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Authors
Tian, Rundong
Dierk, Christine
Myers, Christopher
et al.

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MyPart:
Personal, Portable, Accurate Airborne Particle Counting

Rundong Tian **Christine Dierk** **Christopher Myers** **Eric Paulos**
Electrical Engineering and Computer Sciences
University of California, Berkeley
{rutian, cdierk, chrismyers, paulos}@berkeley.edu

ABSTRACT

In 2012, air pollution in both cities and rural areas was estimated to have caused 3.7 million premature deaths, 88% of those in at-risk communities. The primary pollutant was small airborne particulate matter of 10 microns or less in diameter, which led to the development of cardiovascular and respiratory diseases. In response, we developed MyPart, the first personal, portable, and accurate particle sensor under $50 capable of distinguishing and counting differently sized particles. We demonstrate how MyPart offers substantial enhancements over most existing air particle sensors by simultaneously improving accessibility, flexibility, portability, and accuracy. We describe the evolution and implementation of the sensor design, demonstrate its performance across twenty everyday urban environments versus a calibrated instrument, and conduct a preliminary user study to report on the overall user experience of MyPart. We also present a novel smart-phone visualization interface and a series of simple form factor adaptations of our design.

ACM Classification Keywords

H.5.m. Information Interfaces and Presentation (e.g. HCI): Miscellaneous

Author Keywords

Citizen Science; Air Quality; Environmental Sensors; DIY.

INTRODUCTION

Airborne particles affect more people than any other pollutant, and by far the most health-damaging particles are those with a diameter of 10 microns or less (PM10). These particles can penetrate and lodge themselves deep inside the lungs, contributing to the development of cardiovascular and respiratory diseases including lung cancer [1, 2, 21], not to mention these pollutants' role in global climate change. In most countries, government environmental agencies (the EPA in the US) typically report concentrations of PM10 particles in terms of mass per cubic meter of air volume ($\mu g/m^3$), which maps into a more human readable Air Quality Index (AQI) value. However, these air quality measurements reported by the government (1) use expensive calibrated equipment, (2) operate at fixed locations, (3) are sparsely and strategically distributed for regulatory enforcement rather than situated to provide overall neighborhood coverage for human health, and (4) do not afford a personal experience in terms of data reporting, data collection, or device interaction.

Figure 1. The small wrist-worn MyPart sensor and optional accompanying smartphone visualization and data logging app.

While there are "air quality" sensors even less expensive than our MyPart system, many of them either attempt to "measure" a pollutant that is not the primary health concern, such as mixtures of various gasses (carbon monoxide or ozone), or they do not measure small particles accurately at all and simply report "dust".

As we move towards more personal and crowdsourced environmental monitoring systems, there are numerous HCI research questions - the sensor and hardware design, its usability, accuracy, form factor, expressiveness, visual legibility, interpretation, sharing, and acting on data, privacy, society and community engagement, and long term usage models. In this paper, we focus our contribution on the design of a novel, low-cost, accurate, usable air quality sensor that measures the most critical pollutant affecting human health and well being - airborne particles.

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Through an extensive engineering and HCI iterative design cycle, we have developed a system that for the first time satisfies four primary design equirements when compared to other air quality measurement systems - MyPart is more accessible due to its low cost which makes it available to a much wider demographic; more flexible due to its ease of fabrication and adaptation across a wide range of context specific forms factors (i.e. easily embedded into watches, strollers, carabiners, toys, bicycle attachments, etc); more accurate than any previous air quality system of similar cost; and smaller and more portable than comparable systems. There are air quality sensing systems that may satisfy some of these requirements, but none that satisfy all of these requirements simultaneously - low-cost, accurate, flexible design, and wearable, portable size.

Most often it is the accuracy that suffers. This is an extremely critical component of the overall design since by sacrificing accuracy, the overall reliability and usability of the data from such system is, at best, called into question and, at worst, unusable. In this paper we will demonstrate the novelty of our approach in engineering a solution that is comparable to air quality systems costing thousands of US dollars more than the $50 MyPart.

We address many of these issues in more detail later in the paper. As HCI practitioners, we were motivated to design a low-cost, accurate, portable, and personal particle counter whose design can be readily adapted into a range of form factors, including a small wrist worn device, in order to expand the design space. MyPart is the culmination of that effort (Figure 1). While accurate measurements are critical to our design, we wanted to develop a new mobile phone interface that would provide a compelling real-time visualization that invites curiosity into a deeper exploration of personally collected particle datasets.

In this paper we describe a range of prior work, outline our iterative design process, describe the technical components of our system, report accuracy measurements, explain our mobile interface, describe the results of a preliminary user study, and discuss alternative form factors for our system.

RELATED WORK

In this section, we provide an overview of other technologies that sense air quality and HCI work in air quality monitoring.

Consumer Air Quality Sensing Technologies

There are a number of different techniques for measuring air quality. In this section we detail each and highlight the tradeoffs across various designs.

Thermal Based Gas Sensors

Low-cost air quality sensing devices often consists of some form of gas sensor. These systems typically use a thermal conductivity based detector tuned to respond to carbon monoxide, ozone, nitrogen oxides, or other gases. However, these devices do a poor job of accurately measuring the actual gas concentrations due to sensor response selectivity and gas interaction problems with the sensor. Furthermore, these gas sensors are high-power due to their thermal heating requirements. Most importantly, these gas sensors do not measure airborne particles, the primary air pollutant in regards to human health [19].

Figure 2. Design iterations, from initial cardboard mock-up to current 3D printed wrist worn prototype. The large commercial Dylos & MetOne are shown for comparison.

Low Cost LED and Photodiode Based Sensors

For air quality monitoring of particles at the personal scale, one low-cost solution is LED infrared emitter/detector based sensors such as those produced by Sharp[1], Shinyei[2], and Samyoung[3]. The majority of air quality sensing products, startups, and personal devices also embed this form of sensor. These include the Air.Air![4], Speck [22], and Airbeam[5]. While infrared LED based sensors are inexpensive (typically $10- $30 US) and small (the Sharp sensor is 46.0 x 30.0 17.6 mm), they often give extremely unreliable readings, especially at lower particle concentrations [5]. Many of these systems were engineered to be incorporated into a feedback control circuit for air purifiers, not as general purpose air particle counters [6]. In addition, many of these low cost sensors rely on a heating element to generate flow, which puts strict limitations on the orientation of the sensor, response rate, and battery life when used in a mobile device.

Laser and Photodiode Based Sensors

A second class of consumer-level sensors are those that incorporate a laser, such as the Dylos Indoor Air Quality Monitor[7]($300 US) (Figure 2). While the Dylos performs well against standard commercial instruments [14], it is limited by its large, inflexible size (7 in x 4.5 in x 3 in), cost, user interface, and external computer requirements for data acquisition. More importantly, the Dylos is designed to operate indoors only, meaning it lacks the portability of our everyday mobile

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[1] www.sharpsme.com/optoelectronics/sensors/air-sensors/GP2Y1010AU0F

[2] http://www.sca-shinyei.com/particlesensor

[3] http://www.samyoungsnc.com/products/3%20Specification%20DSM501.pdf

[4] http://www.airair.info

[5] http://aircasting.org/

[6] Samyoung's own product literature lists air conditioners and air cleaners as the primary applications.

[7] http://www.dylosproducts.com

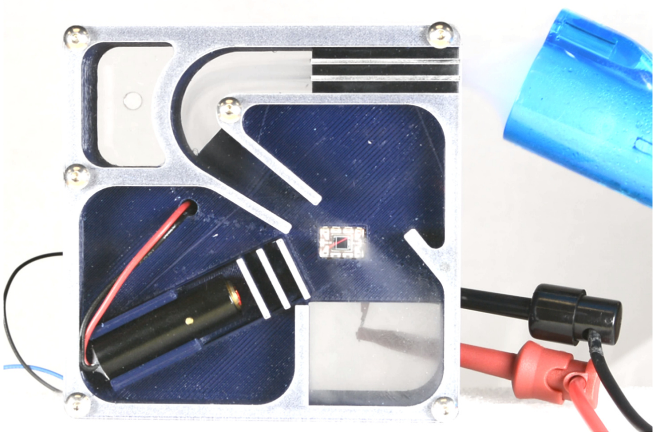

Figure 3. Smoke is injected into an earlier prototype to qualitatively examine the air flow over the photodiode.

Figure 4. MyPart configured as a wrist worn device (40x55x23mm) with LED particle count display illumniated.

devices, severely limiting its ability to truly be on-the-go with people. To emphasize the point, because both the LED/Laser and photodiode systems, by design, respond to light, they perform poorly outdoors since they suffer significantly from ambient light leakage. This restricts the context of their usability to indoors only - the Dylos product literature calls out this limitation directly by warning that it should "not be operated in direct sunlight or other bright light source as this could affect count accuracy".

HCI Research in Air Quality sensing

As environmental monitoring, in particular air quality, becomes more accessible through low-cost components, we have seen its adaption into many HCI and ubiquitous computing projects. It has been truly remarkable to see such a wide range of impressive research into personal air quality sensing across a wide range of contexts - cars [4, 6, 16], municipal vehicles [3, 8], bikes [15], balloons [11], clothing [10], and handheld devices [7, 12, 24] to name a few. Much of this research has made significant contributions towards understanding the design of such sensing tools for interpreting and sharing data, privacy, activism, community engagement, and long term usage models. Because many of these previous studies focused on these important research questions, there was less consideration given to the actual sensor selection, integration, and design. Most incorporated available, off-the-shelf hardware for measuring air quality into their system. As we pointed out earlier, many of these devices contain significant design problems that make them unsuitable for adaption into such HCI applications. In fact, this rich body of prior work has directly inspired us to design and evaluate MyPart. What if a new more accurate, affordable, accessible, low-cost flexible, portable design could be developed and shared with this community? How could such a system encourage a broader landscape of designs, form-factors, applications, and participation all while improving accuracy? MyPart is, in part, a starting point in this research conversation.

SYSTEM DESIGN AND IMPLEMENTATION

The design of the MyPart borrows elements from traditional laser based photodiode systems with several notable improvements: (1) engineered airflow to remove ambient light leakage while maintaining consistent airflow across the photodiode, (2) dense system integration of structural design and circuity to enable wrist worn form factor with ambient visualization, (3) integrated BLE transceiver for low-power networking with mobile devices, and (4) a mobile phone app for visualizing collected data.

In MyPart, a laser and photodiode are arranged orthogonally such that the focal point of the laser is located directly above the photodiode (Figure 5). Air is drawn through the system across the photodiode using a small, low-power, 3 volt, centrifugal fan. Particles in the air stream that intersect the path of the laser scatter light onto the photodiode, and the resulting voltage signal is amplified by an operational amplifier circuit and sampled by a micro-controller. The resulting waveform is analyzed for peaks, which correspond to particle detection. Our final system is able to identify and count particles of 2 different size ranges. The measured values are visualized through a scattered array of eight individually controlled LEDs embedded into the top of the sensor (Figure 4). The MyPart system also has an onboard temperature and humidity sensor to further improve particle readings under high humidity conditions.

As pointed out previously, our innovation is not the use of lasers to count particles. In fact, this technique is used in both high (MET-ONE HHPC-6 at $4,000 USD) and low (Dylos DC1100 at $300 USD) end systems. Rather, MyPart is a result of an iterative design process (Figure 2) and engineering efforts (described below) to lower the cost, reduce the overall size, and provide a flexible design platform for easy integration into other form factors - all while maintaining the overall accuracy of the system. We were particularly motivated to lower the cost in order to increase the accessibility of personal air quality monitoring for at-risk, low-income communities and developing regions where health concerns and air quality are most contentious and misrepresented. The final costs of parts for MyPart is under $50 US.

Mechanical Design: Air Flow and Ambient Light

The design of the airflow channel geometry is constrained by two main factors. First, the flow of air over the photodiode

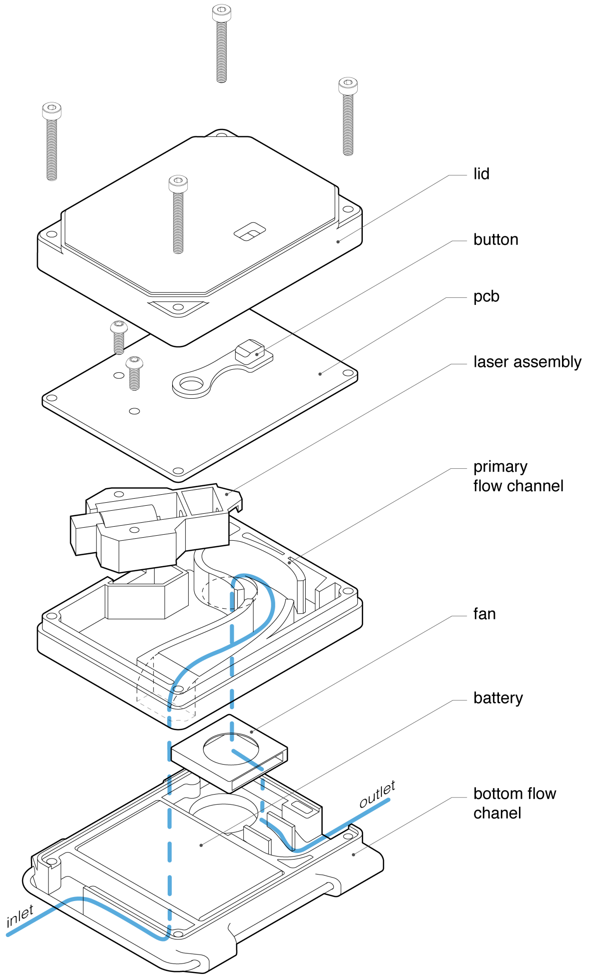

Figure 5. An exploded drawing of the MyPart Design detailing the airflow and laser placement.

must be constant and free of eddies and turbulence, characteristics which introduce unstable flow velocities and particle recirculation that decrease the responsiveness and accuracy of the sensor. Second, ambient light must be shielded from the photodiode such that changing light conditions do not affect the calibration of the sensor. These two criteria often impose conflicting design constraints. For example, a more complex flow geometry designed to reduce ambient light sensitivity can negatively affect the quality of the air flow, introducing eddies and turbulence. No existing consumer sensor has addressed both of these issues simultaneously. This is a significant limitation for air particle monitors if they are to be portable and functional across a wide range of environments where people go, including outdoors.

To maximize the ambient light rejection of our device, the air channels leading to and from the photodiode were designed with multiple turns that prevent ambient light from directly illuminating the photodiode (Figure 5). In addition, a centrifugal fan and baffles at the outlet were used to further discourage light from directly entering the system (Figure 5). Meanwhile, the air flow channel leading up to the sensor region is a gentle curve designed using cubic splines. At each bend, fillets were used to minimize the formation of turbulence at these transitions. A similar effect for reducing the amount of ambient light entering the system can be achieved by decreasing the cross-sectional size of the inlet and outlet. However, this method reduces the air flow rate and the responsiveness of the sensor since it samples less air per unit of time.

Because of the complex channel geometry, qualitative smoke tests were conducted after each major design revision (Figure 3). High speed videos were used to analyze and confirm the absence of undesirable air flow characteristics.

Counting and Sizing Particles

When light is scattered onto the photodiode by incoming particles, a current is induced in the photodiode which is then converted into a voltage through a high gain transimpedance (current to voltage) amplifier. This analog signal is then high-pass filtered, then low-pass filtered to reduce electrical noise as well as shape the characteristics of the pulse waveform. In particular, choosing a higher cutoff frequency for the high-pass filter decreased the pulse width seen by the analog-to-digital converter (ADC) which prevent successive pulses from overlapping and distorting the measured amplitude for each pulse. The rise time of the resulting pulses in our current configuration is approximately 50 microseconds.

The analog signal is sampled at 88kHz using an external 12-bit ADC driven by a low power system-on-a-chip with a microcontroller and Bluetooth transceiver (Nordic NRF51822). A simple thresholding algorithm is used to detect peaks of various amplitudes, and can be calculated in the time between successive ADC captures. Our algorithm is most similar to a hardware comparator with hysteresis and measures the number of times the thresholds are crossed. Though this algorithm is very simple, it yields good results that will be discussed later. More complex algorithms that consider the pulse width, or the maximum amplitude of the pulses can be designed to further increase sensor accuracy.

Electromechanical Design Evolution

The mechanical design of our sensor has evolved significantly (Figure 2), from initial laser cut prototype to our final 3D printed wrist watch form factor. We began with several laser cut designs for rapid fabrication and iteration speed. However, as the requirements for the flow channel were recognized, the complexity of the required flow channel necessitated the use of 3D printing. Our final mechanical enclosure is optimized to be easily 3D printed, as the overall geometry is partitioned in a way that eliminates overhangs. In addition, the consistent wall thickness and minimal undercuts throughout the entire design make it easily adaptable for injection molding.

The laser is mounted onto the PCB with a piece of 3D printed plastic that also has a series of apertures to prevent stray laser light from illuminating the photodiode (Figure 5). For optimal optical performance, the aperture should be metal to block the stray light entirely, and thin to minimize reflection at the inside diameter of the aperture. We used this method at first, and constructed apertures out of milled pieces of 0.005 inch thick steel. Though effective, this added an additional degree of complexity to the fabrication of our device. Ultimately, we found that comparable performance can be achieved by using successive thin pieces of plastic, which were then integrated into the component for fixturing the laser. More than one aperture is needed for plastic because the thin pieces become slightly transparent.

In earlier designs, we used off-the-shelf photodiodes with integrated transimpedance amplifiers, such as the TSL12 produced by AMS, and the OPT101 produced by Texas Instruments. Using these off the shelf sensors decreases the complexity of the electronics, as the high gain transimpedance amplifiers can be difficult to design and be sensitive to noise. However, the mechanical size of these sensors were not suitable for the small form factor we were pursuing and limited the geometry of the the flow channel, as well as the overall device. A device as small as the current version of the MyPart requires tight integration between the electronics and the mechanical enclosure, and the photodiode is the key interface between these two elements of the design. By using a low profile photodiode soldered directly to the PCB, various mechanical design constraints around the interface between the electronics and enclosure were loosened.

Because of the power limitations of a battery powered device, substantial effort was placed to reduce the power consumption of the device, especially in sleep mode. For example, to minimize digital noise affecting the high gain analog circuitry, two separate voltage regulators are used. Conveniently, the entire analog voltage regulator can then be shut down by the microcontroller when samples are not being taken. Cumulatively, these efforts reduce the power consumption in sleep mode to less than 100 micro-Amps.

Our most current design files, as well as a more detailed explanation of the design, is all available open source. These files can be found online at `http://hybrid-ecologies.org/projects/mypart`.

User Interaction Flow

The device is normally in a sleep mode, in which the microcontroller and other components in the circuits are programmed to be in a low power state. The device is configured to wake up from a button press, but can also be activated at a timed interval, or by any peripheral that can generate a hardware interrupt.

When the device wakes up from sleep mode, onboard LEDs, embedded within the top of the device flash and then fade to intimate to the user that an air sample is being taken (Figure 4). The micro-controller turns on all peripheral devices including the fan. After waiting 500ms for the airflow to stabilize, MyPart begins counting particles by size. As particles are counted, the onboard visualization is updated in real-time. Throughout the fifteen second sampling period, the visualization updates as more particle are counted. After the sampling period, the data is broadcast using Bluetooth, and is also displayed on the LEDs of the physical sensor itself (Figure 4). To conserve energy, the broadcast and LEDs stop after 10 seconds, after which the device returns to the sleep mode. However, the data can easily be logged and visualized on another device such as as mobile smartphone (Figure 6). In this configuration, the sampling period consumes an average of 75 mA. Using a 400 mAh LiPo battery, our sensor can conservatively take 250 readings before needing to be recharged. Our wristwatch form factor (Figure 1) uses this battery which gives very reasonable sensor coverage over a full day without the need for recharging.

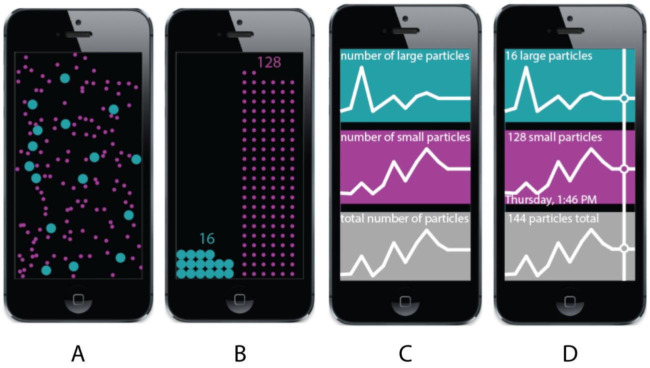

Figure 6. The MyPart smartphone application has an ambient animated particles view (A), stacked column view for visual comparisons (B), and a historical view (C) with numerical values revealed from user interaction with the data (D).

Visualizing Air Quality

While MyPart can operate standalone and log data, its usage is more persuasive and compelling when its data is experienced in real-time through a mobile phone interface. Using BLE, live particle count data is transmitted to an iOS application (Figure 6).

Building off a suite of inspirational related work on air quality visualization [9, 13, 18, 23], the MyPart smartphone interface was designed to support scaffolding a user into the data - from a compelling real-time visualization that invites curiosity, to a deeper exploration of the rich particle dataset with time and location patterns. The actual smartphone app design was intended to augment the overall experience of the MyPart system, not be the primary design contribution. Therefore, we focus on describing the design goals and final app design rather than the intermediate prototypes.

There were several initial design goals motivating the visual and interactive design of our smartphone app. First, it was important that users could access the real data from the sensor. We did not want to obscure or abstract the data in such a way that users would have difficulty visualizing the actual sensor data. At the same time, we felt that by offering exclusively numbers and charts, the users would become disengaged with the overall experience we desired. We wanted to deliver an experience with the data that would feel more alive, invite curiosity, and perhaps even feel playful as a means to draw in and retain user interest in the system. We also wanted our design to accommodate quick (1-2 second) engagements through a glanceable interface that would require little to no interaction with the phone. Next, we expected that exploring related contextual information such as time and location along with the MyPart data would be valuable in engaging users and helping them conduct their own sensemaking. Finally, it was important that there was some visual design language elements linking the smartphone app to the physical MyPart sensing hardware device.

We iterated through several prototype designs that each foreground various elements of our design goals. However, the challenge was to arrive at a smartphone app design that struck the proper balance across all of our design goals and was usable for eliciting feedback with users when operating the entire MyPart system. The final design we arrived at is composed of three screens: (1) an animated, ambient display that allows users to easily visualize the air quality, (2) a bar graph view that communicates precise particle counts and corresponding health related information, and (3) an interactive graph view that displays historical readings across time and location.

The initial screen of the application displays particle counts as colorful, animated circles that move and interact in a particle simulation system (Figure 6A). The two sizes of particles are distinguished by their color (blue/purple), size, and movement (fast/slow). Updates to this screen are deliberate, with particles slowly fading in and out such that the user is made aware of changing air quality conditions. This screen is unique in that it is factual, yet playfully aesthetic. In fact, we envision such a display as a compelling element in ambient situations such as a phone lock screen or smartwatch face since its is both easily glanceable and presents an abstract aesthetic visualization [20].

To explore the data more concretely, the user swipes down to access a bar graph view. From the ambient view, the individual particles quickly animate to form two stacked columns, allowing easy interpretation of the quantity of differently sized particles (Figure 6B). The precise count for each particle size is displayed at the top of the stack. When the user clicks on a particular stack of particles, more information is displayed: the size ranges for each particle category, common origins of such particles, and health concerns associated with the current air quality conditions.

A third view is provided when a user swipes up on either screen. This historical view (Figure 6C) displays past readings over time. On this screen, there are three separate graphs displaying three datasets for large particle counts, small particle counts, and total particle counts. This view is interactive - when the user touches any of the graphs, all three graphs are activated and the relevant particle count information is displayed (Figure 6D).

VALIDATION STUDIES

Throughout our design process, we knew that if the resulting particle counts reported by the sensor were inaccurate, we would not have a usable system. To really have impact, provide actionable data, and be convincing, our system would have to maintain a high degree of accuracy with regards to particle counts. This is a step that is often overlooked or at best partially addressed in most HCI air quality crowdsourcing studies. Our aim here was to be able to develop a system that would hopefully be used in further studies by ourselves, other researchers, and the general public and that in those deployments an improved level of accuracy would be provided.

Laboratory Calibration and Comparison Studies

In the analog signal from the amplified photodiode, the amplitude of the pulses correspond to the intensity of light seen by the photodiode. Though there are other factors at play, such as the location at which the particle crosses the laser beam and the optical properties of the particle, the amplitude of the pulses can be used as an approximate metric for the size of the particles detected.

As a first approximation for correlating the response of the analog circuitry to the size of particle detected, we expose our sensor to particles of known size ranges, such as smoke and household dust. The pulses in the raw analog signal are analyzed, and approximate cuttoffs for large and small particles are chosen. Though approximate, the cutoffs determined using this method resulted in very strong correlations against a calibrated instrument costing $4000 US. In future work, our sensor can be tested with particles of precisely known sizes, such as mono-dispersed polystyrene latex beads to further increase accuracy.

Real World Performance Studies

While laboratory and bench top studies are important to characterizing the response of our system, it is important that we study the performance of MyPart in real world everyday context of use. We conducted a validation study across a series of real-world indoor and outdoor locations to test our sensor with naturally occurring particles in various lighting conditions. For our reference monitor, we chose the Met-One HPPC-6 ($4000 US), a laser based optical detector similar in principle to our sensor. The Met-One HHPC-6 is a professional, industrial grade handheld particle counter that offers six particle counting channels (0.3, 0.5, 0.7, 1.0, 2.0, and 5.0 micron) with built-in relative humidity and temperature sensors. It is suitable for use in clean office settings as well as harsh industrial workplaces, construction and environmental sites, and other outdoor applications. The Met-One provides highly calibrated, independent, ground truth measurements of airborne particles to compare the performance accuracy of our MyPart system.

Our sensor was tested against the Met-One across these indoor and outdoor locations. Twenty locations were tested, and two consecutive data points were taken by each sensor at each location. Locations were chosen to adequately represent a broad range of everyday contexts. They included both indoor and outdoor locations such as parking lots, parks, bus stops, downtown urban areas, office workspaces, and indoor cafes to name a few.

We summed the total particle count on the Met-One from its 0.5, 0.7, and 1.0 micron channel measurements as “small particles”. Similarly we used the 2.0 micron and 5.0 micron count as “large particles”. We used these small and large sizes as comparison against the MyPart sensor’s small and large size particle counts. The results of this study are shown in Figure 7 and demonstrate high correlation in signals for both small ($r^2 = 0.96$) and large ($r^2 = 0.91$) particle counts. These results

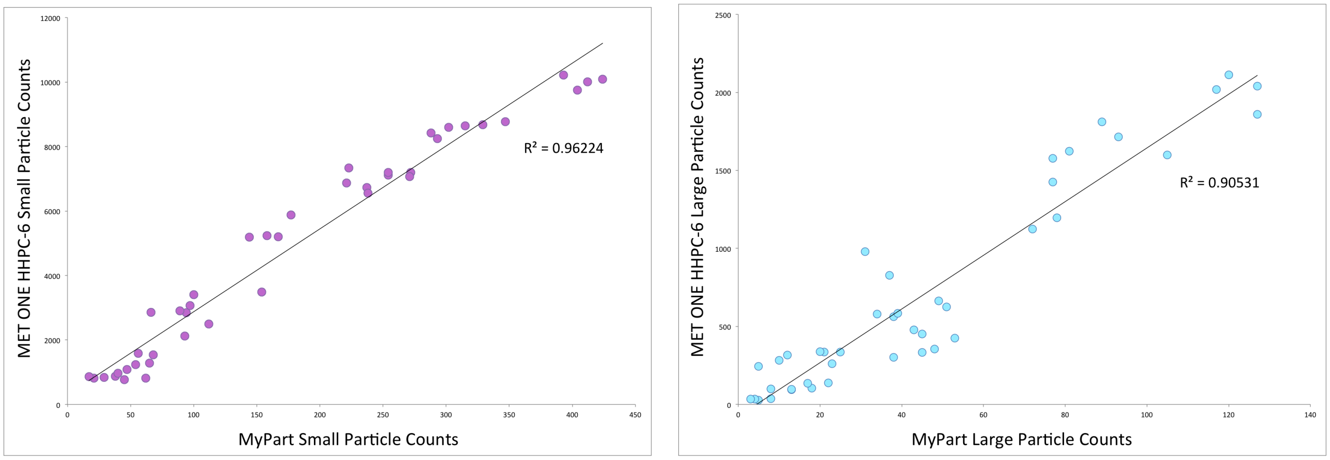

Figure 7. Graphs demonstrating the performance of MyPart ($50 US) in correlation with the calibrated Met-One HHPC6 ($4000 US).

demonstrate the sustained accuracy of the MyPart system in contexts outside of the laboratory setting and in everyday landscapes of typical expected usage.

Calibration to Air Quality Index

The Environmental Protection Agency in the United States reports air quality using an Air Quality Index (AQI) for PM2.5 and PM10. PM2.5 refers to airborne particles smaller than 2.5 micrometers (100 times thinner than a human hair) while PM10 refers to particles smaller than 10 micrometers in diameter, the smaller particles pose the greatest health risk to humans [19]. Environmental statistics for clean air (the AQI) is calculated from mass concentrations per volume using linear interpolation [1].

Since our system, as well as most others, is unable to measure the mass or exact chemical composition of the particles we are measuring, we cannot directly map the particle counts from our system onto an EPA equivalency for "healthy" or "unhealthy" scale. Instead, we report out the particle counts for large and small sized particles approximating the PM2.5 and PM10 particle measurements. This approach is commonly used and provides good correlation with the mass values as measured by the EPA.

PRELIMINARY USER STUDY

In addition to validating the sensor's accuracy, we were interested in evaluating the system with users. In our study, participants were introduced to MyPart and asked to perform a predetermined walking tour of a series of locations with our system. Interviews were conducted before and after the walking tour and focused on perceptions of air quality, feedback on the design and user experience of MyPart, and reactions to MyPart and how it affected air quality awareness.

Study Participants

We recruited 6 participants (3 male, 3 female) through targeted email-lists for a local community center, a homeschooling parents group, and college students. Our study included representation from all of these demographics and across a broad age range (18 to 59 years old). All participants were paid $50 US.

Procedure

The user study consisted of three parts: (1) an initial interview, (2) a "walkabout", and (3) a followup interview. During the initial interview, we asked participants general questions about air quality to gauge their understanding about the topic. Participants were then introduced to MyPart and shown how to operate the device with the accompanying app. A phone was provided to participants to avoid having to load the custom MyPart app onto their personal phones. The participants then took readings at the interview location in order to verify their understanding of the system.

For the walkabout portion of our user study, users took a prespecified walking route through a range of locations around a college campus and the surrounding urban areas. We provided a map marked with the suggested route and eight specific locations, and did not accompany them on the walk. The participants were asked to take a reading at each of the eight locations. The locations were selected to represent broad range of environments and situations, in order to prompt the participants to think about their locations in relation to the air quality. These locations included a bus stop, a grove of trees, a library, a coffee shop, and a construction site. Participants were also told that they were free to take other readings at any time through the walk. The walk was designed to take roughly 40 minutes over a 2.7 km distance. All six participants completed the full study, including the walkabout which lasted from 25 minutes to 38 minutes to complete.

When participants returned from the walk about, we showed them their data and conducted an interview. In this interview, we asked more directly about their experience of using the MyPart system, the visualization, and the legibility of the data. We prompted each participant to discuss how, where, and why (or why not) they would potentially use this system. We also asked them to comment on the the form-factor, comfort, and wearability of the sensor system.

Discussion

We examined our interview data using thematic analysis to reveal patterns across users. These themes become the categories for analysis and are discussed in the subsections that follow.

Lack of General Knowledge About Air Quality

Consistent with previous studies, many of our participants had little understanding of air quality, where it was measured, by whom, and how it was measured and reported. In the initial interview, three participants admitted to not understanding air quality in their area very well and only one participant thought that they understood local air quality and how it affects them.

Engagement and Personal Curiosity

While not required in the study, nearly all of our participants took additional sensor measurements with the system. Five out of our six participants took extra readings for a total of eight additional readings. Participant P4, who did not take additional readings, said that he did not take extra readings because of the weather, but would have taken additional readings given more time. These additional readings came from locations including a building that P1 spent a lot of time in, an indoor space after using a vaporizer (P2), a building vent (P5), a grassy area on campus (P6), and an outdoor exercise class (P5). During the final interview, when participants were asked to discuss additional locations they would use MyPart, all participants listed additional locations that they would like to test including their homes (all participants), their workplaces (P1, P4, P5), higher altitudes (P2, P3, P4), inside of cars (P5), and down by a major highway (P4). Several participants also expressed interest in taking the same readings but at different times, on different days, or during different weather conditions (P4, P6). Overall, we observed that participants easily engaged with MyPart. Many used it to take additional measurements and all had clear ideas of desired future usage, indicating that the MyPart device and visualization were legible and easily understood by participants.

MyPart as part of a larger conversation about air quality

Initially, several participants made assumptions on air quality based on smell (P2, P3, and P6) or other visual cues such as smoke (P3). With our system, participants experienced first hand that these cues do not always accurately reflect air quality. Participants P1 and P6 stated that their perception of air quality had changed in that it is imperceptible and appreciated MyPart as a way to make air quality visible.

Use of the Mobile Phone Data Visualization

Participants noted that the initial ambient display on the mobile application was playful and easy to read (P2 and P4). This view provides a low floor for participants to easily interact with the application and engage with air quality readings, without prior knowledge and experience with the subject. When initiating richer interactions with data, participants preferred the bar graph and chart views (P1, P3, P4, and P5), which allowed the users to associate readings with time, location, weather, and other related factors.

MyPart as a Carryable, rather than a Wearable

Our user study allowed participants to experience MyPart in a unique wristwatch form factor (40x55x23 mm). However, while we found that this form factor was compelling, it was not always desired in all contexts. While participants found the device comfortable and lightweight (P3, P4, and P6), they thought that the device should be much smaller if kept in watch form (P1, P4). This was expected since we have not pushed the system integration to the level that an industrial corporation would for a real product. As such, participants were reacting to the size, which although extremely small, was not close enough to being a usable wristwatch form factor for everyday use. We envision such applications and appropriately sized air quality sensing devices in the near future, however. As such, we were interested in initiating the exploration and understanding of this body location for air quality sensing in our design and studies. Several participants suggested attaching the sensor to a backpack, a briefcase, or another accessory (P1, P2, P3, P4). A few participants wished the sensor could be physically embedded within their mobile device (P1, P5, P6). Overall, participants thought that the device would be most useful if it could be attached to everyday things that the user is already accustomed to carrying (P3, P4, P6). Participant P4 argued that the device should be embedded in a “crucial piece of technology” in order to truly make it ubiquitous. All of these comments strengthen our argument for a small design that can be flexibly adapted into a range of everyday objects and experiences.

Limitations of MyPart

Several participants noted that that the readings are only useful when compared to each other (P3, P4). Participants also expressed interest in knowing exactly what the particles were, rather than just particle sizes (P1, P2). While most of our participants were surprised by one reading or another, two of our six participants thought that using our device consistently would not influence their behavior (P3, P5). One of these participants stated, “day to day I take [the subway], there’s not much that I could do to avoid that” (P3). Two other participants thought that they would only change their behavior in very specific situations: cleaning the house if it were messy and contributing to poor air quality, and exercising indoors rather than outdoors if the air quality was particularly poor (P2, P4). Finally, two participants argued that knowing particle counts might stress a person out more so than influence their behavior (P3, P4). For example, if there is consistently a high particle count in the area that a person lives and they do not have the resources to relocate.

Several other broad themes emerged from our user study. When using on body glance-able interfaces, people were more likely to explore locations other than the ones we specified. This was likely due to the lower activation energy required for taking a sample since there is no need to take out a phone to engage with the technology. In all of our users, we observed increasing awareness and concerns for air quality after using the MyPart system. Overall, the user study helped us validate several of the design elements as well as understand the usage limitations.

FLEXIBLE DESIGN EXPLORATION

As we mentioned earlier, one of the central elements of our design was to develop an easily extensible platform that is accurate, but easily adaptable by others into a variety of application specific form factors. To do this, we engineered all of

Figure 8. Highlighting the flexibility of the MyPart design form factor by demonstrating the ease of adapting it to function as (from left to right): a carabiner, a backpack strap, a wristwatch, and even embedded into a toy airplane

the electronics to be on a single PCB (Figure 5). This includes the power management, microcontroller, photodiode, analog amplification circuit, led driver, temperature/humidity sensor, and BLE radio. We envision this component being either mass produced, sold as a kit, or published publicly. The top and bottom housing are then simply distributed as open-source 3D model files suitable for printing on any 3D printer. However, we lock the internal geometry, since it contains the tested, calibrated, and accurate design for the airflow and particle measurement, and allow free form designs of the remaining model. Again, because we have pushed the engineering efforts to an extremely small form factor, we have enabled what we believe is a range of interesting potential artifacts into which the MyPart design can be embedded. For example, the core design can be used to embed and achieve accurate air quality measurements into watches, strollers, carabiners, toys, bicycle attachments, etc.

Though the geometry of the flow channel is constrained, there are many other opportunities for modification and customization. For example, the default wire loop design (Figure 4) that is currently used to hold the watch strap can be replaced with any other geometry of 1/16 inch diameter wire, allowing for rapid exploration of other body worn and carried form factors. With minor changes, the mounting for the wire loop can be modified to become general mounting points for fasteners, allowing for its integration within other objects - from domestic Internet of Things devices to urban landscape installations. Because of the small size of our sensor, fewer geometric constraints are imposed on the range of potential form factors. In addition, the battery compartment can be easily enlarged to accommodate higher capacity batteries, opening up even more possibilities for remote data-logging.

Several such alternative form factor designs are showcased in Figure 8. We detail some of these designs below:

Carabiner/Clip On - With changes in the exterior loop, this application enables air quality measurements from book-bags, purses, etc.

Bike and Stroller - MyPart can take on a familiar water bottle like form factor, allowing it to be easily integrated into activities with bikes and strollers.

Children's Toy - We have also prototyped the integration of MyPart into a children's toy airplane [17]. The fuselage allows for easy integration of our sensor in its current form and enables a new culture of participation into sensing by children. In this variation, an e-ink display has been added for facial expressions.

We believe that the ease of appropriation and redesign of MyPart into a wide range of everyday objects and contexts is a powerful element of its overall design. Our hope is that by explicitly calling out this feature and providing a direct mechanism to encourage such redesign of MyPart, broader participation of air quality measurements and context will emerge. Specially, those that are more culturally or context appropriate in order to further usage and meaning.

CONCLUSION

Effective personal air monitoring necessitates the combination of accuracy, low cost, and portability into a single design. Lacking an existing solution, we developed MyPart to address this need as well as provide opportunities to redesign and reimagine alternative form factors. In addition to correlating strongly with calibrated commercial instrumentation, the design of our system remains flexible in terms of both shape and size, enabling a variety of personal designs and context specific applications. A mobile phone app was designed to complement the physical hardware, and a preliminary user study was conducted to evaluate the experience of using the overall system.

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