EWH Design Competition Submission for:

Save Your Breath: A Cost-Effective Oxygen Concentration Sensor from Zinc-Air Batteries

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Problem Definition

There is a need for a cost-effective solution for testing the output of oxygen concentrators. The proposed solution involves using zinc-air batteries (often marketed in the US as hearing-aid batteries) as a sensor in conjunction with a basic microcontroller (powered by a separate 9V battery) for interpretation. The zinc-air batteries exhibit changes in electrical characteristics according to the oxygen concentration surrounding it, namely that the maximum current output increases by approximately 80% at and above clinical levels[1] (of 82-96% oxygen concentration)[2]. This is possible because the zinc-air batteries work by using the oxygen in the surrounding air as the cell's cathode[3] (which enters the electrochemical cell through tiny breather holes on the negative face).[4]

Using an i2c current sensor and an Arduino-compatible microcontroller (or a similar pairing), the team plans to write a simple program to store the initial short circuit current and the short circuit current after 5 minutes of exposure to the concentrator output. The circuit will then compare the two currents and decide whether to light a green LED (>82%), a yellow LED (between 30% and 82%), or a red LED (<30%), which will respectively mean clinical level concentration, significantly concentrated but not clinical level, and not significantly concentrated. While more accurate measurement is possible with the given technology, these three levels are enough to diagnose problematic concentrators and differentiate between completely non-functional units and sub-optimal units, while keeping the user interface simple. A similarly accessible design could include more levels within the yellow LED range, with more yellow LEDs to illustrate more precisely how low the concentration is.

The proposed device would aid in ensuring patients with difficulty breathing and/or in need of enhanced oxygen supply get the treatment they are supposed to be receiving.

[1] - confirmed in the lab using a commercial oxygen concentration tester
[2] - World Health Organization - Technical Specifications for Oxygen Concentrators. p.11-14 from https://apps.who.int/iris/bitstream/handle/10665/199326/9789241509886_eng.pdf
[3] - US Patent US9252616B2 - last accessed Feb 2019 from https://patents.google.com/patent/US9252616B2
[4] - See appendix for Figure 1: Zinc-Air Battery

Statement of Impact on Developing World

Certain low-resource areas of the world depend on local on-site oxygen concentrators (as opposed to a central cylinder system, purpose-built gas pipes, and/or gas lines dangerously repurposed for oxygen)[1]. As a result of the lack of resources, the equipment is often neglected, and almost always used past its rated lifetime[2]. One such area is in the poorer sections of Eastern Africa, where the hot, slightly humid climate further shortens the lifetime of oxygen concentrators.

All of this would be just another case of "low-resource medical care centers simply need more of those resources" if it weren't for one very important detail: the most common mode of failure for oxygen concentrators in the climate of Eastern Africa is a worn-out nitrogen filter.[3] Oxygen concentrators work by first filtering out macroscopic particles and compressing the air to remove carbon-dioxide and other trace gases which solidify at high pressures. After the air has been compressed, it runs through a nitrogen filter which removes enough nitrogen to place the output somewhere between 82% and 96% oxygen concentration[4]. A failure in the nitrogen filter can allow the output to fall below the clinical level while still producing compressed air that upon first inspection appears to be concentrated oxygen. This is even more alarming when you consider the repercussions, as the WHO lists oxygen on both the Essential Medicines List and the Essential Medicines List for Children[5],[6]. When an oxygen concentrator is used, and it isn't filtering out what it is supposed to, the false sense of security often compounds with the actual symptoms, leading to neglected patients.

While there are many commercially available concentration testers, these are prohibitively expensive for a lot of medical care centers, usually costing upwards of $500 USD, even within the US. Factor in shipping, handling, and import costs and the cost in many low resource areas is astronomical. To further exacerbate the issue, many technicians without access to commercial testers will simply light a match and hold it to the output, often with explosive results[3], putting more lives at risk than just a faltering oxygen supply would. The proposed solution of LED levels would allow technicians to easily identify if a particular concentrator is in need of a complete service or if it could be extended in life by cleaning filters, lines, etc. at a quicker glance than a traditional LCD design, while reducing cost for those same reasons. The reduced accuracy of this display method is actually optimal, as the accuracy of the zinc-air cell has been shown by lab work as within approximately 2.5-5%. A numeric LCD might lead a technician to incorrectly interpret the reading. As far as cost, the current parts-list is closer to $20 which is around 96% cost reduction compared to the aforementioned $500 commercial device.

[1] - World Health Organization - Technical Specifications for Oxygen Concentrators. p.6 from https://apps.who.int/iris/bitstream/handle/10665/199326/9789241509886_eng.pdf
[2] - World Health Organization - Technical Specifications for Oxygen Concentrators. p.7 from https://apps.who.int/iris/bitstream/handle/10665/199326/9789241509886_eng.pdf
[3] - Anecdotes told to and told by our advisers during needs-finding trips to Tanzania
[4] - World Health Organization - Technical Specifications for Oxygen Concentrators. p.11-14 from https://apps.who.int/iris/bitstream/handle/10665/199326/9789241509886_eng.pdf
[5] - World Health Organization - EML 20e from https://apps.who.int/iris/bitstream/handle/10665/273826/EML-20-eng.pdf
[6] - World Health Organization - EMLc 6e from https://apps.who.int/iris/bitstream/handle/10665/273825/EMLc-6-eng.pdf

Required Performance Specifications

The device must be able to indicate the level of oxygen concentration that is being released from an oxygen concentrator. This would be a test to indicate the effectiveness of an oxygen concentrator device and if it is meeting the clinical level of oxygen needed which is 82% pure oxygen.[1] The device involves using zinc-air batteries as a sensor in conjunction with a basic microcontroller (powered by a separate 9V battery) for interpretation. Zinc-air batteries exhibit changes in electrical characteristics according to the oxygen concentration surrounding it. The zinc-air batteries work by using the oxygen in the surrounding air as the cell's cathode[2] (which enters the electrochemical cell through tiny breather holes on the negative face). Our team was able to demonstrate that the current produced by the battery is related to the concentration of oxygen, and that the concentration can be measured from the amount of current being outputted.[3] The device must be able to incorporate the zinc-air battery into its design and indicate to the user the concentration of oxygen that is determined through current.

The device must also be easy to read and use. Use of LED levels would allow technicians to easily identify if a particular concentrator is in need of service and create a simple interface for technicians to use. The LEDs should be able to indicate the amount of service needed as well. If the oxygen concentrator needs to be replaced or complete service, or if the filters just need to be replace or cleaned. The device must also be inexpensive and relatively simple to use. The goal of our project was to develop an inexpensive concentration tester that would be affordable in low resource areas. Materials will be chosen based on cost and effectiveness. The device should be able to be easily reproducible, and the materials should be able to be easily purchased or obtained.

[1] - World Health Organization - Technical Specifications for Oxygen Concentrators. p.11-14 from https://apps.who.int/iris/bitstream/handle/10665/199326/9789241509886_eng.pdf

[2] - US Patent US9252616B2 - last accessed Feb 2019 from https://patents.google.com/patent/US9252616B2

[3] - See Appendix for Figure 2: Concentration-Current Results

Implementation of Prototype

The device uses a zinc-air battery as a sensor in conjunction with a basic microcontroller for interpretation. We used an i2c current sensor and an Arduino-compatible microcontroller, and wrote a simple program to store the initial short circuit current and the short circuit current after 5 minutes of exposure to the concentrator output.[1] The circuit then compares the two currents, and decides whether to light a green LED (>82%), a yellow LED (between 30% and 82%), or a red LED (<30%), which respectively means clinical level concentration, significantly concentrated but not clinical level, and not significantly concentrated.

In order to demonstrate that zinc-air batteries are effective as electrochemical cells, the team fabricated an air containment device with two inlet check valves used to let in concentrated oxygen and compressed air, with a third valve used as a bleeder to prevent pressure buildup.[2] A zinc-air battery was then connected to wires, placed inside the containment, and then closed off with a commercial oxygen sensor (a Vernier GDX-O2) with the wires leading out of the containment. The battery was measured for open circuit voltage and short circuit current. It was found that the voltage increased approximately 20 mV and the current increased 80% (the values were more variable but the percentage always similar). The voltage changes too little to be detectable by most microcontrollers (MCU), so an external current sensor is used in the device.

Our prototype was built using a breadboard, and an ATtiny84 microcontroller because it is small and Arduino compatible. The MCU interfaces with an INA219 current sensor. The current sensor measures the short-circuit current output of the zinc-air battery, and the MCU compares this to an initial reading.[3] If the readings show that the measured air is within 10% of regular air a red LED lights up, if it is 85% oxygen concentration it lights a green LED instead, and if it is between the two a yellow LED lights up. A blue LED was also added to tell the user if the device is on or ready to read the concentration. The prototype also incorporates a LM7805 voltage regulator and reset and input buttons. [4]

The user of the device would connect the air containment device to the oxygen concentrator, and then turn on the device. The user would simply push the input button, waiting for the blue LED to stop flashing, and then a second LED would turn on the color of which depends on the oxygen concentration, letting the user know what the status of the concentration device is then the user can push the reset button to start over.

The next step to designing our device is developing a PCB design. This is currently in progress and would make the device simpler to handle and use. This is part of our overarching goal of designing the device to be used as an educational EWH kit.

[1] - See Appendix for Figure 3: Code Block Diagram
[2] - See Appendix for Figure 4: Air Containment Device Testing
[3] - See Appendix for Figure 5: Prototype
[4] - See Appendix for Figure 6: Prototype Schematic

Proof of Performance

A variety of measurements were made for the electrical properties of zinc-air batteries under different levels of oxygen concentration. Specifically, open circuit voltage, current across a 5 milliohm shunt resistor load (the resistor voltage was amplified with an op-amp and used to calculate the current), and how both are affected by the time the battery is exposed. In order to contain the gas, a small Nalgene bottle was drilled with two holes and two check valves were used (one as an inlet and the other as an outlet) to allow controlled gas to be input while preventing pressure buildup. The top of the bottle was replaced by a commercial oxygen sensor with wires running to a battery holder between the bottle's neck and the sensor. This allows simultaneously measuring the actual oxygen percentage while also measuring the battery properties. In order to look for trends, each measurement was preceded by allowing a brand new battery to sit in regular air for 5 minutes (as is recommended by manufacturers before using them) then measuring that specific battery's base voltage or shunt current. From there, measurements were compared to the base.

All of the measurements taken seemed to stop changing after the battery had been exposed for 10 minutes, so all of the following observations use that same 10 minute wait. The calculated current across a very low resistance shunt shows a clear trend that concentrations above 82% are roughly 1.75 to 1.8 times that of the equivalent current from a battery in regular air. Similarly, open circuit voltages increase by roughly 20 millivolts when exposed to 82% oxygen concentration and above.[1] It is possible to compare the electrical properties of a zinc-air battery in highly concentrated oxygen to its own baseline electrical properties and use the change in order to calculate the percentage of oxygen in the air. This is significant as it verifies that zinc-air batteries can be used as the electrochemical cell in a low resource oxygen level analyzer, especially allowing the potential use of prebuilt millivolt sensors for microcontrollers. These tests should be done again with more sensitive instruments such as the mentioned millivolt sensors in order to further narrow down the trends.

Currently there are existing commercially available concentration sensors however these are generally expensive, we were able to produce our prototype for about $20 US, making it substantially cheaper.[2] There have been other attempts at producing a low-cost concentration sensor, however they use a comparator. Our team decided against using a comparator like past projects have, because of problems associated that we wanted to avoid. One of these was that the comparator uses a fixed reference voltage to compare to and would have used ADC and register combo to store readings, but this can't be expanded to increase accuracy.

[1] - See Appendix for Figure 2: Concentration-Current Results
[2] - See Appendix for Figure 7: Bill of Materials

Business Plan for Manufacture and Distribution of the Technology

The course of action for getting this product to market is to make it into a soldering kit that can be used by teachers and leaders of youth organizations for teaching their students or members basic soldering and electronics skills. This would be possible through a partnership with the soldering kit branch of EWH, as has been discussed already with Ben Fleischmann.

In its current implementation, the components for the device cost around $20 US using parts available through Newark (EWH's most used major supplier) and Digi-Key (a secondary major supplier with experience in bulk supplying). Factoring in a bulk discount for a small batch (between 50 and 100 pieces per part) of approximately 15%, the cost of manufacturing a single device would end up being less than the $20 our team paid. EWH sells the kits at a unit price of $65 and for EWH chapters and educators at $45 per unit, meaning there would be an estimated maximum profit of $25-45 per unit. The kit would be used around the world to teach engineering and global health concepts. After an organization or class builds the kit they can return the kit to EWH, and they distribute the kits to education programs around the world. Our oxygen concentration testing kit could be used to teach basic engineering concepts as well as filtration, device testing, calibration and the physics behind the zinc-air sensor.

Certain low-resource areas of the world depend on local on-site oxygen concentrators. As a result of the lack of resources, the equipment is often neglected, and almost always used past its rated lifetime. One such area is in the poorer sections of Eastern Africa, where the hot, slightly humid climate further shortens the lifetime of oxygen concentrators. In these areas, hospitals really on trained electrical technicians to repair and monitor hospital equipment. These technicians are trained in engineering programs that teach them electrical engineering basics so that they can repair needed equipment. Distribution of the concentration sensor kit that we developed would help support these programs as well as educate future technicians about oxygen concentration devices and how they should be monitored and repaired. These programs could also use the kits to develop devices that can check the concentration levels and improve the welfare of the patients in their hospitals.

To conclude, our team plans on the manufacture and distribution of the oxygen concentration sensor to be as an EWH kit. We plan on continuing to collaborate with Ben Fleischmann and EWH to finish the design of the PCB and kit, and hope that by distribution to low resource countries, the kit will be advantageous to the education of future technicians.

Appendix

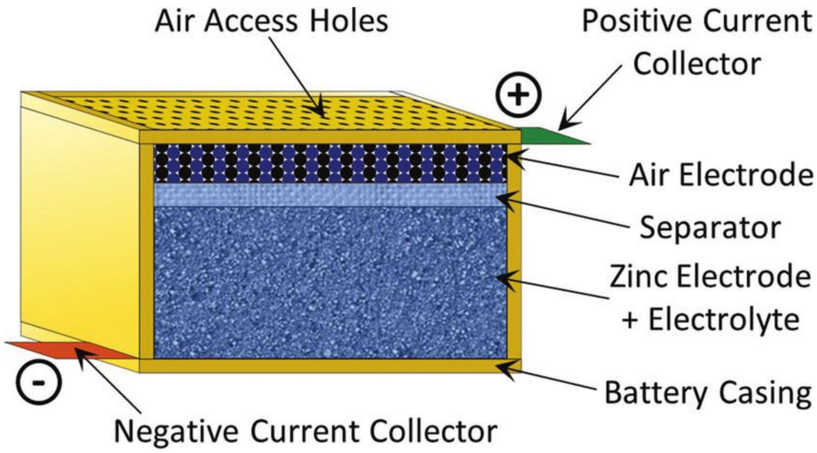

Figure 1. Zinc-Air Battery Diagram. Taken from: Fu, J., Cano, Z. P., Park, M. G., Yu, A., Fowler, M., & Chen, Z. (2016). Electrically Rechargeable Zinc-Air Batteries: Progress, Challenges, and Perspectives. *Advanced Materials*,*29*(7), 1604685. doi:10.1002/adma.201604685

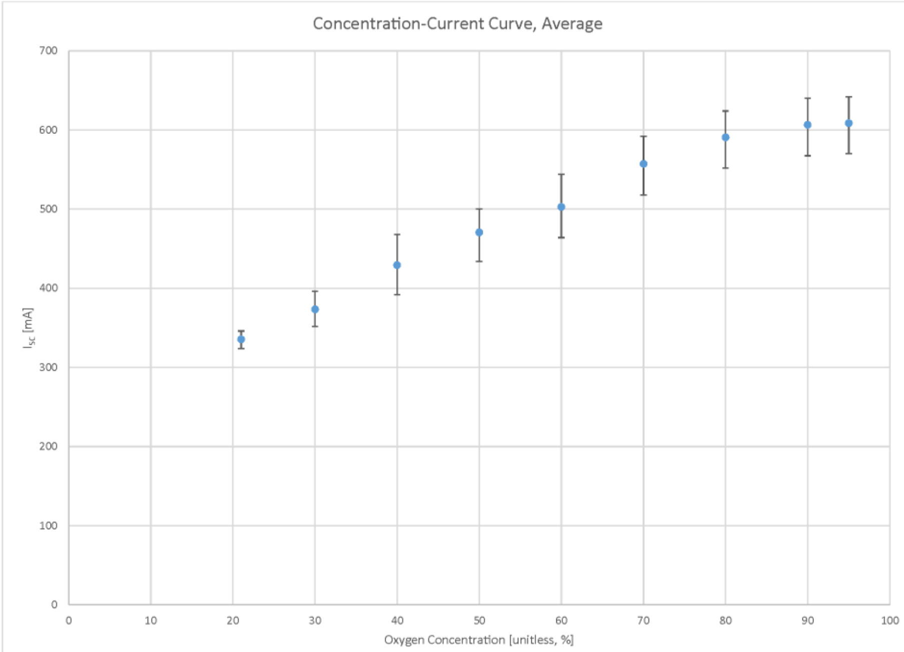

Figure 2. Concentration-Current results collected in lab during oxygen concentration in relation to current output testing.

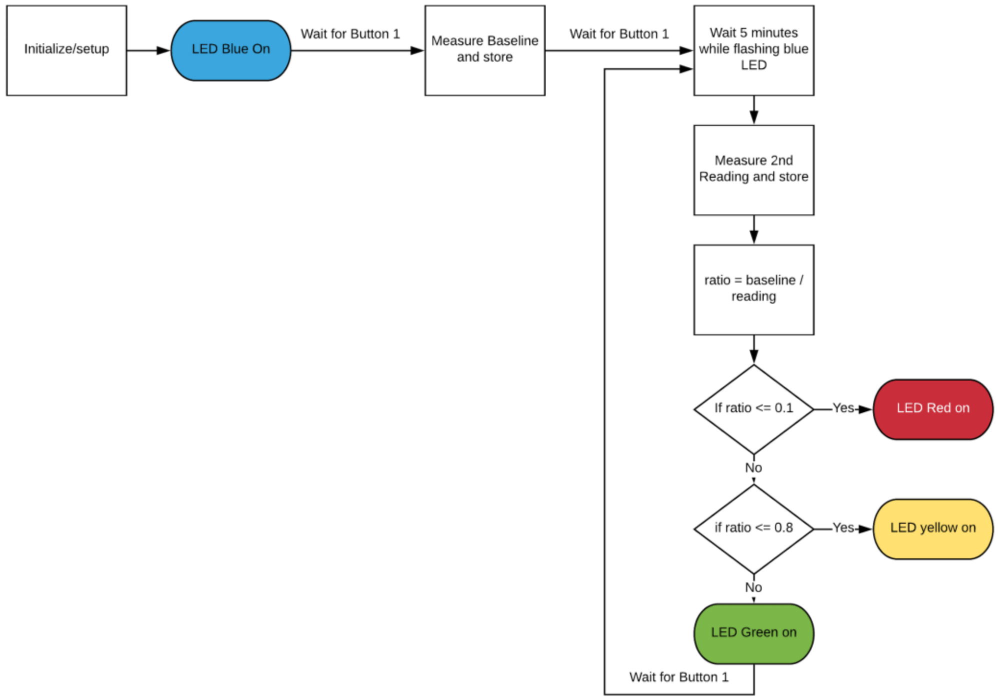

Figure 3. Code Block Diagram for Microcontroller.

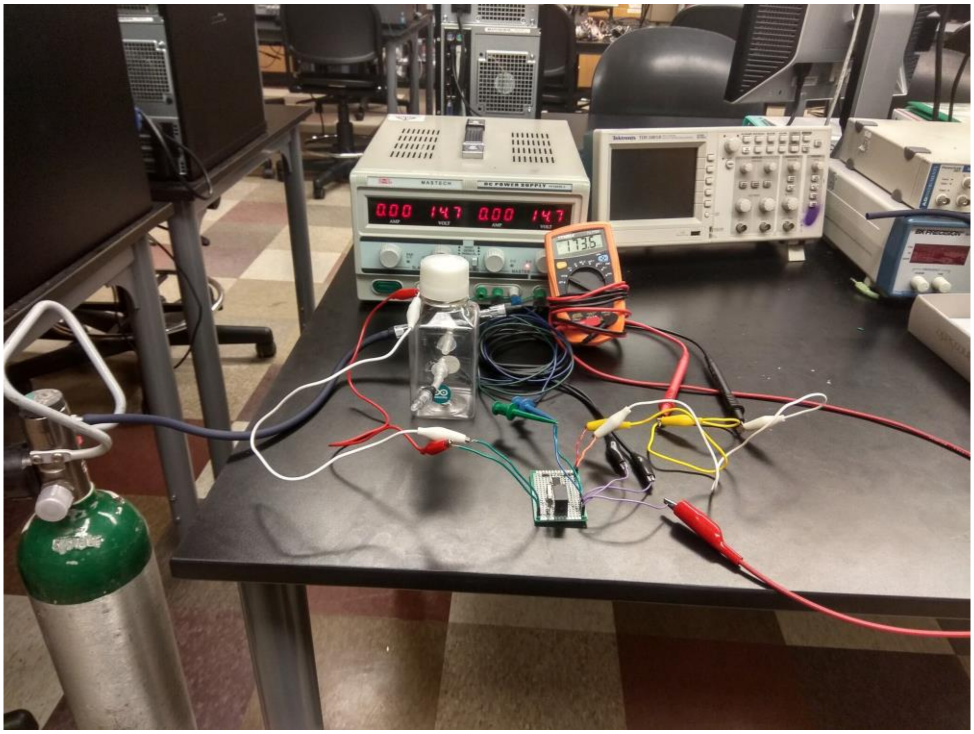

Figure 4. Air Containment Device Testing to see if current-oxygen concentration relationship can be reproduced.

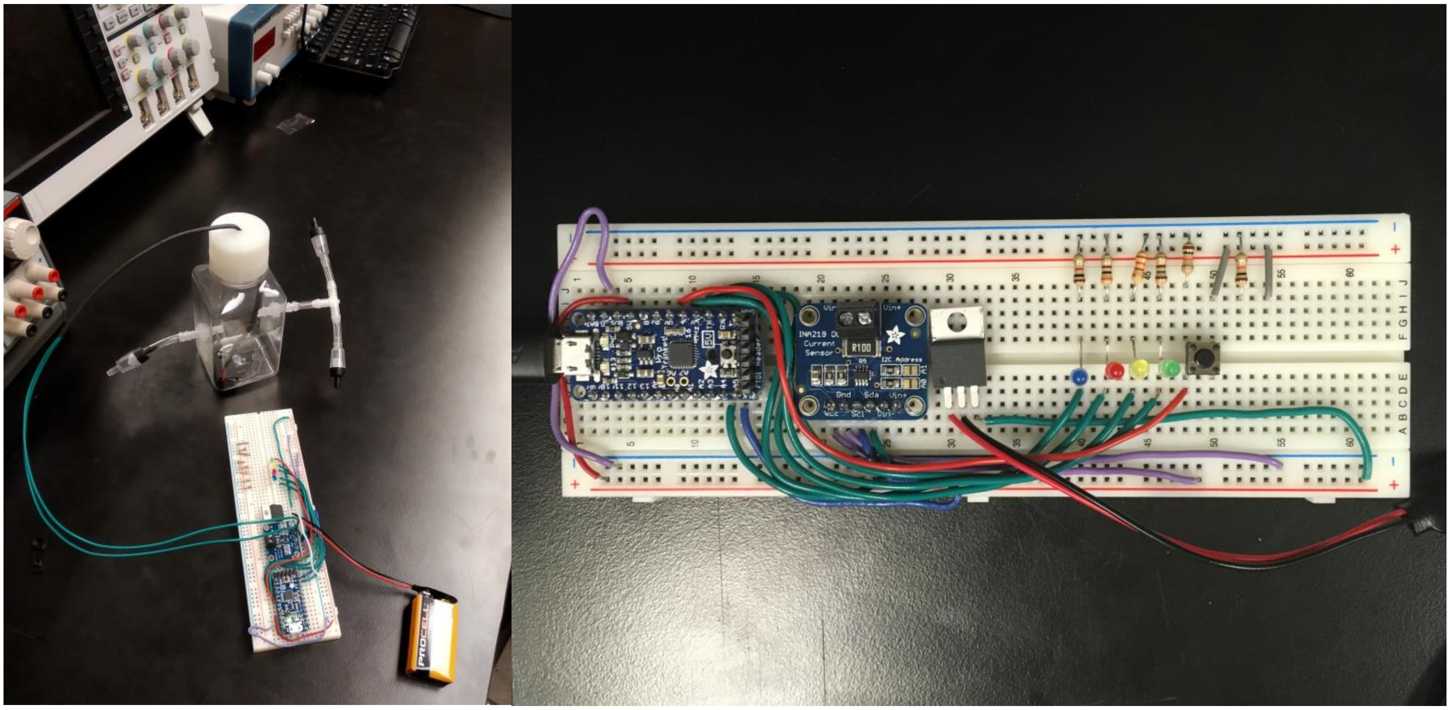

Figure 5. Complete Prototype and Zoomed in Circuit Board.

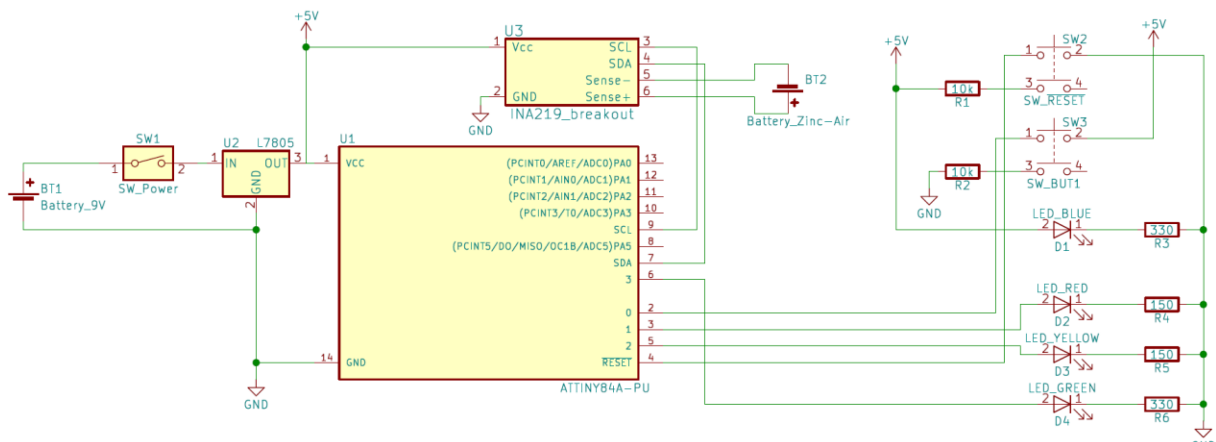

Figure 6. Schematic for Prototype Circuit Board

Subsection	Diagram Label	Quantity	Part	Description	Price each @1	Cost	Price each @25
Microcontroller	U1	1	ATTiny84A-PU	8bit microcontroller	1.19	1.19	1.09
	U3	1	INA219 Breakout	Adafruit Current Sensor, I2c	9.95	9.95	8.96
Power	BT1	1	Keystone 232	9V battery contacts	0.74	0.74	0.693
	U2	1	LM7805CT	5V output, input 7-20V	0.95	0.95	0.805
	K1	1	Relay	5v Relay, 6A switch	1.14	1.14	
	SW1	1	On/Off switch	Low Power DIP switch			
User Interface	D1	1	VCC Blue LED	5mm, 20mA, 3.5V, 470nm	0.45	0.45	0.356
	D3	1	VCC Yellow LED	5mm, 10mA, 2.1V, 585nm	0.42	0.42	0.306
	D4	1	VCC Green LED	5mm, 10mA, 2.1V, 572nm	0.42	0.42	0.306
	D2	1	VCC Red LED	5mm, 10mA, 2V, 630nm	0.42	0.42	0.306
	R3	1	150Ω 1/4 W, ±5%	Resistors for blue LED (@ 1/2 current)	0.088	0.088	0.055
	R4, R5, R6	3	620Ω 1/4 W, ±5%	Resistors for r,g,y LEDs (@ 1/2 current)	0.067	0.201	0.036
	R1, R2	2	10kΩ 1/4 W, ±5%	Pull up resistor for switches	Total	15.969	
	SW2, SW3	2	Interface Buttons	Low Power Momentary button			

Figure 7. Bill of Materials for Prototype (Without cost of Breadboard [$5], which will be replaced by PCB [$4])