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sensors, chips, and ad-hoc networks as tools for urban culture

Městská rozhraní a jejich rozšíření:

sensory, čipy a ad-hoc sítě jako nástroje urbánní kultury

Diplomová práce

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Abstrakt

Diplomová práce navrhuje DIY přístup k měření znečištění ovzduší, který oživí vztah a zájem lidí o městské prostředí, v němž žijí. Jsou popsány dosavadní měřící metody a komunikace dat ze strany oficiálních institucí a na jejich základě je představen koncept participativního snímání ovzduší osobními mobilními zařízeními. Technologický pokrok sensorů, výpočetní síly, skladování dat a možnosti komunikace dat disponují nyní potenciálem proměnit všudypřítomná mobilní zařízení jako jsou telefony, PDA nebo iPady v globální mobilní snímací zařízení a umožnit participativní paradigma zapojování "amatérů" do sběru dat. Teorie je ověřena na prototypu s výměnným senzorem, v našem případě měřícím koncentrace oxidu uhelnatého, který nabízí jednoduché řešení jak získávat informace o své aktuální expozici, jak ji zaznamenávat a na základě získaných dat případně reagovat. Tvrdíme, že takováto data lidem umožní nové typy interakce s prostředím, zvýší povědomí o zdrojích znečištění a potenciálně umožní i změny v chování nebo podnítí komunitní kampaně. Na základě dotazníku a rozhovorů identifikujeme výhody a nevýhody takovéhoto amatérského sběru dat a zároveň definujeme požadavky na design a funkčnost budoucích mobilních zařízení ke snímání prostředí.

Klíčová slova

ubiquitous computing, participativní snímání ovzduší, měření znečištění ovzduší, prototyp, sensory, demokratizace technologií, citizen science, amatérská data, ad-hoc sítě

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Abstract

This thesis proposes a DIY environmental sensing approach that empowers citizens to reinvigorate people's awareness of, and concern for, pollution. Current air pollution measuring techniques are described, and a new concept of participatory sensing is presented. I argue that technological advances in sensing, computation, storage, and communication now have the power to turn the near-ubiquitous mobile phone into a global mobile sensing device, and commence the participatory paradigm employing amateurs in environmental data collection. To test the thesis, PAIR, a prototype with interchangeable sensor, was developed. It aims to enable people to sense environment on-the-go and provide users with immediate feedback. Such data can make people learn about their environment, make them aware of air pollution causes, and eventually even bring behavioral changes. Consequently, a user survey and interviews identify strengths and weaknesses of the mobile sensing device, and based on the usability requirements, we conclude design recommendations for further development. Finally, we identify the main benefits amateur data collection and participatory sensing represent for urban dwellers, and we evaluate issues and challenges they have yet to overcome.

Keywords

ubiquitous computing, citizen science, participatory sensing, air-pollution monitoring, technology democratization, prototype sensing device, amateur data, technology-enabled bottom-up community participation, ad-hoc networks

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Preface

This master thesis follows up research from my bachelor thesis about new possibilities of geographical data, online map applications and mash-ups. I wished to continue researching location based services, locative media, and especially augmented reality. Nevertheless, augmented reality features meanwhile became part of today's smart phones and further research would require bigger research team and a budget. This is why I have decided to take a different angle on data overlaying our physical world and started studying concepts of ubiquitous computing and Internet of Things. The idea of objects producing data, networking and interacting with us or with each other on a higher level started fascinating me to a point where not only people or objects would be involved but also environment. Our environment could also produce data and more importantly, we could somehow materialize it, start measuring it and thus being informed of current conditions on a individual personalized level. Hence, this theses looks at empowerment of everyday citizens by equipping them with sensing devices, at participatory sensing where people share their data with others and cooperate within their communities, and finally at urban interfaces and the extensions such data create.

My aim was not only to defend the promises that participatory sensing and citizen science hold, but also critically evaluate the advantages and disadvantages of such an approach. By designing and developing a prototype device as well as by conducting a survey and interviews I tried to encompass the interdisciplinarity of such project and possibly also encourage necessary future research involving social scientists, designers and policy makers.

I am grateful to many people for help, both direct and indirect, in writing this thesis but I would like to express my deepest thanks namely to Mgr. Denisa Kera, PhD, my supervisor, for all her help, advice and patience; to Thecla Schiphorst, PhD, my Qualitative Research Methods professor from Simon Fraser University where this research started; Jason Pirodsky for the language corrections, and of course to Ing. Jakub Hybler from the Intermedia Institute at the Czech Technical University who embodied my idea and built our own prototype device capable of environmental sensing. Finally, I would like to thank the Foundation of Josef, Marie and Zdeňka Hlávka for financial support of my studies at Simon Fraser University, and especially my family for all the support they have been giving me.

1 Introduction

1.1 Need for Citizen Science

Air pollution is one of the most important factors currently affecting quality of life in big cities. The urban environment is where an increasing share of the world's population resides, and where the impact of pollution is felt the most. According to the World Health Organization [2006 a, b] air pollution effects cause death of 2 million people a year which is twice as much as deaths from car accidents. Direct causes of air pollution related deaths include aggravated asthma, bronchitis, emphysema, lung and heart diseases, and respiratory allergies [Paulos et al., 2007]. Despite the fact that poor air quality has been shown to directly affect human health, our daily exposure to such pollutants has been inadequately captured and publicly shared. There are state agencies measuring the air quality and informing citizens in the press or on their websites, but usually individuals are not fully aware of their personal exposure, either immediate or long-term. However, the lack of awareness is not only caused by ineffective methods of communication from the state agencies; it is also the type of data that their fixed sensors provide.

Air pollution is highly location-dependent [Hedgecock, 2009]; nevertheless, there is insufficient data to accurately evaluate air quality within specific neighborhoods or at well-defined precise locations. The current lack of real-time indicators prohibits accurate decision making and effective personal air quality control. Concurrently, two billion people on Earth carry mobile phones [Burke et al., 2006] and the cost of sensors decreased significantly over the past ten years. Democratization of technology, low-cost sensors and *Do-It-Yourself* (DIY) hardware prototyping platforms, have the potential to enable *everyday citizens* to develop and use personalized air quality sensing tools and turn their mobile phones or PDAs to measuring devices enabling us to learn about our environment. These innovative sensing capabilities bring new possibilities for individuals to take part in air-quality monitoring as well as to raise awareness of environmental issues. Moreover, it also brings new possibilities for researches to use the potential of masses and collect data in larger quantities from locations that were never monitored before. Burke et al. [2006] claim researchers, policymakers, and the public use data to understand and persuade; higher quality data then tends to generate more significant actions and better understanding. Public collection of environmental data, networking of devices, and sharing of the measurements is a means of how to provide more data from more locations and consequently raise awareness to air pollution related issues.

In short, technological advances in sensing, computation, storage, and communication now have the power to turn the near-ubiquitous mobile phone into a global mobile sensing device and commence the participatory paradigm in environmental sensing the same way it has increasingly been used as crowdsourcing of software and hardware development, in peer-to-peer networks or at social network sites. Urban dwellers equipped with the right tools have thus a unique opportunity to become real stakeholders in their city.

1.2 Increased availability of technology for masses

Principles of democracy have recently been extended in many ways in the production of knowledge and content – we see it every day in blogs, social networks, and modern media. However, these principles can be used in a much wider way – participation even on a hardware level that allows us to sense the environment we live in can bring new insights in the field of citizen science. Ubiquitous devices such as mobile phones are increasingly capable of capturing, classifying and transmitting image, acoustic, location and other data, interactively or autonomously. Given the right architecture, they could also act as sensor nodes and location-aware data collection instruments [Burke et al., 2006]. Paulos et al. [2009] asserts that there are two indisputable facts about our future mobile phones: (1) that they will be equipped with more sensing and processing capabilities and (2) that they will be driven by an architecture of participation and democracy that encourages users to contribute value to their tool and applications as they use them as well as give back collective value to the public, e.g. Flickr, Creative Commons, FLOSS. Today, open contributing and sharing the collective repository of knowledge is upheld as the foundational and driving principle of the technology. If more mobile phones are enabled to sense and measure, there is an inevitable and powerful intersection of people-centric sensing with the current online remix culture [Paulos et al. 2008].

As we witness the democratization of technology as well as the increasing use of social network sites and as the trend suggests mobile devices can play important role in bringing people closer to their location and participate in building digital layers on top of it and extending urban interfaces. In the terms of air-pollution, a detailed picture based on real-time data from mobile sensors over a populated area, in contrast to stationary monitoring methods, offers major benefits to air quality control. Given the trend for sensor miniaturization and for ubiquitous wireless communication via mobile phones, it is possible that far greater public involvement in environmental science could take place [Rudman, 2005]. Besides, useful collective data can be collected in numerous innovative ways. Either explicit or passive recording of geo–referenced pollution data in the places that people actually go rather than where scientists expect them to can dramatically increase the resolution of air pollution information and maximize its impact on public life [Hedgecock, 2009].

1.3 Research Questions

This thesis looks at the current state of art of participatory sensing (in the sense of citizen science); outlines the difficulties it has yet to overcome as well as measures to be implemented for its better use and adoption by people-amateurs. It considers today's research agendas such as ubiquitous computing, Internet of Things, crowdsourcing, DIY etc. Considering that nowadays more than 50% of world's population live in urban areas and in developed world the number exceeds even 75% [UNPF, 2009], the focus of my research is on urban areas where air pollution causes affects people at most. A mobile sensing device would, of course, have a beneficial impact at the rural dwellers too (especially were people use solid fuels) but I focus on the phenomena of participation and active citizenship where networking of larger groups is a necessary asset. The objective for this research is to look at how we can measure and contextualize, temporarily and geographically, exposure to air-pollution in a way that allows analysis and interpretation at an individual as well as specific group level, in order to empower citizens and their better understanding of an environment they live in.

My research questions are *''how can urban citizens benefit from air pollution data collected by amateurs in contrast to data collected by stationary government owned air pollution monitoring network?''* and *''what are the issues and challenges participatory air pollution sensing has yet to overcome?''*. In order to answer the first research question I look at current techniques of air quality measuring and on characteristics of mobile sensing and I also conduct a user survey. Based on the two, expert literature and survey, I define the advantages and disadvantages of both fixed sensors measurements of air pollution and amateur data collection from mobile sensors. To address the second question, firstly, I analyze the design and results of three projects prototyping mobile devices capable of environment sensing enabling individuals to sense their personal exposure (and eventually share their measurements). Secondly, in cooperation with Intermedia Institute, we developed our own prototype and run experiments as well as conducted user interviews. Experiments with the device and measured data enabled us to estimate the hardware challenges necessary to address in the future, user interviews allowed us to better consider the usability and potential scenarios of use of such device. Finally, we prototyped and designed a user experience.

2 METHOD

Grounded theory / Prototyping user experiences within citizen science

This thesis aims to initiate an inspirational research into the very essence of the newly emerging technological urban spaces. Its goal is to design future scenarios for possible empowerment of citizens and their decision making by developing a prototype air quality sensing device to illustrate the prospects of citizen science in urban areas. To answer the research questions stated above, I use the methodology of grounded theory.

Primary sources of data for the study are: (1) *expert literature* that provides theoretical background for the study as well as ground my findings; (2) *analysis of current practice in measuring techniques* to map the current state-of-art by government installed measuring stations; (3) *close readings of selected projects* - a look at examples of realized prototype projects that serve as an inspiration and as a valuable resource to identify the most important features and concerns in developing air-pollution sensing devices; (4) *user survey* to evaluate how the air pollution data are received today and to determine the situations when the air pollution information is most demanded and (5) *a prototype device design* that manifests our hypothesis as well as allows us to verify it, and (6) *user interviews* based on individual measuring to design and user-test the potential usage scenarios.

(1) *expert literature*

My research falls into several research domains – urban computing, ubiquitous computing, pollution monitoring, and citizen science. I consult expert literature from all concerned domains to find a proper ground for discussing the theoretical part of the topic. Further, I concentrate especially on our predecessors who constructed sensing devices people could carry or mount on vehicles. Expert literature also contributes to conclude and verify my findings in chapter 8.

(2) *analysis of current practice in measuring techniques*

To identify the advantages and disadvantages of both fixed official sensors and participatory sensing, I examine current practice in two states – the U.S. and the Czech Republic. I look at the number of air pollution monitoring stations, at the measured pollutants and at the communicating of the measurements to the public via official website. Finally, I shortly analyze the asset of government health agencies.

(3) *close readings of selected projects*

Prototyping the sensing device for citizen science necessitates detailed look at and evaluation of predecessors to our prototype. Three projects, e-Sign, Ergo, and AIR, were selected as all of them share the general goal of democratizing the technology in the field of air pollution monitoring and each of them brings a different solution. By having studied these approaches, we can better position our prototype device, defend its innovation and all together we can estimate the advantages, disadvantages, and challenges yet to be overcome, of participatory sensing.

(4) *a prototype device design*

To manifest the theoretical part and illustrate our hypothesis, we design and develop a mobile device with interchangeable air quality sensors. From the process of building the device and from the calibrating of measurements I gain data of great importance to estimate the challenges a DIY approach in environmental sensing has yet to overcome. In addition, comparing our achievements to our predecessors brings a necessary comparison to highlight both similar and distinguishing features of respective devices and allows generalizing how the citizens could benefit from using them.

(5) *user survey*

The people centric nature of the research, the idea of democratization of technology and the notion of citizen science, all aim to enable changes in individual and social perception of air quality related issues potentially leading to changes in behavior or decision making. A survey is conducted to gain a better insight to how people currently inform themselves about the pollution levels, how important role such information plays in their lives and how significant is the demand for a personal sensing device.

(6) *a series of experiments and interviews with volunteers*

Finally, I conduct interviews with 4 users while building upon the personalized data from the prototype device. I inspect the reactions of users, the type of information they are interested in, their preferences in data delivery and visualizations, as well as frequency of use and functional requirements.

A combination of quantitative and qualitative research methods corresponds to the people-centric nature of the studied topic. My focus is on participatory sensing and citizen science in order to bring better understanding how not only researchers and city representatives can benefit from new data collections but also to reflect how this phenomenon can empower the grassroots sensing to support bottom-up activities.

The most influential research for this study is Eric Paulos et al.'s work in Citizen science: Enabling participatory urbanism [2008]. His work has an identical goal - empowering citizens to collect and share air quality data measured with sensor enabled mobile devices and it complements existing participatory models with focusing on an initial capstone application of air quality sensing, emphasizing the measure-share-remix metaphor for "on-the-go" citizen participation, and expanding the integration of newly available sensors for mobile devices. I build upon the idea of *participatory urbanism*, i.e. affording the opportunity for individual citizen participation, sharing and voice. This encompasses the vision of the techno-social potential for emerging ubiquitous urban public or personal mobile technologies to enable citizen action by allowing open measuring, sharing, and remixing of elements of urban living influenced by, requiring or involving participation.

3 Measuring Air Quality and Impact on Health

In this chapter I explore how air quality is measured and reported by state agencies in two countries – the U.S. and the Czech Republic. I examine which pollutants are covered, then communication and visualization techniques for presenting air quality measurements and related health risks. Comparing the current state of art of measuring air pollution by government agencies' stationary sensors to our proposed method uncovers advantages and disadvantages of both approaches as well as draws the potential benefits of combining both.

3.1 United States

In the U.S., the main method of communicating air quality measurements is Air Quality Index (AQI). It is an index for reporting daily air quality based on concentration of 5 main pollutants - carbon monoxide (CO), nitrogen dioxide (NO2), ozone (O3), sulfur dioxide (SO2), and particles (measured as PM10, a measurement that relates to the size of the particle) [AirNow]. For each of these pollutants, Environmental Protection Agency of United States (EPA) has established national air quality standards to protect public health and especially people in the community most vulnerable to the health impacts of the various pollutants. The purpose of the AQI is to help people understand what local air quality means to their health and to make it easier to understand; the AQI values are divided into six categories - ranges, and each range is assigned a descriptor and a color code (Fig.1). Each category therefore also corresponds to a different level of health concern: the higher the AQI value, the greater the level of air pollution and the greater the health concern. Furthermore, the Clean Air Act from 1990 requires the Environmental Protection Agency (EPA) to review its National Ambient Air Quality Standards every five years to reflect evolving health effects information [EPA, 2008]. The Air Quality Index is then adjusted periodically to reflect these changes.

According to the EPA, the Air Quality System stores data from over 5000 currently actives monitors [EPA, 2010]. However, mere measuring without certain generalization for the respective area or zone provides only incomplete information. Flows of pollutants around the city are very complex due to factors such as amount and speed of traffic, building shapes and density, weather conditions etc. Existing public pollution-level displays (in newspapers, on civic internet sites or community information screens in shopping precincts) typically take data from pollution sensors across the city and average these readings over time and space [Hooker et al., 2007]. Different modeling techniques are in use – a representativeness of a measuring station (for the respective matter measured) is estimated and then a map of air pollution for given area is drawn and modeled. There are two types of measuring stations – urban background (or rural) and traffic/industrial. The first has more significant radius of representativeness while modeling the map for a bigger area but the latter is also accounted while being highly localized and usually very important. Paulos et al. [2008] criticizes this approach - the data used for calculating AQI in the U.S. come only from a small number of civic government installed environmental monitoring stations, e.g. San Francisco bay with its over 7 million inhabitants is monitored by mere 40 stations. Yet, the air pollution is highly localized: in micro-scale usually varies dynamically with short time and small space [Jung Hun et al., 2010]. This lack of localized data sources therefore opens the potential area for DIY environmental monitoring, for citizens measuring their environment themselves, learning about their own exposure, and sharing the geo tagged data with others.

Air Quality Index	Levels of Health Concern	Fine Particles PM 2.5	Particles PM 10	Color
0-50	Good	None	None	Green
51-100	Moderate	None	None	Yellow
101-150	Unhealthy for Sensitive Groups	People with respiratory or health disease, the elderly and children should limit prolonged exertion.	People with respiratory disease, such as asthma, should limit outdoor eertion.	Orange
151-200	Unhealthy	People with respiratory or heart disease, the elderly and children should avoid prolonged exertion; everyone else should limit prolonged exertion.	People with respiratory disease, such as asthma, should avoid outdoor exertion; everyone else, especially the elderly and children, should limit prolonged outdoor exertion.	Red
201-300	Very Unhealthy	People with respiratory or heart disease, the elderly and children should avoid any outdoor activity; everyone else should avoid prolonged exertion.	People with respiratory disease, such as asthma, should avoid any outdoor activity; everyone else, especially the elderly and children, should limit outdoor exertion.	Purple
301-500	Hazardous			Maroon

Figure 1: the current AQI classification used by United States Environmental Protection Agency
Source: http://www.sercc.com/airquality, retrieved 27th September 2010

3.2 Czech Republic

In the Czech Republic, the evaluation of ambient air quality is based on the monitoring of levels of pollutants in the ground-level layer of the atmosphere in a network of measuring stations. Assessment of levels of air pollution is primarily based on comparison of measured levels of air pollution and the respective limit values set by Government Order [CHMI, 2009]. The limit values are set for the following pollutants: sulphur dioxide (SO_2), suspended particulate matter, $PM_{2.5}$ and PM_{10}, nitrogen dioxide (NO_2) and nitrogen oxides (NO_X), carbon monoxide (CO), benzene and lead. There are also target values set for ground-level ozone, cadmium, arsenic, nickel and polycyclic aromatic hydrocarbons expressed as benzo(a)pyrene. Moreover, in May 2008, the European Parliament adopted a directive on ambient air quality and cleaner air for

Europe, which establishes a reciprocal exchange of information and data from networks and individual stations measuring ambient air pollution within the Member States that also introduces measuring and limits for PM2.5. Similarly to the U.S., Czech Hydrometeorological Institute estimates also an Air Quality Index (AQI). It accounts concentrations of 5 pollutants – SO_2, NO_2, CO, O_3, PM_{10} and calculates the range where the highest concentrations of measured substances fall and estimates the index. It is to be displayed only if at least NO_2, O_3 and PM_{10} are measured at the location.

Nevertheless, in the 1990s air quality in the Czech Republic underwent significant changes and especially factories and plants, the major sources of sulphur dioxide, were desulphurized as well as new cars produce less significant amounts of SO2. Thus SO_2 is not one of the major pollutants today even if it is still a part of a calculated AQI (when measurements available). On the other hand, concentrations of polycyclic aromatic hydrocarbons (PAH) are increasingly relevant since most of the cars became equipped with catalyzers producing benzoapyrene etc. PAH exposure has been associated with a range of cancer endpoints including lung, skin and bladder cancers [Coleman et al., 2001] but so far PAH concentrations (in spite of the target values set by government) don't account into AQI.

Similarly to the U.S., the network of stations is sparse in the Czech Republic (see Table.1) - in total there are 219 measuring stations in the whole republic [CENIA, 2010]. For example, in Prague and its surroundings, where more than 1,5 million people live, there were 22 official measuring stations in 2008 [CENIA, 2010]. In addition, not all the pollutants with limit and target values set are measured at each station. This implies that the necessary data to estimate one's personal exposure or potential health risks is usually not available as it comes from a station located far from the actual location where one lives or works. Existing public pollution-level display on CHMI website takes data from a number of pollution sensors across the city and average these readings over time and space – this data is thus of a very low resolution both spatially (summarizing over a district or entire city) and temporally (e.g. with daily summaries).

Air pollution monitoring localities, based on the owner, Czech Republic, 2009						
			2009			
Region	**ČHMÚ**	**ZÚ**	**ČEZ**	**P+S**	**KMon**	**Total**
Brno	6	2	-	-	5	**13**
Praha	15	7	-	-	-	**22**
Jihočeský	8	2	-	-	-	**10**
Jihomoravský	5	1	-	-	-	**6**
Karlovarský	5	4	1	-	-	**10**
Králové-hradecký	9	1	-	-	-	**10**
Liberecký	9	2	-	-	-	**11**
Moravskoslezský	23	4	2	-	1	**30**
Olomoucký	5	1	-	-	2	**8**
Pardubický	5	2	1	-	1	**9**
Plzeňský	5	2	-	-	5	**12**
Středočeský	11	9	-	2	-	**22**
Ústecký	19	10	9	1	-	**39**
Vysočina	7	3	-	-	-	**10**
Zlínský	4	1	-	-	2	**7**
Total	**136**	**51**	**13**	**3**	**16**	**219**

Notes:
ČHMÚ - The Czech Hydrometeorological Institute
ZÚ - Health Institute
P+S - industry
KMon - Municipal monitoring

Table 1: The number of air pollution monitoring localities, based on the owner of the measuring device in 2008

Source: Statistical Environmental Yearbook of the Czech Republic 2009

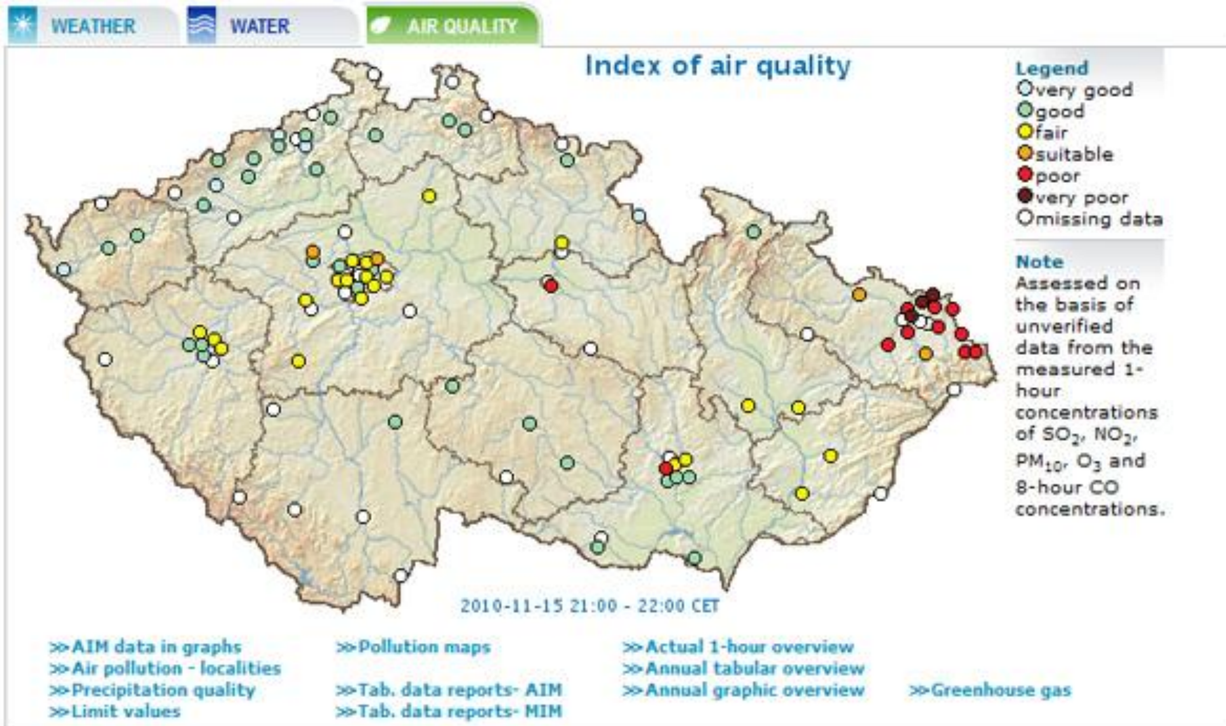

Fig. 2 Map of the Czech Republic overlaid with data from measuring stations.

3.3 Health Impact Monitoring

The quality of the environment significantly affects human health and the whole population [NIPH, 2010]. While the research as to specific health effects is still ongoing, we know that, overall, increases in particulate emissions in the air are linked to poorer health [PEIR, 2008]. According to World Health Organization estimates, environmental pollution causes up to 19% of diseases in the European Region; merely because of the airborne dust pollution in Europe, approximately 280 thousand people die prematurely. The most important health implications of exposure to polluted environment are the respiratory and gastrointestinal diseases, allergies, cardiovascular and metabolic diseases, developmental and reproductive disorders and cancer. Czech National Institute of Public Health [NIPH, 2010] that follows-up environmental impact on the health status of the population states: “the effects of ambient air pollutants on health depend on their concentration and the period in which people are exposed to them. The actual exposure during the year and during individual’s life course significantly varies depending on someone’s profession, lifestyle, or more precisely on the concentrations of pollutants in different localities and environments.” For example, particulate pollution has been linked to significant disease risks, including cancer, heart disease, and asthma and it is a “localized” type of pollution because many kinds of particles don’t make it very far past where they were emitted [PEIR, 2008]. This means that where one goes can significantly change how much polluted air they breathes. Our approach, stressing the DIY sensing, is addressing this exact issue: air pollution is to a certain extent highly localized and by equipping people with personalized measuring devices we could know which places are better to avoid and which routes better to take. In short, we would have more data that would allow making better decisions as well as raise awareness of the connection between the pollution sources (transport, plants, or heavy industry), pollution and effects on health.

4 Citizens: Agents of Change

Recently, the concepts of ubiquitous computing and internet of things gained a lot of attention and both constitute frameworks for research in computing as well as social sciences. The Internet of things promotes the availability of minuscule identifying devices; it envisages a world where sensors would be ubiquitous, attached to most, if not all, of items of everyday life. These sensors would be producing vast amounts of data on an ongoing basis thanks to an ever increasingly sophisticated infrastructure capable of passing and handling this data. Internet of things would then be a self-configuring wireless network interconnecting all these *things*. Ubiquitous computing is a more general term as Greenfield [2006] foresees in *Everyware:* “computing has leapt off the desktop and insinuated itself into everyday life…[everyware] will appear in many different contexts and take a wide variety of forms”. In other words, in the same way that the development of the Internet transformed our ability to communicate, the ever-decreasing size and cost of computing components is setting the stage for detection, processing, and communication technology to be embedded throughout the physical world [CENS, 2010]. Consequently, it is fostering both a deeper understanding of the natural and built environment, and enhancing our ability to design and control these complex systems. Moreover mobile sensing also known as “participatory sensing” [Burke et al., 2006], “urban sensing” [Campbell et al., 2006] or “participatory urbanism” [Paulos et al., 2007] enables data collection from large number of people in ways that weren’t previously possible. For example, over two billion people carry mobile phones and these ubiquitous devices are increasingly capable of capturing, classifying and transmitting information such as acoustic or location data as well as have the potential to sense the surrounding environment [Burke et al., 2006]. Given the right architecture they can act as sensor nodes and location aware data collection instruments. A large variety of low-cost sensors are already readily available including carbon monoxide and dioxide, solvent vapors, electro-magnetic emissions (for example, those coming from mobile phone masts, electricity generators and so forth), and light and noise pollution [Airantzis et al., 2008].

4.1. Participatory Sensing

Participatory Sensing is described as a revolutionary new paradigm that allows people to voluntarily sense their environment using readily available sensor devices such as smart phones, and share this information using existing cellular and internet communication infrastructure [Dua et al., 2009]. In general, the individual citizen has very little direct awareness of the air quality that they encounter daily and almost no specific public forums to debate the situation or strategies for change. However, by embedding microcomputers and sensors into the environment in combination with mobile devices we could enable citizens to collect & share measurements of their city and to monitor the real-time conditions. Through involvement with the collection and sharing, we can empower them to become active participants in their local communities. Paulos et al. even claim [2008]: "We believe that such systems can elevate individuals to have a powerful new voice in society, to act as citizen scientists, and collectively learn and lobby for change within their block, neighborhood, city and nation." Besides, the notion that single authoritative sources of pollution information might be supplanted by multiple, less official pollution sensors is compatible with a more general view that ubiquitous computing will appear in public as well as private settings [Hooker et al., 2007].

Today, increasingly low-cost sensors can measure carbon monoxide, pollen, radiation, epidemiological viruses or wind speed and direction, and we can imagine them as well as onboard sensors - physically built into the mobile device [Rudman, 2005]. As the mobile phone network is emerging as the largest sensor network on the planet, mobile sensing projects thus aim to equip citizens with mobile phone applications and tools that let them acquire quantitative and qualitative environment information directly from their surrounding [Kanjo et al., 2009] and therefore learn about their environment and interact with it through novel interfaces. Having greater numbers of accurate, real-time data from sensors of all types will enable people to make better informed decisions about things in the world around them. [Dickinson, 2010]. We can use the technology around us to observe, discover, and more importantly, act on the patterns that shape our lives [Cuff et al., 2008]. Participatory sensing thus encompasses not only data collection and interpretation, and aims to involve citizens in sensing and measuring their environment but also aim to uses these tools combined with the wireless sensing systems to critical societal pursuits.

Increased public interest in local and global environmental changes together with the increased availability of sensors and wireless transmitters has already engendered a diverse variety of research projects and scenarios how to engage people in conversation about local air-quality, about environmental monitoring and also health-related issues. It has tremendous potential because it harnesses the power of ordinary citizens to collect sensor data for applications spanning environmental monitoring, intelligent transportation, and public health that are often not cost-viable using dedicated sensing infrastructure. The next step to take now is to step out of the research labs and give the people the right tools or encourage the DIY approach.

4.2. Citizen Science

Developing and promoting personal mobile sensing device aim towards the paradigm of citizen science. Citizen science is a term used for projects or ongoing programs of scientific work in which individual volunteers or networks of volunteers, many of whom may have no specific scientific training, perform or manage research-related tasks such as observation, measurement or computation [Paulos et al., 2009]. Citizen scientists are volunteers and basically act as field assistants in scientific studies. The use of citizen science networks, for example, allows scientists to accomplish research objectives more feasibly than would otherwise be possible. More importantly, these projects aim to promote public engagement with the research, as well as with science in general.

Task performed by citizen scientists usually require human perception and common sense but not a lot of scientific education or training. All the tasks are voluntary and volunteers can choose when, and for however long they want to work. Some of the well known citizen science projects are i.e. National Audubon Society's annual Christmas bird count running since 1900 where volunteers observe the habitats of birds, take photographs and report the locations; Clickworkers, an experimental project by NASA, where volunteers help analyze vast amounts of data and photographs from a Mars Global Surveyor spacecraft or . In a broad term, citizen science can also mean distributed computing where people connect to achieve a greater goal – in the case of Seti@home, an experiment that uses Internet-connected computers in the Search for Extraterrestrial Intelligence. The work here is not primarily done by the volunteers but by their computers. In short, citizen science enlists the public in collecting large quantities of data across an array of locations over long spans of time and collaborations between scientists and volunteers have the potential to broaden the scope of research and enhance the ability to collect scientific data [Cohn, 2008].

Volunteers can also provide valuable information in environmental monitoring. The only premise is that they are equipped with a mobile sensing device. The citizen sensing research framework moves sensor based environmental information systems from wilderness areas to cities. It attempts to complement the authority of accredited scientists with that of engaged citizens acting as “agents of change.” [Paulos et al., workshop 2008]. As a means to this end, citizen sensing often attempts to visualize spatial variances in local pollution levels (Fig 3) – air pollution, noise pollution, or water pollution. Those representations can then be used to create “a new political space” [Bratton & Jeremijenko, 2008] for group action or to guide more individual action. The assumption is that “higher quality data tend to generate more significant action and better understanding” [Burke et al., 2006]. Citizen sensing relies fully on individual agency and in our case it considers people as public actors who provide highly localized, reliable information for the community goal to protect them from pollution.

Goodman [2009], in the influential paper Three environmental discourses in Human-Computer Interaction, recognized *Citizen Sensing* as a discourse in HCI next to sustainable interaction design discourse and revisioning consumption discourse. She stresses the fact that “citizen sensing projects often represent outcomes as technopolitical tools rather than products” and highlights the fact that as an environmental discourse citizen sensing doesn’t see the people as *consumers* leaving damaging footprints upon the earth, citizen sensing imagines people as public actors who need highly localized, reliable information to protect them from pollution.

Citizen science works with the fact that production of information, on all levels, has democratized; people are increasingly participating and not just consuming the information. Science-politics interface is no longer only a domain for experts and policy-makers [Bäckstrand, 2003], at an urban level, citizens can use the tools to become policy makers themselves, agents of change contributing to sustainability of their cities.

Citizen science is not to be mistaken with civic science. Civic science has been defined as the efforts by scientists to reach out to the public, communicate scientific results and contribute to scientific literacy/ [Clark, Illman, 2001 in Bäckstrand, 2003]. It hosts many ambitions, such as enhancing public understanding of science, increasing citizen participation, diversifying representation in, and promoting democratization of science. Citizen science, on the other hand, denotes a science that is developed and enacted by the citizens, who are not trained as conventional scientists. [Irwin, 1995 in Backstrand, 2003].

4.3 Pros & Cons

There are number of reasons for enhancing public participation in science and making science democratically accountable. The goal is to enhance the public awareness and understanding, initiate a discussion about scientific topic that have direct impact on our lives and to extend the principles of democracy to the production of (scientific) knowledge. Some of the advantages that citizen science projects within the field of air-pollution monitoring share in common involve:

- opportunity to examine air quality at a more localized resolution
- Environmental sensing is usually done using a few reading stations spread around cities - cell phones can give researchers thousands of mobile sensors gathering rich sets of local data at almost no cost.
- possibility to highlight past activities in the area which could have left an environmental footprint. This type of local knowledge is invaluable and can help locate pollution hotspots that would otherwise require an extensive survey
- data collection by people has the potential to trigger an open dialogue about how pollutant sensing technology placed at a grassroots level can function and its potential applications for community action and interaction. [Airantzis et al., 2008]

In short, use of data from citizen sensors could help air quality professionals identify the location of peak concentrations and determine the concentration gradients between surface monitoring stations and also increase public participation in the production and use of scientific knowledge for their own purposes and benefits. The objective of participatory sensing is therefore to empower the communities as well as to support emerging recognition of the value of people-centric sensing in urban environments.

Yet, there are a number of issues that immediately emerge. Steed [2003] admits that mobile sensors aren't as well calibrated as fixed sensors, Dua et. al [2009] stresses that in any participatory system, such as Wikipedia or online recommendation systems, participatory sensing is vulnerable to abuse from users; critics would argue that the collection of this kind of data by non-experts is not necessarily useful as such activities would lack scientific rigor and would thus not be comprehensive or authoritative. Also, participatory sensing differs from traditional sensor networks in that there is typically no single data producer (i.e. sensor data owner). While sharing the measurements, this can pose another problem - data producers and consumers (sensor data users) are different autonomous entities which can create some boundaries, e.g. producers may want to restrict whom they share their data with, or raise the question of privacy.

To sum up, the concept of participatory sensing tasks everyday mobile devices, such as cellular phones, to form interactive, participatory sensor networks that enable public to gather, analyze, and share local knowledge. This concept can be beneficial to variety of domains but most of the prototypes projects focus on raising public awareness about environmental issues, supporting local communities with the ultimate goal to bring benefits for public health, urban planning, natural resource management or creative expression [Burke et al., 2006]. By analyzing several prototype projects, developing our own sensing device and questioning public in a survey and interviews, I explore participatory environmental sensing in order to bring better understanding how citizen science can be applied to address the issue of air-pollution awareness in urban areas. I define challenges, conditions and limitations of citizen science in terms of technological constrains as well as public readiness to start using such tool and actually become the true agents of change.

5 Case studies / Predecessors

Before designing our own prototype we looked at several projects, done in past years, exploring their strength and weaknesses. We were inspired and recognized some crucial features we wanted to keep or avoid to develop a user-friendly citizen sensing device. There are number of researches dedicated to innovative ways in air-pollution sensing such as Natalie Jeremijenko' playful project called Feral Robotic Dogs [Lane at al., 2006]. She proposed ways to reconfigure toy robot-pets popular in the early 2000s with a variety of low-cost chemical sensors that can sense, record and in some cases trace environmental pollution. By sending out "toys" to detect pollutants in different areas around the country, she aimed to draw local attention to environmental hazards and show that local community members can interpret the displayed data without any help from experts. Another original approach was introduced by Engel-Cox at el. [2004] who suggested complementing the traditional ways of air pollution monitoring by an integration of data coming from ground-based stations with data from satellites. They claimed satellite data can add synoptic and geospatial information to ground-based air quality data and modeling and therefore it can become another tool for monitoring the concentrations and transport of air pollutants, especially particulate matter ($PM_{2.5}$ and PM_{10}).

Some of these projects balance between art technology and activism and therefore bring original ideas how to change current discourse in public engagement. To best represent most relevant to our prototype, I have chosen 3 projects that directly inspired us to analyze. First is Pollution e-Sign [Hooker et al., 2007], a prototype physically mounted in the street and communicating with passers-by devices by Bluetooth; second is Ergo [Paulos et al., 2008], an SMS system delivering, on request, localized information to your cell phone; and last is the AIR [da COSTA et al. 2006], a portable sensing device allowing you to network with others as well as localize the pollution sources through an in-build database. All of these three devices promote personal environmental sensing and pursue the idea of citizen science. Consequently, like a great deal of new media art, they openly challenge stable institutional, disciplinary and technological boundaries [Dieter, 2009].

5.1 Pollution e-Sign

Pollution e-Sign is an electronic street sign that communicates local air quality information by automatically using Bluetooth to send unsolicited messages to other Bluetooth-enabled devices such as cell phones and PDAs passing devices. It is a hybrid between fixed and portable sensing as the sign can be mounted anywhere but the users receive the information only when close to the sensor. Hooker's et al. [2007] goal was first to raise people's awareness of and concern for pollution but more importantly to reconnect people with the day-to-day ramifications of scientific and technical research as well as to encourage people to appreciate the scientific process by building on the ways that mundane negotiations with the world already requires them to reason as scientists do. They claim current communication of air pollution levels measured by state owned stations conveys the impression of a single authoritative source of pollution information that is not open to inspection or question by the public.

E-sign builds upon the phenomena of ubiquitous computing and Internet of Things. It imagines richly heterogeneous city interfaces created by people's devices, buildings, vehicles, all connected via data networks fed by sensors of all sorts – fixed, portable, public, private, expensive and well calibrated or cheap and less accurate. Data from the sensors would then feed higher resolution *pollution maps* available for public. E-sign concentrates on making the scientific side available to the people too – while sampling different readings, characteristics of the sensors might be displayed as well as the information about the particular mathematical models employed to achieve this data. Therefore, users of the *pollution maps* might be encouraged to draw their own conclusions about the causes and effects of pollution by partly exposing the processes of scientific investigation and pollution prediction.

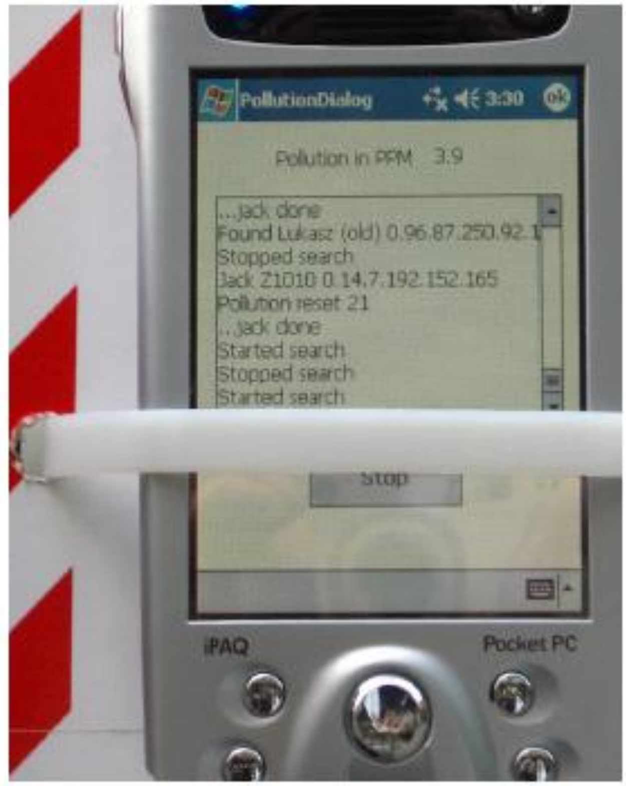

Fig. 3- The prototype Pollution e-Sign

Fig.4 - PDA's logs of successful and unsuccessful transmissions of readings

Pollution e-Sign's design involves a pollution sensor connected to a Bluetooth enabled PDA (see *Fig. 3,4*) both mounted on a road sign indicating what are the components doing as well as pointing the interested passers-by to a project website. The PDA sends messages with sensors current readings to near-by devices via Bluetooth, again with the web address where people can learn more. The data is sent as the sender's identification in requesting a Bluetooth connection (e.g. "message received from Local Carbon Monoxide Level = .05 ppm; see www.escience.com"), so passers-by do not have to explicitly accept a connection to receive the information or interact with the device.

The pollution e-Sign highlights the notion of future mobile devices allowing awareness of localized information in a digital radio network. Consequently, the prototype is designed to primarily raise awareness of the technology of transmitting the information to the passing devices then on displaying and communicating the pollution levels in a user-friendly way (*Fig. 8*). Hooker et al. focused on challenging the official measurements and encouraging the scientific interest of the e-Sign's target group but if there were such e-Signs in the streets it would be necessary to add several features - a visual display (to the e-Sign) where the user can quickly inform themselves of a current situation and not to limit the technology requirements on a user's device solely to Bluetooth.

5.2 Ergo

Ergo was a part of Urban Atmospheres, an inspirational research effort by Eric Paulos. Urban Atmospheres look at a unique synergistic moment - expanding urban populations, the rapid adoption of Bluetooth mobile devices, tiny ad hoc sensor networks, and the widespread influence of wireless technologies across our growing urban landscapes [Paulos, 2008-web]. Paulos looks at urban computing in a futuristic way and aims to better design urban citizens-friendly technology to create urban techno-political spaces where citizens have the tools and power to become true agents of change.

Ergo served as a complementary tool to explore a people centric view of measuring, sharing, and discussing our environment and air quality using mobile devices such as your personal mobile phone with various air quality sensors attached [Paulos et al., 2008]. The system provides users with on-the-go air quality readings delivered to their mobile devices by an SMS. In a scenario where a user questions the current air quality at a location where they are right now (the system was designed only for the U.S.), they can send an SMS to a given number and automatically receive air quality change throughout the day as well as forecasts for the coming days. There are several commands that can be used, i.e. *5 digit zip code* to be sent by an SMS, which will deliver only local information for the requested area; the word *worst* that would deliver 3 worst locations in the U.S.; or *daily zip time*, a service that would send you a daily report for the specified zip code at a time of your choice. In addition, the returned SMS included not only the pollution levels but also a level of health concern (taken from the AQI, see chapter 3) in the SMS message returned.

In short, anyone with a mobile phone can quickly explore, query and learn about their air quality on-the-go using Ergo. More importantly, the system communicates the potential health risks and this feature encourages the user to question the connection between air quality and health possibly resulting in a behavioral change. However, the system uses only data provided by a sparse network of government measurement stations and therefore doesn't bring highly accurate, localized and personalized data. Another disadvantage of the SMS approach is the necessity of knowing the system before you start using it – one must know the telephone number and the commands before they can learn about their environment.

5.3 The AIR

The AIR (Area's Immediate Reading) was a project by Preemptive media that ran in 2006-2008. It was a public social experiment in which people were invited to use portable air monitoring devices to explore their neighborhoods and urban environments for pollution and fossil fuel burning hotspots. The AIR devices are equipped with sensors that detect carbon monoxide (CO), Nitrogen Oxides (NOx) and ground level Ozone (O3), GPS and digital compass. The overall goal of AIR team was to design a tool for individuals and groups to self identify pollution sources, and also to serve as a platform to discuss energy politics and their impact on environment, health and social groups in specific regions [da COSTA et al. 2006].

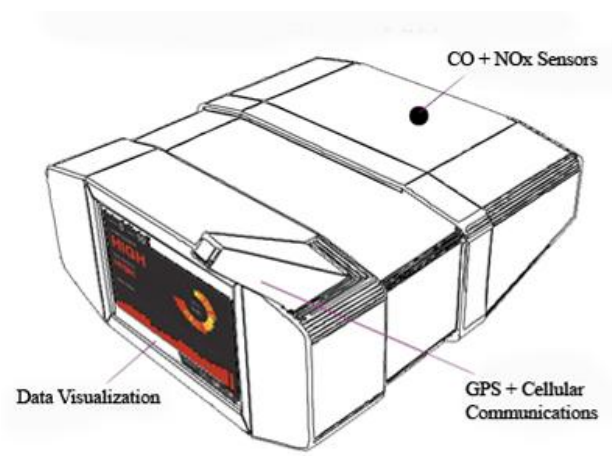

Fig. 5 - Design of the AIR device

Fig. 6 - Users testing AIR device in the street.

The AIR device has dual modes: a personal reading mode and compass mode. When the device is worn on the body using the strap or the screen is parallel to the ground, it is in personal reading mode and displays only the immediate CO and NOx levels. As soon as one brings the device in front of their face and the screen is perpendicular to the ground, it switches into a compass mode. At this point the device indicates the presence of any heavy, industrial or commercial polluters along with their yearly emissions. The digital compass combined with a database of known pollution sources such as power plants or heavy industries allows the AIR *carrier* to see the distance from polluters as well. Data about polluters come from the US Environmental Protection Agency's[1] database of nation-wide polluters called the National Emissions Inventory. AIR has also some basic networking features - while in compass mode, if any other AIR carrier is in line of sight, an icon will appear on the screen along with that device's current readings and distance. Moreover, participants are able to switch from seeing pollutant levels in their current locations, to simultaneously view measurements from the other AIR devices in the local network. The AIR devices regularly transmit data to a central database allowing for real time data visualization on the project website.

To sum it up, AIR fulfills most of the features necessary for a useful citizen sensing device. It is portable; it visualizes the concentration on a heat map and therefore allows even non experts to understand the readings. In addition, the option of switching to a compass mode and displaying the pollution sources directly influences people’s perception of the major polluters’ impact. The only disadvantages of AIR are therefore its considerably big size and the lack of potential health risks warnings.

[1] www.epa.gov

6 PAIR - Prototype

Along the lines of our predecessors, we approached the air pollution in a much more localized and individualistic way than the current standard. While I acknowledge the importance of measuring and modeling in large scale, of large areas, and over a long period of time, I believe it is also important to bring everyday citizens closer to the issue and make them realize what impacts air-contaminants can have on their lives and health. Democratization of tools to sense the air quality can then be the means to achieve better understanding of the air pollution, its effects and related issues, to reinvigorate people’s awareness of and concern for pollution. Goodman [2009] particularly stresses the significance of *exposure* to promote citizen sensing to the general public. She points out the double meaning of exposure: (a) it means a personal encounter with harmful pollution and (b) yet it also highlights how data visualization exposes otherwise invisible environmental conditions, transforming them into tools for personal use or activism. By providing first-hand experience and information about personal exposure, we can potentially achieve changes in human perception and attitudes that can eventually also lead to changes in behavior.

To address the above mentioned issues, we developed a measuring device prototype called PAIR. It is a hardware and software initiative to bring pollution monitoring closer to everyday citizens-scientists and give them a tool to measure their environment on everyday basis. We claim DIY environmental monitoring can lead to a better recognition of a connection between polluters (pollution sources), pollution and health risks as well as necessary prevention. However, it is important to note that while we developed this prototype, it is the future we are designing in the first place. PAIR needs to be understood as a partial prototype of a system, rather than a stand-alone prototype.

After we built the first device, we immediately took it outside in the wilderness of the city of Prague, calibrated it and started interviewing potential users to know what are the situations when they would use a device like PAIR, what are the usability requirements, and how they wish to interact with it and with the results. This chapter focuses on the prototype development, technical limitations we needed to address, and the challenges we encountered during the process of building and calibrating. The next chapter is then dedicated to the user survey and interviews I conducted to question the public' awareness of air-pollution, personal concerns about participatory sensing and remarks about our proposed solution. Outcomes of both are then analyzed and evaluated in Chapter 8.

6.1 Design Criteria

In designing our prototype of a do-it-yourself environmental citizen sensor we studied all above mentioned projects, took inspiration from features that proved to be useful and tried to address the issues that our predecessors encountered. We especially considered following design criteria:

- the product must be wearable or easy to carry
- it must work in a cooperation with a cell-phone (we imagine a future scenario when the sensors are mounted directly onto the cell phone)
- it must be calibrated to be able to accurately convey the measurements
- the readings must be geo-referenced for further usage of the data
- the system must be interactive to a point where the user gets an immediate response
- and, if possible, it should include a social interaction feature

Taking all this into account, in cooperation with the Intermedia Institute at the Czech Technical University (*České vyskoké učení technické*) in Prague, we developed a prototype device (Fig. 7) capable of sensing the environment on-the-go. It is a small (11cm x 6cm) and light (300g) device built on an Arduino platform (see Fig.9) with an interchangeable sensor attached on the top. We worked with a carbon monoxide sensor (see Fig. 8), firstly because CO is one of the pollutants accounted in the Air Quality Index and secondly because of its price. As stated previously, pollution levels can vary at a small scale and carbon monoxide is especially concentrated around transport routes and disperses rapidly over a few tens of meters [Steed et al., 2003]. This is exactly when a mobile sensing device can be most useful and convey information about immediate conditions of an individual. For PAIR we used a basic measuring circuit (see schematic in Appendix II) suitable for sensor type tgs2600. If more sensitive sensors (e.g. type tgs2442) were used, a pulsed electrical circuit would have to be used (application of a circuit voltage pulse condition is required to prevent possible migration of heater materials into the sensing element material), with this adjustment and a change in software, our solution could also be applied for other sensors of similar physical characteristics, e.g. PAIR could therefore possibly sense also NO, NO_2, SO and SO_2. However, it is important to note that sensors from different manufacturers can differ significantly.

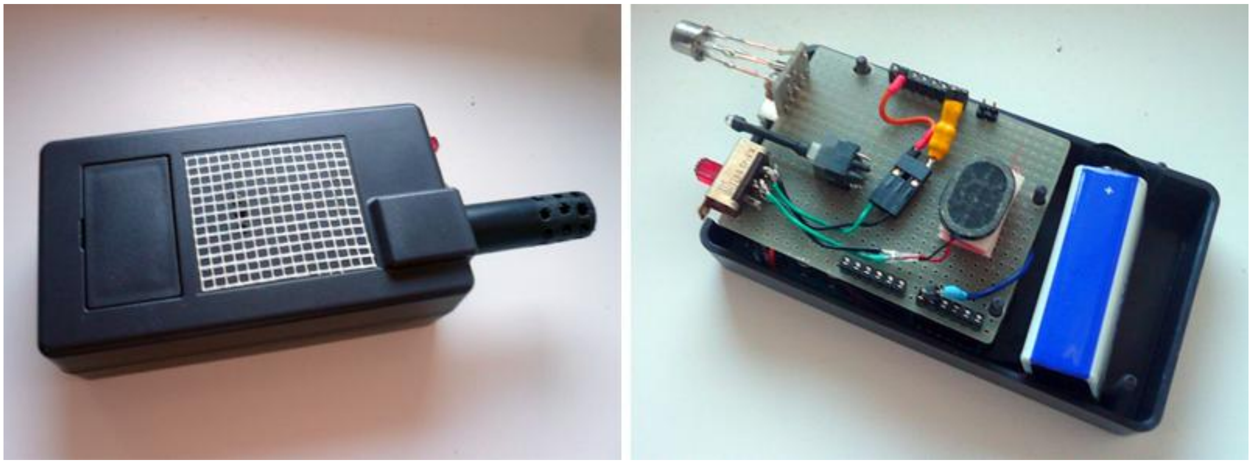

Fig. 7: PAIR –sensing device prototype. CO sensor is situated on the top with power and audio switches, speaker is in the middle of the device

Fig. 8: CO sensor – type tgs2600

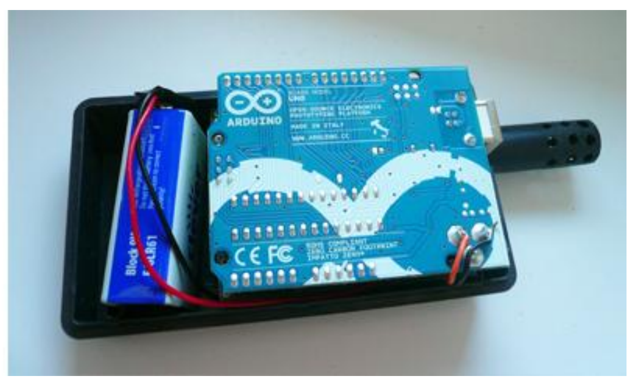

Fig. 9: Arduino board was used as a platform.

F

In the presence of a detectable gas, the sensor's conductivity increases depending on the gas concentration in the air. A simple electrical circuit can convert the change in conductivity to an output signal which corresponds to the gas concentration [Figaro, Product Information, 2005]. For an output signal we applied an “audio hack” – DTMF coding. The signal is encoded as a pair of sinusoidal (sine wave) tones which are mixed with each other. DTMF (dual-tone, multifrequency - system, which is also referred to as tone dialing.) is used by most PSTN (public switched telephone networks) and over private radio networks to provide signaling and transferring of small amounts of data. In our case the sinusoidal signals are replaced with rectangular ones. For tone generating, a standard library for Arduino environment called *tone* was used. For simplicity, the prototype works with the values of the maximum of three decimal places, i.e. max 0 to 999, representing a measured voltage of the sensor between 0V and 5V. Values are then presented as a series of "beeps" each of which stand for a single digit. Thus, whenever we switch on the acoustic output of a prototype, we will hear a sequence in a format ..... *A200D450 A201D450 * * **....... A202D455, where A is the number of the measurement in the sequence and D represents the value of measured voltage, * separates two measurements in the sequence. PAIR's beeping is hence similar to canary birds warning of dangerous gases formerly used in coal mines.

6.2 Calibration, storing and sharing

Once the first prototype was built, we needed to calibrate the PAIR's measurements. The easiest solution would have been to borrow an expensive, highly calibrated retail product and use its measurements for calibrating ours. However, neither Charles University's Faculty of Arts nor Intermedia Institute (IIM) own one, and communication with Institute of Chemical Technology (*Vysoká škola chemicko-technologická*) as well as with private companies proved to be difficult. Another of our "hacks" was thus to use the official measurements from Czech Hydrometeoreological Institute (CHMI) that are available to the public. We have chosen two official air pollution monitoring localities in Prague where carbon monoxide is sensed - Libuš station and the Hot Spot station in Legerova Street (see Fig. 10). At both locations we measured the air with PAIR in an immediate distance to the stationary CHMI sensors. We measured three times at each location in one day, and we returned to Legerova Station for another two pollution readings the other day. After we got this data, we translated the audio files into primary data by applying the Goertzel algorithm in a program in Python (program was written by Ing. Zdeněk Trávníček from IIM). At the same time we applied for the official data from CHMI because the data available online are displayed only in 8hour averages and more importantly, they cannot be accessed retrospectively. When we had both sets of data, we compared the respective values and calculated the correlation coefficient – 0,593. This indicates that the measurements were highly correlated however it is important to note that this was only an experimental calibration.

Fig. 10: CHMI Measuring stations at Praha 4 – Libuš and at Praha 2 – Legerova St.

Storing and sharing the measured concentrations were other issues that we needed to resolve. For the future, we count with an inbuilt memory capable of storing the measurements but for the moment the easiest way we found was in cooperation with iPhone. An iPhone app DTMFdec is capable of capturing the audio and decoding tones into following digits: 1234567890*#ABCD. Moreover, with an iPhone, the decoded readings are also very easy to *tweet*. Twitter also automatically geo-tags every *tweet* and, in our case, even eliminates the need for a built-in or stand-alone GPS. Also, while using the right # it is possible and easy enough to share, filter, or store the readings. Currently, the decoded readings need to be converted into the contaminant concentration (in ug/m^3) on computer; nevertheless, we envisage a tailored iPhone app that would allow the user to see the exact concentration on the display as well as to *tweet* it directly.

For the purpose of sharing, a web-based platform is necessary. We envisage the future application as a social network where everyone would have their own data stored and shared. It would be possible then to look up your daily cumulative exposure, compare it to others, look up the current conditions in places where you want to go or where you want to permanently move to. A Pachube platform can serve as an inspiration – it is a web-based application that allows thousands of sensors worldwide to be connected within a single visualization using a Google Map. As Dickinson [2010] claims, today, it becomes possible to collect and handle data from thousands or millions of deployed sensors in the world; ideally, web-enabled sensors for anyone to use. Pachube is an excellent example of this data management. It acts as a real-time data "brokerage" site, allowing users from around the world to post their sensor data to the Pachube site for anyone in the world to use [Haque, 2008]. Besides, Pachube has a powerful set of APIs for pushing and pulling data from the site. The site allows users to register, and create "feeds" of data in logical groupings according to metadata profile of the feed or they can post data from any type of sensor. Data is time-stamped when posted, and units are attached (e.g degrees Celsius) but including metadata about position is optional. Some key functionalities of Pachube must be necessarily a part of the participatory sensing application. While it is important to have a web based app containing all the data and enabling us to share the results, on on-the-go solution is even more desirable. As the data is geo-tagged, an augment reality experience should be the ideal outcome. Creating new personalized layers of information from the individuals' mobile devices would represent new and extended urban interfaces encouraging novel ways of interacting with the city.

6.3 Challenges to be overcome

During the design and development process, we recognized several challenges that need to be addressed to achieve a fully user-friendly sensing experience. To evaluate them and to outline future work, we describe the major ones we encountered:

- **Warm-up Time**: Electrochemical sensors require warm-up time in order to reach a stable operating temperature and function properly [McDermott and Ness, 2004]. The sensor we used for PAIR needs approximately 10 minutes of warm-up time, if it has been powered off for a significant length of time, and this delay can discourage the user from sensing on-the-go. The other option is to have the sensor on constantly but this would significantly affect the power consumption.

- **Temperature & Humidity**: Sensor performance is dependent on changes in temperature and humidity. Under extreme conditions of high humidity and temperature the accuracy can be affected. This is crucial to note especially in a scenario when people would carry the device (or, in the future, a sensor-equipped cell phone) in their bags, pockets etc. The sudden change of temperature and humidity after the device was taken out and switched on could significantly influence the accuracy of the measurements. The next prototype will be thus equipped with both thermometer and humidity sensor, the circuit will be adjusted (see Appendix II) and the results correlated accordingly.

- **Power**: New hardware, new sensors, more data logging and more radio power for sharing this data, puts extreme demands on power management for these new mobile devices. Creative strategies for opportunistic sampling, sharing and processing of these new data feeds must be developed. Delay Tolerant Networks (DTN) and similar approaches currently hold much promise [Paulos et al., 2008].

- **Ease of Use**: In order to gain wide-spread usage non-experts must be able to easily attach sensors to device that one already uses (cell phone, PDA etc.). Ideally the sensor should be on-board a cell phone but if a stand-alone device for sensing is developed, it must be small enough to be worn on clothes, backpacks or purses. For such solution standard connectors providing power and standard protocols for communication with sensors need to be adopted across vendors [Paulos et al., 2008].

- **Sensor Selection**: Air Quality Index is calculated with pollutants such as CO, SO, SO_2, NO, NO_2, Ozone, Particulates and other depending on a country legislative. We must ask the question what would be a reasonable set of sensors to use and what conditions make sense to measure? Certain sensors also cannot be in a close distance to others as they affect the results of each other and so a device with several sensors would be considerably bigger. Moreover, particulate matter ($PM_{2.5}$ or PM_{10}) and ozone, both pollutants with harmful effects on respiratory system, are so far very expensive to sense with small mobile devices.

- **Water-proofing**: Similar to humidity, water from rain or snow can affect the accuracy. A waterproof case must be provided with the device or, in case of cell phones, they must be constructed as waterproof.

- **Calibration & Accuracy**: While sensing on-the-go during our everyday regime, we will find ourselves in very different situations and under very different conditions. As participatory sensing relies fully on non-experts, their devices must be calibrated for all these different conditions. Statistic methods can be applied to maintain the integrity and to eliminate obvious anomalies. Approximate comparison with official data may also serve as an indicator.

- **Sensing Context**: Sensing context is the metadata that describes the conditions to which the sensing hardware is exposed and affects both the sensor data and its ability to perform the sensing operation. Knowledge of sensing context is required as an input to a number of operations of an opportunistic sensing system; it helps evaluate potential candidate sensor devices in terms of a given application request and, during servicing of application requests, indicates when sampling should be started and stopped. More generally, the sensing context is important for understanding the sampled data, especially when samples might be taken under suboptimal conditions — for example, when the device is in a pocket or purse [Campbell et al., 2008]. Context, in our case, means photographs (of pollution sources, sensing circumstances, weather conditions such as inversion etc.) and commentaries of unusual conditions.

- **Open Platforms & Abuse**: the very openness of such system makes it vulnerable to abuse by malicious users who may poison the information, collude to fabricate information, or launch Sybils to distort that information [Dua et al., 2009]. Erroneous or intentionally bogus measurements by an adversary need to be easily detected and flagged as such for removal from the system. The validity and integrity of the entire system are based on insuring this fundamental level of trustworthy data [Paulos et al., 2008].

- **Common file format**: geo-tagged measured data is supposed to be shared with the public and a developing a common file format is necessary.

- **Content protection**: sharing geo-tagged personal data also means disclosing the locations through which they pass and patterns of their movements. There must be an option for users to choose if they want to supply their data anonymously and their privacy must be secured. Currently we are witnessing more and more personal data published by people themselves on social networks so a scenario where people would have their public profile, interact with others or, for example, “compete” with others based on their cumulative exposure is also imaginable but a separate research would be necessary.

- **Environmental Impact**: Paulos et al. [2008] add a challenge, as he says perhaps of greatest importance. While the vision is to provide millions of sensors to citizens to empower new collective action and inspire environmental awareness by sampling our world, the impact of the production, use, and discarding, of millions of pervasive sensors must be addressed. Does the overall benefit of citizen science enabled by these new devices offset their production, manufacturing, and environmental costs?

Through personal and community pollution monitoring, citizen empowerment can be achieved if such a device was affordable for everyone – people living in big cities or rural areas, NGOs supporting eco transportation, or scientists who could use the data within larger research projects. Above all the already mentioned challenges, the biggest remaining challenge is hence *how to design a device and operating software easy enough to be operated by any user*. Anyone should intuitively understand how to work with the device, how to interpret their immediate measurements, and how to share the results with others. It is also necessary to design the system so that it provides an “enjoyable experience” for users – they must be encouraged to continue using the system and keep being interested in collecting and sharing the data. This can only be achieved by providing immediate response to their measuring which can be understood as a direct reward for the user’s effort. The other part of this enjoyable experience must be the web or mobile application for storing and sharing the data. Users sending or uploading data regularly to such application would see their personal air intakes retrospectively with possibility to see graphs and statistics of cumulative exposures. We believe only continual quality data accessible on-the-go as well as with hindsight can bring increased environmental awareness and potential behavioral change.

This thesis’s foci on outdoor air pollution in urban areas as the world population increasingly resides in big cities and urban areas are usually also the place where new technologies are adopted first. Nevertheless, concept of our prototype and participatory sensing in general can be used even in rural areas where air pollution is generally less of a problem but for example in winter time when people burn solid matter and the air can be extremely contaminated. PAIR can similarly serve as a prototype device for indoor pollution that is necessary to address especially in developing countries where people usually still cook on an open fire.

To sum up, we can empower individuals to personally collect, share, compare and participate in interpreting the personal measurements of everyday life by enabling networked, personal, mobile devices to become easily augmented with novel sensors but the outlined challenges remain to be addressed. These devices could be then used in a variety of situations and ideally, we should take them all in account while designing next PAIR like devices.

7 Air-pollution awareness

One of the key components of citizen science is general public awareness and public understanding benefits and potential uses of data collected by citizens, i.e. volunteers. In the case of participatory sensing it is also a public readiness to adopt such an approach. Hence, as part of the study, I conducted a survey about air pollution perception and air quality monitoring awareness as well as interviews to question the user requirements on PAIR's functionality and information delivery. The main purpose was to gain an insight into how big impact currently available information about air quality has on people's everyday lives; to research how the information is perceived and used; and what would be most beneficial to incorporate into mobile sensing devices. Both survey and interviews enabled us to better understand how our potential users learn about air quality today, when it impacts their decision-making, and when a personal sensing device would influence the decisions even more. The research also helped us uncover additional challenges in design and usability.

7.1 Survey

An online questionnaire was created focusing particularly on ways the information about air-pollution is conveyed by official agencies and media, how often people search for such information and which situation, in people's eyes, would benefit from an availability of real-time conditions.

The survey ran for 14 days and was answered by 98 respondents. The majority of them, 92.8%, live in bigger cities, and 72% even live in cities with more than one million inhabitants. This corresponds with the aim of the study – a look on and evaluation of current situation in urban areas, participatory air-pollution monitoring, and visualizations of the outcomes and thus extensions of urban interfaces. I present the most important results in precise numbers and a summary here; analysis and comments about both survey and interviews are to be found in Chapter 8.

- *How do people find air-quality at locations where they most often go?*

From all the respondents only 5% chose the best on a scale of five – excellent, 22% think it is good but most of the participants, 46%, chose third option – acceptable (in Prague this number increases up to 55%). 21% think the air they breathe is poor and 6% even find the air quality very poor.

- *Do the respondents suffer from any respiratory problems, allergies etc.?*

More than 45% of respondents claim they suffer from respiratory problems. To be precise, over 39% have allergies, 9% suffer from unspecified respiratory problems, and 6% have asthma. (Note: the respective numbers are together more than 45%, this is because some of the respondents checked several options)

- *Does the air-pollution at the locations where one most often goes represent significant potential health risks?*

77% of all respondents claimed they consider air pollution in locations where they spend most of time as an important health risks factor. According to the survey, situations when air pollution matters the most (and directly influences the decision making) are a) *decisions of where to spend leisure time* (70% of respondents), b) *choosing an apartment/housing* (58%), c) *doing sports* (53%), d) *spending time with kids* (24%), and e) *at work* (10%). It is interesting to note that mere 12% claimed they do not consider air-pollution while making decisions about their whereabouts.

- *Where do you inform yourself about air quality? If you don't, why?*

These two questions helped to reveal that 24% of participants don't obtain any information about air quality. From the other options, for example, 21% chose television as their primary source of this kind of information, however, major TV stations in the Czech Republic usually do not inform about pollution unless it is an extreme situation when limits have been exceeded several days in a row.

A considerably high number of respondents, 45%, answered they would like to be informed but they do not know exactly where to look for the information and another 27% don't understand the information as it is communicated even if they know where to look for it. This is a very high number supporting our goal to find different ways how to monitor the air quality by involving everyday citizens in the process.

- *Do you know where the official monitoring stations are?*

As stated in Chapter 3, the network of state owned monitoring stations is rather sparse and the survey shows that the respondents also do not have a clear idea where these stations are located. 20% of respondents think there is at least one station in every neighborhood, 67% of people think there is at least one in every city in the Czech Republic but, in fact, there were only 219 stations in 2009. 40% of respondents considered this number, when told, as too low. The numbers provided by state owned stations are too general to have significant impact on individuals. Air pollution is highly location specific and people would appreciate having localized information from places they go to, to have it in real-time and to be informed immediately so that they can immediately react accordingly.

- *If your mobile phone was able to measure the air-quality, you would be interested in..?*

By this question, I wanted to question our design goals for developing PAIR, we gave participants 6 options to choose from: 66% of participants would be interested in knowing their actual exposure at a given moment; 56% would like to be able to see their cumulative daily exposure visualized e.g. on map; and 53% would welcome to see the potential health risks for their personal exposures. Approximately a third of the respondents would also be interested in data measured by other people and 19% would only let their phone feed the online application or research projects but wouldn't interact directly with the measurements. Another 19% don't think that they would use sensing functionalities at all.

Different functionality preferences of potential users suggest sensing devices like PAIR could be applied in a variety of ways while allowing the user to choose their preferred mode. Also, when designing the prototype we can define groups of users with different goals and create personas to envisage different scenarios of use. Some users are willing to actively analyze the data to make better decisions, some are not yet ready to use such an information or, possibly, cannot imagine the scenario when (now unavailable) information about pollution could play a significant role in their lives. In that case it is possible to imagine the user familiarizing themselves with the device and appreciating more features later on as the link between the personal sensing and its impacts (or benefits) becomes clearer. Another option to consider is an approach used by for example Seti@home – a distributed computing effort to gather data from the mobile devices, e.g. thanks to applications running on the background without direct interaction with the user. Such data could be then used for scientific purposes or as a feed to a web-enabled application for sharing the sensed values but wouldn't impact the individual user which is one of the aims of participatory sensing and environmental awareness.

7.2. Interviews

While designing our prototype, the main questions were how and when the users are going to use the mobile sensing device, and what information is and is not relevant to them. 4 interviews were conducted to gain better insight on functionality concerns, scenarios of use and usability requirements (especially the data display and visualization). The interviews allowed me to ask more targeted questions about current air-pollution monitoring and its communication via media and CHMI website and to identify the missing areas of concern that mobile sensing device could cover. I selected 2 men and 2 women with very different biases and knowledge about the environmental monitoring. I briefly sum up each of the interviews with interviewees background details and then analyze the resulting common points for design and usability of citizen sensors.

Jan: Jan is a sales-representative in a successful company. He spent over 10 years living abroad and doesn't consider himself as too interested in environmental issues. While he finds the quality of air where he lives and works good, he thinks there are neighborhoods in Prague where the air pollution causes real problems (e.g. Zborovská St. in Prague 5). He also believes there is a direct connection between air-pollution and health risks. For example, he never runs near big roads and minds air-quality when choosing location to live. However, he is not aware of being informed about air-pollution. For him, the presented data is "indigestible", i.e. not easy to understand for non-professionals.

Jan would appreciate more localized information in situations of high and dangerous concentrations of pollutants and buying a property. He analyzed the CHMI website and claims he would like to know more than what CHMI is offering, and especially be able to access data from wherever and whenever; he would also welcome the knowledge of his potential health risks or health recommendations. For him, measurements on-the-go are not as important as a centralized web database of all the data from everywhere that he could access when needed.

Pavla: Pavla studied environmental protection and today she works in a research institute for geology. She is highly interested in ecology, nature and healthy lifestyle. Pavla suffers from respiratory problems and allergies and considers the quality of air she breathes to be bad. She is also persuaded there is a direct link between air-pollution and health risks. Air quality plays an important role in her decision making in general, she would even like to move to countryside, however, as she says, job availability is a more important factor.

Thanks to her studies and interests, she is informed about air-quality especially by her friends and acquaintances but she also relies on her smell and her own judgment (she tries to avoid routes with high traffic etc.). The information available on CHMI website is relevant and useful but a more descriptive legend including methodology of the calculated AQI would be useful for her. Particularly, she would like to know what the presented limits are based on (Czech law, EU law?).

If she had a device like PAIR, she would use it for sensing the places she most often goes to (work, leisure time) and she would like to compare the concentrations caused by high/low traffic. She thinks of these measurements as exploratory and exemplary, not as an everyday tool. On the other hand, if there was a web application, she would find it beneficial to be able to access history of her exposure to, for example, consult it with her allergist. To see the data by other users would be interesting too but in general her measurements would be the most important for her.

Jiří: Jiří is a project manager in a local NGO. He finds the air in Prague is generally worse than in Cheb, his city of origin, but still acceptable. He agrees that bad quality of air we breathe can cause health problems but he doesn't suffer from any. Air quality plays an important role in his life when deciding about his leisure time, when doing sports or when choosing a location to live at. His work is located next to a much polluted Legerova Street in Prague, where pollution as well as noise levels exceed the limits regularly.

Jiří is not aware of being intentionally informed about air-quality – he supposes that media communicate the pollution levels, especially in cases of danger. He also doesn't know where exactly he would look for the information if needed. At the same time, he realizes there is a very direct connection between traffic & industry and air pollution. He is persuaded that if air pollution levels were available for any property, they would be directly influencing the prices of real-estate.

If he had a device like PAIR, he would use it from curiosity; especially at the beginning he would be interested to see his own exposures especially on his way to work. He would refer to the first measurements later on; he doesn't need to sense the air regularly, but would like to have it in extreme or dangerous situations. If a networking site was online, he would look at the data of others but his personal data would be most beneficial to him.

Jana: Jana works as a coordinator in another local NGO. She finds the air in her city is acceptable and she doesn't suffer from any allergies. She is sure, though, that air pollution has a negative impact on health. She considers it while deciding about her leisure time and she would consider it if moving to countryside otherwise she thinks the air quality in a city is the same, not depending on a particular neighborhood or street. She doesn't obtain any information about current air situation; nevertheless she has been to situations where people discussed it because of smog and bad dispersion. As a reason why the media does not inform about air quality along with the weather conditions, Jana reckons it is because it would be hard to display the information for every location.

By looking at the official CHMI website, she would prefer to have more information about the data – what, exactly, do they mean by moderate pollution? The legend should be more descriptive and also the standards they are using better explained. As she is working with many foreign NGOs and is used to a comparison between countries in all aspects, she would like to know how the Czech Republic stands compared to others, if the same limits for concentrations are used internationally, etc.

When presented a mobile sensing device, Jana thinks of her immediate exposure in situations of smog, etc. She would use such device occasionally and she would be interested in a web application where others share their data. She doesn't suffer from any respiratory problems but realizes that for people who do, a database with localized data would be very useful. For her, personally, an overview of her daily exposures would be important and on an occasional basis she would like to be informed what health risks such concentrations represent. Jana also thinks if this data was mashed with real-estate offers, it would change the market significantly.

Results from all 4 interviews conclude that there is a certain fascination about personal measuring devices, about having a tool how to turn our environment visible and measurable, especially when the official data are almost unknown to general public. The only person who knew exactly where to look for the official air quality information was the interviewee who studied environmental protection. Besides, all respondents believe air pollution directly impacts one's health. All of them would like to measure their own exposure, if they had an easy-to-use mobile device, preferably their cell phone equipped with sensors. From both, the survey and the interviews, it turns out people consider the air quality while making choices they can influence, e.g. when spending the leisure time or moving to a new neighborhood but it is rarely a determining factor. The interviewees said they would probably use the device especially at the beginning when the curiosity and novelty factors are in play – to explore their exposure at places they most often go to - and they would refer to these results as exemplary ones.

Visualization of data was discussed as well. It is necessary to convey the results in a comprehensive way. More than the exact numbers, users would appreciate a scale of, for example, 6 grades of air quality from excellent to very poor. The scale should be complemented by potential health recommendations and also offer possibilities to access more detailed information about used limits, methods etc. All of the interviewees would use a web application for storing and sharing measurements. They would be primarily interested in seeing their sensing history, statistics and data evaluation but they would also use the data from other users occasionally (in the survey, 30% of respondents). Prevailing opinion was that this would be interesting for comparison but the most important data would be one's own. This partly contrasts with the discourse of many papers about citizen science. They often tend to judge it as a tool to bottom-up political action and increased grassroots activism is envisaged where technology serves as a means to revelation and also provides evidence, hard data that can be used in civic campaigns. It is probable that such scenario would occur too but from this study it seems that a more reserved adoption of participatory sensing would take place. People primarily think of the possibility of sensing their environment in first person – what can *I* learn about the air I breathe, what impact does it have on *me*, but of course they also imagine that sharing such data could generate bigger assets. In survey and in interviews, choosing housing and leisure time were the most popular situations when people need air-quality data and these are both representative examples when shared knowledge would help the best.

8 Data Analysis - Fixed Sensors vs. Amateur Data Collection

Expert literature, analysis of current measuring techniques documented on the examples of practice in United States and in the Czech Republic, case studies of the preceding projects, prototype device design, a user survey, and interviews were my main sources of data. In previous chapters I introduced them in detail, analyzed them and presented my findings together with commentaries. This chapter takes a look at all the data and generalizes the main results and outcomes. It presents an assessment of the potential and the limitations of citizen sensors and their data products; it also comprises design and usability recommendations.

8.1 Advantages and Disadvantages of both approaches

Large-scale, publicly accessible environmental sensing projects hold a lot of promise. It is important, though, to critically approach the potential benefits and limitations to understand how we could use them for lasting and profound changes in society. In terms of air pollution sensing, we identified key advantages of using sensor equipped mobile devices as:

- *Better coverage*

  The network of official measuring stations is sparse even in the most developed countries. It provides data useful at a national level and serves the state environmental protection strategies; for individuals, personalized, finer-grained data would be more relevant. Besides, mobile devices are already ubiquitous and thus can become excellent physical sensing infrastructure. They can even provide coverage where static sensors are hard to deploy and maintain.

- *Increased environmental awareness*

  If devices that people already use start conveying information about pollution levels and contaminants concentrations in an understandable way, we can achieve an increased sensitivity to the environment issues. For example, it would allow the users to compare their existing perceptions of pollution to actual CO (or other contaminant) levels in the area. The results of personalized sensing can also potentially lead in making a clear link between pollution sources, pollution and its impacts.

- *Exploring neighborhoods*

Having a personal sensing device would allow people to explore their neighborhoods and urban environments. They could easily identify pollution hotspots, find the respective contaminant's peaks, or identify *lines* of the same concentration level (lines denoting the distance from the pollution source where the contaminant value is consistent). Users could also investigate highly localized CO variations, i.e. differences between sides of a street, sides of a pavement, around corners, etc. This could be applied as an innovative navigation tool – we are already familiar with online maps offering us directions based on a means of transport, the shortest way, avoiding highways; now we could have an option to choose the "least polluted" way.

- *Increased air pollution issues knowledge*

From the survey and interviews, people realize air-pollution represents potential health risks but they base their knowledge on reasoning, not on any hard data. Better knowledge of environment they live in could directly affect decision making. There is a space for research to bring better understanding how general accessibility of air pollution data could influence for example marketing strategies or real-estate. Today, popular mash-ups of real-estate offers displayed on a map could be complemented by a layer of data including air pollution. Such visualization would be a very powerful tool allowing people suffering from allergies or respiratory problems to better choose their housing, their vacation spots or it would serve for urban/rural comparisons.

- *Behavioral changes*

Sustainable living gains a lot of attention today and is only possible if it is fueled by necessary behavioral changes. Realizing what the issue is and learning how an individual can take action are the first steps to such changes. I claim a personal sensing device should always be complemented by a mobile phone or web application providing a look back at our own data. We should be able to see our immediate as well as daily cumulative air quality exposure, to inspect up and down trends and see it visualized on a map of our city (or movement). Only by making the trends and longer pattern visible, can we promote behavioral changes that can eventually result in improved outdoor air quality.

- *Educational tool*

In Czech Republic, there is an increasingly popular environmental education among pre-school and primary school children in cities. They introduce the basics of recycling, food chain, farming etc. Air pollution sensing devices could serve as an educational tool during these lessons or support physics, chemistry or biology lessons. Children could learn how their immediate environment affects their body (e.g. cough, headaches, asthma or dizziness). They can be encouraged to gather data and then rank their exposure levels with their classmates. They can even write an air journal to, for example, compare weekdays and weekends, to see when and where they are exposed to highest concentrations of pollutants etc.

- *Citizen Science*

Citizen science helps people collect, share, compare, and participate in interpreting the personal measurements of their daily lives, and reciprocally, people measuring and gathering data are indispensable for citizen science. Long-term research projects rely on volunteers supplying data on a scale that could never be manageable by research teams. Crowdsourcing ideas entered science with the same power as they entered industry – user generated content is relevant not only for the users themselves but can also be studied and applied in other research areas. Volunteers can gather GIS data and map invasive plants, document water sources in drought or create a digital layer of air pollution or noise data from everywhere they go. There are many applications of citizen science and sensing air is only one of them.

- *Increased activity at a community level*

Mobile sensor technology can benefit from local communities to become a driving element for environmental sensing and many research projects stand to reinvigorate environmentally focused civic engagement. Especially in neighborhoods with a lot of traffic or industry, grassroots activism can be supported by the right tools. By measuring the exact conditions in their community, citizens can raise awareness of their needs and support it by measured data. Mobile phones can also acquire, process, store, and transfer contextual data such as notes, photos, observations [Kanjo et al., 2009] and thus point out and highlight pollution sources and foster open debates. However, as Anne Galloway [2008] notes that given public concerns around environmental risks and their connections to technological progress, we cannot expect sensing projects to create such profound changes. They promote more critical reflection on the values and goals of the very projects, and carefully consider the limits of active citizenship's power. Her words were confirmed by this study where people at first think of their own benefits but eventually their joint efforts can lead to a community action.

- *Complementary data for official agencies*

Government installations use extremely sensitive and accurate measuring devices but as discussed in Chapter 3, there are only few of them in biggest cities, 1 or 2 in medium sized cities and usually none in smaller ones. Highly accurate data measured over a long period of time from the exact same locations are, of course, necessary especially as data for the legislative of environmental protection. At the same time, air pollution affects the health of everyone and currently we don't have any means how to obtain information about our personal exposure. Data from participatory sensing can thus complement the official measurements and can be used also as an inspiration for a closer cooperation between state agencies and civic organizations or individuals. Moreover, mobile sensing devices can also be used to validate places for new fixed sensors or they can investigate the local areas if current stations are at a representative location.

These were the key advantages and potential uses we identified during the research. Nevertheless, there are also challenges that are still yet to be resolved.

8.2 Challenges to be overcome

Key disadvantages of mobile air sensing currently are:

- *Accuracy*

Accuracy is the key concern for participatory sensing. In an ideal case, the sensors should provide accurate measuring in all situations and under all conditions. Sensors we used for PAIR are for example, to a certain degree, dependant on temperature and humidity and to calibrate the sensors for all the anomalies remains a challenge to solve. It is not necessary to have as accurate data as the fixed stations provide but at the same time, the data must be of good quality. If the user is making effort in measuring with his own device, he must be rewarded with useful data otherwise he will quickly abandon new attempts. However, how to calibrate sensors for all types of conditions remains a real challenge.

- *Privacy*

It is necessary for a mobile sensing device that the data it produces is geo-tagged. It also means that when participants of public data collection share their data over unattended wireless sensor networks they disclose the locations through which they pass and patterns of their movements. There already are popular applications revealing people's exact locations such as Google Latitude or Foursquare but the possibility of anonymous sharing of personal data is desired. Privacy of the data should be a key concern for any participatory sensing application.

- *Reliability*

Our approach supports openness of the whole system where everyone can take part and contribute. The system is therefore open also to malicious users who wish to infiltrate erroneous or intentionally bogus measurements. Those need to be flagged and reported, e.g. through statistical methods, comparisons to official data or systems of thrust.

- *Sensor selection*

Air Quality index as it is calculated in most of the countries, comprises from 4 to 7 contaminants concentrations. A device operating with one sensor can be considerably small and light but the more sensors we add, the bigger it needs to be as the sensors could affect the accuracy of each other. Sensor selection can thus mean to choose one and concentrate on the contaminant that causes the biggest problems in the location of interest or to have a wider selection of sensor but in a bigger device. AIQ also usually includes particulate matter ($PM_{2.5}$ or PM_{10}) and ozone. Both of these health affecting pollutants are, so far, impossible to measure with a small mobile device. So far, we can envisage measuring of at least CO, SO, SO_2, NO, NO_2.

- *Information display and visualization*

Interviewees of this study were commenting on inapprehensible communication of data from the fixed sensors by state agencies. There is not enough data to display to satisfy everyone's needs but also the data that is presented is not displayed well. For example, there are several issues with a map on the CHMI website (see Fig. 2): it is very small and not zoomable - in the areas with more stations such as Prague, the colored dots (or pins) overlap each other and we, firstly, cannot exactly see what the situation is like at our location and, secondly, we cannot easily click on these overlapping dots to access the actual numbers. Moreover, the information is not displayed for all the stations as not all of them measure all contaminants from AQI.

A user-friendly application solving all of the issues could be a map mash-up with several options of views such as current location, history of measurement at this place, my history displayed on a map and as a graph where the longer patterns are visible. Functions of general index rating the air quality on a scale as well as more detailed information about each pollutant, its concentration limits etc. would be appreciated and used. Seeing data shared by others is an asset but own data was more important for participants of this research. Most of the users would also, along the pollution maps, welcome seeing their health recommendations resulting from their own data and this function could be of great help for people suffering from respiratory problems.

9 Conclusion

We often think of mobile devices simply in terms of their communication capabilities, but they are increasingly capable of tracing our movements, offering location-specific information, and also collecting information about the spaces through which we pass. Recently, augmented reality devices moved from the research labs to industry production, and more importantly, they entered our everyday lives. Today, augmented reality becomes an actual reality with “iPhones” and “Androids” capable of overlaying the physical world seen through a cell phone camera lens by layers of digital information, imagery, etc. Besides, current trends support the notions of ubiquitous computing and Internet of Things that envision a future where everything can turn into a networked data source. PAIR, the prototype I presented above, is a partial manifestation of this possible future where physical world is interweaved by digital data from various sensors, chips, and ad-hoc networks.

While government-based organizations such as the Environmental Protection Agency in the United States or Czech Hydrometeorological Institute calculate air quality based on highly sensitive readings, their Air Quality Index is produced through fixed monitoring spread over a wide geographic distance. This approach doesn’t bring enough fine-grained data important to raise air pollution awareness among individuals and it doesn’t provide people suffering from respiratory problems with the personalized information they need about the places they go to and about their exposure. However, democratization of technology and connection of mobile devices with low-cost sensors promise an alternative way, DIY environmental sensing that augments the official knowledge and allows a relatively accurate estimate of an individual’s exposure.

The objective for this research was to look at how we can measure and contextualize, temporarily and geographically, exposure to air pollution in a way that allows analysis and interpretation at an individual as well as specific group level, in order to empower citizens and give a better understanding of the environment they live in. I presented a concept of air pollution sensing based on community engagement, envisaging people equipped by mobile sensors measuring the air as they go and sharing the contaminant levels with others. Wearable sensors or sensors mounted onto devices such as mobile phones, PDAs or iPads detecting and measuring the air pollutants can enable people to learn about their immediate air intake and exposure on-the-go and can also allow them to examine their data retrospectively. A web application or a database of such measurements, past as well as real time, where data would be stored and made accessible for everyone can motivate further sensing as well as encourage new users. Participatory sensing thus holds a lot of promise to reinvigorate people's awareness of and concern for pollution changes; it can be considered a persuasive technology - immediate feedback can make people realize what they can do, make them aware of air pollution causes and eventually even bring behavioral changes.

As part of this research, a prototype device called PAIR was developed. It is a small and light mobile device with an interchangeable sensor currently capable of sensing carbon monoxide (a contaminant counted in AQI) but possibly also SO, SO_2, NO and NO_2. PAIR is an embodiment of the initial hypothesis and shows that building a reasonably inexpensive device capable of sensing air is already possible. Nevertheless, to achieve a wide spread use of such devices in the future and an adoption of participatory sensing concept by masses, we need to consider mobile phones and other devices people already use and aim towards equipping those with more sensing and processing power. This thesis then identified and evaluated the advantages and disadvantages of personalized mobile sensing as well as outlined challenges it has yet to overcome.

Undoubtedly, sensors, chips and ad-hoc networks play increasingly important role in our everyday interaction with people, objects, and the environment. Novel extensions of urban interfaces allow us to connect and control the physical world by sensing. Through personal and participatory sensing, people are empowered with sensors to resolve their critical problems, they are enabled to react immediately and improve their everyday processes. Citizen sensing technologies have big potential in supporting bottom-up community participation, in connecting individuals with scientists, policy makers and NGOs. Also, they have use in preserving one's health (respiratory problems, cancer prevention), in raising environmental awareness, or in the application of monitoring air quality where no ground-based monitoring networks exist.

I focused on air pollution sensors but the concept can be generalized and used as an overall trend in a tighter interacting with the environment we live in. There are various low cost sensors that scientists as well as artists increasingly use in exploring the innovative ways of interaction; pollution sensors are only a small part of them. In the future we imagine, one will have the possibility of choosing the right combination of sensors that best meets their needs, whether it is healthier air to breath, improved physical performance, or the reduction of utility costs. It is not difficult to imagine that, thanks to these new functions of our already adopted and wide-spread devices, our interaction and relationship with the space will undergo significant changes in near future. In fact, it is already happening.

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Appendix I – Online Survey

1. V kterém kraji žijete?
    a. Brno
    b. Praha
    c. Jihočeský
    d. Jihomoravský
    e. Karlovarský
    f. Králové-hradecký
    g. Liberecký
    h. Moravskoslezský
    i. Olomoucký
    j. Pardubický
    k. Plzeňský
    l. Středočeský
    m. Ústecký
    n. Vysočina
    o. Zlínský

2. Stav ovzduší ve místech kde se běžně pohybujete považujete za:
    a. vynikající
    b. dobrý
    c. přijatelný
    d. špatný
    e. extrémně špatný

3. Trpíte nějakým z následujících onemocnění:
    a. alergiemi (včetně senné rýmy)
    b. astmatem
    c. respiračními 59ice59em
    d. jiné:
    e. ničím z výše uvedených

4. Souhlasíte s tvrzením, že znečištění ovzduší v místech, kde se pohybujete nejčastěji, představuje významná potenciální zdravotní rizika?
    a. ano, souhlasím
    b. spíše souhlasím
    c. spíše nesouhlasím
    d. nevím/chybí mi dostatečné informace k posouzení

5. V čem hraje/hrála roli kvalita ovzduší ve Vašem životě? (i 59ice odpovědí)
    - při výběru bydlení
    - při volbě trávení volného času
    - při aktivitách s dětmi
    - při sportu
    - v zaměstnání

6. Kde získáváte informace o stavu ovzduší
    a. z tisku (prosím upřesněte)
    b. z 59ice59em59
    c. online 59ice59 (prosím upřesněte)
    d. web ČHMÚ

e. informace nezískávám

6.a Informace nezískáváte, protože

a. zajímaly by mne, ale nevím, kde je hledat
b. vím, kde informace hledat, ale jsou pro mne nesrozumitelné
c. znečištění ovzduší nevnímám jako 60ice60em/nezajímá mne

7. Jak běžné jsou podle Vás státem spravované měřící stanice pro kvalitu ovzduší ve městech v ČR?
    a. domnívám se, že je v každé ulici alespoň 1
    b. domnívám se, že je v každé čtvrti alespoň 1
    c. domnívám se, že je v každém městě alespoň 1
    d. nevím/žiji na venkově

8. V České republice bylo v roce 2009 celkem 219 měřících stanic, myslíte si, že je tento počet
    a. dostatečný – odborníci ví, kolik stanic je potřeba
    b. nedostatečný, mělo by jich být 60ice

8.b Počet měřicích stanic je nedostatečný, protože (i 60ice odpovědí)

a. získaná data jsou příliš lokální a nedají se z nich účinně vyvozovat obecné závěry
b. bylo by přínosné mít údaje přímo z 60ice, kde se pohybuji
c.

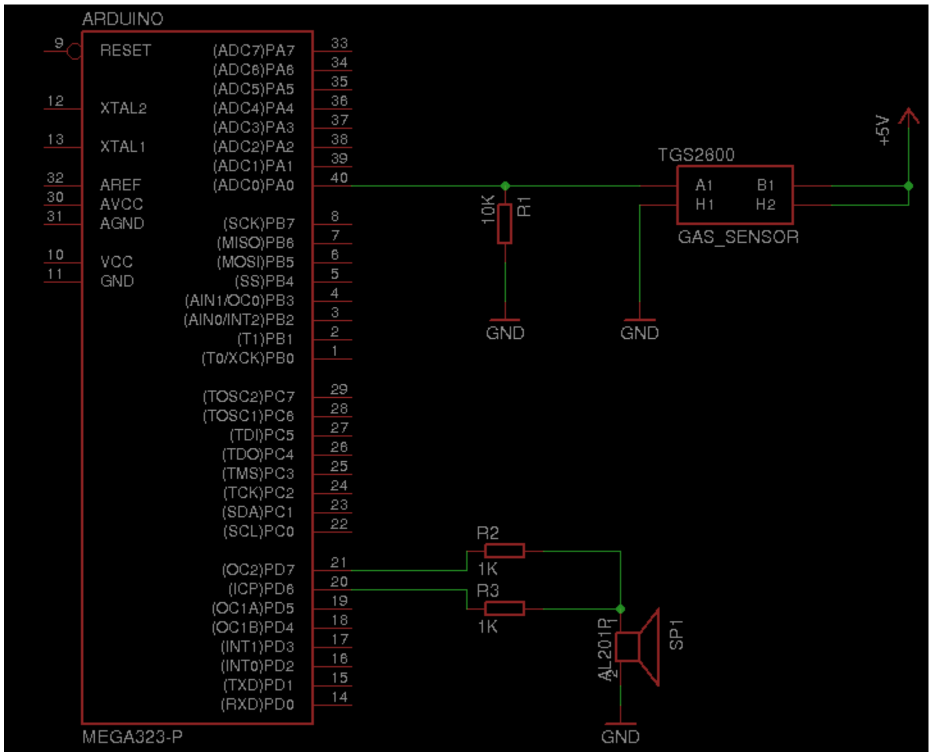
9. Pokud by Váš mobilní telefon uměl měřit znečištění ovzduší, zajímalo by Vás:
- aktuální stav znečištění v místech kde, se pohybuji
- má celková expozice, které jsem denně vystaven (zobrazená např. na mapě)
- zdravotní rizika, která z mých konkrétních údajů vyplývají
- data naměřená ostatními uživateli ve městě, kde žiji (zobrazená např. na mapě)
- pouze by mi nevadilo, že můj telefon odesílá naměřená data, např. pro vědecké účely
- taková funkce telefonu by pro mě byla zbytečná

10. Jste
    a. muž
    b. žena
11. Žijete
    a. na venkově
    b. ve městě

12. Věková skupina
    a. do 20 let
    b. 20-30 let
    c. 30-50 let
    d. 60ice než 51 let

Appendix II – Prototype schematic

A) PAIR's schematic



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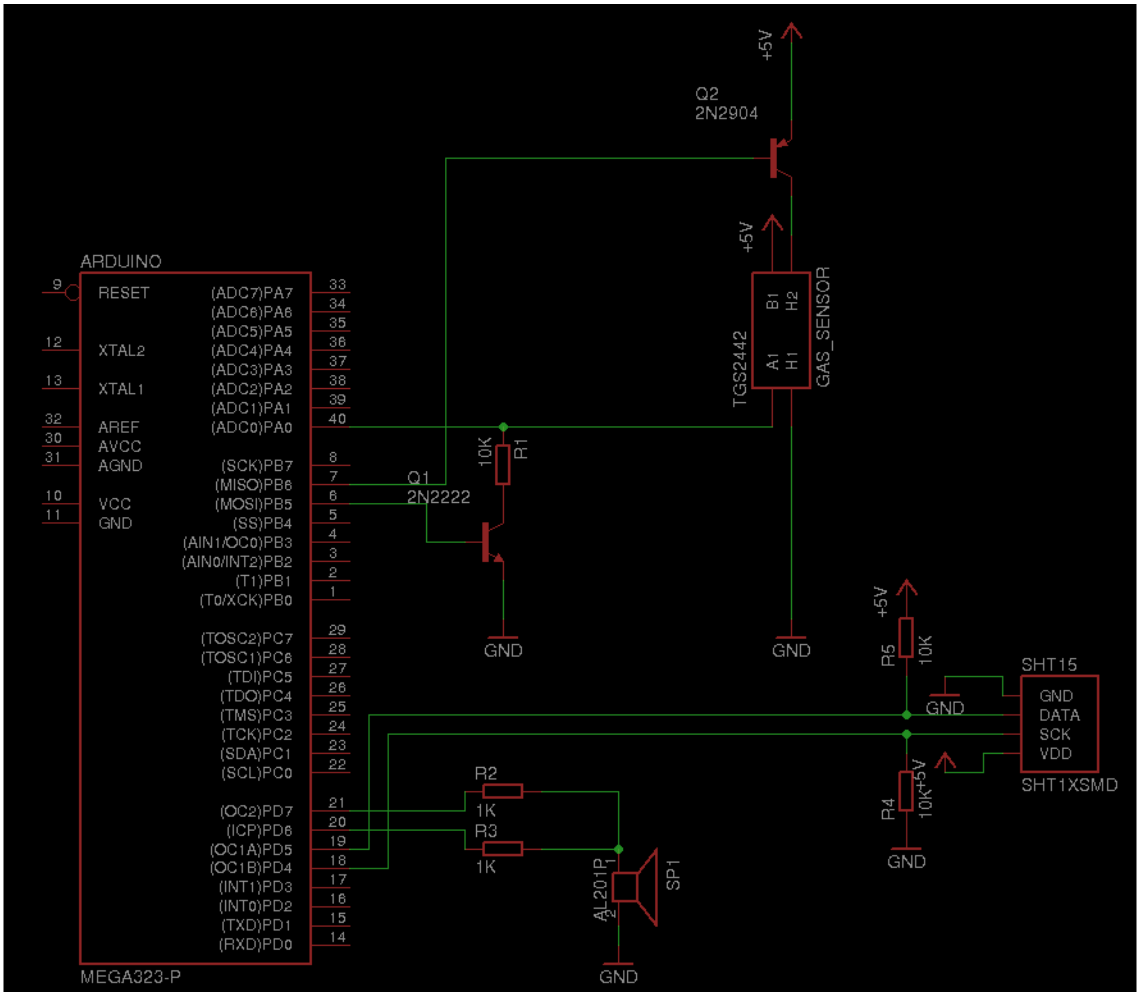
B) Prototype schematic for a circuit with included temperature and humidity sensors



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Evidence výpůjček

Prohlášení:

Dávám svolení k půjčování této diplomové práce. Uživatel potvrzuje svým podpisem, že bude tuto práci řádně citovat v seznamu použité literatury.

V Praze, 1.1. 2011.

Radka Peterová

Jméno	**Katedra / Pracoviště**	**Datum**	**Podpis**