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HYPER-LOCAL AIR ZONE EVALUATOR (HAZE): AN OPEN SOURCE SYSTEM FOR PERSONAL ENVIRONMENTAL EXPOSURE MONITORING

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ABSTRACT

Personal environmental exposure monitoring is an important method for evaluating detrimental effects of pollutants (or otherwise) on human health. We present an open source, affordable personal environmental exposure monitoring system based on off-the shelf components. The system is meant to be worn around the neck for continuous environmental monitoring, which can be useful for future epidemiological studies as well as personal exposure monitoring. We provide the schematics for the Printed Circuit Board as well as the firmware to run the system under a permissive license. Specifically, the system is designed to count airborne particles (PM0.5, PM1.0, PM2.5, PM4.0, PM10), measure CO, CO_2, O_3, H_2S, as well as temperature, pressure, motion, and the relative presence of Volatile Organic Compounds (VOCs). This low-cost and open-source device presented here is an important step to empower individuals, researchers, and underserved communities alike to better understand how daily life within one's own environments impacts our health and welfare.

Keywords: Environmental Sensing, Internet of Things, IoT, Wearable Sensors, Open Source Hardware, Air Quality

1. INTRODUCTION

Wearable air quality monitors are promising tools for assessing individual-level exposure to airborne pollutants. Traditional air quality monitoring methods rely on fixed sensors located at only a few predetermined locations, which may not accurately capture the environmental conditions where people spend significant amounts of time, such as homes, schools, and workplaces. Additionally, these methods may not account for the spatial and temporal variability of pollutant concentrations within a given environment. In contrast, wearable devices allow for more personalized and precise monitoring of pollutant exposure, considering factors such as individual activity levels, proximity to emission sources, and breathing patterns. as wearable devices such as the FitBit and Apple smart watches become more ubiquitous, it becomes easier to gain insight into people's daily activities. These devices typically monitor movement, sleep, heart rate and possibly users' SpO_2 [1]. Missing from this collected data, however, are key environmental variables such as humidity, temperature, particulates, and concentrations of pollutants–all of which can provide critical context for wellness studies and public health research. We present a device intended to be worn around a person's neck in order to gather hyper-local, head-level information on certain gasses of concern as well aforementioned environmental variables. The initial prototype version of our device can be seen in Figure 1.

Hyper-local air quality sampling is essential for better public health as it helps to identify and monitor air pollutants in specific locations. As a major global health hazard, exposure to air pollution is associated with a wide range of adverse health outcomes including respiratory and cardiovascular diseases [2]. However, the level and composition of air pollutants can vary significantly across different areas, depending on factors such as traffic density, industrial activity, and weather patterns [3]. By conducting microenvironment-scale air quality sampling, public health researchers, citizen scientists, and advocates can obtain accurate, spatiotemporal data on air pollution levels in specific neighborhoods or communities which can be used to develop better targeted interventions and policies to improve air quality and reduce the health risks associated with exposure to air pollutants.

FIGURE 1: INITIAL FUNCTIONAL PROTOTYPE OF THE DEVICE, HAND-ASSEMBLED FROM OFF-THE-SHELF COMPONENTS. THE DEVICE FEATURES A SINGLE BUTTON AND A SMALL LCD SYSTEM IN ORDER TO PROVIDE FEEDBACK TO THE WEARER. ACTUAL DATA COLLECTION CAN BE DONE FROM THE ON-BOARD SD-CARD LOGGER OR VIA BLUETOOTH LOW ENERGY (BLE)

Several devices exist in literature which aim to accomplish similar goals. Jin et al. [4] describe a device which can measure temperature, humidity, ambient light, and acceleration. Wilhelm et al. [5] describe an integrated system of devices for large-scale urban deployment and localization. Our system adds to this body of work by integrating on-board sensors which can count airborne particles at more scales [6] (PM0.5, PM1.0, PM2.5, PM4.0, PM10), sense CO, CO_2, O_3, H_2S as well as temperature, pressure, motion, and the presence of relative VOCs. We present open-source designs for our device (including the Printed Circuit Board (PCB) design files and the firmware code) and describe the available sensors in some detail in order to enable the next generation of environmental exposure experiments, both by our group and others.

2. MATERIALS AND METHODS

The design of this system was inspired by the broad availability of Commercial off-the-shelf (COTS) sensors and other electronics. The primary constraints in selecting components and designing devices were the broad availability of COTS sensors, the accuracy and repeatability of individual sensors and complete devices, durability, and a per-unit cost under $300 USD depending on the vendor and market. Critical to meaningful data collection using such platforms is the broadest possible distribution of the device within a study, necessitating a cost-effective, low price-per-unit configuration which can be widely distributed and modularly repaired.

2.1 Microcontroller System

Control of the system is based around the Arduino Nicla Sense ME platform. The Nicla Sense ME is a development board with a 64 MHz Arm Cortex M4 (nRF52832) microcontroller, 512KB Flash / 64KB RAM, 2MB SPI Flash for storage, 2MB QSPI dedicated for BHI260AP, USB, WiFi, Bluetooth Low Energy (BLE); finally, it hosts a built-in 6-axis IMU sensor (BHI260AP), magnetometer (BMM150), pressure sensor (BMP390), and a 4-in-1 gas sensor (BME688). The BME688 gas sensor can estimate Volatile Organic Compound (VOC), Volatile Sulfur Compound (VSC), and H_2 in the ppm range as well as measure relative humidity, pressure and temperature sensors.

All selected sensors either support the I2C protocol or produce analog outputs. Since this is the case, a different set of sensors using the same protocols can be integrated into our device and swapped for one another.

2.2 Power System

Although the Nicla is equipped with a BQ25120 battery management solution from Texas Instruments, the total current for all additional peripherals, the peak current draw of the CO2 sensor, and a higher 5V supply voltage required for the particulate sensor necessitated a custom power solution. A very low quiescent current is also desired to minimize current draw between sensor polling and maximize battery life for extended deployment. To achieve these requirements a combination of three chips were selected: the BQ27441 battery fuel gauge for accurate estimation of battery state, the TPS61253A boost converter to supply 5V and additional current to the peripheral sensors, and the BQ24075 to handle battery charging and power management. It is still possible to use the Nicla's included USB port for power input and the BQ25120 LDO to supply 3.3V by routing the VIN pin to the new battery management solution. Allows the Nicla to be used as is while still supporting the high peak current draws from peripherals like the CO_2 Sensor.

2.3 Additional Sensors Integrated

In the base configuration, we have chosen to integrate the following sensors:

Particulate Sensor: The SPS30 is a compact optical laser scattering particle counter manufactured by Sensirion. This sensor was chosen for its combination of small size, low power consumption, and detection abilities. The sensor is capable of counting and binning number concentrations of PM0.5, PM1, PM2.5, PM4, and PM10 class particles [6]. The fundamental sensing principle relies on the detection of laser light scattered from particulates traversing the detection channel.

Carbon Monoxide and Ozone Gas Sensors: This design utilizes two electrochemical sensors for CO (SPEC Sensors, part

3SP_CO_1000, Package 110-109) and O_3 (SPEC Sensors, 3SP_O3_20, C Package 110-407). Many gas specific sensors were considered but the power savings of the electrochemical sensing and the small form factor differentiate the SPEC sensors while still being affordable. SPEC calibrates all the sensors in batches and provides a calibration factor on the label of each sensor. Additionally, SPEC provides correction for humidity and temperature [7]. SPEC recommends a power-on stabilization period of multiple hours and a two-point calibration, with zero gas and typical conditions, of sensors in the finished device. These sensors are read using the LMP91000 analog front end from Texas Instruments. This is a highly flexible front end that can be easily configured for many of the other gas sensors from SPEC to accommodate other needs for the device. Although a discrete transimpedance amplifier was considered, the space savings, performance, and flexibility offered by the integrated chip make it a superior choice. The only drawback is the unconventional I2C configuration requiring an enable pin for each LMP91000 when there are multiple on the same bus.

Carbon Dioxide Sensor: The CO_2 sensor is the SCD41 module from Sensirion. It was chosen for its compact size and low power consumption. At the time of writing, it is the most compact CO_2 by a large margin and enables a significantly smaller design. Moreover, the sensor has a low power mode suitable for battery powered applications. It is based on a photoacoustic sensing principle. The sensor has an appropriate and wide sensing range with good linearity.

GPS: A smôl ZOE-M8Q Global navigation satellite system (GNSS) module was chosen for enabling correlated, real-time tracking of geo-spatial location and associated environmental metrics. An external Molex 206560 GNSS antenna is also utilized in the design for improved gain and reliable connectivity.

2.4 User Interface and Data Management

The device outlined in this paper includes an on-board interface enabling users to review basic trends for detected parameters over the course of different temporal extents, presenting live metrics or general trends through the day. This data can be presented via a 1.27" OLED display on the front of the device with a single multi-function button for navigation.

Data is stored (per user configuration) with an on-board micro-SD card in a CSV format to ensure uninterrupted collection and easy access to long term data. Furthermore, by utilizing the BLE module on the Nicla, the monitor can connect to other smart systems or be used with a mobile phone app to provide more detailed monitoring and control of data and other functions. A mobile app is being developed for this device and information will be available on the GitHub project page provided in the end-matter below.

2.5 Device Schematic

A simplified schematic of the design is given in Figure 2. The schematics and the PCB designs were created with the Open Source KiCAD software.

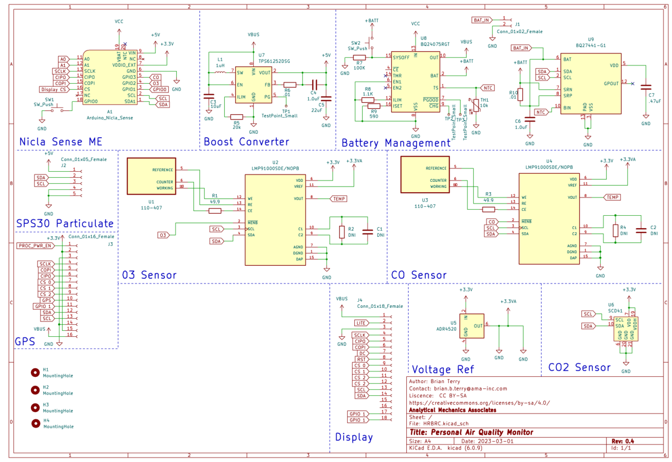

FIGURE 2: SCHEMATIC OF THE DEVICE

2.6 Printed Circuit Board Design and Assembly

The printed circuit design is illustrated in Figure 3 and Figure 4. Figure 5 shows the completed 3D assembly. The CAD files for the design can be downloaded from the GitHub repository provided. It should be kept in mind that the device can also be assembled using a standard perfboard and soldering techniques if PCB fabrication is not practical.

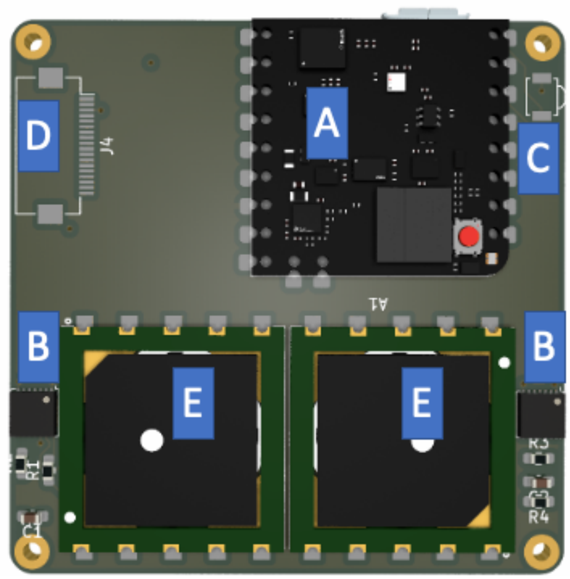

FIGURE 3: FRONT OF THE PCB DESIGN FROM KICAD. A: NICLA B: ANALOG FRONT END ICS FOR READING THE SPEC SENSORS C: NAVIGATION BUTTON D: FLEXIBLE PRINTED CIRCUIT CONNECTOR TO OLED SCREEN

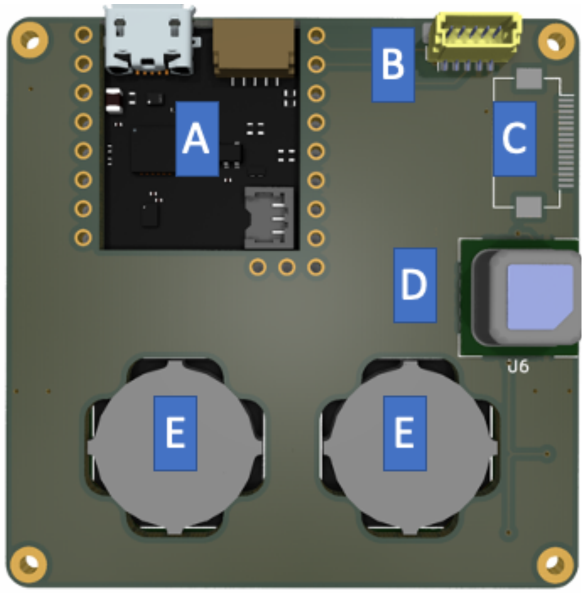

FIGURE 4: BACK OF THE PCB DESIGN FROM KICAD A: NICLA B: CONNECTION TO SPS 30 PARTICLE COUNTER C: FLEXIBLE PRINTED CIRCUIT (FPC) CONNECTOR TO GPS MODULE D: CO2 SENSOR E: SPEC GAS SENSORS

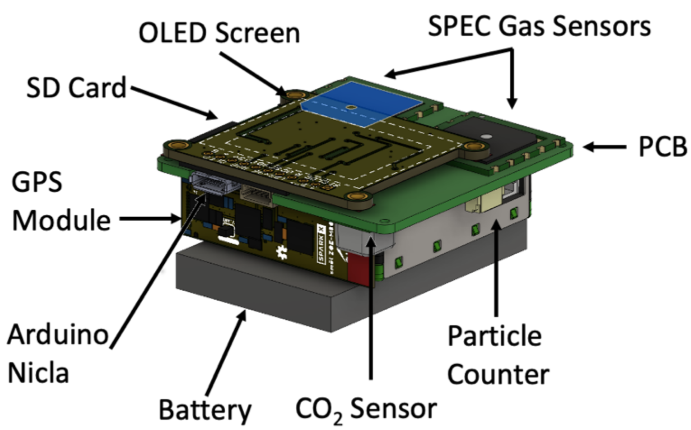

FIGURE 5: ANNOTATED 3D RENDER OF THE DEVICE DESIGN

2.7 Enclosure Design

A custom enclosure was designed for this work to accommodate the necessary airflow requirements needed by the various sensors and to provide a robust design for infield use with a quality aesthetic. The design was modeled using SolidWorks and curated for fabrication via standard additive manufacturing methods such as Stereo Lithography (SLA), Filament Deposition Method (FDM), or Laser Powder Bed Fusion (LPBF). The designs will be available in several formats such as STL, Step, and Parasolid for direct printing by users or for further modification as necessary for expanded applications.

3. RESULTS AND DISCUSSION

We present an integrated device built primarily out of off-the-shelf components. The design of the envisioned final device can be seen in Figure 6.

FIGURE 6: EMBODIMENT OF THE PROPOSED FINAL DEVICE. US QUARTER SHOWN FOR SIZE. OVERALL SIZE IS APPROXIMATELY 58MM W X 30MM D X 60MM H

Researchers who choose to use our design should keep in mind that, like all devices, it has limitations. For particulate measuring devices in general, accurately assessing particulate measurements can be difficult due to variations in particulate size and distribution, as well as variations in reference instruments due to differences in maintenance and calibration procedures. The SPS30 as deployed is therefore evaluated for calibration precision and long-term drift from the manufacturer and not absolute accuracy.

However, in supporting the stated goals of a replicable, wearable, low-cost COTS solution for collection of hyper-local environmental conditions, we believe the device as specified provides a viable platform health and environmental researchers can utilize to monitor experienced air quality with a finer granularity than fixed sensor arrays. The device provides a modular baseline configuration which can support ongoing modification and development within the Open Source community and provide significant value in the study of public health from the perspective of individual subjects within their environments.

4. CONCLUSION

We present the design and materials for what we believe is a feasible wearable environmental monitor capable of collecting data and providing insights to environmental conditions and pollutants to which individuals might be exposed and encourage the broader community to contribute and adapt these resources in kind. Open source hardware has become a critical element in supporting citizen science environmental initiatives due to its cost-effectiveness and accessibility [8]. Unlike traditional proprietary hardware, open source hardware is designed to be publicly accessible, modifiable, and shareable by anyone, making it possible for researchers and enthusiasts to use existing designs or develop their own to suit their specific project requirements. Future opportunities for community contribution of highest impact include additional configurations for alternate gas sensors from SPEC, better power management, alternate enclosures and power sources, software for multi-device collection within studies, and integration with existing health tracking and air quality applications and platforms.

We have chosen off-the-shelf components which can be assembled by individuals of moderate project assembly skill.

All resources are released under CC BY-SA 2.0 license, including updated KiCAD files, firmware, and sensor data sheets, which can be accessed and contributed to at: https://github.com/AMA-Labs/wearable-air-quality

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