A Universally Designed and Accessible Indoor Air Quality Monitoring and Warning System

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***Abstract* – A Universal Design (UD) approach to develop technology for combating health problems due to Indoor Air Pollution (IAP) from burning solid fuels leads to better accessibility and inclusivity. This concept guided the design and implementation of the prototype designated as Universally Designed and Accessible Indoor Air Quality Monitoring and Warning System (UD-IAQMWS). The system is a network of sensor-nodes that collaboratively check the Indoor Air Quality (IAQ) and notify users by means of a three-color code, auditory, visual and tactile notifications, of changes in the air quality. The notifications are designed to serve visually and hearing impaired for improved accessibility. Data from the World Health Organization (WHO), Laboratory tests, field interview data from potential users, and the use of personas in system evaluation, address user disabilities to render the system inclusive. The integration of Human-Computer Interaction (HCI), as well as a special feature (concept) specifically designed to prevent child exposure to IAP for increase accessibility, are a few innovative aspects of the system.**

Keywords - Universal Design; Accessibility; HCI; Solid fuel; Indoor Air Quality; Indoor Air Pollution; Sensor Network; UD-IAQMWS.

I. INTRODUCTION

Many systems have been invented, designed and developed to combat Household Air Pollution (HAP), a global health problem as declared in the WHO Factsheet 292, (updated May 2018). This Factsheet shows a high mortality and morbidity rate of about 3.8 million annual deaths due to HAP [1][2]. Good Indoor Air Quality (IAQ) is essential for households dependent on solid fuels for sustenance. However, some smoke detectors and fire alarms are audible but not visual, hence not very practical for hearing impaired users [5]. How then does a smoke detector address the needs of a blind or deaf person? Could there be a better way to design such a system so that it is accessible to users with disabilities or impairments?

Indoor Air Pollution (IAP) as a result of cooking with solid fuels accounts for most health-related issues, of which respiratory diseases are responsible for the high worldwide morbidity and mortality. Many WHO studies and publications confirm indoor air pollution as one of the major contributors to the causes of pneumonia, bronchitis and other chronic obstructive pulmonary diseases worldwide [1]. Also, from Figure 1, it can be observed that the pneumonia rate is rather high in children with increased exposure to carbon monoxide. That is, hypoxemic cases rise to about 25 and above for levels higher than 3 ppms, and more than 50 children are affected, for CO levels exceeding 3 ppms.

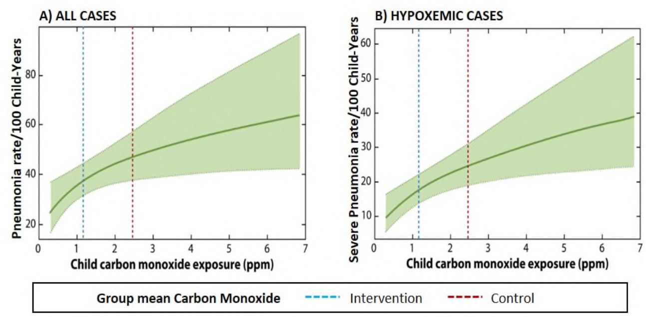

Figure 1. Physician-diagnosed pneumonia due to Carbon Monoxide (CO) exposure [2].

Any solution proposed as a means of solving or preventing some of these health problems must be without impediments. Otherwise, these would have to be studied, understood and overcome. Perhaps through research, development, and innovation, a proper technological solution can be found. This would lead to designing a system that monitors IAQ in homes using solid fuels for cooking or heating as a preventive measure to any resulting health hazards.

The Universally Designed and Accessible Indoor Air Quality Monitoring and Warning System (UD-IAQMWS) we propose is a universally designed IAQ sensor warning system integrating sensor network and Human-Computer Interaction (HCI) that offers a more accessible innovative approach to detect pollutants. A network of sensor-nodes checks IAQ and provides visual, auditory and tactile warning signals to any user or users exposed to IAP or HAP [2][4]. The system is mainly composed of the hardware unit and the mobile app that enables the system to connect to a smartphone via Bluetooth. The power and the potential of the mobile platform are harnessed for accessibility and inclusivity. The concept of UD-IAQMWS came as a research and development project partly sponsored by the Mozambique-Norway Accessibility Partnership (MAP) that was carried out in Mozambique. This paper presents a simplistic view into an otherwise complex project, with the hope of reaching the widest possible audience.

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The goal of the project is to research, design and develop an IAQ sensor and warning system for homes using solid fuels as the main energy source. Its deployment where the risk for harmful emission could be hazardous to human health must provide an effective preventive solution. The system could hence be described as a Sense-Detect-Warn system, easy to use and maintain. The design and development are in accordance with the Universal Design (UD) principles. UD is defined as the design of products and environments to be usable by all people, to the greatest extent possible, without the need for adaptation or specialized design [3]. The system also encompasses accessibility, inclusivity and the integration of a sensor network with HCI [4].

Through research, experiments, measurements, and testing, pollutant properties and the threshold for detection were determined. Built to specification, the system must be able to detect the pollutants given their characteristics. For example, an odorless and colorless gas, such as CO, is a dangerous gas to breathe in. It is about the same density as air, it is emitted from burning solid fuels and, if concentrated at 12.5% to 74.5%, it would explode. However, at concentrations of about 75%, it will burn in the air if ignited and can thus be used as fuel [5]. To detect CO, a standard sensor must be used to calibrate the sensor intended for use to keep all detection levels and thresholds on a par.

After the introduction section, Section II discusses related works. The research methodology is described in Section III. Section IV presents the design and development process. Section V describes user testing. Section VI presents the results and the results are evaluated and discussed in Section VII. Finally, Section VIII concludes the paper.

II. RELATED WORKS

IAP has been a serious problem ever since human beings started cooking inside their homes instead of out in the open, and it has health as well as economic and environmental impact.

A. *Health effects*

Research by the WHO shows severe health outcomes due to emissions from indoor cooking. WHO states on its website in Factsheet number 313, updated September 2016, the following summarized points [6]. In 2014, 92% of the world population was living in places where the WHO air quality guidelines levels were not met [6][7]. Three billion people are also at risk due to exposure to indoor pollution from using biomass and coal [7][8].

In poorer communities, the way of life requires men to be out fending for their families. Therefore, women and children who spend more time home, especially in the kitchen, cooking, are the most affected by HAP [9]. For example, the 95,000 Nigerian annual deaths related to cooking with solid fuels, include children below 5 years. The Nigeria Demographic and Health Surveys (NDHS) 2003-2013 study also indicates an about 0.8%, 42.9%, and 36.3% of neonatal, post-neonatal, and child deaths respectively [10].

B. *Economic and environmental impact*

Energy potential decreases with poverty, therefore, reliance on solid fuels often leads to the environmental quagmire of deforestation. A 2011 World Bank project reports health and environmental benefits from the promotion and use of cooking stoves. Improvements in the efficiency of the stove would greatly reduce emissions, such as carbon monoxide (CO) and carbon dioxide (CO_2) [9].

The impact of burning biomass is often stated as a global environmental problem that affects poorer countries and hence poor people [2]. In the United Kingdom, solid fuel emissions were 24.7 $\mu g/m^3$/ppm relative to CO for Manchester [11]. In 2000, household use of coal and biomass in India and China produced 86% of their combined Black Carbon (BC) emissions [12].

C. *Available solutions*

Conventional, technological and innovative solutions are the different approaches to limiting HAP, reducing health hazards and improving IAQ. Conventional solutions involve taking preventive measures without the use of any advanced technology to stop emissions from the source. Essentially, indoor pollution is tackled by rudimentary means and improvisation.

Studies show that applying WHO guidelines for source control significantly reduces risks in the health outcomes for children and adults by 20 to 50 percent [13]. According to the United States Environmental Protection (EPA), the basic techniques (conventional solutions) for an improved IAQ must involve source control, improved ventilation and air cleaners. Also, homes must be designed to include external and or well-ventilated kitchens [14]. In summary, controlling the source of indoor pollution is like closing the tap, thereby stopping the flow [14][15].

Technology and innovation centered sense-and-detect systems are arguably the most effective solutions for combating HAP. Detection of indoor pollutants is a preventive measure and detection devices include smoke detectors, such as the one developed by Loepfe et al. [16], which detects the presence of smoke from two spectrally different scattered light measurements using the principle of diffraction.

Yang's Wireless Sensor Networks (WSNs) harness a cluster of autonomous nodes that are commanded to wirelessly communicate with the controlling infrastructure whose environmental condition is being monitored [17]. Jung and Kim [18] collaboratively developed a system that incorporates a sensor network into an air conditioning and ventilation system to monitor and maintain healthy levels of IAQ. The system sounds an alarm when the measured concentrations of pollutants, such as CO and CO_2, exceed healthy levels.

Of the many commercially available systems developed to deal with HAP, most are designed for detection and warning. These systems vary in design, size, type, and technology from the simplest to the most sophisticated.

However, despite innovation and advances in technology, these detection systems have the following limitations in common:

- ***Chirping***: It is common for most smoke detectors to produce a chirping noise when the battery power is low or runs out. Many users would remove the battery when chirping noise becomes a nuisance. Due to human negligence, users may fail to replace the batteries thereby exposing the entire household to the effects of pollution and its consequences.
- ***Loud Alarms***: Many home smoke detectors have loud noisy alarms or sirens that may be a nuisance to users. Some impatient users who cannot bear the noise would then disconnect the device thereby risking their health and possibly death from pollution.
- ***Limited notification modality***: Most devices or systems offer mostly auditory notification in the form of an alarm, typically in the form of a loud alarm and a blinking light.
- ***Single sensor***: Most of the systems use a single sensor, whose sensitivity largely depends on sensor positioning. If the sensor is too far from the source, detection could occur when pollution levels are already too high. On the other hand, false alarms might also be frequent if it is placed too close to a heated or steaming source. Therefore, the sensitivity of such systems would largely depend on the position of the sensor.
- ***Lack of UD***: To our knowledge, none of the existing systems took into account the UD and accessibility aspects. One system described as a Tactile and Visual Smoke Detector System, as per patent [26], is among a few existing accessible systems. It is a multi-feedback fire alarm that includes one or more wearable (bracelet-style) signal detection and notification devices. Users are notified even when not in proximity of the detection unit. The wearable delivers different lighting and vibration patterns and alarm signals depending on the risk of pollution and informs hearing-impaired users of the threat type. However, the audible notification is not a voice notification but an alarm sound signal of sorts.

III. RESEARCH METHODOLOGY

The research method most suitable for carrying out this research project would be a mixed method. It combines both quantitative and qualitative data to achieve a design that meets the objectives of the project. Wisdom and Creswell [19] from George Washington and Nebraska-Lincoln Universities, respectively, in their paper titled, "Mixed methods: Integrating quantitative and qualitative data collection and analysis", have defined mixed research method as an emergent methodology of research that advances the systematic integration, or "mixing," of quantitative and qualitative data within a single investigation or sustained program of inquiry.

Information, data, and guidelines from WHO led the project's development. As shown in Figure 2, quantitative and qualitative data from WHO is complemented by the data from laboratory experiments and measurements, as well as from test and qualitative data from user interviews to accomplish the goals of the project. This methodology assures an interlock of qualitative and quantitative data to achieve an almost flawless convergence to the objectives of the study and, hence, the project [19].

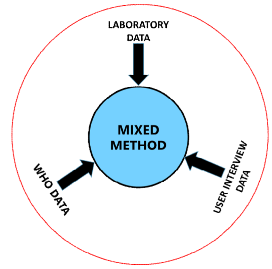

Figure 2. Applied mixed research method and data collection mechanism.

IV. SYSTEM DESIGN AND DEVELOPMENT

The system consists of two main blocks (the Hardware Unit and the Mobile Application) and their sub-systems. Figure 3 shows the two main blocks, the air quality sensor and how they connect.

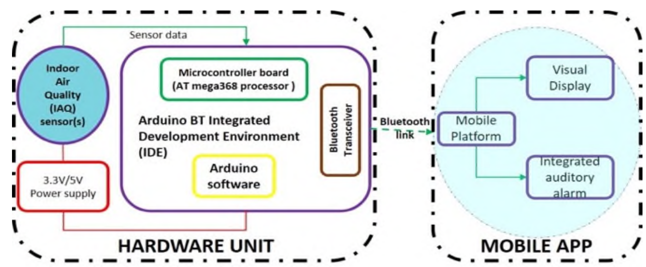

Figure 3. A block diagram of the main system units.

Simplicity, flexibility, portability, and accessibility guided the development throughout the design process. The hardware, software and mobile app are all built on open-source platforms. The design process considers the most essential features that would render the system inclusive to address the needs of users with disabilities or impairments [6].

A. Hardware

The hardware unit is essentially a sensor-node designed in the KiCad Electronic Design Automation (EDA) Suite [8]. The node integrates a Grove-air quality sensor v1.3, responsive to carbon monoxide (CO), alcohol, carbon dioxide (CO_2), and Particulate Matters (PM), such as smoke, liquified petroleum gases and other volatile substances [2]. The node also has an ATmega328 powered microcontroller, a Radio Frequency (RF) and Bluetooth transceivers. All components are fused into one Printed Circuit Board (PCB) unit compatible with the Arduino Integrated Development Environment (IDE). There, sketches (small C-language programs written in Arduino IDE) are compiled and uploaded to run the hardware or sensor-node [9]. Figure 4 shows a complete sensor-node.

B. *Software*

The software combines an Arduino sketch and a mobile app developed in MIT App Inventor 2, which is a drag-and-drop, block-based visual programming language for creating Android devices mobile apps [7].

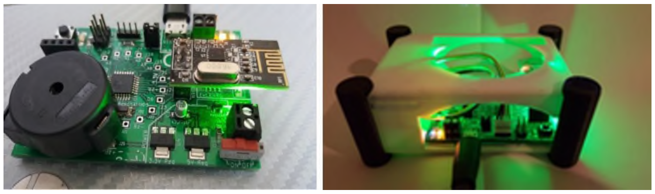

Figure 4. Complete Sensor-Node; open and encased unit.

C. *Concept and system functionality*

The concept is built around an IAQ monitoring and multiple forms of user notification of the IAQ-status. Suppose the IAQ status in a room changed, say due to cooking with wood, with the system installed, one or more sensors on the sensor-nodes might pick up emissions. When this happens, the sensor-node determines if the IAQ is good, poor or bad by processing the sensor data pollutant level. A good IAQ level sets a 3-in-1 Light-Emitting Diode (tri-LED) to Green. However, if the IAQ is poor, the tri-LED changes to Yellow and sounds the alarm. On the other hand, if the IAQ is bad, the tri-LED will be Red.

Figure 5 shows a mother and a child in the kitchen cooking with a wood stove, close to the right-hand corner of the room. The child is holding a toy in which a sensor-node has been embedded. Node 2 is designed to be wearable; Node 3 is mounted on the wall and is linked to a mobile smartphone via Bluetooth. All three nodes plus the toy are connected in an RF network with each other.

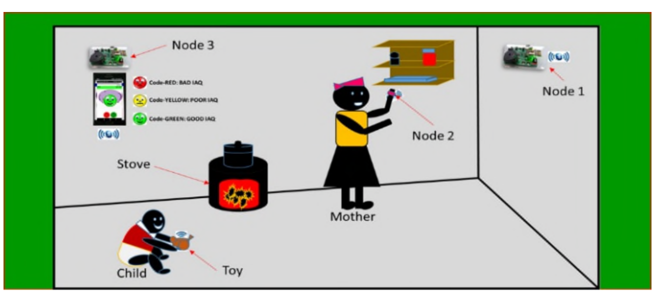

Figure 5. A pictorial diagram illustrating the UD-IAQMWS concept.

The IAQ status is displayed and audio notifications are made in the smartphone. Poor IAQ status will cause the toy to stop working. Consequently, the child will most probably complain to the mother and she would take the child out of the kitchen, open the windows or ensure proper ventilation of the room [7][10][13]. If the mother's actions improve the IAQ status back to 'Good', the child's toy would start to work again. With time, parental guidance, education or basic infant instinct, the child learns to avoid areas with poor IAQ, thereby staying healthy. Depending on the sensor readings, the phone will also display the Green or Yellow or Red emojis (as can be seen in Figure 6) on the screen, with text, and audio-voice message that would say "Code-Green, Good" if the IAQ was good or "Code-Yellow, Poor" if the IAQ was poor and "Code-Red, Bad" if the IAQ was bad. Except for the "Good IAQ", each node will sound alarms different in tone and frequency depending on whether the IAQ status was poor or bad. Note that every user action on the app is complemented by voice feedback describing the action.

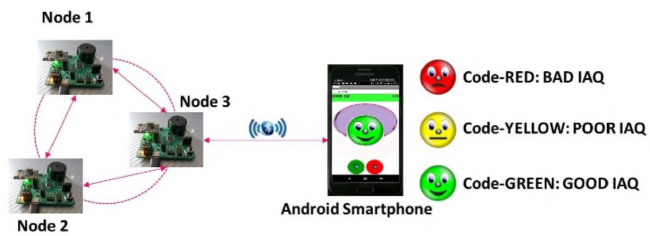

Figure 6. Network communication, system function, and notification.

V. USER TESTING

User testing was done in 2 phases. First, measurements were taken in the kitchen while the participant was cooking. They could operate the system (mobile App) by themselves or observe. Afterwards, an interview session in which participants had to answer 12 questions in about 30 minutes was scheduled according to mutual consent. There were 6 interviewees, 4 males, and 2 females. Each participant was given a unique identification number or ID. For example, #111-F corresponds to participant 1, household 1, interview position 1, and gender female [20].

Participant #111-F did not know much about technology but liked that the system could potentially keep people safe. Both #534-F and #333-M thought it would have been better if they were about to test a commercial sample. However, all participants agree they would buy the system at a reasonable price and all of them said they had an overall positive opinion about the system. Also, participant #222-F suggested that the final product should include a smartphone in the package and #535-M liked the multiple warning levels and the different notifications associated with the IAQ-status at each level.

VI. RESULTS

The results from the laboratory experiments show that the system can detect and respond to alcohol, CO, CO_2, smoke, as well as Liquified Petroleum Gas (LPG). Table I shows their detectability along with the sensor's calibration status. The system's sensor is calibrated such that the threshold for CO detection keeps the user well within the exposure levels proposed by the WHO guidelines, which provide a comprehensive, scientific and ethical standard for measures taken to curb pollution and ensure a healthy environment.

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The carboxyhemoglobin (COHb) levels resulting from the reaction of CO with the Hemoglobin (Hb) in the blood must not exceed 2% of the blood hemoglobin for a typical indoor situation. 100 mg/m^3 for 15 minutes and 35 mg/m^3 for an hour are recommended for exposures occurring no more than once a day [21]. For 24 hours of exposure, 7 mg/m^3 is recommended for a no-exercise daily routine. Exposure patterns vary with age, socio-economic status, type of home, and duration of exposure. Pollution levels that reach 50 times the WHO guidelines for clean air confirm the health outcome risk for women and children who typically spend more time inside the home than men [7][22].

TABLE I. RESULTS FROM LABORATORY EXPERIMENTS.

Test element	Detection	Status
Alcohol	Possible	Uncalibrated
CO	,,	Calibrated
CO_2	,,	Uncalibrated
Smoke	,,	,,
LPG	,,	,,

The system is by design sensitive to the risk levels; thus, detections and warnings are issued to the users, based on a series of leveled thresholds, starting from IAQ status Good through Poor, to Bad with increasing pollutant levels and risk.

VII. Evaluation And Discussion

Of all the interviewees, five said the Mobile App was simple and easy to use (one touch to connect, one-touch ‘ON’, one-touch ‘OFF’). It works as long as the Bluetooth connection is active or even when the phone’s screen is locked. Anyone with a basic mobile phone knowledge could use the app intuitively with ease. Although the evaluation of health outcomes was not the focus of the project, the interviewees were still asked if they had experienced any health problems that might have resulted from the use of solid fuels. All 6 initially answered they had not. However, participant #333-M specifically stated that he had migraines. A follow-up question was asked to ascertain how the respondent could be so sure. He then responded he experienced that only when he was using charcoal for cooking, implying the migraines could only have resulted from the use of charcoal.

The challenges encountered during the research were due to low statistical samples for testing, lack of participants qualified for the indoor (not outdoor) context of testing, language barrier and lack of participants for accessibility and inclusivity evaluation, which led to the use of personas. Persona characters, such as Karol–deaf and Xendu–blind, were correspondingly served by the tactile, auditory, and visual notifications on the smartphone [23]. Ngong–motor-impaired could still use the app since no complex gestures were required. Persona characteristics that bare a direct relation to requirements defined by the project, ensure that the context is preserved [24].

Distinguishing between systems designed to carry out similar tasks, such as detection of pollutants or monitoring of IAQ on the bases of technology and innovation is not an easy task. Systems that employ the same technology might differ in concept, design and implementation but not necessarily in principle. These coupled with the speed of development of the Information and Communications Technology (ICT) field diminish the ease of developing a novelty. However, when fully developed, the prototype UD-IAQMWS will stand apart from the other systems due to the following attributes:

- ***Accessibility/HCI***: The system is built for all persons, whether impaired or unimpaired. A special system further utilizes HCI to address child exposure.
- ***Multimodal notification***: The system offers visual, auditory and tactile (distinctive mobile vibrations that notify the visually and hearing impaired) notifications on a mobile device.
- ***Multiple sensors***: A network of many sensor-nodes offers possibilities for multiple sensor connection system. Thus, different kinds of pollutants can be detected simultaneously or contrastingly (by comparing the oxygen-to-pollutant ratio in a target area) if an oxygen sensor was also used in the network.
- ***Interconnecting systems***: Neighboring systems can communicated by configuring them properly. Such information exchange between the systems enables an assistance to an impaired neighbor (who could be a family member).
- ***Hardware flexibility***: The hardware can operate as a standalone system or in a network with other sensor-nodes. The user can also choose whether to connect a mobile phone or not. Each node has an inbuilt charging circuit and can charge its batteries via USB or solar panel.
- ***Open technology***: Both hardware and software are built for simplicity and on open-source platforms. The user can change the sensors by simply plugging in another compatible sensor. However, such changes might require slight modifications in Arduino with either serial or Universal Asynchronous Receiver-Transmitter (UART) protocol.
- ***Wireless connectivi*****ty**: The system connects and sends user notifications to a mobile device via Bluetooth. IAQ status and values are also sent and displayed on the phone screen.
- ***Compliance with UD principles***: The system complies with at least the first five UD principles [25], therefore, is accessible to a wide range of users, more than traditional smoke detectors or similar systems ever could provide.

There were some limitations in the study due to language barriers, low number of participants, limited time, and resources. However, we think that the design and implementation of the prototype presented in this study can be considered as a novel start. As it is still under development, we believe that further study can be done with

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more participants and hope that the system will reach its full potential in the near future.

It should be noted that the system was designed and tested only on Android systems. However, it could easily be ported in other platforms such as iOS and Windows.

VIII. Conclusion

In this paper, we present a universally designed and accessible Indoor Air Quality Monitoring and Warning System (UD-IAQMWS). The system can detect several pollutants, such as alcohol, carbon monoxide, carbon dioxide, smoke and liquified petroleum gas. IAQ status notifications are provided audibly, visually, and through tactile vibrations. The displayed status can be made accessible to the users with vision problems using a screen reader. Moreover, the system is customizable to fit any user's needs by simply updating the software. The mobile app's simplicity cannot be overemphasized: only 2 buttons are required to operate and there are no complex gestures needed. Any mobile user, including people with disabilities, can use the system with ease; no special training is required.

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