Development of a Personalised Environmental Quality Monitoring System (PONG)

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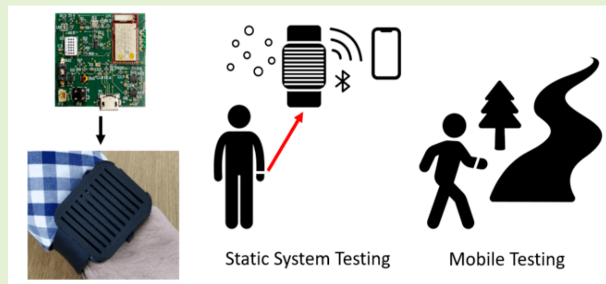
***Abstract*—This article describes the design, development and testing of a Personalised envirONmental quality monitorinG system (referred to as PONG). The custom-built sensing solution monitors environmental factors relating to air quality (VOC and NO_2), light quality (UV intensity and index), acoustic comfort (ambient sound levels) and thermal comfort (temperature, humidity and pressure). Location information is also tracked for subsequent data mapping. The device transmits measurements via Bluetooth Low Energy to a nearby Android smartphone, which logs and displays the measurements to the user, on a bespoke Android application. The hardware consists of an in-house designed PCB, for microcontroller and sensors, enclosed in a 3D-printed case with a wrist-strap. The device was tested in a static location (countryside environment) and utilised as a mobile environmental tracker, worn by a volunteer. The functionality of the system was successfully demonstrated for both static and mobile testing.**



***Index Terms*— Android Application, Bluetooth, Air pollution, Environmental Quality, Pollution, Smartphone, Wearable**

I. Introduction

IN recent years, air quality monitoring has gained significant interest within both research and commercial domains. According to the World Health Organisation (WHO), exposure to air pollution is the single largest environmental global health risk. It is estimated that 9 out of 10 people regularly breathe in air that exceeds WHO guidelines for pollution limits, resulting in an estimated 7 million annual deaths [1]. Pollution levels are generally monitored by measuring airborne contaminants and gaseous compounds, such as volatile organic compounds (VOCs), carbon dioxide (CO_2) and oxides of nitrogen [2]. Factors not often considered when evaluating pollution levels are the physical surroundings of the target area, such as light intensity or sound levels. Inclusion of these parameters is referred to as 'environmental quality monitoring', which is a holistic concept encompassing elements of air quality, light quality, acoustic comfort and thermal comfort (temperature and relative humidity) [3]. Although these attributes do not necessarily have a direct impact on physical health, they are known to affect mental health and contribute to an overall reduced environmental quality, and therefore quality of life [4].

Outdoor air pollution has been shown to intensify asthma symptoms [5] and can have carcinogenic effects [6]. In cities with high levels of air pollution, such as Beijing, it has been suggested that there is a reduction in the UV radiation reaching the ground, which is associated with the increase of tropospheric ozone and nitrogen oxides [7]. Ozone is known to have negative health effects [8], so monitoring and management of such pollutants provides an insight into the effects the surrounding environment has on health. Pollution levels are also known to impact happiness. A study by Welsch et al., demonstrates a link between wellbeing and pollution levels, with an economic impact also seen in areas of higher pollution [9]. Air quality therefore has a profound impact on society. As sensing technology and data sharing continues to improve and increase, it may be possible to investigate and establish currently unknown links between pollution levels and other environmental characteristics – potentially leading to better prediction and management of pollution levels.

To monitor air pollution, a variety of devices are currently available. These range from portable, personal, clip-on devices, to commercial units designed to operate in a static location. Examples of these include the Flow 2 (Plume Labs, Paris, France), which is a small device designed to be attached to a bag or belt loop. It contains sensors to monitor particulate

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matter (less than 2.5 and 10 micrometres in diameter – PM2.5 and PM10, respectively), nitrogen dioxide (NO_2) and VOCs. The Flow 2 communicates with a nearby smartphone via Bluetooth Low Energy (LE) and costs around £179. Although portable, this unit is not a true wearable, given it must be attached to a bag or item of clothing. An example of a commercial solution is the AQMesh monitoring system, which can detect over 15 characteristics (when fully equipped). It can be specified to monitor a single gas or up to 6 gases (such as CO, NO, NO_2, SO_2 and O_3), as well as particulate matter, noise, wind speed/direction, temperature, humidity and pressure. A single unit can cost upwards of $10k for the highest specification device. The monitoring station communicates wirelessly to a remote server, where data can be accessed from multiple connected units. While this device is likely to provide accurate readings, the unit price makes it prohibitively expensive to be deployed in a wider setting. It may be appropriate to use static monitoring stations where recording pollution levels is desired over a prolonged time period, such as busy road junctions. However, a mobile device should be more cost-effective in analysing large areas, at the expense of some measurement accuracy.

A similar approach to this was developed by Cheng et al. in AirCloud: A Cloud-based Air-Quality Monitoring System for Everyone [10]. The work describes the development of two monitoring solutions, mobile and stationary. Both feature PM2.5 sensors and have communication capabilities (Ethernet for the stationary unit and Bluetooth LE for the mobile unit). The mobile device utilises the Bluetooth LE connection to communicate with a smartphone app, before transmitting readings via Wi-Fi/4G to a server. This demonstrates the possibility of developing a system that is operational on a large scale. Data was gathered for 2 months using 12 devices, and the system implemented a machine learning model to allow the units to estimate pollution levels where sensors had not actually been deployed. This feature further increases the usability of the system, in a commercial context. Another approach to monitoring large areas is using a vehicle-mounted sensor array. Cheng et al. used this method to measure CO, NO_2 and SO_2 and transmitted the data to a remote server [11]. This work was limited to a single sensor device attached to a bus, preventing a wider area from being surveyed. Moreover, the readings may have been affected by pollutants emitted from the bus itself, despite being attached to the front of the vehicle.

Monitoring of environmental characteristics is less commonly undertaken, except for noise pollution. In two independently developed approaches to monitor noise levels, Martí et al. and Maisonneuve et al. utilized the built-in microphones in participants' smartphones to monitor ambient noise. This approach aimed to capture ambient noise levels in cities, with Marti et al. using a game-based approach to encourage users to use the app and obtain measurements [12], while Maisonneuve et al. simply used an application to log levels wherever the user travelled [13]. Although only a limited dataset could be collected in both studies, these works indicate that there is potential for a mobile-based noise pollution monitoring system.

The aim of this project is to combine the previously described concepts to create a compact, wearable, sensing solution for the monitoring of environmental quality. This personalised environmental quality monitoring system will be referred to throughout the manuscript as PONG.

II. Hardware Design

The sensing device is designed to be worn upon the wrist, in the manner of a conventional watch or smartwatch. The advantages of this placement are that the device is wearable, easily accessible for the user and is directly exposed to the user's surroundings and environment. There are, however, some technical constraints associated with this solution. These include limited PCB area, the requirement for low-power operation and a high degree of durability. To address the limited PCB area, the smallest and fewest number of electronic components had to be selected for the PCB design. The casing should provide sufficient protection of the device for regular/daily use and the intended battery life was 12 hours.

Since the proposed system is intended as an environmental monitoring unit, the measurement capabilities must go beyond a traditional air quality monitor. To capture the additional parameters of light quality, acoustic comfort and thermal comfort, the PONG was designed to monitor the following metrics:

1) *Air Quality*
   VOC and NO_2 concentrations.
2) *Light Quality*
   UVA/UVB (UV types A and B) intensity and UV index.
3) *Acoustic Comfort*
   Ambient sound level.
4) *Thermal Comfort*
   Temperature, humidity and ambient pressure levels.

These parameters provide a suitable basis from which a sensing device can be designed, developed and tested. WHO guidelines indicate NO_2 concentrations have no observable effects below 1880$\mu g/m^3$, for short term exposure, and advise levels no higher than 40 $\mu g/m^3$ annually. The WHO also provide guideline values for a variety of specific VOCs; however, the unit uses a single gas sensor to provide total VOC (TVOC) readings. The term TVOC recognises the combined effect of detectable airborne compounds, as a single measurement value.

The unit consists of a custom 4-layer PCB, featuring an ARM Cortex M0 processor and Nordic Semiconductor nRF51822 Bluetooth LE module, used for processing incoming sensor data and communication with a smartphone, respectively. The sensors deployed in the PONG include a Bosch BME680 (for temperature, humidity, pressure and VOC), Vishay VEML6075 (for UVA/UVB intensity and UV index), Knowles SPH0645ML4H-B (for ambient sound level) and an Amphenol SGX Sensortech MICS-2714 (for oxidising gas measurement, such as NO_2). An RGB LED was also integrated, to provide user feedback regarding device connection status and a single LED was connected to the battery charging system. The battery used is a Varta 56445-201-012 Lithium-ion unit, with a 660 mAh capacity – sufficient for extended device run-time. Details of these components are given in Tables I and II, and a block diagram of the system is in Fig 1.

TABLE I
MAJOR COMPONENTS USED IN PCB

Component	Manufacturer	Type
ATSAMD21G18A-AUT	Microchip Technology	Processor
nRF51822	Nordic Semiconductor	Bluetooth Low Energy Module
BME680	Bosch	Temperature, Humidity, Pressure, VOC sensor
VEML6075	Vishay Semiconductor	UVA/UVB intensity and UV index sensor
MICS-2714	Amphenol SGX Sensortech	Oxidizing gas sensor
SPH0645LM4H-B	Knowles	Ambient sound sensor
SMLP36RGB2W3R	Rohm Semiconductor	RGB LED

TABLE II
COMPONENT MEASUREMENT RANGES

Component	Types	Range
BME680	Temperature, Humidity, Pressure, VOC	– 40 to 85 °C 0 to 100% r.h. 300 to 1100 hPa min. 5 ppm C_2H_6
VEML6075	UVA/UVB intensity and UV index	UVA: 0.93 counts/μW/cm^2 UVB: 2.1 counts/μW/cm^2
MICS-2714	Oxidizing gases	NO_2: 0.05 to 10 ppm
SPH0645LM4H-B	Ambient sound	– 29 to – 23 dBFS

The components listed in Table I were selected due to their compact form-factor and low power consumption (where possible with the technology). Fig 1 shows the block-diagram of how these components are connected. Fig 2 shows photographs of the manufactured board.

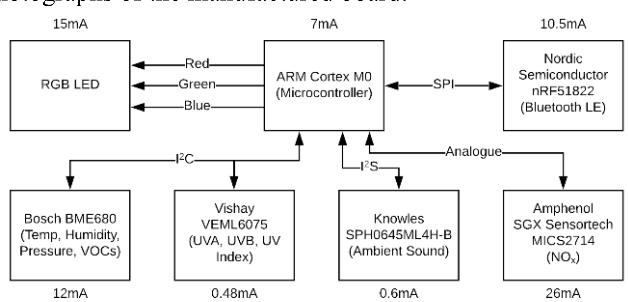


Fig. 1. Personalised environmental quality monitoring system (PONG) block diagram.

The PCB is able to take 10 different measurements, using 4 separate sensors, while consuming minimal power. Table III shows the approximate total current consumption of the components. Given the 660 mAh battery capacity, it is estimated that the wearable device can operate for around 9 hours, without applying energy saving approaches. This assumes the RGB LED is operating constantly. If this assumption is removed (i.e., current drawn from the LED is negligible), then the run-time extends to 11.5 hours – sufficient for a full day's use. This time could be increased further by applying various power saving modes on the microcontroller, Bluetooth LE and sensors, but was not needed here since the required specification had been achieved.

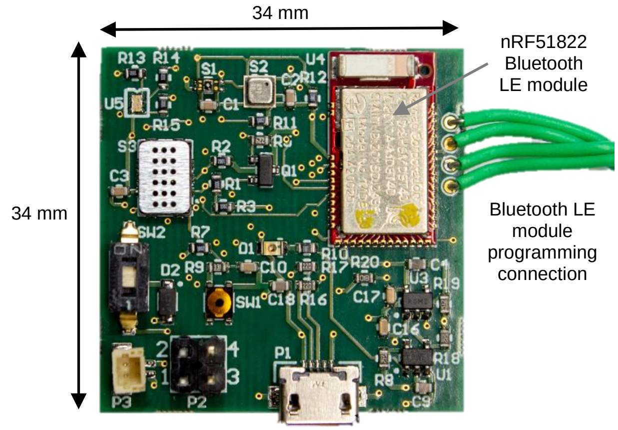


Fig. 2. Personalised environmental quality monitoring system (PONG) PCB layout: S1 = VEML6075 UVA/UVB Sensor, S2 = BME680 VOC/Temperature/Humidity/Pressure Sensor, S3 = MICS2714 NO_X Sensor, D1 = Charging LED, U5 = RGB LED, SW1 = Reset switch, SW2 = On/Off switch, P1 = Micro-USB connector, P2 = Bootloader programming connection, P3 = Battery connector.

TABLE III
CALCULATION OF APPROXIMATE CURRENT CONSUMPTION (OPERATING VOLTAGE = 3.3V)

Component	Consumption (mA)
Microcontroller	7
Bluetooth module	10.5
BME680 sensor	12
VEML6075 sensor	0.48
MICS-2714	26
SPH0645LM4H-B	0.6
RGB	15
Total Consumption	**71.58**

The PONG is enclosed in a modified Letopro Smartwatch housing. After detaching the existing smartwatch components, other unnecessary plastic supports were removed using a small rotary tool. A suitable slot was then cut for the PONG PCB micro-USB port. When placed inside the housing, the sensors are exposed to airflow through the open casing top. The battery is located underneath the PCB and power is supplied via an upward facing JST connector. A spacer is fitted between the casing backplate and the main body, as the battery protrudes slightly, preventing the cover being replaced. A 3D printer (Ultimaker 3) and Autodesk Fusion360 CAD software were used to create a design to achieve this. The plate is attached to the casing, followed by the backplate. The spacer does not result in a significant increase in thickness – measuring only 4 mm thick and providing enough room to fit the on-board battery. The assembly components for the PONG are shown in Fig 3.

To protect the PCB during regular use, a top cover was designed. The top cover clips directly onto the existing casing, without the need for any additional modifications. This consist of two plastic components: a baseplate and a lid, which press-fit into each other and allow a paper filter to be secured between them (for additional PCB protection). A small cut-out exists to expose the light sensor and prevent any restriction to UV light. The assembled PONG hardware is shown in Fig 4.

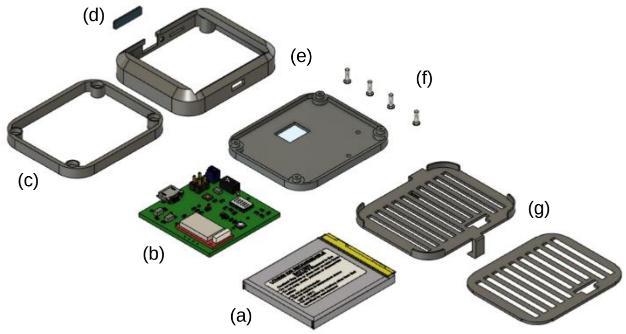


Fig. 3. Personalised environmental quality monitoring system (PONG) assembly components: (a) Battery, (b) PONG PCB, (c) 3D printed spacer, (d) USB socket cover, (e) Modified smartwatch housing, (f) Fixing screws, (g) 3D printed sensor cover.

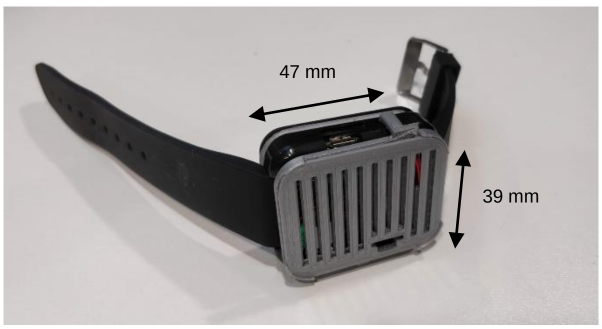


Fig. 4. Assembled personalised environmental quality monitoring system (PONG).

III. Software Design

The system is composed of two software components. The first is an Arduino C application running on the microcontroller, which provides an interface between the sensors and smartphone via a Bluetooth LE connection. The second is a Java application installed on an Android smartphone, which provides data logging functionality. This allows environmental readings to be analysed at a later time. The application also displays the sensor data to the user and manages the Bluetooth LE connection between the Bluetooth LE module on the PCB, and the smartphone.

A. Microcontroller Software

Using the Arduino C language, an application was created to interface with the sensors connected to the microcontroller and package the data appropriately for transmission to a smartphone via Bluetooth LE. The device uses a custom Bluetooth LE profile, containing a single environmental monitoring service (service ID 0x181A), which in turn contains a characteristic for each sensor measurement. The application communicates with the sensor using I^2C, SPI, I^2S and analogue protocols, from which raw measurement data is supplied. The application then updates each characteristic with the most recent sensor reading, which can be viewed on the connected smartphone. Sensor data is requested every 30 sec., providing a balance between power consumption and sampling frequency. Setting a limit to the size of the device constrains the battery size. Reducing the sample rate achieves greater run-time.

B. Smartphone Software

A custom application was created using Android Studio – a free-to-use Integrated Development Environment (IDE) from Google, targeting the Android Operating System. The application is based on the Bluetooth LE Gatt template. This provides the necessary framework to manage Bluetooth connections and reduces the amount of additional code that needs to be written. The application was tested on a smartphone to be used with the PONG (Motorola Moto C, running Android 7.0). The application features two different displays; the first sets up the connection to the sensing hardware, while the second displays sensor readings to the user and allows data logging to be enabled or disabled. The application also uses the phones integrated GPS sensor to geo-locate every reading and record this information alongside the measurement data. The recordings are logged to a CSV file, with each row containing measurement date/time, sensor readings and GPS co-ordinates of measurement location.

The phone shown in Fig. 5 (left) is the connection screen, where the unique identifier for the device can be entered. These identifiers are specific to each Bluetooth LE module and thus ensures the application only connects to the target PONG board. Fig. 5. (right) shows the main screen, where measurements are displayed to the user. The measurements are updated only when the Arduino application provides new values of the sensor characteristics being broadcast by the Bluetooth LE module. This approach is taken to reduce the amount of space consumed by the log file on the smartphone.

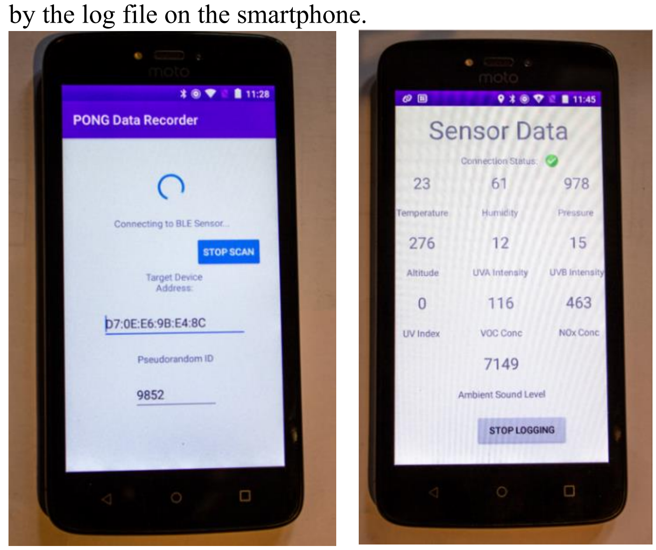


Fig. 5. The PONG Smartphone Application.

The functionality of the Bluetooth LE connection management and the logging system are separated into two services, allowing them to run in the background on the smartphone. This ensures that data can still be logged in the background, even if the application is minimised. Logging is stopped when the user actively closes the application. This reduces battery consumption and allows for continuous data collection – similar to the noise pollution monitoring approach proposed by Maisonneuve et al. [13].

IV. Results and Discussion

Initial testing of the PONG involved checking whether the device was able to record environmental and location data and transmit this to the smartphone to display/log it. Following these tests, a set of static and mobile tests were conducted. For the static tests, the device was placed in a stationary location (in this case, a countryside environment). For the mobile tests, the device was worn by a volunteer undertaking daily activities.

The approximate maximum communication rage of the device is 3.5 meters (tested in open air). This is somewhat lower than the maximum expected range for Bluetooth LE, of 10–15 meters; however, the PCB design does not feature a built-in antenna and therefore this is the likely cause of range degradation. The range is nonetheless sufficient to permit stowage of the smartphone in a pocket and the device to connect successfully when worn on the wrist.

A. Mobile and Static System Testing

Initial mobile system testing demonstrated that the device functions as intended – data is transmitted from the wearable device to the smartphone and stored as a CSV file in memory. The location information of each reading is also correctly recorded alongside the measurement data. Fig. 6 shows temperature measurements taken around the University of Warwick campus.

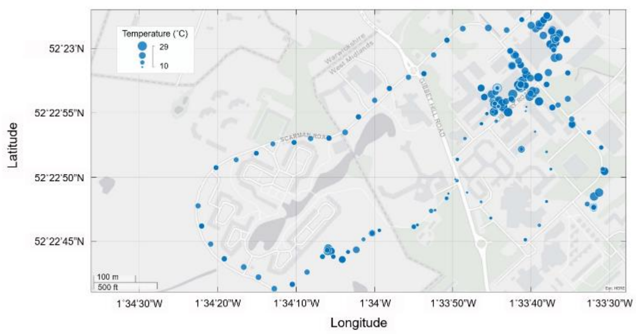


Fig. 6. Mobile data collection with the personalised environmental quality monitoring system (PONG).

When placed in a static location, some of the PONG device readings deviated slightly from reference measurements; this is shown in Fig. 7 and Fig. 8, using temperature and humidity data [14]. It is worth noting that the general trends are being followed.

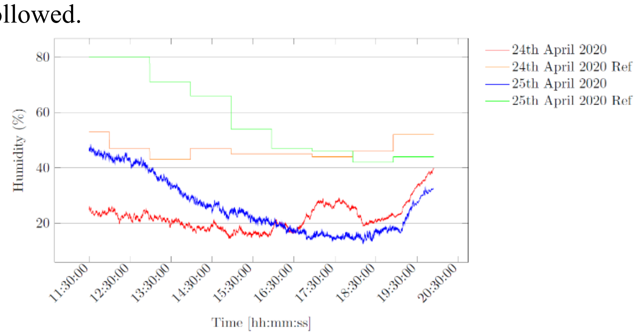


Fig. 7. Static data collection of humidity, with personalised environmental quality monitoring system (PONG) and reference measurements.

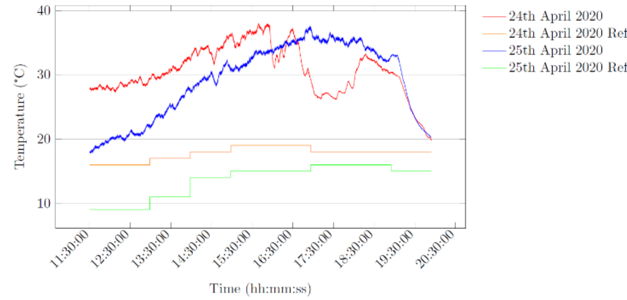


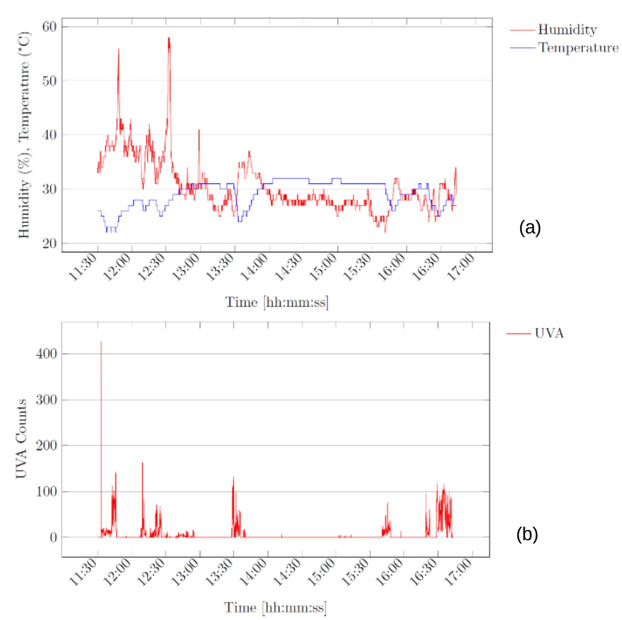
Fig. 8. Static data collection of temperature, with personalised environmental quality monitoring system (PONG) and reference measurements.

These differences may result from exposure of the device to the sun – leading to increased heating of the sensors and therefore skewing the readings. This may also account for the humidity rise seen in Fig. 7 at 17:00, and the temperature drop in Fig. 8 at the same time. Moisture content would have remained stable, but the fall in temperature would have increased the relative humidity. Moreover, given that the BME680 gas sensor also contains an internal heater for the VOC sensor, this too may impact the accuracy of the thermal comfort parameters. For note, the unit was not being worn in these experiments and no additional calibration was performed on measurements, beyond factory calibration.

B. Volunteer Testing

Ethical approval for volunteer testing was granted by the University of Warwick BSREC (ref: 55/19-20). Examples of volunteer data is presented in Fig. 9–12. The first volunteer undertook a walk through Birmingham city centre (the second largest city in the UK) and includes time indoors and outdoors, shops and restaurants over a period of hours.

Figure 9 shows the unit in operation. As can be seen, there is a correlation between UVA (when the volunteer is outside) with peaks in humidity and VOCs. It shows that the air pollution in a major city is higher outside than inside.



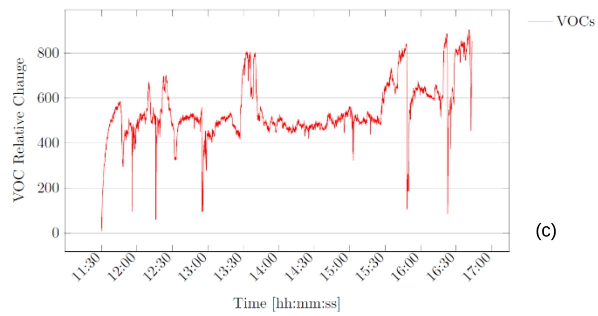


Fig. 9. Mobile data collection of relative changes in: (a) Humidity and temperature, (b) UVA, (c) VOC concentration, with PONG.

The second volunteer wore the unit on two journeys: a morning grocery shopping trip and an afternoon walk. The data was amalgamated to present the two journeys in a single plot. These are shown in plots 10, 11 and 12.

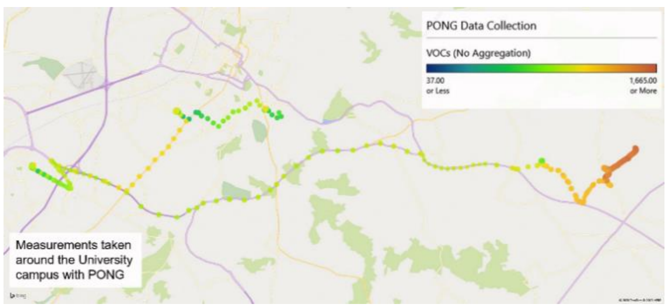


Fig. 10. Mobile data collection of relative changes in VOC concentration with PONG.

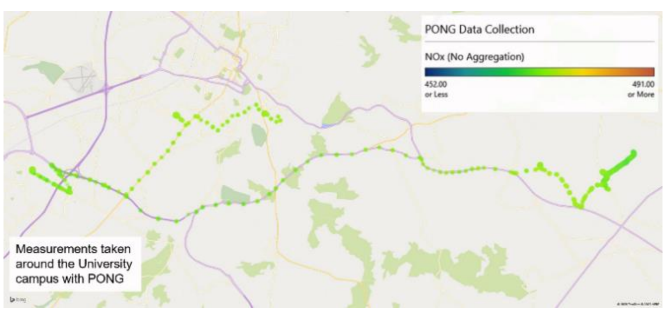


Fig. 11. Mobile data collection of oxidising gas concentration, with personalised environmental quality monitoring system (PONG).

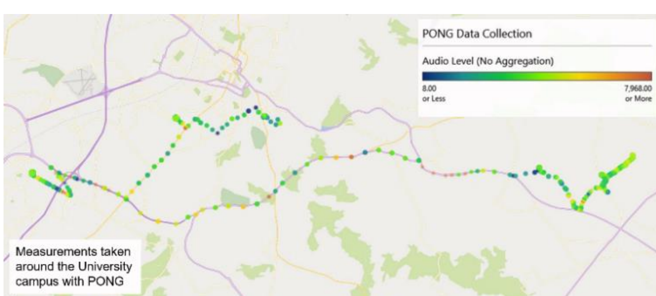


Fig. 12. Mobile data collection of ambient noise levels, with personalised environmental quality monitoring system (PONG).

As shown in Fig. 10, the device is also successfully able to capture VOC readings and location information. These measurements were not verified with reference values. As shown in Fig. 11, there is little variation in the NO_2 concentration data; however, a general trend is observable. The air quality seems to improve in rural areas (right portion of the map), as expected. Ambient sound measurements are shown in Fig. 12. These have a high variation across the map. Since the device is worn on the wrist, it is possible these readings were impacted by clothes rubbing against the device or air movement as the user moves their arms. These readings were taken in a countryside location, so motor vehicles would be loud when the measurements were taken.

V. Further Work

This paper shows the design and the basic functionality of the PONG device. Our next step is to deploy PONG in a wider study, with 20 volunteers and a duration of 1 month. This would enable the gathering of a substantial environmental dataset. This information could then be used to further our understanding of the local environmental quality and an optimal methodology for measuring it. A wider study would also enable data to be gathered across a greater geographical area, thus enabling better comparisons to be drawn between urban and rural areas. Furthermore, at this point in time, we have not integrated all the readings together to create an "environmental quality score". This in itself is a major piece of work as there is currently no standard for how these readings can be combined.

In our previous work, we developed an indoor environment quality (IEQ) index to notify users about the quality of an indoor environment, using an intuitive display [3]. This method can also be applied to environmental quality (EQ) in general. Here, a single word description (good, moderate, unhealthy and very unhealthy) and percentage score could be used. These classifications are determined based on how far EQ parameters deviate from known ambient and health risk levels (e.g., humidity: good = 40–50%, average = 50–60%, 60–70% = poor and $70>H>40\%$ = bad). These levels are then associated with scoring impacts (0.0, 0.2, 0.5, and 1.0, respectively) and category weightings (70% for air quality, 10% for light quality, 10% acoustic comfort, and 10% for thermal comfort). The EQ score reflects a perfect 100% if all EQ parameters fall within the 'good' boundaries. If any values are not considered 'good', a weighted calculation determines the impact on the overall EQ index score = 100% – (parameter impact % × scoring impact). This method of EQ scoring can be applied to the PONG device in future tests.

Regarding the PONG hardware, it is not as aesthetically pleasing as commercially available smartwatches and may undergo substantial wear-and-tear with prolonged use. The structural integrity of the casing was impacted by the modifications required to fit all of the hardware. With improved 3D printing technology and materials, it would be possible to design a more durable and stylish enclosure.

The smartphone application of the PONG could be further developed, to include additional features. These could involve an environmental quality score, which provides a quick and intuitive metric to indicate the current quality of the environment. The application could also provide suggestions with regard to how the environmental quality can be improved – such as moving to a lighter area or opening windows (in an indoor setting). The application could also be developed to work on the iOS operating system, to expand the range of devices it would be compatible with.

Lastly, a web server-based application could be developed, which receives data from the smartphone application via Wi-Fi or cellular networks to collect data from many participants, across a wider area. This would eliminate the requirement to gather the devices together to obtain the recorded data and would also enable easy monitoring of pollution across geographical areas. The server-side application could integrate a machine learning approach to predict environmental quality for monitored areas, based on past data. This would allow users to take actions such as avoiding poor environmental quality areas.

VI. Conclusion

This paper describes the design, development and testing of a wearable environmental pollution monitor. The compact, wearable device operates in conjunction with a bespoke Android application. The PONG is able to detect and monitor a variety of environmental factors, including air quality (VOC and NO_2), light quality (UV intensity and index), acoustic comfort (ambient sound levels) and thermal comfort (temperature, humidity and pressure). In addition to this, the readings can be linked to location data for mapping. Static testing in a countryside location and mobile testing with volunteers were conducted. Basic functionality of the device, with regard to data collection and mapping, were successfully demonstrated. Further work is required to investigate the accuracy of the data. The developed device has the potential to serve as a personal pollution monitor.

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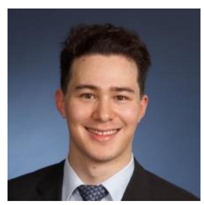

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