not operational in final prototype). The energy harvester receives an incoming current from the solar cells, stores the current to boost up the charging voltage, and charges the battery at a lower current buy higher voltage. The fuel gauge was placed in parallel with the battery to estimate the capacity remaining in the sensor board and communicate this information with the MSP430 through I2C, but the code was very difficult to implement (see *Summary and Lessons Learned* section). The energy harvester also has a boost converter that supplies a constant 3.3 V to the rest of the prototype. In future iterations, a second boost converter could be attached to supply a constant 5 V to higher voltage sensors.

Our specifications required that we would be able to produce 12 mW of power in direct sunlight and be able to power the prototype for 12 hours without charging. These requirements went in to selecting our battery and solar cells. The battery needed a high enough capacity to power the prototype for extended periods of time without charging. The solar cells needed to provide enough current such that after the energy-harvester boosts up the charging voltage, the charge current is large enough to charge the battery.

The communications system consisted of the CC2652R Wireless Chip from TI, the trace antenna, and the MSP430. The wireless chip connected to the MSP430 through SPI and could be programmed to handle multiple wireless protocols. These include BLE, WiFi, and multiple others. The data that the MSP430 wants to transmit is also sent to the wireless chip through SPI. The antenna could also be replaced with a larger or smaller antenna, surface mount or trace.

Our specifications required that our prototype be able to support different wireless transmission architectures and support transmission over a range of at least 5 meters. Because of our power constraints, we had to be very selective of the transmission schemes we chose. Furthermore, our specifications for size (less than 50 mm x 50 mm x 20 mm), we couldn't choose a very large antenna that would have a transmission range of a few kilometers. We went with BLE for our first transmission scheme because of its small size and low power, and selected a small antenna that could be generated using PCB traces.

The sensing system consisted of the sensors (in our final prototype, these included an accelerometer and a temperature/humidity sensor) and the MSP430. The MSP430 could send a command through I2C to these sensors, after which the sensor will in turn send data to the MSP430. The MSP430 would then send the data to the wireless chip to be transmitted. Of course, because the sensors are on an I2C bus, multiple other sensors could be added, assuming they don't pull more power than the power board can provide. Furthermore, the MSP430 has multiple A\D converters that would allow multiple analog sensors to be utilized.

Our specifications required that we be able to incorporate multiple types of sensors that use different data transmission schemes. We thus chose microprocessor that had hardware support for I2C, SPI, and UART schemes. The MSP430 was also small and extremely low power, helping us to stay within our power and size constraints.

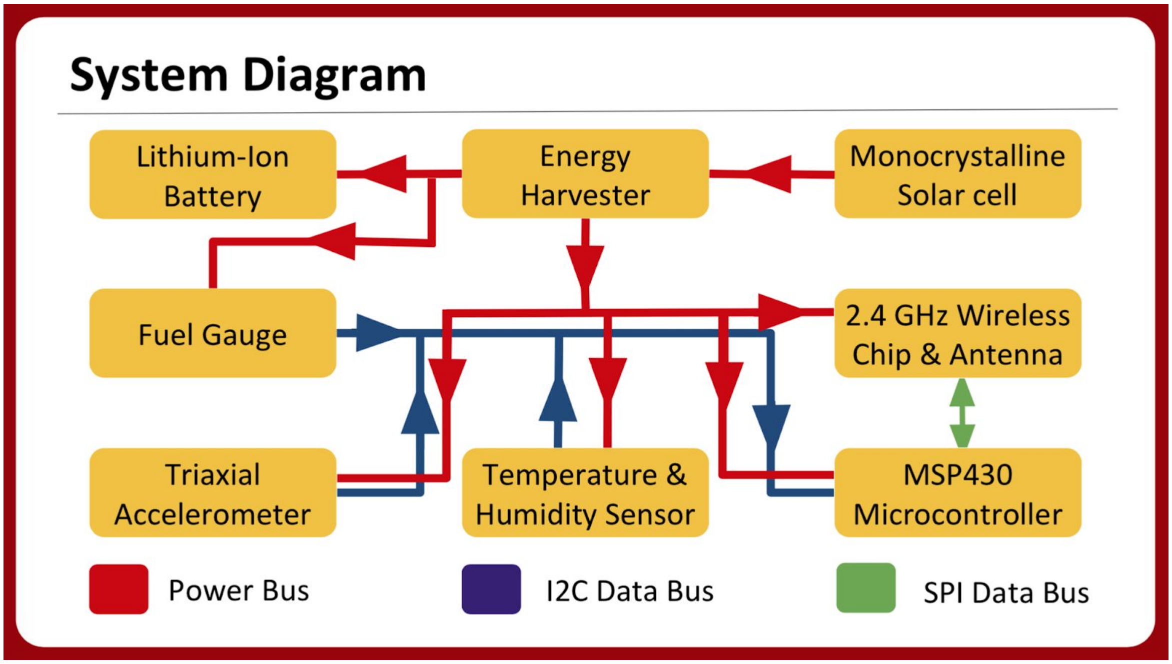


Figure 1: System Diagram (Final Design)

SPECIFICATIONS

1. Sensor Support Specification

Design supports SPI, I^2C, and analog sensors, which draw less than 5 mA combined.

The purpose of this specification is to make sure that our design is modular and could support a variety of different sensors. SPI and I^2C are two of the more common digital sensor communication methods, so we chose to at the very least support these two connection schemes. In addition to these digital communication methods, we also wanted our design to support analog sensors as well.

In order to make sure that the sensors supported by our device are low-enough power, we also included an upper limit of 5 mA on the total combined current draw of the sensors, just so we could be sure our power system can handle the current draw. Our design could potentially support sensors with a higher current draw as well, but we only want to guarantee support of low-power sensors.

2. Energy Harvester Specification

Energy Harvester can produce 12 mW in direct sunlight.

One of the main design criteria for our node is that the system is self-powered. To that end, we included this specification so that we could be sure that the energy harvesting system produced enough power to be useful for a sensing and transmitting application. After some research on the general power requirements for a BLE transmitter and lower-power sensing applications, we decided that 12 mW would be a sufficient amount of power to be useful for our node.

3. Battery Specification

Battery can power system for 12 hours without charging.

This specification for our design was included to make sure that our system could remain powered and operational during periods of time where little to no power is produced by the energy harvesting system. For example, the solar panels on our node will produce essentially no power during the night, and during a severe storm like a hurricane, the solar panels again are unlikely to produce any power. During temporary environmental conditions like these that result in a power outage, we want our node to at least remain partially operational.

We chose 12 hours as a base value such that our node could at least remain operational during the night. During extended periods of low-power environmental conditions, our node could scale back the frequency of sense and transmit operations to conserver more power, until more favorable environmental conditions return.

4. Transmit Frequency Specification

Can sense and transmit once every 2 hours throughout a sunny day.

This specification deals with the environmental condition opposite to that of the Battery specification: instead of dealing with the operation of the system in low power environments, this specification deals with the operation of the system under optimal energy harvesting conditions.

We wanted to make sure that the energy harvesting system could produce enough power and the power draw of the node was low enough such that our node could transmit often enough to produce useful data. To that end, we specified that our node should be able to transmit data to the aggregator at least once every other hour.

5. Wireless Range Specification

Wireless range of at least 5 meters.

In order to be useful as a wireless system, our node also needs to be able to transmit at least a decent distance. Keeping in mind that our node is designed for very-low-power applications, and that RF designs can be tricky, we were anticipating our node to have decent but not great range. Therefore for this specification we stated that the range at which our node can reliably transmit data should be at least 5 meters.

6. Wireless Architecture Specification

Design can support different wireless transmitters that include appropriate communications stack and draw less than 30 mA peak.

Sticking with our goal of modularity, we wanted to make sure that the communications system could easily be switched out to another communication system. We therefore added the specification that our general design should be able to support other low-power communication systems, meaning that with only a few changes (ideally no changes) on the power and sensor boards, the communications board could be swapped out with another communications board.

Because communication systems can be fairly complicated, we included the stipulation that switching to another transmitter is easy to do assuming that the required software stack is already provided. Also, to enforce our system's low-power constraint, we specified that the communication system should not draw more than 30 mA peak current. Our end design could support transmitters with a higher power draw, but we won't guarantee it with this specification.

7. Footprint Specification

Maximum footprint size of 50 x 50 x 20 mm, or equivalent volume.

Keeping in mind that eventually this design could be scaled down even more (beyond the scope of this project), we wanted to keep our final prototype at a reasonably small scale. To that end we specified that our final design should fit within 50 x 50 x 20 mm. We also included the portion on equivalent volume in the event that we changed our design such that it no longer had a square footprint.

8. Cost Specification

Less than $500 to produce a single node, at prototype scale.

In order to make sure our design had a reasonable cost for a final end product, we wanted to make sure the cost of one prototype node fell within a reasonable price point. After looking at the costs for the various components and the costs for PCB manufacturing, we decided that $500 was a reasonable prototype cost, and the final production-scale price should then also be a reasonable price.

MAJOR CONCEPTS

Concepts were primarily derived from our small size, low power, and modularity goals. Most fundamentally, we chose a three-board design to enable rapid redesign and flexibility for different applications. For indoor versus outdoor applications, the energy harvesting layer could be changed out. For dense, short-range wireless connections versus sparse, long-range networks, the communications layer could be redesigned. And for different sensors, the sensor layer could be changed. In each case, however, the overall architecture and interconnections would remain fixed.

Solar Power for Energy Harvesting

Initially, there were four viable sources of energy for consideration: solar, RF, vibration, and thermal. Ultimately the transducers we selected were solar cells. The key factors were 1) conversion efficiency, 2) harvested power, 3) application suitability, and 4) size. According to Texas Instruments, the supplier of our energy harvesting IC, solar cells could reliably have a 10%-24% conversion efficiency. Thermal has only a 0.1%-3% conversion efficiency, and vibration is highly source dependent. RF has a conversion efficiency of up to 50%, but fails in other metrics. Because many of the applications for our concept were environmental sensing /outdoor monitoring, solar was by far the most suitable and versatile energy source. Depending on indoor or outdoor conditions, harvested power could be expected to fall within a range of $10\ \mu W / cm^2$ to $10\ mW / cm^2$. Additionally, the smallest commercially available solar cells were 7mm x 22mm and thus met our size constraint.

Choosing a Low-Power Microcontroller

The three primary factors involved in choosing a microcontroller were power consumption, non-volatile memory, and input/output flexibility. Since our system needed to be low power, the processor could not afford to be power-hungry, which narrowed down our options to those shown in **Table 1** below. The TI MSP430s are classic low-power microcontrollers, while Microchip's SAM L-series microcontrollers actually achieved even lower power consumption albeit with generally fewer GPIO. Since energy harvesting (especially from solar power) can be inconsistent, we also wanted non-volatile memory for program and data so that the system would continue to function in the event of temporary power loss. And finally, for flexibility in sensor support, we wanted the microcontroller to have a lot of GPIO options.

Table 2: Pugh Matrix for choosing a microcontroller

	TI MSP432 (ARM M4F)	TI MSP430 with LEA, 16-bit RISC (ultrasonic)	TI MSP430, 16-bit RISC (value line)	Microchip SAM L10 (ARM M23)	Microchip SAM L21 (ARM M0+)
Power (μA/MHz)	100	118-120	81.4-142	25	35
DMIPS/MHz	1.25 (1.27 w/FPU)			0.98	0.95
SRAM	32-256 KB	Up to 8 KB	0.5-8 KB	Up to 16 KB	4-40 KB
Flash	128-2048	128-256 KB FRAM	0.5-256 KB FRAM	Up to 64 KB	32-256 KB
GPIO	48-84	68-80	12-83		Up to 51
CPU (MHz)	Up to 48	Up to 16	Up to 24	Up to 32	Up to 48

Most of the options shown above fulfilled our basic requirements for a microcontroller. Ultimately, we realized that the most interesting and difficult portions of our project (energy harvesting and wireless communications) would not involve the processor directly, so we chose the MSP430 with Low-Energy Accelerator, specifically the MSP430FR5994. This microcontroller included 256 KB of non-volatile FRAM, multiple low power modes, a hardware multiplier, an AES encryption engine, 68 I/O pins, and many serial communication modules. In short, it contained everything we could possibly need while still consuming very little power. And most importantly, our entire team was familiar with programming MSP430s, allowing us to rapidly prototype using this microcontroller.

Choosing a Wireless Transmission Scheme

We choose to use BLE instead of LoRa because BLE tends to be much lower power. While it does not have as much range as LoRa, its low power consumption fit out design goals. We also liked the smaller size the BLE antennas needed to be compared to LoRa due to its higher carrier frequency of 2.4 GHz compared to 900 MHz.

DETAIL DESIGN & PROTOTYPING

Prototype 1 Design (Proof of Concept)

Our first prototype was a proof of concept that our device could sense and transmit through BLE without consuming excess power. The prototype consisted of evaluation modules for each component of the system that were connected together via breadboard. The system successfully gathered a sample of temperature data, transmitted it via Bluetooth to a smartphone, and was completely powered by the components in the power subsystem (i.e. evaluation modules were not powered by computer). A photo of prototype 1 can be seen in the **Figure 2** below.

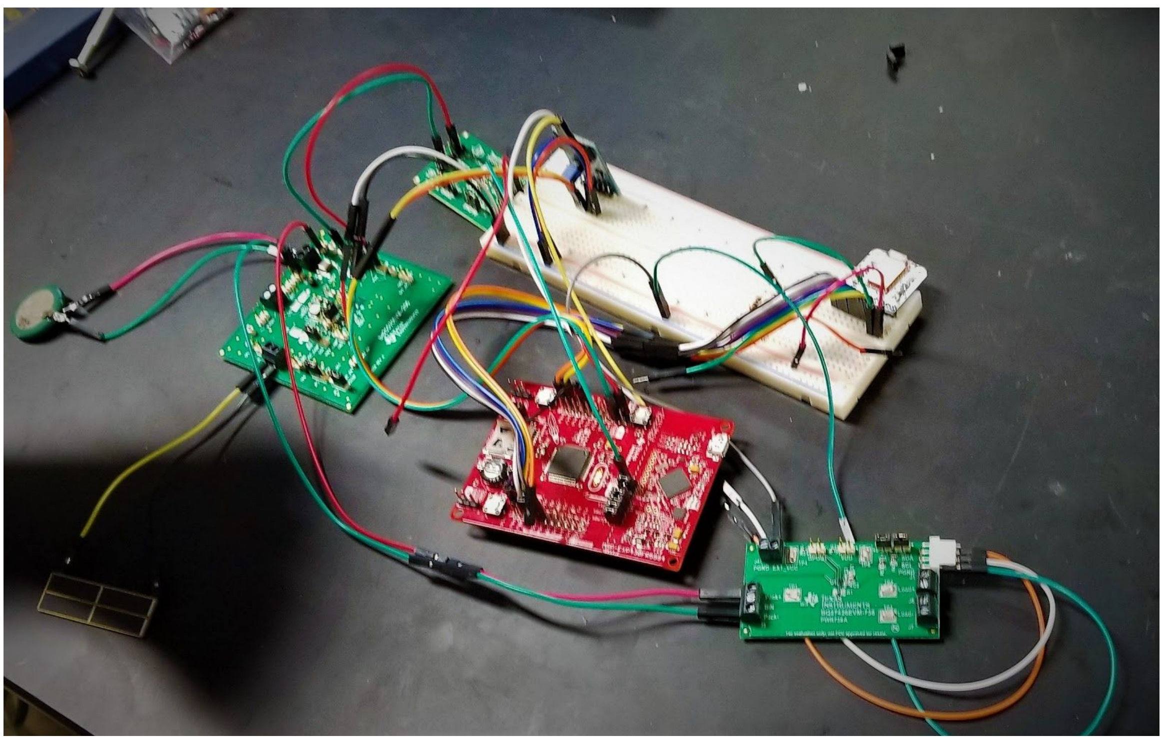


Figure 2: Prototype #1 (breadboarded proof-of-concept)

In order to select a good battery for the system, we emphasized high charge capacity with small form factor. The one we chose has 110 mAh capacity, a nominal voltage of 3.7 V, diameter of 24.5 mm, and height of 3.15 mm. In addition, we wanted to incorporate a fuel gauge with our battery to monitor its charge status, and we discovered that many fuel gauge chips required a minimum capacity of 110 mAh, so to keep open the possibility of working with a fuel gauge, we selected this battery.

In terms of selecting an energy harvester, we wanted to use a TI chip to keep open the possibility of scaling down to a SiP in the future. Our sponsors work closely with Texas Instruments and believe they could receive bare-silicon chips to put in a SiP. The only energy harvesters that TI produces are the BQ25505 and the BQ25570. We decided to go with the BQ25570, as it had an on chip boost converter for producing a configurable output voltage line. Before choosing a solar cell, we tested the 7 smallest commercially available solar cells over a variety of weather conditions at different times of day.

For selecting solar cells and fuel gauges, our main concern was selecting components sufficiently small for our prototype, but still capable of producing enough power and measuring voltage across our battery respectively. We selected a small solar cell that produced a sufficiently high output current, and a fuel gauge capable of measuring the capacity of our Li-Ion battery.

For selecting a microprocessor, the easy choice was the MSP430. The MSP430 is a very small, low-powered, and intuitive chip that our team had extensive experience using. We wanted a device that could support I2C, SPI, and UART, so we selected the MSP430FR5994. This particular chip has hardware support for all of these data communication schemes, as well as on-chip FRAM and multiple hardware accelerators for more intensive data processing. For choosing a sensor, we selected one that could communicate with our processor through SPI or I2C while drawing low amounts of power. As a proof-of-concept, we chose the HDC1080 TI temperature and humidity sensor so that the data would be easily verifiable.

Finally, for selecting components for our communications system, we simply chose the Bluefruit LE module from Adafruit. This device had an on-board ceramic antenna and could reliably receive data from the processor through SPI and connect to our smartphones through the Adafruit app. This module was more than adequate for our first prototype, although we soon realized that the module couldn’t initiate communications on its own, leading us to choose a different chip for subsequent prototypes.

Because of our low-power application, we found that our device was sufficiently safe from shock hazards, and we had little issue adjusting our prototypes for safety concerns in future iterations.

Prototype 2 Design (First PCB Design)

For prototype 2, our size and power specifications came into play. In moving to prototype 2, we created PCBs for each board (power, communications, and sensor) that fit within the size constraints. This prototype was 50 mm x 50 mm x 30 mm, which almost satisfied the size specification, but the vertical distance of 30 mm was only limited by the header connections between the board, which could easily be decreased. In this prototype, we did not create any physical supports to go between boards.

Using the software Eagle, we created PCBs for each board, which can be seen in **figure 3** below.

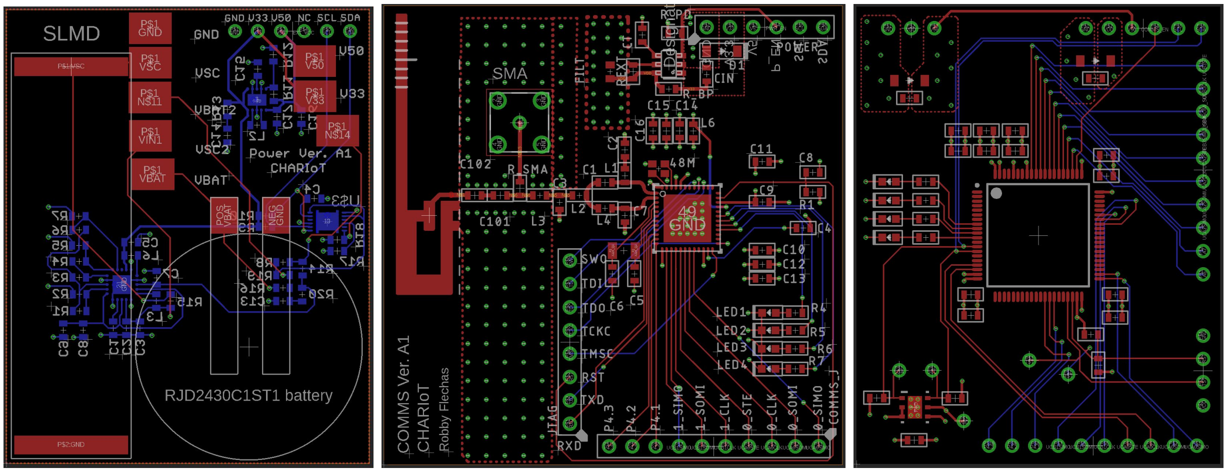


Figure 3: Prototype 2 PCB Board Design (left to right: power, comms, sensor)

We switched from the Adafruit Bluefruit to the TI CC2652R wireless transmitter for our second and third prototype. One of the main reasons we switched was that the Bluefruit was unable to talk to another Bluefruit since it could only act in peripheral mode. This prevented the option to make a mesh network. The TI chip is able to perform in central and peripheral mode, thus allowing a mesh network. The TI chip also had a much lower power consumption, which can be seen in test results section. These two key differences make the TI CC2652R chip the better choice for our device.

When we designed our communications board, we had to deal with the RF path from the CC2652R to the antenna. We needed to treat this path as a transmission line since the signal on this path is at 2.4 GHz. In order to accommodate for this, we need to make sure we tried to keep both halves of the path even, all the turns to be smooth curves, and pick the width of the traces to have a 50Ω impedance. In order to compute the correct width for the traces, we used an online pcb trace impedance calculator [8]. It required that we know the height of the copper layer, how thick the dielectric was between the copper layers and the dielectric constant of the substrate between the copper layers. All of these values could be found on a manufacturer's website. If we had used a different vender or even a different thickness board, the RF traces would have been a different width.

Prototype 3 Design (Final Prototype)

In prototype 2, we had already proved that we could meet all of our design specifications within the size constraint of 50 x 50 x 20 mm. In moving to prototype 3, the final prototype produced by this team, we wanted to show that the technology we had used could be aggressively scaled down. The resulting prototype we produced was 40 x 35 x 20 mm. Again, this 20 mm height vertical distance was limited by the headers between the boards. We went with the shortest male and female headers we could find, which still allowed empty vertical space in our prototype.

Again using Eagle, we produced the PCBs for the 3 boards shown in **figure 4** below. Some important changes were made to each board in this final iteration. For the prototype as a whole, we discussed multiple possible mechanical supports for the prototype, including 3-D printed rods and LEGOs. Eventually, however, we decided to use 2 headers in each corner of the 3 boards. These headers were electrically disconnected from the board and were only present for mechanical support.

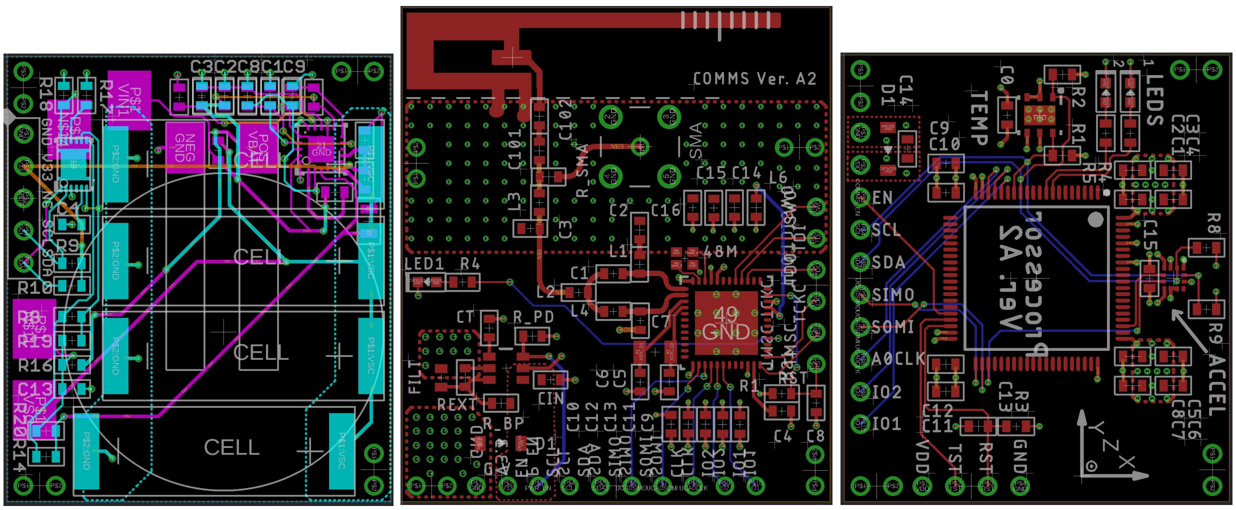


Figure 4: Prototype 3 PCB Board Design (left to right: power, comms, sensor)

The power board was the most difficult board to aggressively scale down. The main factors limiting the size of prototype 2 were the solar cells. We selected a solar cell that consisted of 4 smaller solar cells connected in a 2 x 2 array, so that the dimensions of the solar cell was 14 mm x 44 mm. We instead put 4 of these individual solar cells in parallel on our board, arranged in such a way that they instead took up 22 mm x 28 mm. Furthermore, for our final prototype, we no longer wanted to include a 5 V supply line, allowing us to remove the buck-boost converter included in prototype 3. The rest of the components remained the same. Redesigning the board then involved putting the solar cells on one side of the board, putting the battery on the other side of the board, and putting the necessary chips and components in the remaining spaces.

While we did not change any components on the communications board, its entire layout had to be changed due to the new size and locations of headers and antenna. Beyond reorganizing the PCB files and ensuring the RF line was clean, however, these changes were very minor.

The sensor board was perhaps the easiest board to redesign for prototype 3. However, in this redesign, we wanted to include 2 sensors that we believed would be simple to demonstrate at our final showcase. The sensors we chose were a temperature/humidity sensor and an accelerometer. We also removed several headers that were unnecessary for the function of the device in order to reduce the size of the overall prototype (headers removed from the sensing board meant less headers on the other boards). In general, the boards were easy to compress to a smaller size from prototype 2, and they could be further compressed in future prototypes.

Future Prototypes

If the project were to go forward with commercial manufacturing on the order of 10,000 units, major design changes would not need to be made given that prototype 2 and 3 was made by a PCB manufacturer. The only improvement that significantly affects the current fabrication process is the soldering of header pins on the communications PCB. In order to cut costs and reduce the vertical distance between boards, we did this manually in the OEDK. This entailed taking standard male header pins, removing the spacer, and aligning them such that short female headers can connect to both ends of the pins. Additionally, the overall system of header pins and mechanical support could be an issue when scaling up, because the current design requires all pins to be carefully aligned for all three boards to fit together.

However, the commercial manufacturing of a SiP is an entirely different process from the manufacturing of PCBs. We would have to work with Octavo Systems and discuss more specific changes that need to be made on our system. Currently, the footprint of our system can be reduced by switching to a ceramic antenna, using a smaller transducer such as a piezoelectric plate, and using a solid state battery. Despite its size, an external timer may be beneficial because a longer sleep cycle will allow for smaller batteries and transducers. The energy harvesting IC, transmitter IC, and processor are compatible with these specific changes and would not result in a major redesign.

Several other minor changes could be helpful in future designs. A switch could be added to the SiP so that the battery can be disconnected and won't discharge in situations devoid of energy for the system transducer. A replacement for the fuel gauge could also be added to help with dynamic power control by the microprocessor. Future teams could also develop protocols for node-to-node communication between these sensor nodes so that networks of these devices can be developed in the future.

TESTING RESULTS

Power Tests

See specifications 1 and 6 in the Specifications section

Table 3: Power Test Results

	Sensor Board	Comms Board
Mean Current Draw	0.596 mA	8.1 mA
Max Current Draw	4.867 mA	15.5 mA

As seen in **Table 2** above, our sensor board only draws a 0.596 mA on average while awake and 4.867 mA at peak current draw. We got these numbers by placing a 30Ω resistor in series with the ground line of the sensor board and then measuring the voltage over the resistor. **Figure 5** below shows the oscilloscope readings for the sensor board.

The entire sensor board draws about 5 mA peak current while sensing, showing that our system can support a sensor with peak current draw of at least 5 mA (specification 1).

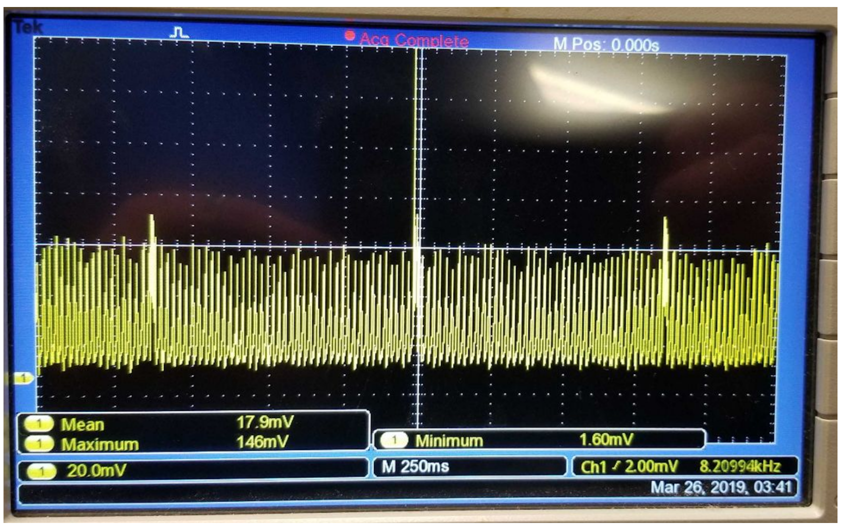


Figure 5: Processor Board Voltage Drop over 30Ω Resistor

Table 2 also shows that the communications board draws significantly more current than the sensor board with a mean current draw of 8.1 mA and a peak current draw of 15.5 mA. We got the data in a similar manner to the sensor board, except we used a 10Ω resistor instead of a 30Ω resistor. **Figure 6** below shows the oscilloscope readings for the communications board.

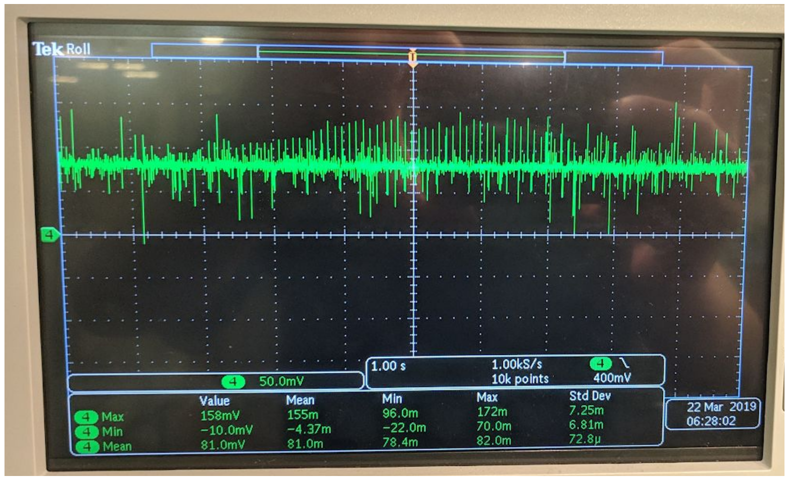


Figure 6: Comms Board Voltage Drop over 10Ω Resistor

The Bluefruit module that we used in Prototype 1 had an average current draw of 33 mA while transmitting. This mean the peak is more than the 30mA that we guarantee will work, but we were able to get it working. This highlights the modularity of our design in respect to wireless transmitters, showing that our design supports multiple wireless transmitters (specification 6).

Charging Tests

See specification 2 in the Specifications section

For our charging tests, we put several test points on our prototype 2 and prototype 3 power boards that allowed us to measure voltages at strategic locations in the circuits. We took our prototype 3 into both direct sunlight and shade and recorded the current going into the energy harvester from the solar cells, the current going into the battery from the energy harvester, and the voltage across the solar cells. A chart showing the information can be seen in **Table 3** below.

Table 4: Charging Test Results

	Sunny	**Shade**
Solar Cell Current	~36 mA	~2 mA
Solar Cell Voltage	~1.5 V	~1 V
Charge Current	~10 mA	~0.3 mA

We can assume that the voltage across the battery is at least 3 V and at most 4.2 V. Thus, the power produced by the solar cell is 54 mW in direct sunlight and 2 mW in shade, while the power received is between 30 and 42 mW in direct sunlight and between 0.9 and 1.26 mW in the shade. On average, we can then conclude that our energy harvester has a charging efficiency of around 50%. The loss of efficiency can be attributed to boosting the charging voltage and quiescent power loss throughout the circuit.

Battery Capacity Calculations

See specifications 3 and 4 in the Specifications section

In order to determine how long the battery can power the system we derived the following equation. One sense and transmit draws 8 mA for 5 seconds, the battery capacity is 110 mAh, and quiescent current is 200uA.

$$21.7 \text{ days} = \frac{110 \text{ mAh}}{(8\text{mA} \cdot 5\text{s} \cdot \frac{1 \text{ hr}}{3600\text{s}} + 0.2\text{mA} \cdot 1\text{hr}) \cdot \frac{24 \text{ TXs}}{1 \text{ day}}}$$

Thus, the node can sense and transmit once per hour for roughly three weeks.

Range Tests

See specification 5 in the Specifications section

Figure 7: Comms Board Range Test

We placed the node on the 90 degree statue while it was transmitting data 3 times a second to a tablet. We then slowly walked away with the tablet until we could not longer get new data. We could go 45m before the transmission rate slowed down (still received all the data, it just took longer get it). We could go 119m before losing all connection. This surpasses our minimum requirement of 5m from specification 5.

Board Size Measurements

See specification 7 in the Specifications section

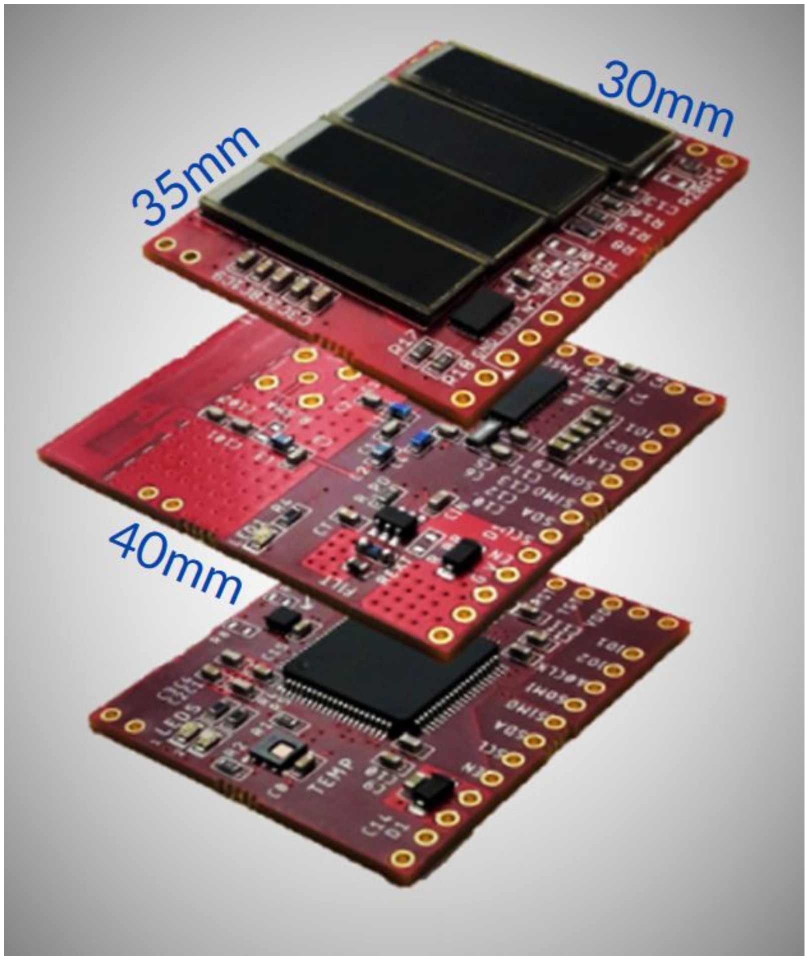


Figure 8: Final Prototype Size

Both the power and sensor board measured 30mm x 35mm. Communications board measured 40mm x 35mm. It has a larger size since the antenna needs to hang over with nothing above or below it. Once stacked, the entire node measured 40mm x 35mm x 50mm.

Cost Calculations

See specification 8 in the Specifications section

Table 5: Final Prototype Cost Breakdown per Unit

	Power Board	**Communications Board**	**Processor Board**	**Final Prototype**
Components	$44.58	$14.28	$12.17	$70.98
Base PCB	$7.47	$8.95	$7.45	$23.87
Labor	$48.37	$61.18	$51.25	$160.80

Total	$100.40	$84.42	$70.87	**$255.69**

Table 6: Estimated Cost Breakdown at 10,000 Unit Scale

	Power Board	**Communications Board**	**Processor Board**	**Final Prototype**
Components	$27.71	$5.92	$6.54	$40.17
Base PCB	$0.86	$1.08	$0.86	$2.80
Labor	$2.24	$2.27	$2.25	$6.76
Total	$30.81	$9.27	$9.66	$**49.74**

SUMMARY AND LESSONS LEARNED

Throughout this academic year, we have successfully created a self-powered and modular IoT device, capable of using multiple sensor types and communicating sensor data to a tablet or other wireless communication device. The device we created can be easily programmed and deployed in any environment that features sufficient sunlight. The data can be easily accumulated on our customized app. Furthermore, we have created a platform for easily redesigning a sensor node to fit a desired application. The interfaces between each board include a few architectural and firmware features that should remain constant across different iterations of these sensor nodes. To redesign the sensor node to fit an application, all that is required is replacing the power transducer, sensor, and antenna. Because of our component and firmware choices, the remaining system can remained unchanged excluding a few rare exceptions.

There were many lessons to be learned throughout the design process. In designing PCBs, we learned that impedance matching is indispensable, and that great care must be taken when designing a transmission line or other RF feature. Pours are another good way to make solid connections between power planes and allows you to use multiple vias to connect signals to inner planes. These methods help retain signal integrity and reduce parasitic power draw, which helps increase battery life.

Another lesson we learned involved the use of the fuel gauge in the power system. We designed our system around using this component at times: we had to leave room for the fuel gauge in our PCB files, it draws power to operate (and even when not in operation), and we couldn't use a battery less than 110 mAh if we wanted to utilize the fuel gauge. Unfortunately, the fuel gauge didn't end up working correctly in the final prototype, meaning that board space, power, and component choices were wasted on a system component that provides no utility to the prototype. In the future, if a component doesn't work in initial prototypes, we now know to exclude it in final prototypes to more optimally utilize resources.

An important lesson we learned in communicating with vendors is to: 1. Use an email address not ending in ".edu" at all times. 2. Be very clear and direct with what we want. When we had questions about the components that TI had provided for us, we were unable to get quick and helpful replies to our inquiries. TI, along with most companies, will spend less time providing assistance to those who are not paying customers, and using an email address not ending in ".edu" will lead to more expedited communication. When ordering PCBs from the local company MacroFab, our orders consistently were confused with the orders for another team using very similar components. Although it did not happen to our team, MacroFab also mailed the other team's PCBs to the wrong address (including mailing a package to their own address) on three separate occasions. These situation have made it clear how important clear and concise communication with vendors is to timely completion of prototypes.

Finally, this project was an important exercise in working closely as a design team. Throughout the design process, we maintained communication with one another, scheduled our time appropriately, and had clearly defined tasks for each member. In general, our group was successful at creating an operational device and working as an effective team.

REFERENCES

[1]
D. Pinkney, "Bain & Company predicts the Internet of Things market will more than double to $520 billion by 2021," *Bain & Company, Inc.*, 08-Aug-2018. [Online]. Available: https://www.bain.com/about/media-center/press-releases/2018/bain-predicts-the-iot-market-will-more-than-double-by-2021/. [Accessed: 30-Apr-2019].

[2]
K. L. Lueth, "State of the IoT 2018: Number of IoT devices now at 7B – Market accelerating," *IoT Analytics*, 08-Aug-2018. [Online]. Available: https://iot-analytics.com/state-of-the-iot-update-q1-q2-2018-number-of-iot-devices-now-7b/. [Accessed: 30-Apr-2019].

[3]
"Wireless Harvesting with EnerChip™," *Cymbet*. [Online]. Available: https://www.cymbet.com/design-center/wireless-harvesting/. [Accessed: 26-Apr-2019].

[4]
"System in Package - SiP Technology," *Octavo Systems*. [Online]. Available: https://octavosystems.com/sip-technology/. [Accessed: 26-Apr-2019].

[5]
M. Berger, “3D-printed, fully integrated wireless sensor devices,” *Nanowerk*, 02-Jun-2017. [Online]. Available: https://www.nanowerk.com/spotlight/spotid=46930.php. [Accessed: 26-Apr-2019].

[6]
G. Xu *et al*., "System integration for miniature node of wireless sensor network (WSN)," *2012 13th International Conference on Electronic Packaging Technology & High Density Packaging*, Guilin, 2012, pp. 94-96. doi: 10.1109/ICEPT-HDP.2012.6474577

[7]
“Sensors,” *Sensors*. [Online]. Available: https://www.renesas.com/us/en/products/sensors.html. [Accessed: 30-Apr-2019].

[8]
“Electromagnetic Compatibility Laboratory,” – *Electromagnetic Compatibility Laboratory | Missouri S&T*. [Online]. Available: https://emclab.mst.edu/resources/tools/pcb-trace-impedance-calculator/microstrip. [Accessed: 30-Apr-2019].

APPENDIX

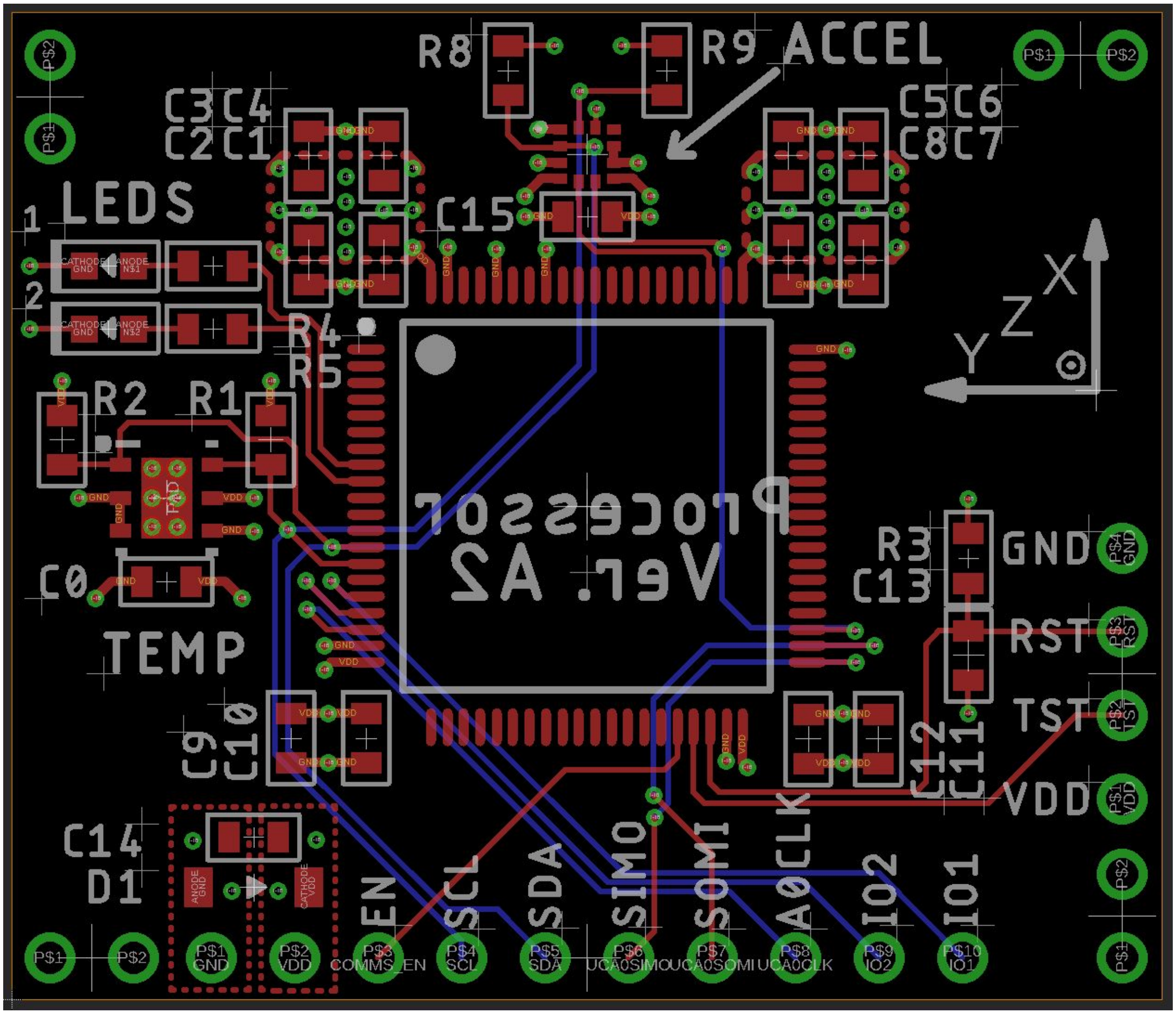


Figure 9: Prototype 3 Sensor Board PCB

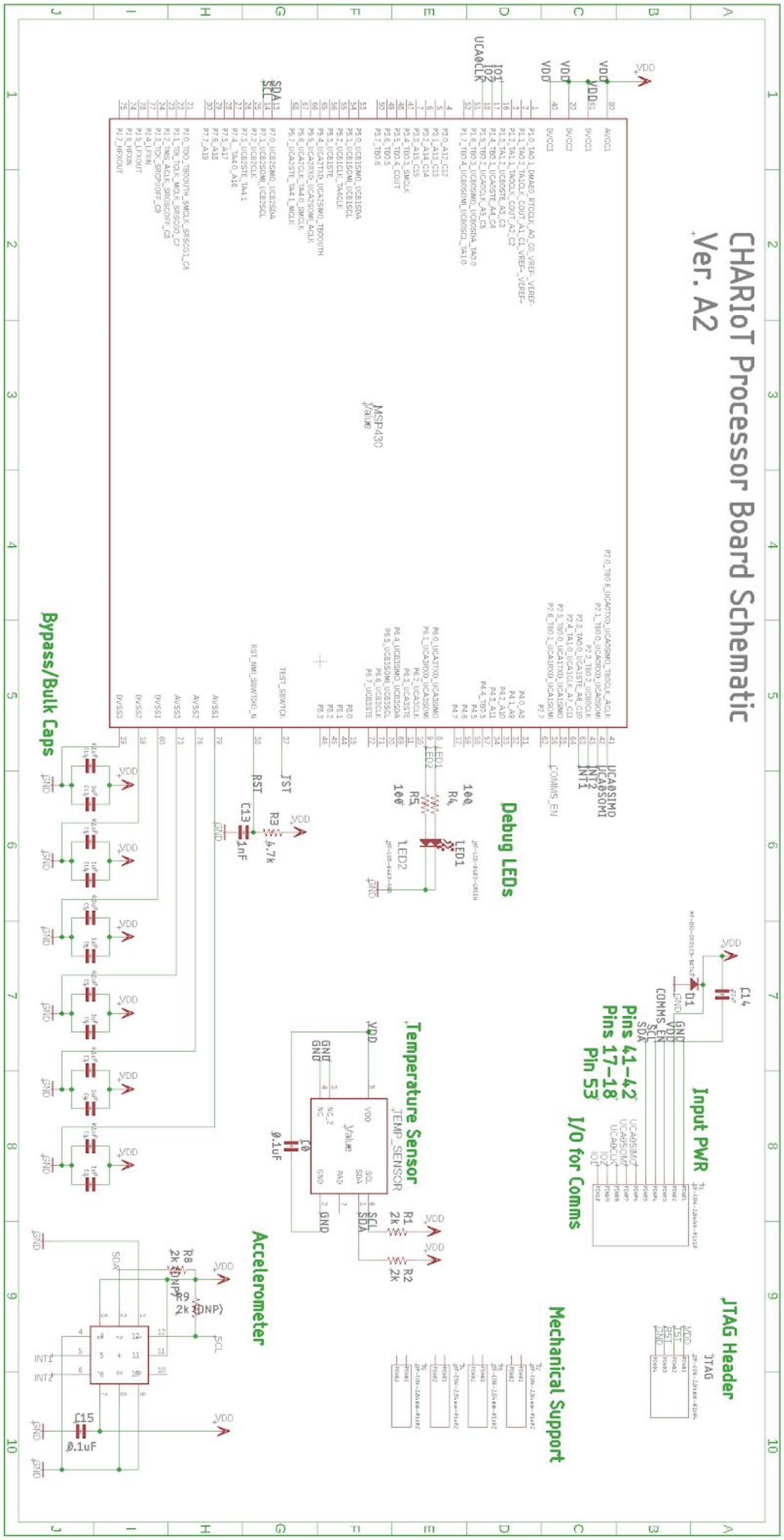


Figure 10: Prototype 3 Sensor Board schematic

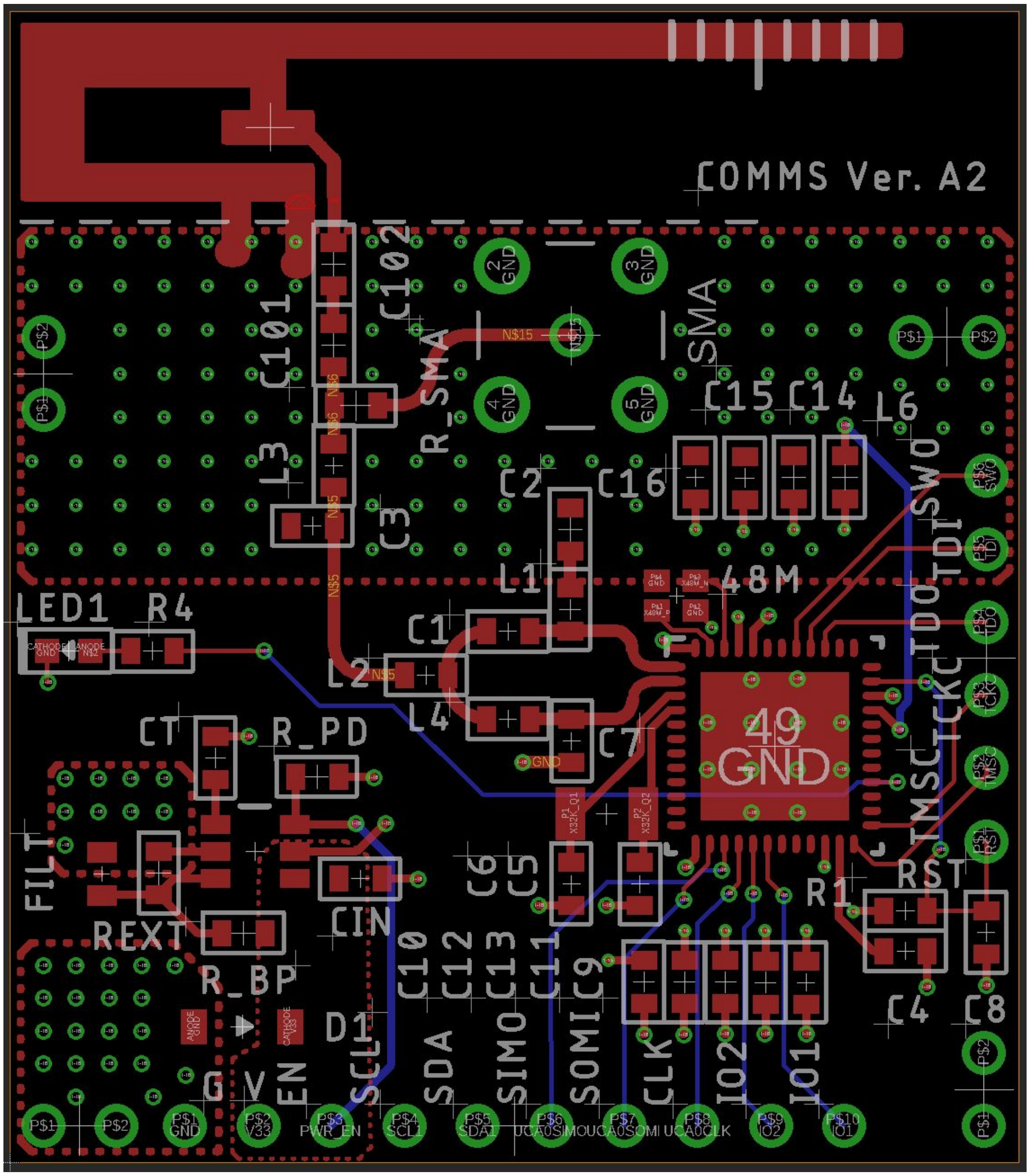


Figure 11: Prototype 3 Comms Board PCB

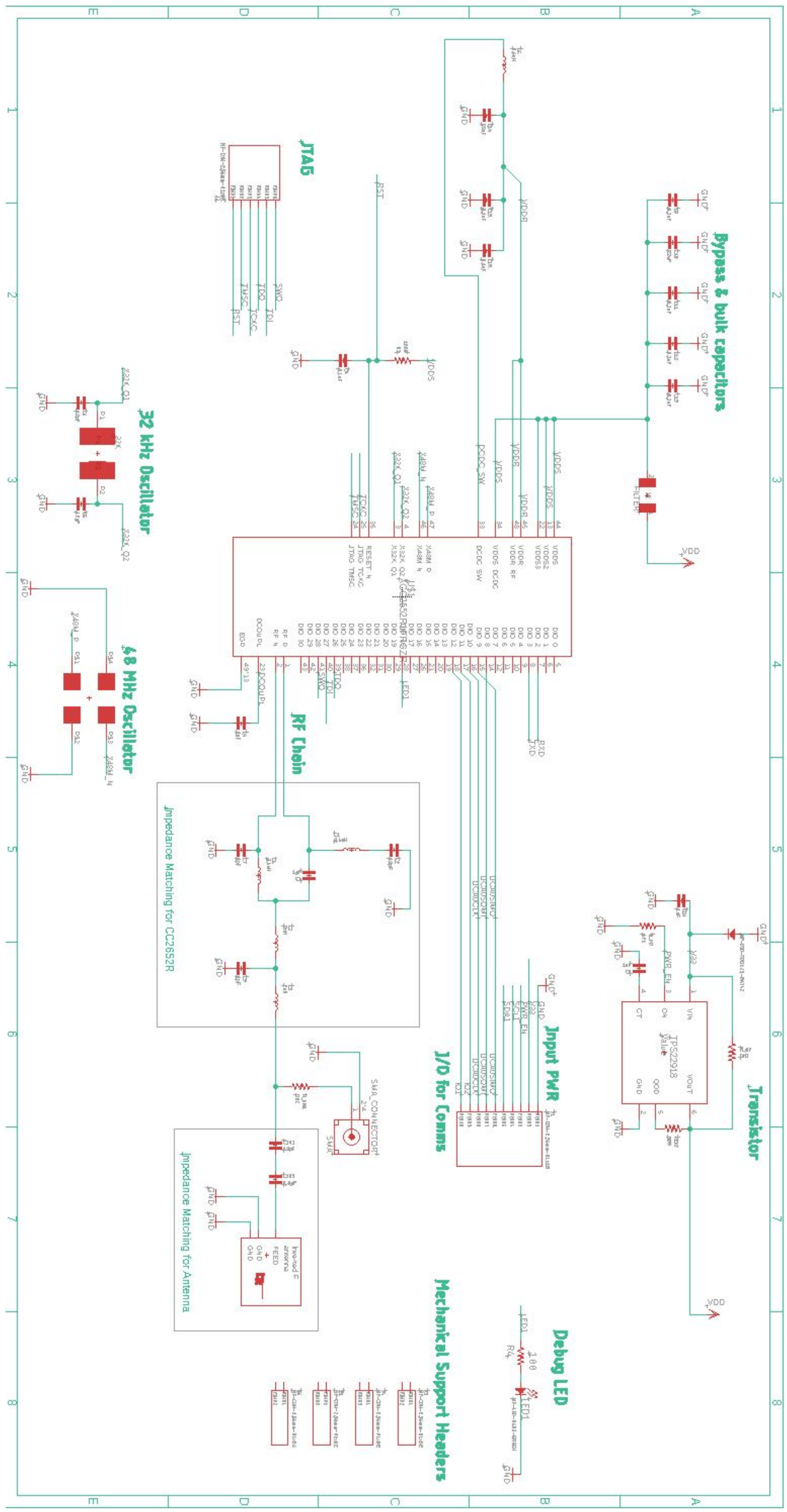


Figure 12: Prototype 3 Comms Board Schematic

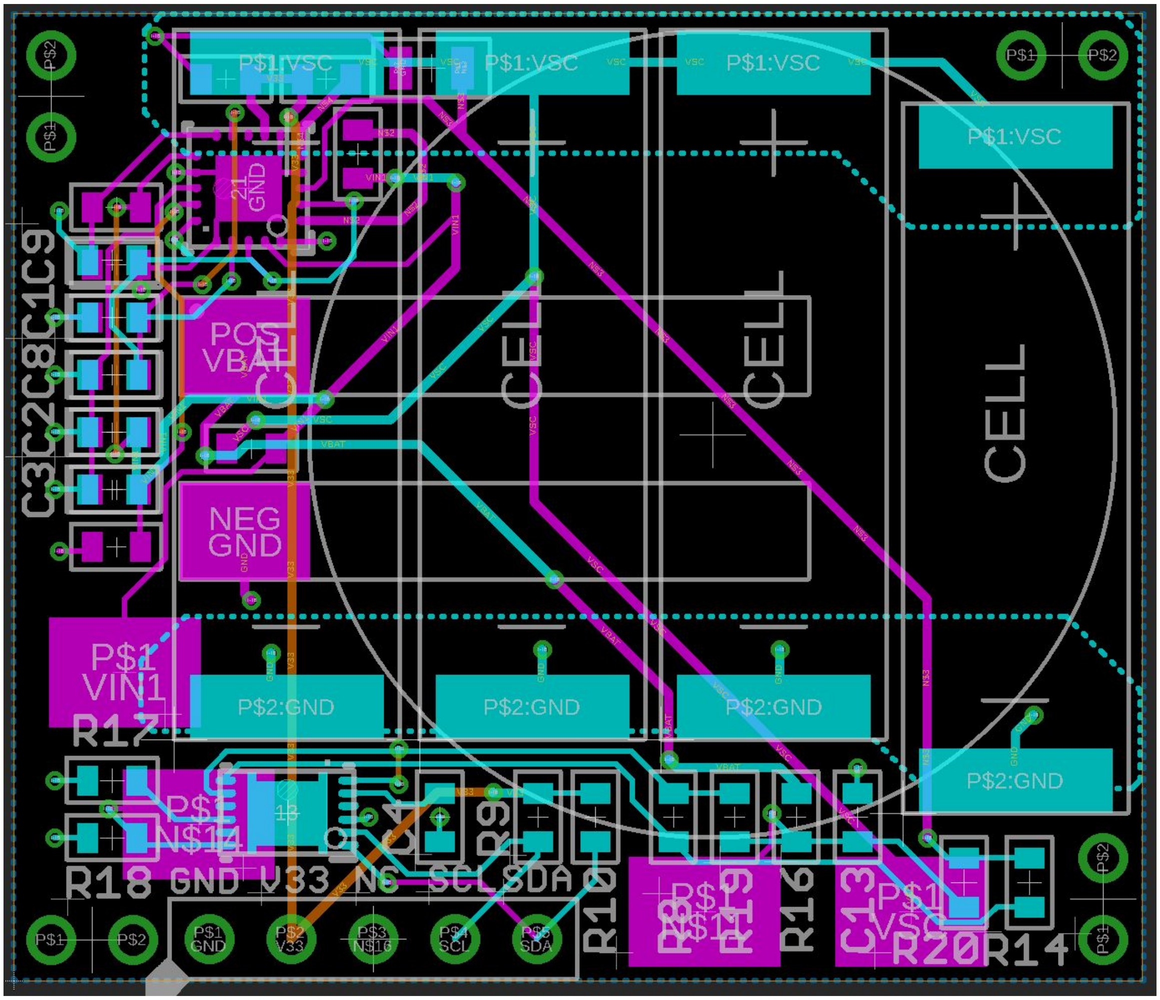


Figure 13: Prototype 3 Power Board PCB

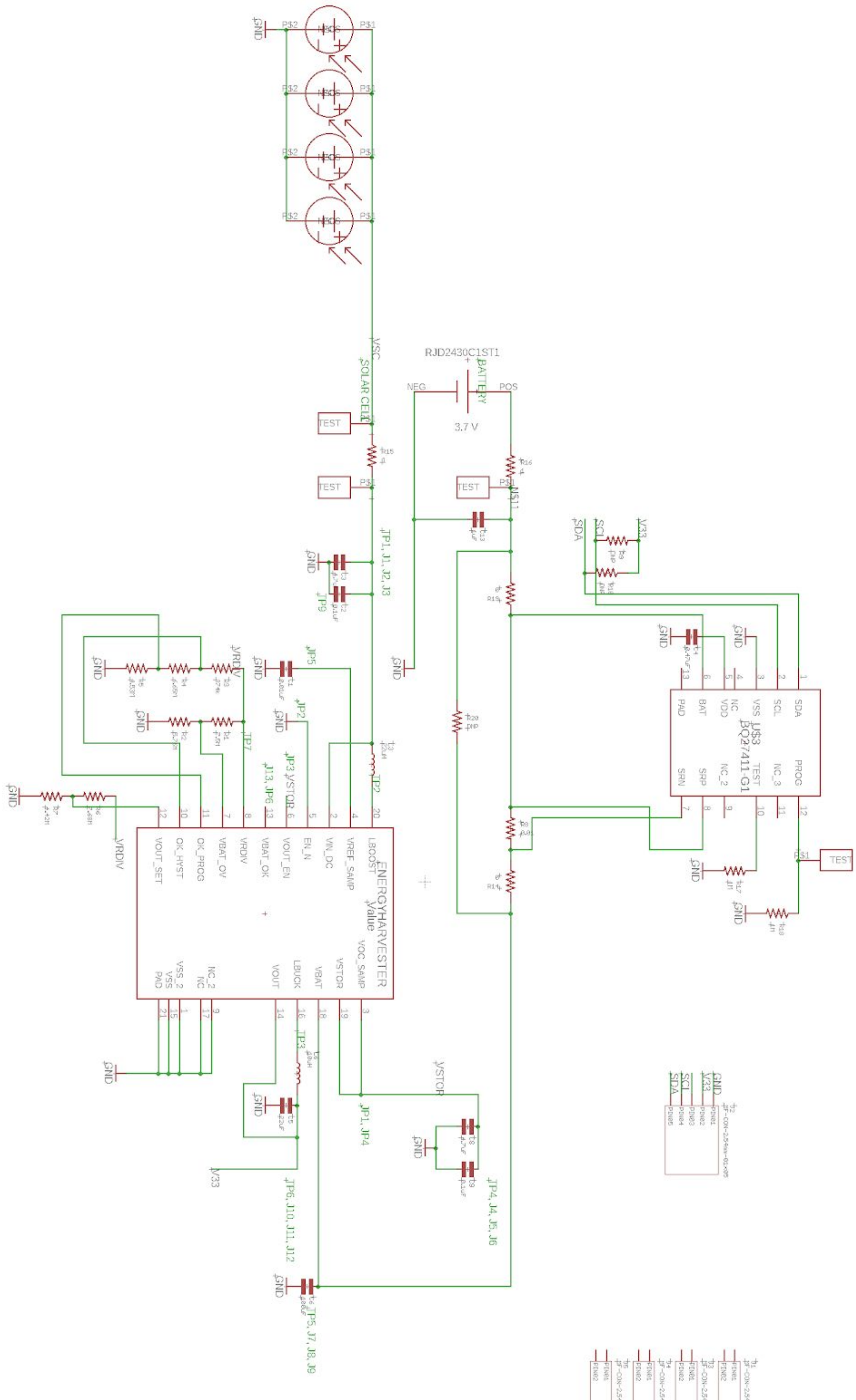


Figure 14: Prototype 3 Power Board Schematic

We are including Prototype 2 Schematics for the comms boards because we have two different designs, one with a trace antenna and one with a ceramic surface mount antenna. We did not test our ceramic antenna design, however, since our trace antenna worked correctly. Thus the ceramic antenna design did not make it to prototype 3. However, it is still valuable and future teams may wish to use the design as a stepping stone to incorporate the ceramic pcb antenna.

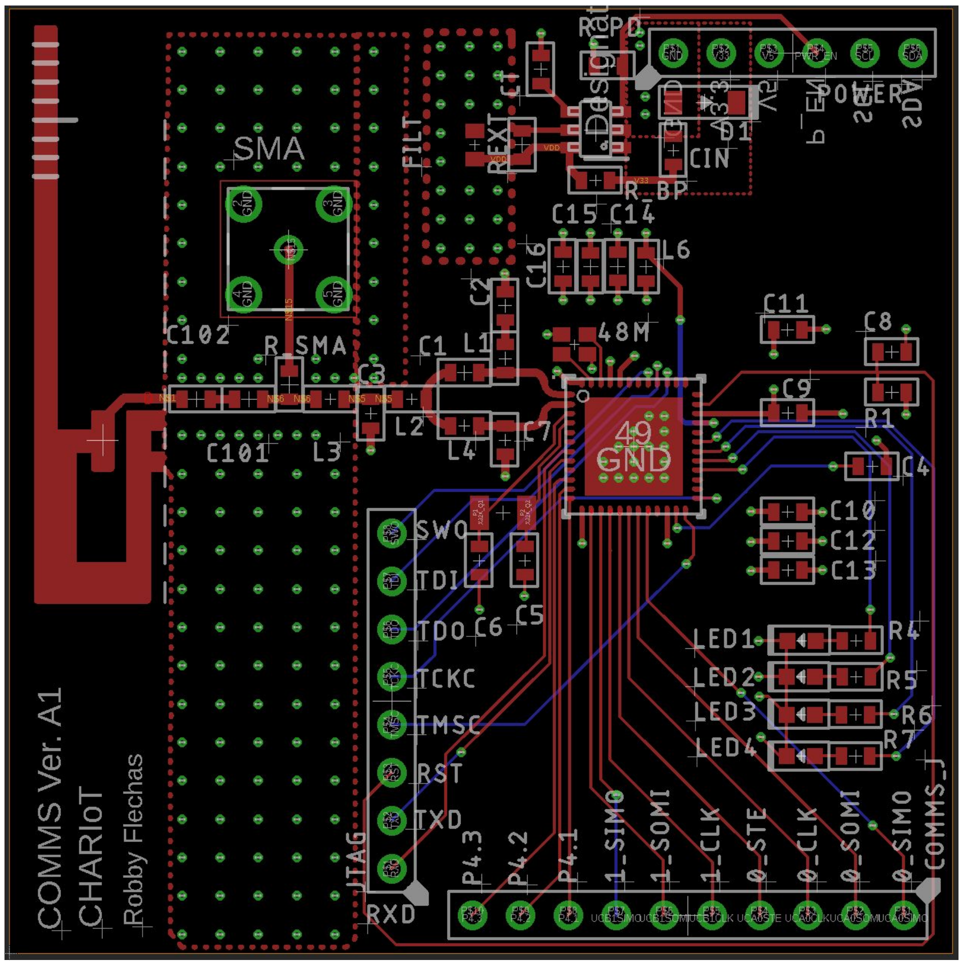


Figure 15: Prototype 2 Comms Board with Trace Antenna PCB

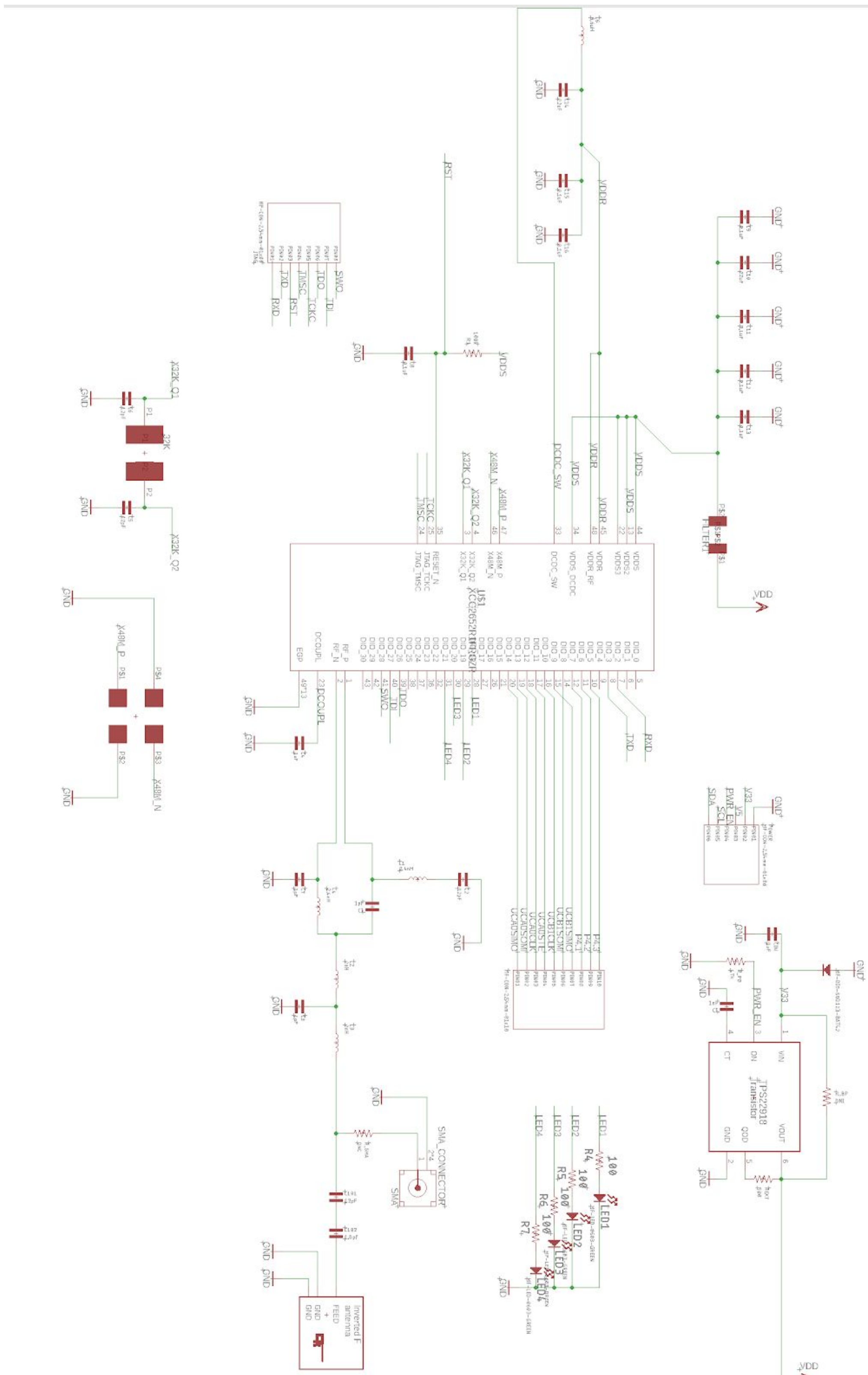


Figure 16: Prototype 2 Comms Board with Trace Antenna Schematic

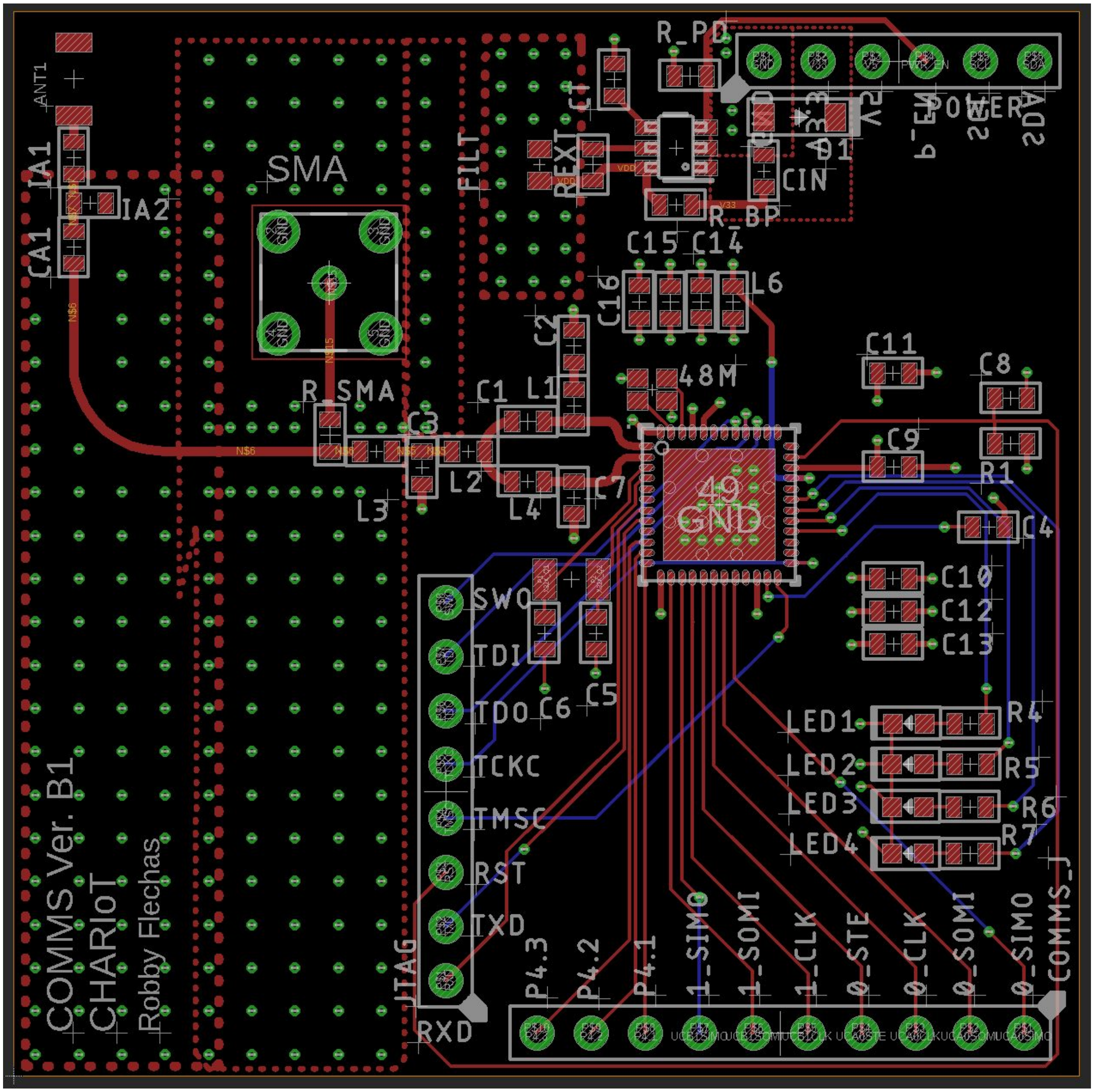


FIgure 17: Prototype 2 Comms Board with Ceramic Antenna PCB

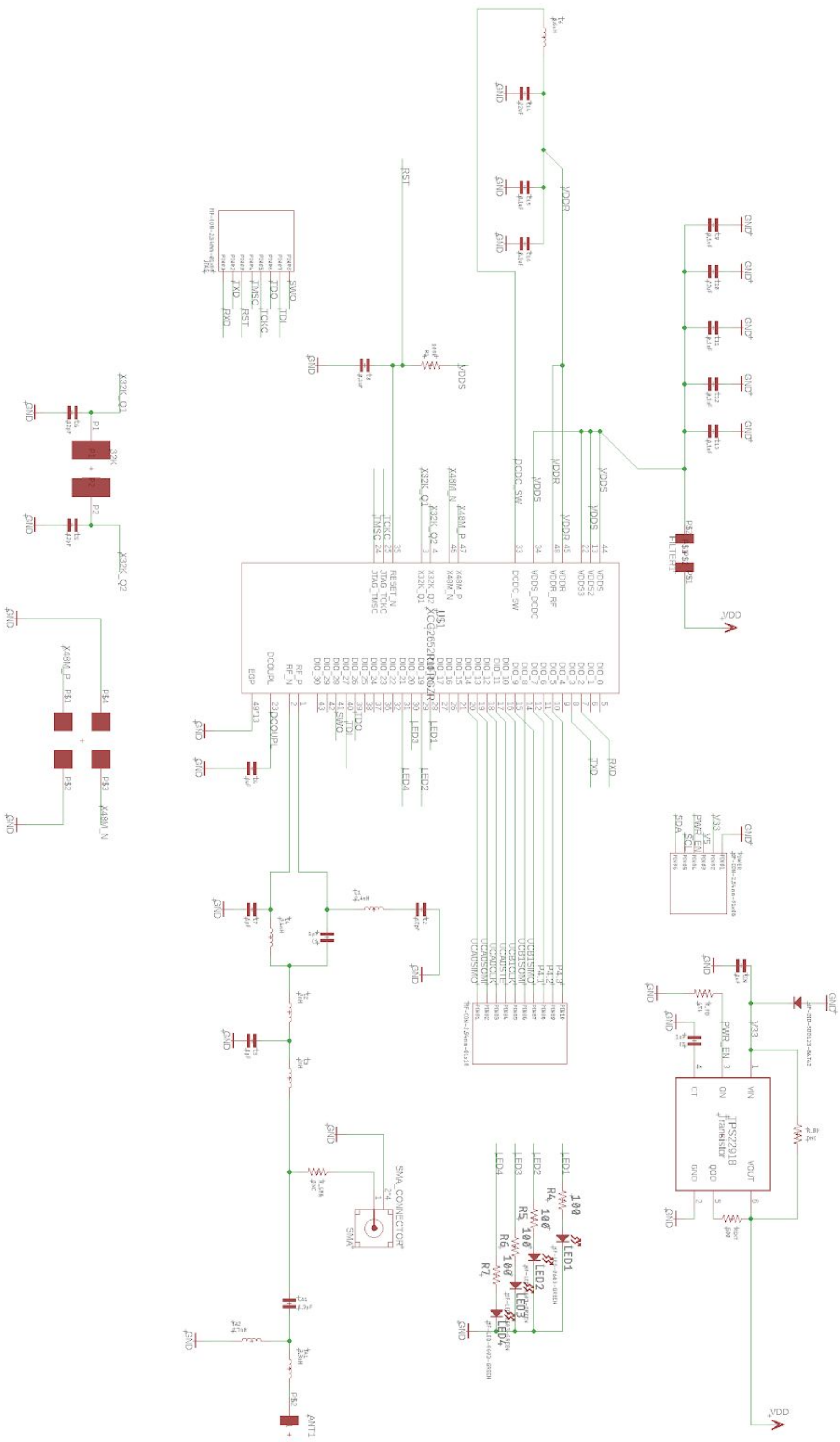


Figure 18: Prototype 2 Comms Board with Ceramic Antenna Schematic

Table 7: Comms Board Bill of Materials

Item	designator	Min # of Units	Price/Unit	Total Price	10000 Price/Unit	10000Total Price
32KHz crystal oscillator*	32K	1	0.46	0.46	0.2134147671	0.2134147671
48MHz crystal oscillator*	48M	1	0.86	0.86	0.48	0.48
12pF	C2,C5-C6,C101	4	0.0286	0.1144	0.01663	0.06652
1.8pF	C102	1	0.061	0.061	0.0153	0.0153
22uF	C10,C14	2	0.3	0.6	0.08	0.16
0.1uF*	C8-C9,C11-C13,	7	0.00853	0.05971	0.004878	0.034146
1pF	C1,C3,C7	3	0.061	0.183	0.0153	0.0459
1uF*	C4,CIN	2	0.0243	0.0486	0.019512	0.039024
1nF*	CT	1	0.0109	0.0109	0.006098	0.006098
schottky diode*	D1	1	0.1097	0.1097	0.071951	0.071951
ferrite beads*	Filter	1	0.16	0.16	0.0650367814	0.0650367814
headers	J1-J6	4	0.59	2.36		0
2.4nH	L1,L4	2	0.21	0.42	0.09782	0.19564
2nH	L2-L3	2	0.244	0.488	0.1097	0.2194
8.6uH	L6	1	0.471	0.471	0.22874	0.22874
green led*	LED1	1	0.219	0.219	0.060976	0.060976
100kΩ*	R1	1	0.0097	0.0097	0.003659	0.003659
100Ω*	R4	1	0.0097	0.0097	0.003659	0.003659
500	REXT	1	2.812	2.812	1.28	1.28
DNP	R_BP	0		0		0
47kΩ	R_PD	1	0.02	0.02	0.00395	0.00395
DNP	R_SMA	0		0		0
DNP	SMA	0		0		0
load switch	TPS22918	1	0.38	0.38	0.20365816	0.20365816
mcu	U1	1	5.29	5.29	3	3
		Total Components Cost		**15.14671**		**6.397072708**

Table 8: Processor Board Bill of Materials

Item	Designator	Min # of Units	Price/Unit	Total Price	10000 Price/Unit	10000Total Price
Accelerometer	ACCEL	1	$1.61	$1.61	0.63	0.63
0.1uF*	C0-C1,C3,C5,C7	8	0.00853	0.06824	0.004878	0.039024
1uF*	C2,C4,C6,C8,C1	6	0.0243	0.1458	0.01951216667	0.117073
1nF*	C13	1	0.0109	0.0109	0.006098	0.006098
22uF	C14	1	0.3	0.3	0.08	0.08
Schottky diode*	D1	1	0.1097	0.1097	0.071951	0.071951
headers	J1-5	1	-	-	-	-
headers	JTAG	1	-	-	-	-
green led*	LED1	1	0.219	0.219	0.060976	0.060976
red led*	LED2	1	0.219	0.219	0.060976	0.060976
msp430fr59941pnr	MSP430	1	$6.91	$6.91	4.18	4.18
2kΩ*	R1-R2	2	0.00975	0.0195	0.0036585	0.007317
4.7kΩ*	R3	1	0.00975	0.00975	0.003659	0.003659
100Ω	R4-R5	2	0.00975	0.0195	0.0036585	0.007317
2kΩ*	R8-R9	2	0.00975	0.0195	0.0036585	0.007317
temperature & humidity sensor	TEMP_SENSOR	1	$2.51	$2.51	1.27	1.27
		Total component costs		**$12.17**		**6.541708**

Table 9: Power Board Bill of Materials

Item	Designator	Min # of Units	Price/Unit	Total Price	10000 Price/Unit	10000 Total Price
Energy Harvester	U1	1	6.236	6.236	3.915	3.915
Battery	U2	1	11.09	11.09	7.033	7.033
Fuel Gauge	U3	1	2.33	2.33	1.27	1.27
Solarcell	U4-U7	4	$3.30	$13.20	1.9536	7.8144
7.5MΩ	R1	1	0.12	0.12	0.02	0.02
5.76MΩ	R2	1	0.04	0.04	0.004	0.004
374kΩ	R3	1	0.05	0.05	0.01	0.01
6.65MΩ	R4	1	0.1	0.1	0.004	0.004
4.53MΩ	R5	1	0.01	0.01	0.002	0.002
7.68MΩ	R6	1	0.04	0.04	0.002	0.002
4.42 MΩ	R7	1	0.01	0.01	0.002	0.002
0.01Ω	R8	1	0.47	0.47	0.2	0.2
DNP	R9-R10, R20	-	-	-	-	-
0Ω	R14,R19	-	-	-	-	-
1Ω	R15-R16	2	0.41	0.82	0.16	0.32
1MΩ	R17-R18	2	0.04	0.08	0.002	0.004
22uH	L3	1	0.14	0.14	0.0632	0.0632
10uH	L6	1	0.12	0.12	0.0542	0.0542
headers	J-	1	7.95	7.95	6.36	6.36
.01uF*	C1	1	0.012	0.012	0.004878	0.004878
0.1uF*	C2, C9	2	0.00853	0.01706	0.009756	0.019512
4.7uF	C3, C8	2	0.36	0.72	0.12	0.24
0.47uF	C4	1	0.32	0.32	0.1	0.1
22uF	C5	1	0.3	0.3	0.08	0.08
100uF	C6	1	0.38	0.38	0.17	0.17
1uF*	C13	1	0.0243	0.0243	0.019512	0.019512
		Total component costs		**44.57936**		**27.711702**

Table 10: Vital Component Part Numbers

Part Name	Part Designator	Part Number
Energy harvesting	U1	BQ25570RGRR
Battery	U1	RJD2430C1ST1
Fuel gauge	U3	BQ27411DRZR-G1A
Solarcell	U4-U7	KXOB22-04X3F
Processor	MSP430	MSP430FR9941PNR
Temperature & Humidity Sensor	TEMP_SENSOR	HDC1080DMBR
Accelerometer	ACCEL	BMA253
32KHz crystal oscillator	32K	FC-135 32.7680KA-A3
48MHz crystal oscillator	48M	NX2016SA-48M-EXS00A-CS05517
schottky diode	D1	MF-DIO-SOD123-BAT42
ferrite beads	Filter	BLM18HE152SN1D
load switch	TPS22918	TPS22918
MCU	U1	CC2652R