Halo: A Personal IoT Air Monitor

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***Abstract*—Urban air pollution leads to widespread respiratory illness and millions of deaths annually. PM2.5, which refers to particulate matter with a diameter less than 2.5 μm, is the product of many common combustion reactions and poses a particularly serious health risk. The small size of the particle allows it to penetrate deep into the lungs and enter the bloodstream. Due to the highly localized nature of air pollution, and to enable individuals and institutions to monitor their real-time exposure to PM2.5 easily, we designed Halo, an air quality monitor costing less than $100. Halo, powered by solar energy, measures reflected IR light to determine the particulate concentration in the air, and it uses Bluetooth Low Energy (BLE) to communicate pollution levels to a users phone. From the phone, users can examine personal air quality levels or view aggregated data from multiple devices on a crowd-sourced pollution map. Field test results at Santa Clara University and in a Santa Clara County elementary school demonstrate that Halo can accurately track and measure personal air quality.**

***Index Terms*—Air Pollution; Mobility; PM2.5; Healthcare; Wireless; BLE**

I. Introduction

Air pollution causes irreparable damage to the health of human beings and harms our environment, yet many people are not aware of the sources of pollution in their everyday surroundings. According to the World Health Organization, polluted air contributes to one in eight deaths worldwide [1], and 92% of the worlds population lives in places where air pollution exceeds safe limits [2]. On top of this, outdoor air pollution has increased 8% in the last 5 years [3].

Of great concern is PM2.5, particulate matter less than 2.5 micrometers in diameter. These tiny particles are created in combustion reactions. PM2.5 particles are extremely light, so they stay in the air for an extended period of time. They penetrate deep into the lungs and bloodstream, which can result in disastrous health effects after long-term exposure [4]. According to the Journal of the American Medical Association, a buildup of PM 2.5 can lead to heart-attacks, strokes, and is directly associated with an increased risk for cardiopulmonary and lung cancer mortality [5].

PM2.5 is also extremely localized. It not only varies from city to city, but also from street to street and room to room. Simply knowing the air quality of a city is not enough to give an individual a true picture of their air quality. For example, driving down crowded city streets during rush hour can introduce individuals to a high level of PM2.5 [6]. Even cooking in a kitchen without proper ventilation can increase the number of hazardous particles in the air [7]. It is difficult for individuals to truly know if they are breathing in clean air without constantly knowing their localized PM2.5 level.

TABLE I
Current Market Air Quality Monitors

	Aerotrack [8]	Uhoo[9]	Speck 2.0 [10]	Flow [11]
Cost	$2380	$299	$199	$199
Particles Measured	0.5μm 1.0μm 2.0μm 2.5μm	2.5μm, VOC Ozone Carbon monoxide	2.5μm	2.5μm, 10μm VOC Nitrogen dioxide
Portable	Yes	No	No	Yes

A. Current Market Solutions

Table I offers a comparison between four air quality monitors to illustrate the general functionality of devices on currently on the market.

Over the last few years, researchers have conducted considerable work on the effects of poor air quality and how to create devices that can accurately measure air quality; however, there is still a minimal number of air quality devices on the market today, and most are limited in scope, cost, and longevity. Of the tools that do exist, the majority of these devices are stationary and meant for home use or research devices that are very accurate but not intended for an everyday user. There is one new device, Flow by Plume, that is portable, which enables users to track their air quality as they go about daily activities. While Flow offers the critical feature of portability, it costs $200, which makes it unaffordable to many who would need it.

The air quality monitors on the market today are lacking a few essential qualities. Besides research-grade devices and Flow, most air quality monitors are not portable, which limits their usage. As described earlier, air quality is very localized, so measuring the air quality in one room is not enough to provide individuals with an accurate picture of their air quality. Another key element missing is affordability. Almost all of the devices on the market are over $200, which limits their audience. All people deserve to know the quality of the air they are breathing regardless of their economic status.

B. Use Cases

From our research we realized that air pollution is a immense problem all around the world, and knew that we were not going to be able to help everyone facing this issue. We decided to narrow our users to three categories. We determined these categories to be personal use, use in schools, and use by firefighters.

1) Personal: After researching the various current market air quality monitors, we found that most of them were expensive and not portable. We determined that air quality is such a prevalent issue, there needed to be a low-cost, air quality monitor that could reach a wider audience than many of the current air quality monitors. We also wanted to create a portable device, so that users could track their exposure to air pollutants throughout the day instead of use in one room in their house.

2) Schools: Inner-city schools often experience higher levels of air pollution due to their proximity to highway and city traffic pollution. This is particularly troubling because youth are especially susceptible to developing asthma from extended exposure to air pollution. We met with Dr. Iris Stewart-Frey, from the Santa Clara University Environmental Studies department, who is doing research to measure the air quality at schools in San Jose. She expressed that a stationary air quality device that could be permanently placed in these schools would be helpful to her research.

3) Firefighters: Sean Lanthier, a firefighter we met through the Frugal Innovation Hub, told us that firefighters experience a much higher risk of getting cancer due to their exposure to air pollutants. He also told us that firefighters actually experience the most exposure to air pollutants after the fire is out. They will take their masks off, assuming they are safe, but the air is still swarming with hazardous particles. Firefighters could use a personal air quality monitor that could alert them to when it is safe and when it is unsafe to take off their masks.

C. Contribution

Due to the prevalence and urgency of air pollution issues, there needs to be a low-cost, portable air quality monitor available to a broader audience than current solutions. To increase awareness and access to air pollution information, we propose such a device, called *Halo*. A 500 mW solar panel and 500 mAh Lithium-Ion battery power halo to handle 150 mW peak power consumption and operate continuously for over 24 hours without power input. The device is small enough to be clipped to a backpack or bag for easy portability, and it can be used in personal or public settings. Using an IR emitter and detector pair, Halo measures the reflected IR light to determine the particulate concentration in the air, and it uses Bluetooth Low Energy (BLE) to communicate these values to a users phone. From the phone, data can be time-stamped, stored in a cloud database, and displayed in an app for easy monitoring of exposure and pollution trends. Additionally, the cloud database allows for the aggregation of data from multiple devices to create crowd-sourced pollution maps.

Halo is meant to draw awareness to the issue of air quality and enable healthy decisions in both the personal and public realm. On a personal level, users can know how to plan their outdoor activities when the air quality is excellent, open a window while cooking if the room has become smoky, or move out of a city where the air quality is consistently poor. Governments and citizens will have access to aggregate information that can be used to implement policies to protect the health of the community. Schools will be able to safeguard children, as children are more sensitive to the health effects of poor air quality. Often, inner-city schools are close to freeways, which can present serious pollution risks for the students. In this case, Halo can be stationed in the school, where it will continuously monitor, track, and display the air quality, allowing schools to take appropriate action to protect student health.

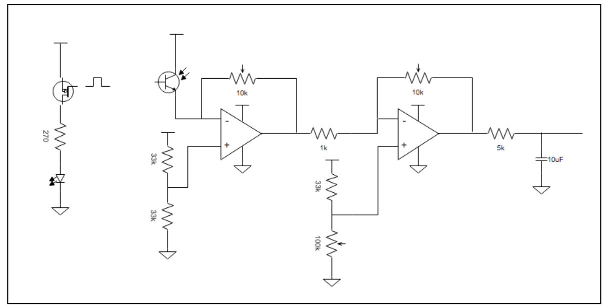

Fig. 1. Schematic of the analog front-end for the PM2.5 sensor.

In the subsequent sections of this paper, we detail the design and implementation of the air quality monitoring device and visualization platform (Section II), present lab and field testing results (Section III), examine device impact (Section IV) outline future work to improve the device and platform (Section V), and then summarize and conclude the paper (Section VI).

II. Design and Implementation

The final device consists of four interacting modules. The first of these is the PM2.5 sensor, which includes the optical detection circuitry as well as preliminary amplification and filtering. From there, the second module handles data acquisition and transmission (DAT), using a microcontroller to manage the sensors, perform digital filtering, and broadcast collected data to a user's device. The third module consists of the solar panel, boost converter, battery, and a regulator used to harvest energy and power the first two modules. The data visualization and user interaction, handled through the web and mobile applications, makes up the fourth and final module. The following sections go into detail on the design and implementation specifics for each module.

A. PM2.5 Sensor

Due to its ubiquity and danger as a pollutant, PM2.5 is one of the best indicators of air quality. It is also one of the easiest ways to measure air quality because other hazardous pollutants like volatile organic compounds (VOCs) and carbon monoxide require electrochemical detection methods. Despite the simple optical mechanisms, PM2.5 sensors on the market are either expensive, inaccurate, or are power hungry, which motivated the custom design for this device.

After looking at several reference designs and on-the-market solutions, we settled on an optical solution that uses an IR emitter and detector pair to detect the light reflected by particulates in the air. The emitter and detector are placed in a dark enclosure, with the detector outside of the direct path of the emitter. In this way, the detector picks up on the light reflected by PM2.5, and the intensity of light measured by the IR detector correlates to the concentration of particulates in the air.

The usage of IR light with a wavelength of 940 nm is intentional, since visible wavelengths will more readily scatter off of atmospheric water molecules. Since this application requires sensitivity rather than speed, IR detection is accomplished with a phototransistor rather than a photoresistor or a photodiode.

Fig. 1 illustrates the analog front end used to interface with the sensor. To generate the output signal, the phototransistor is connected to a transimpedance amplifier, then a secondary amplifier that increases gain and removes any offset caused by additional scattering of light within the enclosure. To eliminate 60 Hz noise and smooth the output, a passive RC filter with a 20Hz cutoff frequency is placed out the output. The overall simplicity of the PM2.5 sensor design helps to ensure that it is inexpensive and low-power, which are critical for a personal, self-powered device like Halo.

After the design of the sensor was finalized, a printed circuit board was also designed and fabricated, improving consistency and reducing the footprint of the overall device.

B. Data Acquisition and Transmission

In order to interface with sensors, perform processing and filtering on the acquired data, and send the data to a user's mobile device, a Texas Instruments SimpleLink Launchpad with a CC2640R2F microprocessor is used [13]. The main criteria for selecting this board are its low power consumption (61 μA/MHz active current, 100 nA shutdown current), high-resolution ADC (12 bits), and built-in module for Bluetooth Low Energy (BLE). Respectively, these features allow the device to run continuously on harvested energy, make accurate samples of air quality, and communicate sampled data to a user's mobile phone.

The software to implement device functionality centers around a main thread that manages the BLE connection [12] to a mobile device. This thread maintains the connection and handles connection events. ”Read” events, when the phone attempts to read a new value, spawn a secondary thread that samples the sensors. The ADC takes 10 samples from the PM2.5 sensor, then outliers are removed and the remaining samples are averaged. For added digital filtering, a two-period weighted moving average is computed to determine the final sampled value. Then, the controller reads the Si7021 [14] temperature and humidity sensor via I2C, and the humidity and PM2.5 values are used to compute a value corresponding to the Air Quality Index (AQI), an air quality scale developed by WHO [15]. Once all of these operations are performed, Bluetooth characteristics for PM2.5, humidity, and temperature are updated, allowing the connected mobile device to see the latest readings.

C. Energy Harvesting

A major criteria for Halo is to provide a device powered by energy harvested from renewable sources. Not only does this keep with the environmental motivations of the project, but it also improves device usability by eliminating the need to replace a battery or plug the device into a wall outlet periodically.

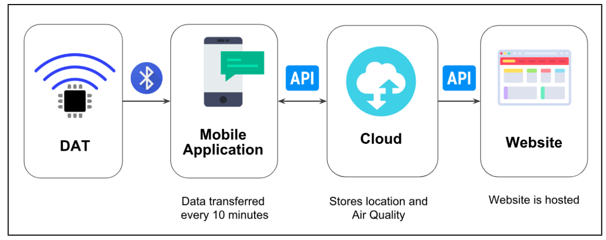

Fig. 2. An overview of data transfer mechanism.

Many sources for energy harvesting were considered, including solar, RF, and vibrations. Out of these, however, the only that offered a significant amount of power on the scale needed by the device is solar. The final prototype used a 5 V, 500 mW solar panel connected to a TI BQ25505 boost power converter [16]. The boost converter charges a 500 mAh battery, which in turn connects to a TI TPS7A89 [17], a low-dropout (LDO) regulator that maintained the 3.3 V rail for the rest of the devices.

After verifying this prototype, a final design was made, including the layout for a printed circuit board. This final design incorporates a TI BQ27741 fuel gauge [18] to monitor the battery's state of charge. Incorporating all of this onto a PCB allows us to shrink its footprint and keep the form factor of the overall design as small and portable as possible.

D. Data Visualization: Web and Mobile App

The purpose of the iOS application and the website is to display the data collected in a simple and easy way for users to understand their own air quality and quickly take action based on the air quality around themselves. Since AQI is not a measurement that most people are accustomed to, the app uses colors and simple suggestions to convey the information.

The iOS application connects to the air quality monitor using BLE. Once the data is collected, the API (application program interface) is used to send the data from the phone to the cloud. The cloud is currently Adafruit IO, a free service with a well-documented API. The website then fetches the data from the cloud and uses it to populate and update the data on the website.

The iOS application provides an easy method of collecting data as well as a way for the users to understand the meaning of their air quality. Figure 2 graphically explains how the data is transferred throughout the system.

The iOS application is able to read the data from the TI board in real time. The color and AQI value update as the air quality changes, helping the users to visually understand the data. The final iOS application is shown in Figure 3.

The website features an aggregate map of the user data. Users are able to see their locations throughout the day and what the air quality was in those locations. The website also features a graph of the user's air quality throughout the day. The final website, shown in Figure 4, features a map and a graph.

Fig. 3. The iOS Application.

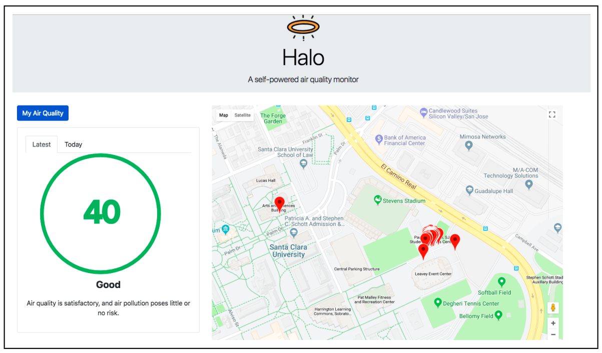

Fig. 4. The website developed.

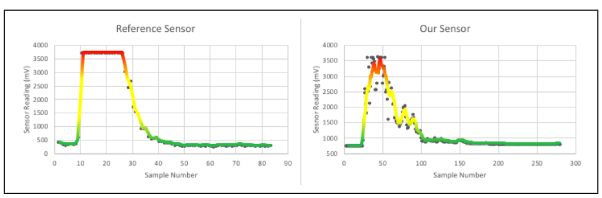

Fig. 5. Performance of the developed sensor in a lab setting.

III. Testing and Results

Initial prototyping and testing was performed in a laboratory environment, allowing the device to be tuned and modified until accurate. Once a final prototype was constructed, it was brought into the field to verify its performance in a real environment. The following section describes the testing performed on the sensor throughout each stage, and provides results illustrating the sensor's sensitivity.

A. Lab Testing

In order to determine the functionality of the designed PM2.5 sensor, it went through various tests to examine its performance. First, it was placed alongside a reference sensor in a chamber with clean air. Then, smoke was introduced to the chamber to mimic poor air quality. Fig. 5 shows the results.

Both the output of the designed sensor and the reference sensor show an increase in voltage when the smoke is introduced. As the smoke dissipates, both sensors gradually decrease back to their respective baselines. Our sensor shows a range similar to that of the reference sensor, swinging about 3V. This wide output range, coupled with the high-resolution ADC from the microcontroller, provides the sensitivity necessary to detect fine changes in particulate levels, which was then tested in the field.

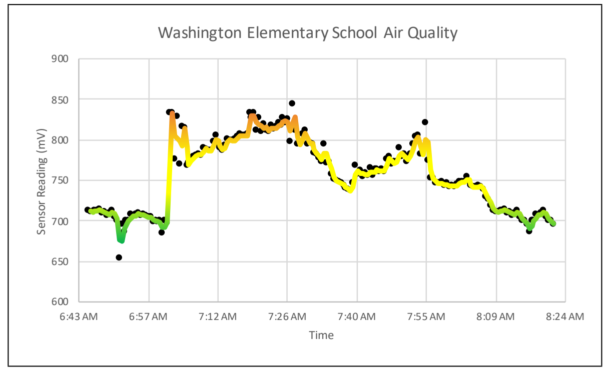

Fig. 6. The air quality measured at a local elementary school.

B. Field Testing

Several field tests were performed to determine how the proposed sensor would perform in an actual application. These included tests to look at the long-term stability of the sensor and its ability to pick up fine levels of changes in air quality in the environment.

One such field testing took place at Washington Elementary School, located in San Jose, CA. The sensor was tested alongside a research-grade air quality monitor used by the Santa Clara University Environmental Studies Department, and it showed the same trends and events as the research-grade sensor. Fig. 6 shows the Halo sensor's results from the test at the elementary school.

The black dots represent the actual test points, and the line represents the moving average of these points. The line is color coded to match the EPA's method of categorizing different levels of air quality. The test began in Santa Clara where the air was measured as relatively clean. The sudden spike in the graph at around 7:00am coincides with arrival at Washington Elementary School. The middle portion of the graph occurred while walking around the school campus, with the highest spike representing the location where students enter the school. This test illustrates the ability of the Halo sensor to detect fine changes in particulate levels, and placement at schools like Washington Elementary School can provide helpful health information for students and researchers.

To test the sensor's stability while operating over extended periods of time, it was placed in one outdoor location for two days. The results of this test are displayed in Fig. 7.

The test data aligns with expectations for the area. The air quality is generally good, with a peak AQI of just above 50 for a few hours during the morning rush hour. The data fluctuates as air quality changes, but is never unstable or stagnant, indicating that it is reacting to environmental changes.

In order to test the integration of the device with the website, the sensor was walked around the Santa Clara University campus for 45 minutes, logging air quality as it went. Fig. 9 illustrates the path taken around the campus, with flags for

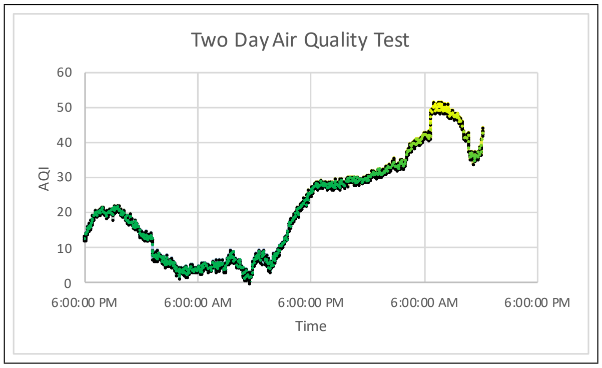

Fig. 7. Long-term air quality test.

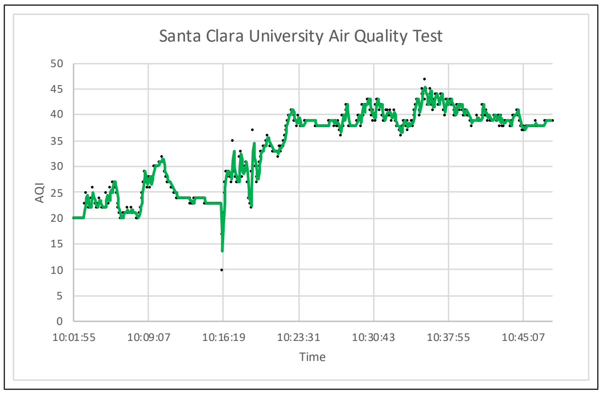

Fig. 8. Graph of air quality on SCU campus.

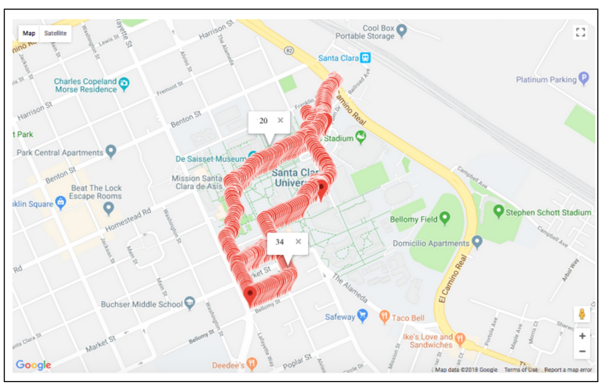

Fig. 9. Map of the data taken around SCU campus.

each air quality reading taken. Fig. 8 shows the air quality measured over the course of the walk.

Fig. 8 shows that overall, the air quality on campus was good. It did fluctuate slightly throughout the test, with an upward trend. This trend is likely the air quality getting worse overall rather than one specific location on campus having worse air quality.

Each of the red pins on Figure 9 represents a location were data was taken. Selecting the pin from the web interface will display the AQI value associated with that measurement. Two of these pins are highlighted in the figure to illustrate the functionality. By connecting the AQI value with a location, this feature helps the users to easily detect where area of poor air quality might be.

TABLE II
FINAL COST BREAKDOWN FOR SYSTEM PROTOTYPE

Item	Cost
Custom PCB	$33
Microcontroller	$35
Electrical Components	$32
Solar Panel	$5
Battery	$5
Casing	$5
Total	$129

C. *Failure Modes*

During device assembly, we recognized that inaccurate or inconsistent measurements are one significant failure mode that would impact the performance of *Halo*. Incorrect or inconsistent measurements caused by improper calibration and poor casing design could mislead users, lead to device distrust, and negatively influence decision making. There are a couple of ways to mitigate this potential failure mode. One method to decrease the failure modes potential is to calibrate and extensively test a *Halo* device before giving it to the user. Extensive testing can highlight any possible calibration problems. A second method would be to standardize casing design and assembly. By ensuring that casing is uniform, we can allow adequate space for device components and separate them from the sensor to prevent light from creeping in. Component spacing is crucial for elements like the battery. If not appropriately sized and placed this can increase casing size and reduce compactness. A reduction in compactness increases the likelihood that light enters the device and disrupts the measurement process.

IV. IMPACT

Air quality is an issue common to people throughout the world, disproportionately impacting impoverished and heavily populated areas. People often have no means of measuring their air quality, which leaves them unaware of a key health risk. Inspired by the Fairness or Justice Approach from the Markkula Center for Applied Ethics, we place major emphasis on designing an inexpensive system that can be used by people anywhere, regardless of their economic standing. In this way, our project can contribute to the public good, rather than a small audience with the economic means to buy an expensive sensor.

1) Final Cost: The final cost the prototype of our device is $120. The breakdown on the costs are shown in Table II. The areas that were more expensive than we expected them to be were the custom PCBs and the electrical components to use on the boards; however, if we were to manufacturer many of these devices, the costs per device in those two areas will go down significantly. This would put the final cost well under $99. This means that we achieved our goal of creating an air quality monitor that is much less expensive than current market solutions.

V. FUTURE WORK

While the final prototype represents a significant result, time and budget constraints limited the final feature set of the device. Given more time and more funding, many more features could be integrated into the device, improving its functionality, usability, and scalability.

Further shrinking the size of the device to a portable size would require us to move away from the bulky evaluation boards we are using for the energy harvesting system. During the project, we were unable to print the custom energy harvesting PCB due to time and budget constraints, and so the footprint remains large until we can order the new PCB. Integrating the energy harvesting, controller, and sensor circuitry onto a single PCB would help us to further shrink the form factor. Another constrain on our device size is the solar panel, which could be improved with alternatives such as flexible solar panels, which could wrap around the casing of the device, giving us more panel area, more power, and more flexibility in design.

We have additional pollution sensors for carbon monoxide (CO) and volatile organic compounds (VOC), but we have not yet integrated these sensors into our device. Expanding our pollution sensitivity beyond PM2.5 would help us to alert the users to more possible hazards in their environment, improving the overall effectiveness of the device.

As of now, our mobile application is being developed on an iPhone. We would like to deploy it to all potential users, which requires us to get a licence to push the app onto the Apple store. We will need to ensure compliance with Apple's policies and rules so that the application is approved to be placed on the App Store. We also want to port our app to Android to increase the number of potential users for the device.

A major goal for our project was the creation of a network of air quality sensors that could be aggregated into crowd-sourced pollution maps. Now that we have produced a functional sensor, we hope to replicate the design and distribute it to multiple users, allowing us to collect data on a much wider scale. Distributed sensors will allow us to create city-wide air pollution maps to pinpoint areas of very poor air quality and begin finding geographic or temporal trends. In addition, we plan to profile the energy consumption of the device carefully (using [19]) and reduce the cost of the energy harvesting system.

Finally, an important area of future work would be the development of machine learning algorithms to interpret the data from the air monitor network. From this data, we can predict air quality trends based on collected pollution and weather data. By synthesizing data from these various sources, we can better inform users and government entities how to mitigate the damage from air pollution.

A. Paths to Commercialization

A Halo device provides valuable information that can contribute to the overall health of individuals and communities, and the value it can provide would increase with widespread adoption. It is well-suited to take advantage of the growing markets for wearable health sensors and fitness trackers. The prices listed in this paper are for an initial prototype, and expanded manufacturing would help to dramatically drop the overall cost of the device, as the largest cost contributors were from PCB printing and evaluation kits. It is reasonable to expect a competitively priced product within the connected health market.

It is worth reiterating, however, that impoverished and underserved communities tend to bear the brunt of the damage from air pollution. At the estimated cost, it is not reasonable to expect the widespread adoption of such a device among these communities, but they will still be able to see the benefits from commercial adoption. The aggregate data collected by the sensors is available online to anyone, not just device users. Additionally, alternate versions of the device could be developed without the energy harvesting system. Instead, these devices could be charged by USB or replaceable batteries, decreasing the overall cost of the system. Finally, the Halo devices could be promoted to key advocates for these underserved communities. These advocates could use the information from a few devices to leverage government and community action and reduce the pollution-related health issues faced by at-risk communities.

VI. Conclusion

The objective of this project was to design and build a network of low cost, portable air quality monitors, powered by renewable energy that allowed users to visualize their personal air quality and the aggregate date of others. The final design includes a new low-power, low-cost PM2.5 sensor design, as well as a self-sustaining power system for that sensor. The device successfully implemented a two-way communication system to control and monitor the sensor, and it included a platform for aggregate air quality data visualization. Experimental results indicate that the final design is more than sensitive enough to provide users with the data they need to make informed decisions about their health. The *Halo* air quality monitor promises strong and beneficial development in the field of personal air quality monitoring, and in the broader emerging field of connected health sensors.

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