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The AirSpeck family of static and mobile wireless air quality monitors

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***Abstract*— The Automatic Urban and Rural Network (AURN) [1] is a set of high quality reference monitoring sites for recording air quality in the United Kingdom. They are costly to install and expensive to run, and are therefore limited in numbers. The data from these networks are used to inform regulatory compliance with the Ambient Air Quality Directives [2]. There is also a requirement to monitor air pollution at sufficiently high spatial and temporal resolutions around people to estimate personal exposure to particulates, and gases such as Nitrogen Dioxide and Ozone for better understanding their health impacts. Such high resolution measurements can also be used for validating the air quality models' estimates of variability over space and time due to complex interactions. Networks of air-quality monitors using inexpensive sensors offer a cost-effective alternative approach for recording trends in air quality at a higher spatial resolution, albeit not as accurately as the reference monitoring sites. This paper describes the design, implementation, and deployment of a family of air quality monitors: stationary (AirSpeck-S) monitors for measuring ambient air quality, and mobile wearable AirSpeck-P for monitoring personal exposure to air borne particulates (PM_{10}, $PM_{2.5}$ and PM_1), and the gases - Nitrogen Dioxide and Ozone. Results are presented for characterising the ambient air quality in public spaces gathered from people wearing the AirSpeck-P monitors who are out and about in two cities as pedestrians (Edinburgh, Scotland) and as car passengers (Delhi, India). The paper demonstrates the viability of using inexpensive static and mobile AirSpeck monitors for mapping trends in particulate concentrations in urban spaces. Results are presented for comparisons of the mobile personal exposure data from pedestrians with static AirSpeck-S monitors along the same route, and the characterization of urban spaces based on levels of particulate concentration using the AirSpeck-P monitor.**

Keywords— Ambient air quality; wearable sensors; AirSpeck; k-NN classifier.

I. INTRODUCTION

Progress in electrochemical sensors and laser-based compact optical particle counters, such as Alphasense's OPC-N2 [3], has led to the development of low-cost air quality monitors. This paper presents the AirSpeck platform for connecting particulate counters and electrochemical gas sensors, for processing the raw sensor data and transmitting them wirelessly to remote servers for analysis. The platform is configured in two ways: AirSpeck-S is a static version tethered to street furniture such as lamp posts (Fig. 1(L)), or attached to vehicles such as buses and cars; AirSpeck-P is a personal exposure monitor worn as a belt by pedestrians (Fig. 1).

AirSpeck platform is equipped with two wireless radios for transferring sensor data to the server: a Bluetooth Low Energy (BLE) radio connection to a mobile device such as a phone or a tablet for onward transmission using a WiFi link to the broadband internet; an on-board GPRS radio for uploading data via the cellular network. Stationary air quality monitors would normally use the GPRS radio whereas personal exposure monitors would use BLE to transfer to an App on the mobile phone to store and forward to the server.

The wearable AirSpeck-P personal exposure monitors can be used to map ambient air quality in public spaces based on numerous personal exposure readings taken when the wearers are out and about. The preliminary experiments in fingerprinting the urban environment using particulate data was conducted in the Meadows area in Edinburgh and then extended to a route in the city which spanned six urban environments.

The novel contributions of this paper are the design of the AirSpeck platform which can be easily configured for stationary measurements of ambient air quality and for mobile measurements of personal exposure, and pedestrians and car passengers contributing data to characterise air quality in urban spaces.

II. THE AIRSPECK PLATFORM

The principal consideration in the design of the AirSpeck-S (Fig. 1) is the ability to deploy for a period of several weeks powered by a battery pack housed in a water-resistant enclosure. The stationary configuration supports the OPC particulate counter, up to 4 gas sensors, an auxiliary fan to circulate the flow of air to the gas sensors, a battery pack, a switch to turn off the system between deployments, and data transmission over the GSM network (Figure 2).

In contrast, the design of AirSpeck-P as a body-worn personal exposure monitor gives prominence to size, weight and wearablity issues and an App running on the mobile device orchestrates its operation to measure particulate matter and two gases (NO_2 and O_3).

Fig 1. (Top-left) AirSpeck-S monitor attached to a lamp post in the Meadows area in Edinburgh (Top-right); (Bottom-left) AirSpeck-P monitor worn as a belt (Bottom-right).

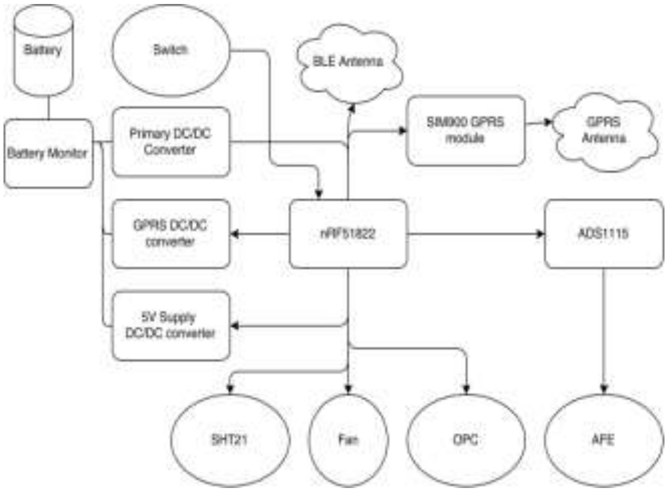


Fig 2. Block diagram of the principal components of the AirSpeck hardware platform.

A. Sensors

Optical Particle Counter (OPC): The OPC is connected to the AirSpeck using an SPI interface and powered from the 5V rail along with the other external sensors. It provides particle counts in 16 bins categorised in terms of ranges of spherical equivalent sizes between 0.38μm to 17μm (Figure 3). It uses a high intensity laser source to illuminate the particle as it passes through the detection chamber and the redirected light is detected by a photo detector. It also outputs derived concentrations in PM1, PM2.5, and PM10 equivalent ratios. The 5V rail supplying the OPC and other external sensors are switched off between measurement sessions to extend the battery lifetime.

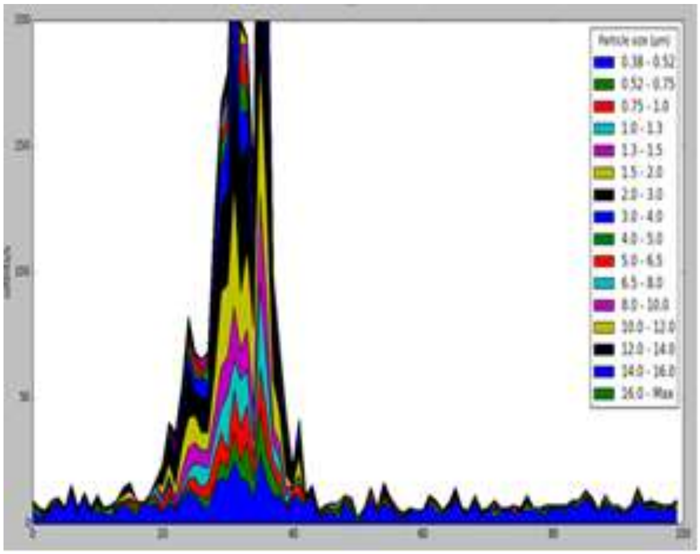


Fig. 3. A "spectrum" of particulate numbers (Y-axis) over time (X-axis) ranging in diameter sizes between 0.38μm and 17.0μm distributed across 16 bins (inset) detected by the laser-based Optical Particle Counter (OPC).

Temperature & Humidity Sensors: A Sensirion SHT21 temperature and humidity sensor [6] is included on the AirSpeck PCB to enable integrated sensing of temperature and humidity without requiring the connection of external sensors.

FS200 Temperature & Humidity Sensor: An interface is provided for the FS200 waterproof temperature and humidity sensor, comprising a Sensirion SHTXX series temperature and humidity sensor [7] in a waterproof (sintered metal) enclosure. This sensor is placed to protrude outside the enclosure either into the ambient air or into the soil for measuring soil moisture content.

B. Processing and Communication

Bluetooth Low Energy (BLE): The NRF51822 SoC [8] has an in-built Bluetooth LE radio which communicates with a custom Android Application on the mobile device for receiving and stamping the sensor data with time and location (GPS) information and then forwarding them to the server via the cellular network or WiFi.

GPRS module: A SimCom SIM900 GPRS module [9] in the AirSpeck platform is used to transfer sensor data to the server over the GSM network for the stationary AirSpeck-S monitors. Transmissions take place every third sampling period (once every 5 minutes) to reduce battery drain due to the GPRS module. It consumes considerably more energy to connect to the GSM network, and initialise an HTTP connection, compared to transmitting each additional byte of data once connected.

C. *Power Supply*

In the AirSpeck-P configuration, a compact, rechargeable 7.4V (2S) LiPoly battery pack is used. For the stationary AirSpeck-S, an 8400mAh, 13.2V (4S) rechargeable LiFePo4 battery pack is used with sufficient capacity for around 20 days of operation. LiFePo4 chemistry was chosen as it has a higher intrinsic safety than LiIon type of batteries, while still providing a high energy density compared to sealed lead acid and other rechargeable battery types.

The AirSpeck board requires 3 power rails, 3.3V for the microcontroller, BLE radio, the on-board sensors and sensor interfaces; 4.2V for the SIM900 GPRS module; and 5V for external sensors and the auxiliary fan. Each power rail is supplied using an LMZ12003 DC/DC converter module capable of sourcing up to 3A of current. A key switch enables the system to be turned off between deployments.

The OPC and the auxiliary fan each consumes around 200mA when active, and the GPRS module around 100-150mA, depending on its state (idle/transmitting) of operation. Due to their higher power consumption, care is taken to only enable them for the minimum period of time. The AirSpeck-S is configured for long battery life and operates at an average current of around 30mA, whereas AirSpeck-P keeps the OPC turned on continuously for sampling when mobile and consumes around 250mA.

D. *Firmware*

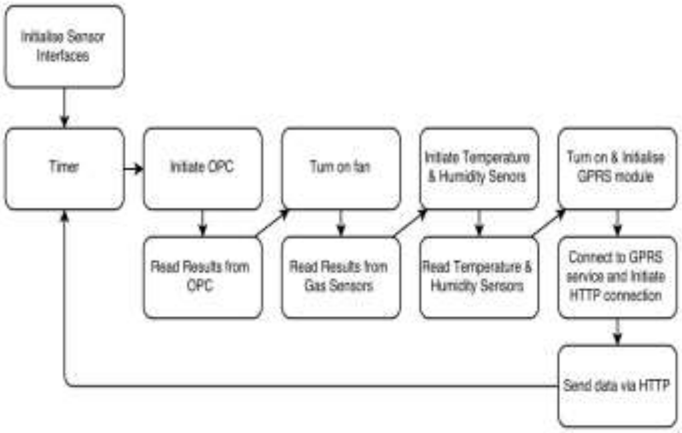


Fig. 4. Block diagram of the principal components of the AirSpeck firmware.

The AirSpeck firmware has been designed to operate primarily in a sequential fashion which simplifies the code for interfacing with the sensors, and increasing the reliability of operations. A timer peripheral supports both low-power delays during sequential operation as well as global events such as starting a new measurement cycle. Once initialised, the firmware sets up interfaces to the sensors (I2C for the temperature and humidity sensors, SPI for the OPC, I2C for the ADCs for reading the output from the gas sensor interface module, and UART for the GPRS module), as well as setting up the startup power supply states for the 5V, 4.2 and 3.3V rails.

At the start of each measurement cycle, the firmware turns on the 5V rail used for the OPC and the gas sensors, then initiates the measurement cycle of the OPC, including turning on the built-in fan in the OPC. A sequence of OPC measurements is taken at 1second intervals and the results aggregated. Once the OPC measurement cycle has completed, the OPC fan is turned off and the gas sensor fan is turned on for 2 seconds. At the conclusion of the gas sensing period the output voltages from the gas sensor interface board are read using the ADS1115 ADCs and the 5V power supply rail is turned off. The temperature and humidity sensor readings are next initiated for the measurement period and the sensor results are read out. Results from all the sensors are aggregated in a results array and uploaded using the GPRS module every third sensing cycle. The 4.2V rail for the GPRS module is turned on when an upload event is scheduled and instructed to connect to the GPRS service of the service provider set up for the SIM card inserted in the AirSpeck board. Once connected to the network, an HTTP service connection is set up, the data is uploaded to the GPRS module and instructed to perform a HTTP POST request to the server. At the conclusion of the HTTP request, the AirSpeck enters a low-power state waiting for the timer event to start a new measurement cycle.

The firmware for the AirSpeck-P version operates in a fashion similar to the AirSpeck-S firmware; however, unlike the stationary firmware, the personal one keeps the fan for the OPC turned on permanently and performs readings from the OPC at 1 second intervals. In contrast to the stationary firmware, the GPRS module is not normally used and instead the Bluetooth LE radio is used to transmit the sensor readings to the mobile device at the conclusion of each measurement interval.

III. POWER OPTIMISATIONS

The AirSpeck platform is required to operate for extended periods in the field, without the opportunity to recharge the batteries or with reliable access to solar energy (in the northerly latitudes), and therefore an important consideration is the optimisation of the energy consumption by the hardware and firmware.

A. *Hardware Power Optimisation*

The use of switching DC/DC converter modules allows for efficient interfacing to different battery types. By utilising three separate DC/DC converters, the efficiency of the energy conversion is maintained for each of the separate power domains in the design.

During optimisation of the power consumption of the gas sampling subsystem of AirSpeck-S it was found that replacing the whole volume of air inside the enclosure was consuming considerable energy, as the fan needed to be operated for an extended period of time to replace the full volume of air in the enclosure.

A custom baffle was designed in which the gas sensors were placed and connected directly to the outside of the AirSpeck-S enclosure. A smaller fan is adequate to replace only the volume of air inside the baffle. The lower-power fan (100mA at 5V) was required to be turned on for only 2s compared with 5s for the larger fan (200mA at 5V), while still ensuring sufficient turn-over of the air in the gas sampling chamber. Additionally, the baffle is equipped with a series of apertures designed to trap rain falling on the ingress port, allowing the baffle to be directly ported to the exterior of the enclosure without risking water entering into the system.

B. Firmware power optimisations

Optimising the energy consumption in the firmware was an important consideration in its design. Key parameters affecting energy consumption are the sensor sampling interval and the duration of each sampling period. The NRF51822 SoC used at the core of the system is based around a very energy-efficient ARM Cortex-M0 microcontroller core.

The firmware has been designed to put the microcontroller to sleep between the different state machine transitions. The Cortex-M0 core consumes around 4.1mA while executing code from Flash, but less than 5uA while in sleep state (with the 32.768kHz oscillator running).

Data collection from the OPC sensor was optimised to achieve a tradeoff between energy consumption and accurate data collection. The OPC sensor is typically used in a continuous monitoring scenario, and will aggregate readings over periods of time. The sensor is equipped with an internal fan which requires a startup period before providing accurate readings. The firmware first activates the fan in the OPC and then takes a succession of readings at 1s interval, aggregating the results from the sensor. Such a sampling approach was found to result in more accurate readings when optimising the sensor for lower average energy consumption. In the AirSpeck-S, the OPC is sampled for a 30s period in each 5-minute interval, thus giving readings with a high degree of accuracy.

The electro-chemical gas sensors used in AirSpeck consume less energy than the OPC. However, for accurate readings it is important that the gas sensor is exposed to air for a period of time which is achieved by a fan pulling fresh air into the sampling chamber in which the gas sensors are placed.

The proportion of energy consumed in the different subsystems of the AirSpeck-S were as follows: OPC sensor – 54%; GPRS module – 36.5%; Gas Sensors – 4%; Power distribution – 3%; Gas fan – 2%; NRF51822 SoC – less than 0.5%.

IV. RESULTS

The AirSpeck-P was used by pedestrians to characterise the air quality in the cities of Edinburgh, Scotland and Delhi, India. The pedestrian data in Edinburgh was also used to “fingerprint” a route by classifying it in terms of six urban environments based on the OPC particulate data from Bin0 (particulate diameter ranging between 0.38µm – 0.42µm) as it was by far the most active bin in the relatively clean environment in Scotland.

A. Characterising the urban environment in Edinburgh

Figure 5 shows the visualisation of the quantiles of particulate data collected along three routes in the Meadows area in the city of Edinburgh. It is a green space south of the central University campus which is bounded on the north by a path (North Meadows Walk) favoured by cyclists and pedestrians, and on the south by a road (Melville Drive) with moderately busy vehicular traffic. Three routes were walked carrying the AirSpeck-P, and the resulting dataset contains 260 data points, including 85 readings from within the park, 86 readings on North Meadows Walk, and 89 readings along the pavement on Melville Drive. Figure 6 shows the differences in Bin 0 counts as a boxplot for the three environments and the results of one-way ANOVA applied shows significant differences with a p-value < 2e-16.

Fig. 5. Characterisation of three routes in the Meadows area in Edinburgh using Bin0 (0.38µm – 0.42µm) particulate data.

The walk in the centre of the park is confidently picked up as a stretch of points with values below the median. The only outliers were at the intersection of the route with a busy pedestrian walk in the middle of the park. Finally, the route in North Meadow Walk is a mixture of mainly red and yellow points with outliers in the zone where all the walkways meet which has a heavy footfall from pedestrians. The graphs in Figure 7 show the PM10, PM2.5 and PM1 particulate data for a period of 70 hours from three stationary AirSpeck-S monitors placed along the three routes in Figure 5: Melville Drive (Blue) showing diurnal variations due to vehicular traffic, interior of the Park (Green), and the Upper Meadow Walk (Yellow). The results in Figure 5-7 confirm that the AirSpeck-P mobile personal exposure monitor worn by pedestrians does differentiate between the three types of urban environments in the Meadows area, and which was validated by the data from the stationary AirSpeck-S monitors along the same routes.

Next, a pedestrian route (Figure 13) in the centre of Edinburgh was characterised in terms of Bin0 (0.38µm – 0.42µm) particulate data for six types of urban environments enumerated in Figure 8: (i) Indoor environment inside the university library; (ii) Middle of the park; (iii) Pedestrian walk; (iv) Quiet street - one with little or no traffic; (v) Medium-traffic street; (vi) Congested street/junction. Figure 9 shows the box plot of the OPC particulate data points for the six different types of urban environments. One-way ANOVA test applied to the data gives a p-value < 2e-16. The particulate counts are the lowest inside the Library and the highest in the street with moderately busy traffic and the traffic junction with high traffic. The environment types inside the park, the park walk, and the quiet street have small differences in PM counts.

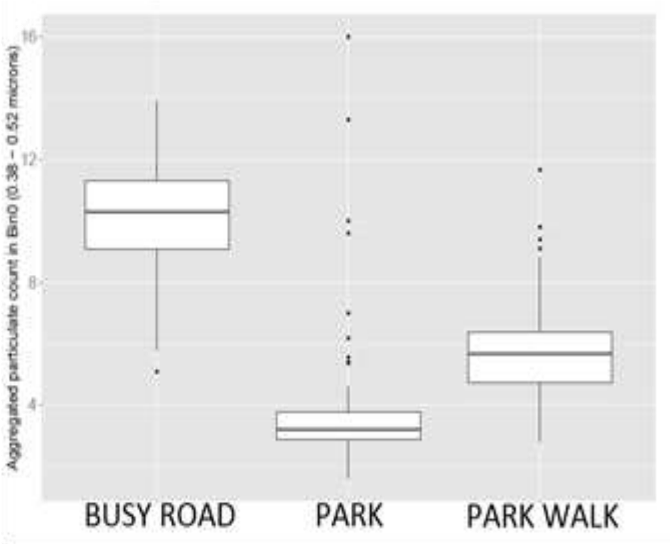
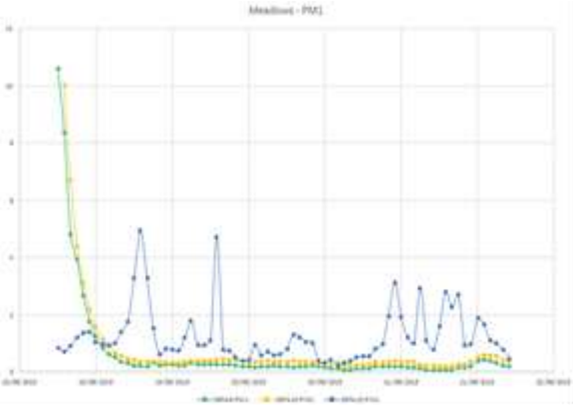
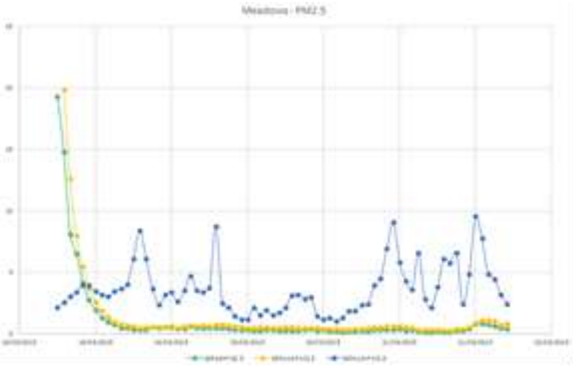


Fig. 6. Box plot for the walks along three paths in the Meadows





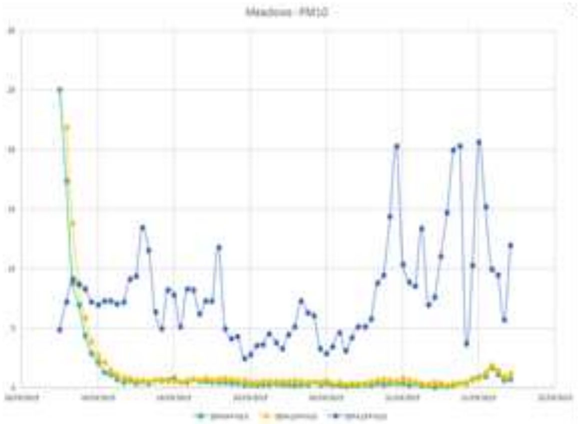


Figure 7. PM10, PM2.5 and PM1 particulate data for a period of 70 hours from three stationary AirSpeck-S monitors placed along Melville Drive (Blue), interior of the Park (Green), and Upper Meadow Walk (Yellow).

B. *Characterisation of the particulate concentration in Delhi*

Fig 8. Map of the route in Delhi, India for personal exposure data collection using AirSpeck-P indoors in a shop, walk in a park, and the car journey.

The results in the previous section had established that the AirSpeck-P was capable of monitoring the personal exposure to particulates when attached to the subject moving around. The Figure 8 shows the map of the circuit taken in New Delhi on 11th May, 2015 during the period from 10:00 to 14:00, covering three distinct types of urban environments. Figure 12 displays this journey to better effect: the top graph shows the speed of the person (in m/s) – three phases of car journeys (identified by the elevated speeds), firstly to a shop followed by 90 minutes stay within the indoor environment; next to a park with roughly 60-minute worth of exposure data in the outdoors; and finally the car journey back to the starting location. The other three graphs in Figure 12 shows the PM10, PM2.5 and PM1 values measured by the AirSpeck-P during the circuit. The three distinct plateaus of high particulate exposure coincides with the phases of the car journey, and the bottom two graphs in Figure 12 shows elevated values for PM2.5 and PM1 values during the journey. A comparison of the boxplots in Figure 11 and Figure 9 for the two cities reveals that worst case exposure in Delhi during the road journey is approximately 60 times higher compared to the equivalent type of environment in Edinburgh. These two graphs are directly comparable as they used the same AirSpeck-P device for monitoring particulate levels.

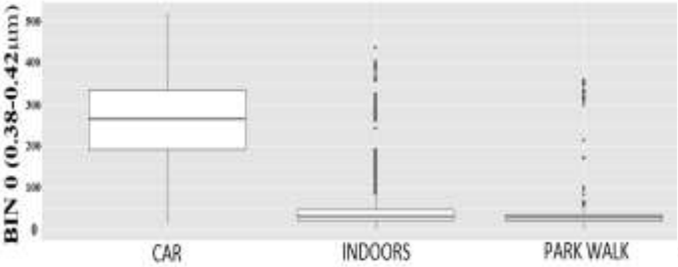


Fig 9. Boxplot of personal exposure using AirSpeck-P in terms of Bin0 (0.38µm – 0.42µm) particulate count for three environments: inside a shop (middle), in a garden (right), and in the car (left) when travelling between the two sites.

Fig. 10. (Clockwise from top-left) Inside of the University Library; Middle of the park; Pedestrian park walk; Congested street/junction; Moderate traffic road; Low traffic street.

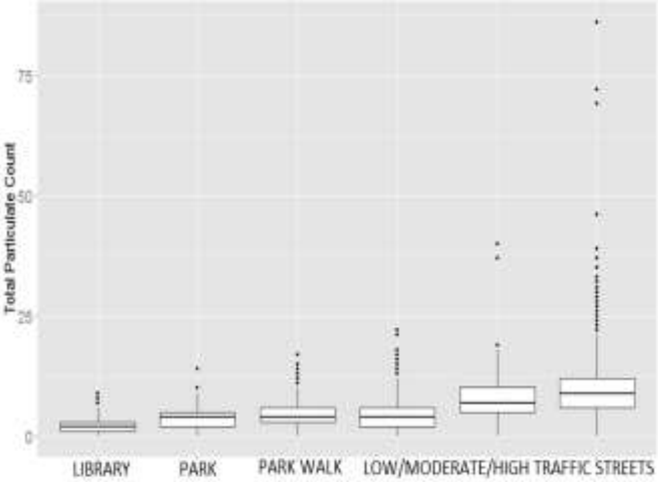


Fig. 11. Boxplot for the Bin0 (0.38µm – 0.42µm) particulate dataset for a route differentiating six types of urban environments in Edinburgh.

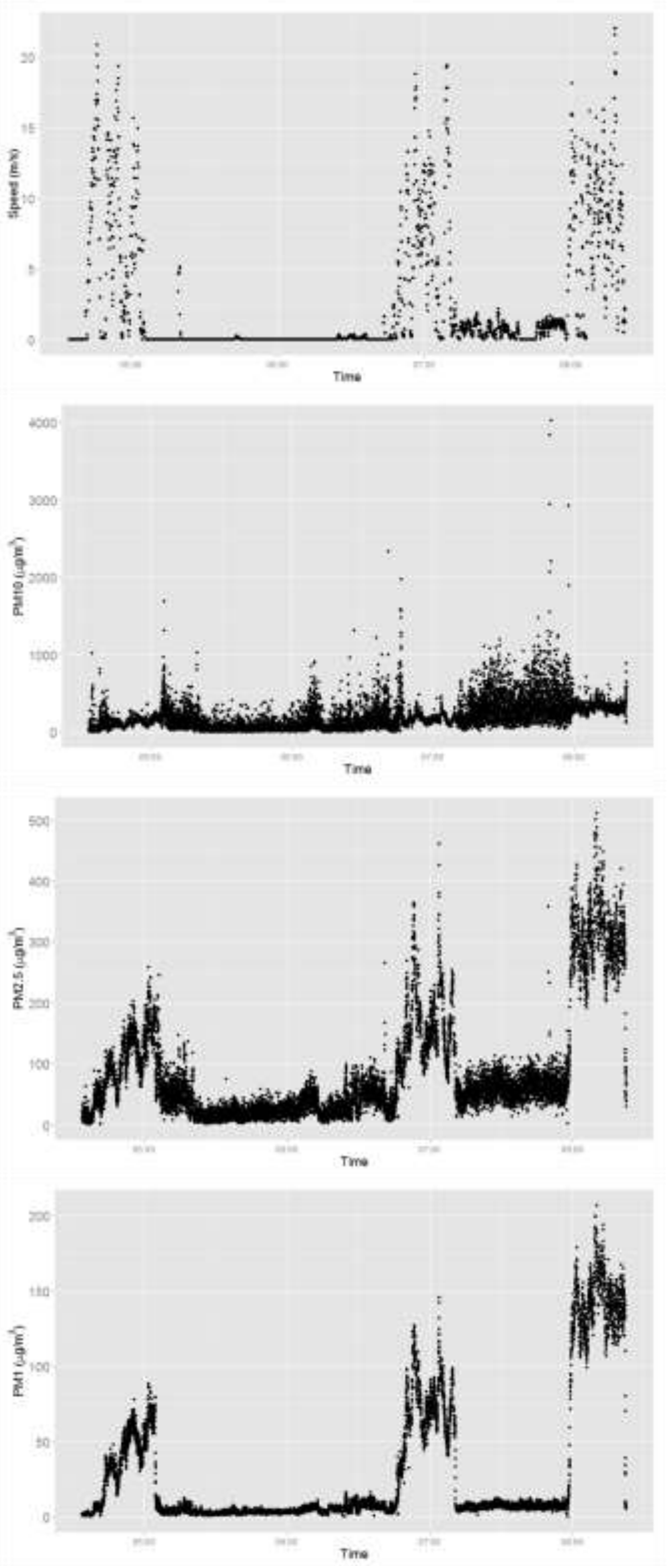


Fig. 12. (Top) Speed (m/s) of the person carrying the AirSpeck-P personal exposure monitor; (Middle) Bin0 (0.38µm – 0.42µm) particulate count during the journey; (Bottom) PM_{10} values during the journey.

C. Classification of urban environments in Edinburgh

Figure 13 summarises the results of personal exposure datasets collected over seven walking trips in Edinburgh and the route has been automatically classified into six types of urban environments described in Figure 10. Data preprocessing involved aggregating on the GPS location within each sample and applying the k-means clustering technique to discover 50 clusters of points based on their location along the route.

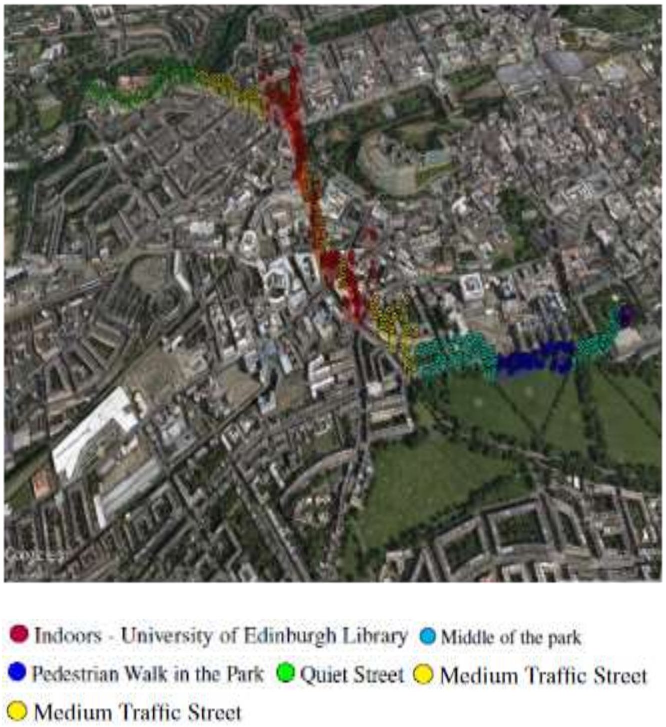


Fig. 13. Classification of six urban environment types for seven walking trips in Edinburgh with the AirSpeck-P personal exposure monitor.

The data points are then aggregated by location clusters and the mean of all the readings within the cluster was taken. Each point in the final data set can be thought of as a summary of the sensor readings around the cluster centres. k-means clustering technique in R [10] was once again applied to the size-resolved bin counts and total particulate counts to discover six types of urban environments with each cluster shown as a distinct colour in Figure 13. A visual examination of classification of the route tallies with manual classification, with the nuances along the route such as air quality effects due to waiting at traffic lights and different levels of traffic along a long street, being discernable.

V. RELATED WORK

Steinle *et al* [14] present a review of the myriad of issues to be considered for quantifying personal human exposure to air pollution when moving away from static measurements. Cho *et al.* [11] examined the relationship between exposure to particulate matter and mortality. Particulate mass (PM10 and PM2.5) and size-resolved particulate counts from 0.3µm to 25 µm were measured. The interquartile range of fine and respiratory particles number concentrations were associated with a 5.73% and a 5.82% increase in respiratory disease associated mortality, respectively. Stationary sensors using Optical Particle Counters have been used to study the effects on the environment at Healthrow airport in the UK [12].

Pedestrian exposure to particulate matter was studied by Ozgen *et al.* [14] along a selected route in the city centre of Milan. Data was collected using an optical particle counter and a GPS receiver carried in a backpack. Particulate counts were collected by the OPC every minute in the range from 0.3µm to 10µm and PM mass concentrations were calculated from the counts. Colombi et al. [13] studied passenger exposure in the underground transport system in the same city.

VI. CONCLUSIONS

The paper has presented the AirSpeck static and mobile air quality monitors and methods for pedestrians (Edinburgh) and car passengers (Delhi) to characterise urban environments wearing the AirSpeck-P personal exposure monitors. The same monitor was used to gather data in Edinburgh and Delhi for comparison which showed that the exposure to particulates in Delhi could be as high as 60 times that of Edinburgh. The statistical differences between six locales in the urban environments have been characterised for fingerprinting a walking route in Edinburgh and the exposure to particulates visualized in a map. The data from the mobile AirSpeck-P was validated against equivalent measurements along the same route using stationary AirSpeck-S monitors in the Meadows area in Edinburgh. Future work will investigate the spatial and temporal predictions of PM2.5 and PM10 concentrations using data from network of static AirSpeck-S monitors located in the Meadows and supplemented by mobile data from subjects wearing AirSpeck-P monitors moving within the area covered by the static network.

REFERENCES

[1] http://uk-air.defra.gov.uk/networks/network-info?view=aurn

[2] http://ec.europa.eu/environment/air/legis.htm

[3] http://www.alphasense.com/index.php/products/optical-particle-counter/

[4] http://www.alphasense.com/WEB1213/wpcontent/uploads/2015/05/OX-A421.pdf

[5] http://www.alphasense.com/WEB1213/wp-content/uploads/2015/05/NO2-A42F.pdf

[6] http://www.sensirion.com/fileadmin/user_upload/customers/sensirion/Dokumente/Humidity/Sensirion_Humidity_SHT21_Datasheet_V4.pdf

[7] https://www.google.co.uk/webhp?sourceid=chrome-instant&ion=1&espv=2&ie=UTF-8#q=Sensirion+SHTXX

[8] https://www.nordicsemi.com/eng/Products/Bluetooth-Smart-Bluetooth-low-energy/nRF51822

[9] http://www.simcom.eu/index.php?m=termekek&prime=1&sub=40

[10] J. A. Hartigan and M. A Wong. A K-means clustering algorithm. Applied Statistics 28, pp 100-08, 1979.

[11] Yong-Sung Cho, Jong-Tae Lee, Chang-Hoon Jung, Young-Sin Chun, and Yoon-Shin Kim. Relationship between particulate matter measured

by optical particle counter and mortality in Seoul, Korea, during 2001. Journal of Environmental Health, 71(2):37 – 43, 2008.

[12] Sensor Networks for Air Quality at Heathrow Airport. http://snaq.org/. Accessed:2015-03-29.

[13] C. Colombi, S. Angius, V. Gianelle, and M. Lazzarini. Particulate matter concentrations, physical characteristics and elemental composition in the Milan underground transport system. Atmospheric Environment, 70:166 – 178, 2013.

[14] Senem Ozgen, Giovanna Ripamonti1, Alessandro Malandrini1, Martina S. Ragettli, Giovanni Lonati. Particle number and mass exposure concentrations by commuter transport modes in Milan, Italy, AIMS Environmental Science, 2016, 3(2): 168-184. doi: 10.3934/environsci.2016.2.168.

[15] S. Steinle, S. Reis, C. E. Sabel. Quantifying human exposure to air pollution—Moving from static monitoring to spatio-temporally resolved personal exposure assessment, Science of the Total Environment 443 (2013) 184–193.