

A Low-Tech Sensing System for Particulate Pollution

Stacey Kuznetsov¹, Scott E. Hudson¹, Eric Paulos²

Human-Computer Interaction Institute¹
Carnegie Mellon University
Pittsburgh, PA, USA
{stace, scott.hudson}@cs.cmu.edu

Electrical Engineering and Computer Sciences²
University of California
Berkeley, CA, USA
paulos@berkeley.edu

ABSTRACT

We present an ultra low-cost sensing system, which enables participants to see and reflect on the particulates in their air. Drawing on prior work in paper computing, we introduce small sensors for particulate pollution that can be easily assembled from common paper materials for less than \$1 USD, and mailed by regular postal service to residents of entire neighborhoods, cities, or geographic regions. Recipients collect particulate samples using these sensors and mail them back to a central location, where the particles are viewed and analyzed via a microscope. The data, which includes rich images of actual air pollution particles, can then be broadcast to larger audiences. This paper details the design of our system and its deployment with a local air quality activist community. We conclude by highlighting the tradeoffs between high-tech and low-tech sensing, and suggest opportunities for tangible interaction to support rich, new ways of seeing our environment.

Author Keywords

Paper computing, low-tech sensing, DIY.

ACM Classification Keywords

H.5.m. Information interfaces and presentation (e.g., HCI): Miscellaneous.

INTRODUCTION

Citizen science research enables ordinary citizens to collect, share and act on scientific data. Within the scope of human computer interaction (HCI), low-cost sensors and DIY (Do It Yourself) methods have led to the development of numerous environmental monitoring tools. From early on, HCI participatory sensing projects have leveraged mobile phones and handheld monitors to gather data in the domains of water pollution, air quality, noise levels, and personal health, among others [8, 9, 21, 25, 38]. In parallel, participatory design research has also enabled stakeholders to envision and build sensors from the bottom up [11, 36].

The majority of these sensing systems visualize environmental data through graphs, charts, maps, or traffic-

light-style metaphors. These visualization techniques, while extremely effective in supporting higher-level engagement with environmental issues, create a layer of abstraction between digital representations and the underlying physical phenomena. For instance, air quality—a fundamental component of human life and health, as well as a cornerstone for local and global ecosystems—is often represented as a heatmap or number in HCI visualizations. The reduction of rich physical phenomena to discrete digital representations has been shown to narrow focus and potentially disengage users from broader context [6, 16, 24]. In addition, despite being relatively low-cost, most citizen science systems still face the challenge of scaling to larger participant groups by necessitating users to have access to specific devices (e.g., smart phones or other sensing platforms), or possessing technical skills (e.g., basic electronics knowledge).

We present a low-tech, paper-based approach to explore the “physical-digital divide” [5] between sensors and the phenomena being sensed, and the deployment of sensing systems on a large scale. As part of our system (Fig. 1), participants collect air quality samples with particulate matter traps that are easily assembled from common paper materials for less than \$1. Unlike many digital devices, these traps are not much thicker than paper, and do not require a power source. The collected samples are returned to central community locations, where participants can view, count, and reflect on the particulates in their air using high-precision microscopes. High-resolution images of the particles could then be shared with broader audiences online, via mobile phones, or public displays.

Our system thereby separates environmental sensing into two steps: low-tech sample collection, and high-tech sample analysis. This approach is radically different from many existing solutions, where environmental samples are collected and analyzed by a single sensing device. Furthermore, our visualization approach (high-end magnification) removes a layer of abstraction by enabling participants to see the physical pollutants in their air.

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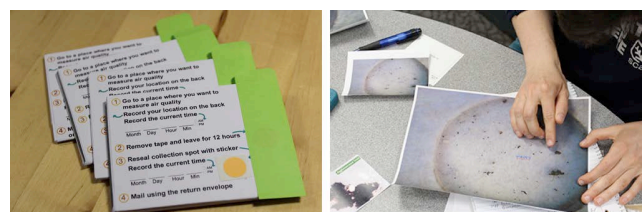


Figure 1. Particulate matter traps, ready to be mailed to participants, and participant examining microscope image of collected particles during community workshop.

Research objectives

Our goals are threefold. First, our work aims to support rich ways of seeing air quality beyond digital graphs or charts. Second, we hope to create a system that can be scaled across broader stakeholder groups, such as entire neighborhoods or cities, or areas with limited technological infrastructure (e.g., places without wireless coverage). Lastly, we envision sensing tools that could be assembled from widely available paper-based materials, such that our sensing approach could be taken on and self-propagated by activist groups. We continue by highlighting prior work in participatory sensing, and related literature in low-tech/no-tech solutions and paper computing. We then detail the design of our sensing system, and offer insights from its deployment with a local air quality activist group. We conclude with design implications that highlight trade-offs between low-tech and high-tech sensing, and opportunities for tangible interaction to support new ways of seeing.

PRIOR WORK

The emergence of DIY methods and materials, along with online sharing tools, resulted in new modes of scientific data collection. In the context of air quality sensing, handheld monitors have been developed to measure outdoor pollutants such as VOC (volatile organic compounds), carbon monoxide, ozone, and traffic exhaust among others [14, 38]. Sensors have also been deployed on street sweepers [1], bicycles [14], robotic dogs [18], and even live homing pigeons [10]. In addition, systems such as InAir and MAQS enable users to measure pollution levels indoors [19, 22]. We contribute to this research by exploring a scalable, low-cost approach for tracking outdoor particulate pollution, a factor that is often overlooked by existing tools.

From prescription to reflection

The vast majority of participatory sensing systems employ conventional visualization methods such as graphs, maps, or numeric data. These visualizations tend to be prescriptive: the Common Sense Community project displays air quality as ‘good’, ‘moderate’, or ‘bad’ [38]; users of inAir have been shown to track ‘peaks’ and ‘spikes’ on their monitors [22]; CitiSense presents the air quality index as an extended traffic light metaphor [28]. Likewise, public representations include WearAir [20]—a T-shirt that lights up if air quality worsens, CO2RSET—a corset that constricts when the air becomes toxic [29], and air quality balloons that light up to show pollution levels [23]. While immediately actionable and relevant to personal health, systems that convey a single, authoritative point of view have also been shown to potentially disengage users from broader contexts [6]. A parallel body of work draws on ambiguity and pluralism as design strategies to support multiple interpretations [3, 35]. Our system builds on these ideas by enabling users to see and reflect on the particulates in their air rather than reporting counts or high/low values. This approach supports ‘new ways of seeing’ the environment through magnification [24].

Community engagement

We envision our system to serve as a prompt for community-based discourse around issues of local air quality. Prior participatory design research has involved communities in the development of sensing systems from the bottom up [15, 11, 36]. Platforms such as the Canary [11], for example, aim to foster collective engagement with and political participation in local issues. Other tools support scaffolding between scientists and non-experts: digital augmentations of the environment facilitate learning [32]; while mobile phone platforms encourage outdoor observations [34]. Likewise, our approach, which involves large groups of stakeholders in air quality sensing, goes beyond personal behavior change and towards “*politics of scale*” through collective dialogue and action [12].

Paper computing

Our sensing tool, which can be assembled from common paper materials, draws inspiration from paper computing [7]. Paper computing is a growing area of research within the tangible interaction community, focusing on the integration of paper materials into computations artifacts. For instance, a recent TEI workshop by Rosner, *et. al* combined traditional bookbinding practice with new building techniques and electronics [33]. littleBits [4] is an open source kit that integrates digital components with materials such as paper and cardboard. Likewise, Eletronic Popables is an interactive book comprised of craft materials along with conductive paints, sensors and microcontrollers [31]. In this paper, we show that paper computing has promising applications within the domain of citizen science.

LOW TECH PAPER-BASED SENSING SYSTEM

Motivation

Particulate matter (PM) consists of coarse particles (2.5-10 microns) that result from tire and asphalt wear, pollen, or dust, and fine particles (2.5 microns), emitted by industrial or vehicular combustion, as well as the recombination sulfur dioxide, nitrogen dioxide, and volatile organic compounds [13]. Particulate pollution has been linked to increased risk of respiratory illness, cardiovascular disease, and shorter life expectancy, not to mention the pollutants’ role in global climate change [30]. PM continues to affect urban air quality, especially in our city, where air quality has been rated as among the worst in the U.S. [2].

PM can be monitored with commercial sensors, such as the ones used to determine the daily Air Quality Index (AQI) [27]. However, these measurements are interpolated across a large region and do not show variations between streets or neighborhoods. Though several sensors, such as the Dylus Air Quality Monitor (\$300), have been developed for PM sensing on a consumer-level, these devices represent air quality as the total number of particles per unit of air, without reporting particle size, type or origin. Our approach makes sensing more transparent by enabling communities to view the physical particulates in their air on a local scale.

Viewing the particles

Samples can be viewed with a magnification device (digital or analog microscope, or a simple magnifying glass). For our proof-of-concept deployment, we chose to use a Venus USB 2.0 microscope with 200x magnification. We designed a custom 3-D printed microscope stand to add stability while viewing the samples. A future system might interface the magnification device directly with a public visualization such as a map overlay of the particulate images.

DEPLOYMENT

Our system was evaluated through a deployment with GASP, a local air quality activist group. This community has been active for over 50 years, working on public engagement, remediation, and policy-level initiatives to improve local air quality. We consider this group to be early adopters of new sensing methods, and a representative of the type of group that might implement our sensing system on a larger scale. An announcement was sent to the community mailing list, inviting members to use our sensor and attend a workshop whereby they could view and analyze the particles. Similar to our pilot deployment, a particulate matter trap was mailed to each participant. Recipients used the sensors in locations of their choice and returned them to our workshop by mail or in person.

Community workshop

In preparation for the workshop, we created 12 cards with high-resolution microscope images of particles and their descriptions from Microlab Gallery [26]. Focusing on particles that are more common in urban areas, our cards included agglomerated soot, grass and tree pollens, coal dust, road dust, and tire wear, among others. During the workshop, participants used a microscope to view and measure the particles collected by their sensors. Images from each sensor were printed, and participants could use our information cards to identify particles in their samples. The printouts were then assembled onto a physical (paper) map of our city based on where each sample was collected (Fig. 4). In addition, participants learned how to create sensors from scratch and were invited to take them home with them. After the workshop, we conducted informal phone interviews (20-40 minutes) with participants to gather feedback. Data from the workshop and interviews was audio recorded, transcribed, and coded to themes, and serves as the basis for the findings reported below.

FINDINGS

We recruited 8 participants (3 male, 5 female; ages mid 20's to late 60's), with varying degrees of involvement in the organization: two people work closely with the group as staff and board members, while others attend group events, and/or check the mailing list and website for news and updates. All participants stated that they have been interested in air quality prior to our study, with 5 people checking the AQI on a regular basis. However, only one person, the community staff member, has used a handheld monitor to measure air quality before.

Participants' motivations

Participants cited different reasons for getting involved in our project, ranging from pure curiosity to specific air quality concerns such as pollution from traffic, industry or construction. Most people used the sensor near their homes, except for P7, who used it in his office at work. To varying degrees, all participants expressed a similar motivation for their sensor placement—to monitor the air they are most often exposed to. As P5 explained, *"I put it on a windowsill at my house. It's the air I breathe"*.

However, within their broad interest in surrounding air quality, participants also expressed unique concerns about specific factors. P2 noticed *"that last few years that my car just gets coated with these fine particles during the day [near her home]"* and wanted to monitor diesel truck pollution, which she thought to be the cause; P3 was concerned about emissions from coal plants in the area, which she associated with a *'sulfur smell'* she sometimes felt in the morning; and P4 was worried about construction:

That location is very close to where they're working on construction so it's of concern to me, to my house... Also I found it to be interesting that there's a hospital right there, so I thought it would be interesting to see what the area is like around the hospital. [P4]

Above, P4 notes that she placed her sensor close to a construction site that might be impacting air quality near her home and a nearby hospital. In summary, participants shared an interest in air quality prior to our project, and wanted to use the sensors to track different air pollutants.π

Ease of assembly and ease of use

To evaluate our design, we intentionally mailed the particulate sensors without any additional instructions,



Figure 4. Air quality workshop: measuring and counting particles; particle information cards; participant's microscope data.

beyond the ones printed on the sensor itself. All participants reported that the sensors were ‘standalone’, ‘really easy’ to use, or ‘straightforward’, and no one expressed difficulty or confusion regarding the sensing procedure. All of the used sensors (5 returned by mail) were properly sealed, with deployment times and locations filled out by participants. Moreover, participants reported that the length of deployment (12 hours) easily fit their schedules, with 7 people leaving their sensor in the morning and resealing it in the evening, and one person leaving it out overnight.

Likewise, participants reported that assembling the sensors from scratch during our workshop was also easy (“*It actually pretty easy to put this together, so it would be fairly easy to do,*” P1; “*I thought it was easy.*” P5; etc.). Participants, unprompted, discussed the potential for mass-producing these tools through conveyor belt style assembly:

I could see mass producing them, having people do you know a 100 of them a night or maybe even 200 or 300 because they're not that difficult, and then more people cutting the index cards and getting things to size as opposed to putting them together. P2

Above, P2 suggests that the steps required for assembling particulate traps could be split between people, and the process could be streamlined. To summarize, all participants agreed that using and assembling the particulate sensors, as we designed them, was easy.

Seeing air quality

Throughout our workshop and during follow-up interviews, participants reflected on how our system enabled them to see air quality differently. Below, we report on three themes from our findings: seeing different types of pollution; seeing local and temporal variations; and transparency—seeing the workings of the system itself.

Types of air pollution. Our system enabled participants to see the sizes, colors and textures of the particles in their air. This led participants to reflect on the physical composition of the samples collected by their sensors. For instance:

Well I guess I learned more about what's actually in the air in that spot and the examples on the table, those were very nice to compare to, and I just thought that it was soot and exhaust and things like that, things that could be affecting the air quality. P5

Above, P5 describes how he compared his air quality sample with the particle information cards at the workshop, and speculates that soot and exhaust might be present in his air. This type of comment—which highlights being able to see what's in the air—was common across most of the participants. For instance, P4 suggested that our sensing system can be used to see “*what is in the air, is it pollen or dust or smoke, I mean how to break down whatever topic we're interested*”. Likewise, P1 noted that through the microscope, he “*could look at different kinds of pollution and how they'd show up*”.

Being able to see the particles collected by other people's sensors at the workshop also led participants to reflect on, and sometimes learn new information about the causes of pollution. For example, P2 noted that she tended to associate particulate pollution with coal plants and was surprised to see another participants' high particle content near a street:

It's interesting that hers had a really high content cause it was more on street level so it showed me at least that... I never thought much about the diesel as much as I thought about the coal plants and the air pollution. P2

Above, P2 notes that seeing particles from another location prompted her to reflect on a different type of pollution (diesel).

Local and temporal variations. Participants also discussed how our sensing system might reveal variations in air quality between different streets and neighborhoods, as well as across different times of the day/week. They emphasized being able to see results from “*my neighborhood*” or “*my location*” as opposed to the general AQI interpolated for the entire city. For example, below P3 explains that although the Environmental Protection Agency (EPA) air quality monitors are not far from where she lives, these measurements may still fail to capture the way pollution moves through the region and affects her home:

I'm interested in air quality and ways to monitor my own air pollution here in my home... even though I'm not on the other side of the river where the [EPA] monitors are... and that's where the coal emissions are and they go in different ways depending on the valley. P3

Other participants wanted to use the system to track the movement of polluted air across the region:

Normally, with the EPA website, it's a kind of broad monitoring of the air so I'd be curious to see if it's worse near Clairton, where it's a major source of pollution in the county. P5

When we talk about the air kind of moving it comes west to east and we get all of Ohio's pollution, so I'm wondering if it comes up or if it's coming up... So I would like to see lots of people doing it [using the system] at higher elevations to see if there's a difference in the air vs. below that. P2

In the excerpts above, P2 and P5 suggest using our system in a nearby township that is considered be a source of pollution, as well as across different elevations within our city. Here participants are highlighting the value of seeing local variations that are not captured by EPA monitoring. Similarly, P2 also suggests tracking air quality patterns over time:

If I could do it [collect samples] 7 days in a row, 24 hours a day, and I could detect patterns to see something different on some days, it would be more beneficial for me to be able to see that as opposed to what the general number is saying. I know that it would be my block as opposed to the entire county. P2

Above, P2 envisions using our system to detect air pollution variations over the course of a week.

Transparency. Lastly, several participants commented on the transparency of the sensing system. Below, P4 compares our sensing procedure with her previous experience of measuring pollution with a handheld monitor:

Once again I think the other monitors are giving good readings and accurate reading, but it doesn't have that extra affirmation where you can see it for yourself. With the air monitors you can't see what it's taking in and why it's giving you the reading it's giving you um so the wonderful thing about this project is you can see that. P4

Here, P4 notes that unlike other 'black-box' sensing devices, our system shows how the air sample is being collected and visualized. This 'affirmation' enables users to see not only the pollutants in the air, but the workings of the sensing system itself. To summarize, this section highlighted how participants were able to see air quality differently through the use of our system: by seeing the physical particulates and the local and temporal variations in pollution, as well as seeing the process by which the samples were collected and visualized.

SHARING SENSING TOOLS AND DATA

Seven of the participants said they would share the project with their family and friends, and several said they would send the sensors they made during the workshop to other people. Participants envisioned a digital (online) version of our paper map to show particulate images and counts to a bigger audience and discussed several ways that the system could have broader impact.

Education and awareness. First and foremost, participants saw our approach as an educational and outreach tool for both adults and children. For instance, participants suggested deploying the system in areas with poor air quality to make residents more aware of air pollution:

It's definitely worth continuing, especially giving it to people who don't think much about air pollution. P2

[use the system] to make aware and educate Pittsburgh'ers about the fact that our air isn't of the best quality. You get so used to it unless you go out of state. P3

These excerpts represent examples of how participants discussed the system as an awareness tool for the general public. Moreover, several people also suggested working with local schools to deploy the system with children:

It would be a great project for kids to take home and then take a look at it on the computer screen, these small tiny particles that just- that's in the air is what's on that. P2

P2's suggestion—to use our system to show children particulates in their air—was not unique. Others, especially P4 and P3, emphasized the project as a 'marvelous teaching tool' or a 'great visual' for younger audiences, who might be less engaged with numeric data such as the AQI.

Action. In addition to raising awareness, participants emphasized that the system could serve to change public behavior towards alleviating air quality problems.

It's not just like a number. There's different things that are in the air, and there's different situations that positively or negatively effect these types of pollutants. You can kinda get people thinking about things they can do, on days that are worse. P5

Here, P5 discusses how seeing the particles present, as opposed to a single number, might result in public actions serve to reduce specific pollutants. Similarly, P1 notes that the system could show her how she personally contributes to the pollution in the area and help change her commute:

I think being able to visualize [air quality] would really help me with my commute and how I would be contributing to the pollution in the area. P1

Data validity. Two of the participants highlighted a limitation of our system: the particulate matter visualization is not calibrated to readings from a high-precision sensor. The particle counts conducted during the workshop, therefore, do not directly correlate to professional data. As P3 pointed out, the data from our system may not be convincing to the health department or city officials:

You can't take this information to the environmental protection department because it's not from an official monitor. P3

In summary, this section outlined some of the broader implications of our system as discussed by participants: as an education and awareness tool or an approach for influencing behavior. However, the system also has limitations, as the data is not calibrated against high-precision measurements.

DISCUSSION AND IMPLICATIONS

So far, we presented the design and deployment of our low-tech, paper-based sensing system. Our deployment is limited in that it involved a relatively small number of environmentally-oriented individuals. Our system is intended to scale to large numbers of people as an approach for raising air quality awareness. Our deployment offers insights into how a community of activists might appropriate this tool. Furthermore, while in its current form, the processing of particulate data is labor-intensive—it involves inspecting each sample under a microscope—in the future, this process could be automated and particle counts could be conducted using vision techniques. We continue by summarizing key themes from our findings and discussing several implications for tangible interaction.

Low-tech vs. high-tech sensing

The sensing system we presented was intentionally designed as an ultra low-cost, scalable approach for monitoring air quality. As was confirmed during our workshop, the particulate traps can be easily assembled by people with no prior experience, and the assembly could be streamlined to create the sensors in bulk by a small number

of volunteers. The sensors, which consist of widely-available paper materials, can be sent to large groups of stakeholders. These sensors are easy to use, and samples collected by thousands of people can be processed with a single microscope at a community location. The resulting data—images and counts of particulates—can show relative variations in air quality and serve to engage a wide audience, including children, in issues of air quality.

However, as some of our participants pointed out, this data is not calibrated against precise measurements such as parts per million (ppm). Although the use of low-cost/low-precision sensors is common throughout participatory sensing research [e.g., 1, 9, 23], this approach has limitations. Data that shows relative rather than absolute (e.g., ppm) pollution levels may not serve as a convincing tool to lobby government officials, or be indicative of specific health effects. The big challenge for participatory sensing research is therefore to balance issues of affordability, scale, and precision.

While it is not feasible to send professional-level sensors to residents of a whole city, or expect people with varying degrees of expertise to know how to use these, future tangible interaction systems may take on a more hybrid approach. High-precision sensors could be coupled with low-resolution inputs and outputs. For instance, thousands of low-cost sensors such as the ones we designed might be deployed in conjunction with a few high-precision devices. The paper-based sensors can enable citizens to collect and compare samples around their homes, raising general awareness. Upon learning about air quality through this easily accessible system, citizens might then come together and use data from a professional device to initiate dialogues with policy makers. Alternatively, low-precision crowd-sourced data might be calibrated against readings from a high-precision device. Interactive or tangible visualizations might then show how data collected by everyday citizens correlates with scientific measurements such as the AQI.

Rich ways of seeing

Our system enabled participants to see air quality in new and different ways. Most directly, the system magnified and revealed the physical particulates in the air, showing variations on a local scale, and potentially across different times of day and week. The transparency of the system itself also enabled users to see how the samples were being collected and visualized. Our findings suggest that there is tremendous value to these new ways of seeing. On one hand, our system enabled participants to observe the specific pollutants they were interested in—diesel truck, construction, or coal plant emissions—as well as to reflect on causes of particulate pollution they have not previously considered (e.g., traffic exhaust). Moreover, participants envisioned using the system to track complex processes, such as the movement of polluted air across the topography of the region, which may not be captured by single-point professional sensing such as the AQI. Meanwhile, physical

involvement in the construction of the system itself supported a sense of ‘*affirmation*’ in the data.

Our findings suggest moving beyond digital representations of environmental phenomena as a design opportunity for future tangible interaction research. Prior work has shown that digital sensing may limit our attunement with the environment [16], while more traditional tools—e.g., magnification—and the living systems themselves—e.g., biomarkers—can support rich engagement with environmental processes [24]. Consistent with this research, we suggest reframing our view of sensing to include low-tech and no-tech approaches along with digital devices.

Similar to our paper-based sensing system, future work can leverage paper computing and other non-electronic materials to create richer representations of environmental systems. For instance, soil composition could be visualized and evaluated through soil chromatography—a technique whereby soil compounds are separated and visualized on paper by capillary action¹. Likewise, communities might track water quality by viewing water samples from local streams and creeks through a microscope, magnified glass, or microscope-enabled mobile phones². These approaches may result in systems that are more physically connected to the phenomena being sensed. Furthermore, shifting from digital to low-tech materials as sensing mechanisms might reframe our understanding of what a sensor feels and looks like, as well as what it means to use one.

On a higher level, our work highlights low-tech environmental sensing as an opportunity area for future tangible interactive systems. We have shown that paper-based, analog sensing can support deep community engagement and reflection on local issues. Future research can continue to explore the intersection of paper computing and citizen science, inviting new materials, new forms of making, and new ways of seeing.

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¹ Similar to this soil chromatography method. <http://milkwood.net/2011/11/06/soil-chromatography-with-eugenio-gras/>

² See <http://hackaday.com/2011/10/19/cellphone-microscope-for-about-20/> or <http://hacknmod.com/hack/turn-an-iphone-into-a-microscope-for-10/>

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