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Authors

Hojaiji, Hannaneh
Kalantarian, Haik
Bui, Alex AT
et al.

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Temperature and Humidity Calibration of a Low-Cost Wireless Dust Sensor for Real-Time Monitoring

Hannaneh Hojaiji[1], **Haik Kalantarian**[2], **Alex A.T. Bui**[3], **Christine E. King, PhD**[2,*], and **Majid Sarrafzadeh, PhD**[2]

[1]Department of Electrical Engineering, University of California, Los Angeles, Los Angeles, CA USA

[2]Department of Computer Science, University of California, Los Angeles, Los Angeles, CA USA

[3]Department of Radiology, University of California, Los Angeles, Los Angeles, CA USA

Abstract

This paper introduces the design, calibration, and validation of a low-cost portable sensor for the real-time measurement of dust particles within the environment. The proposed design consists of low hardware cost and calibration based on temperature and humidity sensing to achieve accurate processing of airborne dust density. Using commercial particulate matter sensors, a highly accurate air quality monitoring sensor was designed and calibrated using real world variations in humidity and temperature for indoor and outdoor applications. Furthermore, to provide a low-cost secure solution for real-time data transfer and monitoring, an onboard Bluetooth module with AES data encryption protocol was implemented. The wireless sensor was tested against a Dylos DC1100 Pro Air Quality Monitor, as well as an Alphasense OPC-N2 optical air quality monitoring sensor for accuracy. The sensor was also tested for reliability by comparing the sensor to an exact copy of itself under indoor and outdoor conditions. It was found that accurate measurements under real-world humid and temperature varying and dynamically changing conditions were achievable using the proposed sensor when compared to the commercially available sensors. In addition to accurate sensing and reliable sensing, this sensor was designed to be wearable and perform real-time data collection and transmission, making it easy to collect and analyze data for air quality monitoring and real-time feedback in remote health monitoring applications. Thus, the proposed device achieves high quality measurements at lower-cost solutions than commercially available wireless sensors for air quality.

Keywords

environmental sensing; dust density; temperature; humidity; calibration; wearable sensors; biomedical sensors

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[*]Corresponding Author: Christine E. King, PhD, kingce@cs.ucla.edu.

I. Introduction

Wireless air quality sensors are widely used to measure airborne particles in the environment, and have become increasingly important in various remote health monitoring applications [1, 2]. Their ability to measure dust density, particulate matter 2.5 to 10 micrometers in diameter, ozone, carbon monoxide, sulfur dioxide, and nitrous oxide, has allowed for finer air pollution monitoring than online current application programming interface (API) sources such as AirNow.gov. However, many of these wireless sensors are often costly and temporally variable under real-world conditions [3, 4]. Moreover, many wireless sensors are not capable of providing real time data, and only provide stored data to be uploaded. This is problematic, as these sensors require the stored data to be uploaded and analyzed after the study is performed, which does not guarantee accurate or reliable results [5]. Motivated by these limiting factors, we report on the development of a simple low-cost wireless air quality sensor for real-time monitoring of dust density in remote health monitoring applications.

II. Related Work

With the advancement of wireless sensing, there has been significant previous research on smart phone-based air pollution monitors [2]. Many of these applications utilize low-cost dust density sensors, such as the Shinyei PPD42NS (Shinyei Technology Co., Ltd., Japan) dust sensor [6] or Sharp (Sharp Corporation, Japan) sensor [7]. However, the Shinyei sensor has been found to be less sensitive, especially in high humidity or high saturation conditions, is less wearable due to its size than the Sharp sensor [8], and both do not provide accurate results under various temperature conditions [9, 10]. Thus, it is necessary to include an accurate calibration so that real-time monitoring can be provided by these low cost sensors.

In previous studies, temperature calibration was attempted to allow for more accurate results under various real-world conditions [10]. However, these studies performed measurements over long periods of time, which is unsuitable for real-time feedback in remote health monitoring studies. Furthermore, the experiments were performed under controlled outdoor air conditions with constant humidity rather than indoor microenvironments and temporally varying humidity conditions. Finally, the results of the study showed significant outliers in some normal and high humidity conditions, which need to be removed if the system is used in health applications, as false warnings must be prevented.

Due to the limitations of previous work and the need for accurate real-time sensing of air quality for remote health monitoring systems [11], this paper presents a low-cost wireless air quality sensor that can accurately measure dust density under both varying temperature and humidity conditions, as previous studies only focused on temperature varying conditions. We have found that in addition to temperature, humidity also has a large effect on output dust concentrations, as these values greatly vary in indoor real-world conditions (e.g. when near a humidifier or a shower). Furthermore, automatic outlier removal must be applied to the sensor system in real time to allow for more accurate results, as well as less false positives and omissions detected by the sensor. This is necessary to further improve the robustness and accuracy of the readings in real-world conditions so that it can be relied upon for alerts in remote health monitoring systems. Under various real-world indoor and outdoor conditions, the wireless dust sensor system was calibrated against a commercially available wired and costly air quality monitor that has been widely used in various environmental air quality monitoring studies [12], the Dylos DC1100 Pro (Dylos Corporation, Riverside, CA). Furthermore, the sensor's reliability and accuracy were tested against an identical prototype dust sensor, the Dylos DC 1100 Pro sensor, and the commercially-available Alphasense OPC-N2 sensor (Sensor Technology House, Essex, United Kingdom). This set up allowed the sensor to be acquired and analyzed in real time, which is more applicable for healthcare applications where changes in air quality must be observed immediately to provide just-in-time feedback and intervention.

III. Methods

Based on prior work, we chose the Sharp sensor as the basis of our sensor system, as it is low-cost, small in size, and sensitive to changes in environmental conditions. To allow for wireless sensing in remote health applications, the low-cost sensor was integrated with a Bluetooth module and microprocessor, and appropriately housed to avoid errors due to light interference with the sensor's infrared stream. The sensor system was then calibrated using an integrated humidity and temperature sensor, and validated under indoor and outdoor real-world conditions and for several hours.

A. Assembly

The wearable wireless dust density system was assembled as follows and is depicted in Fig. 1. First, the Sharp optical dust sensor was integrated with a custom circuit and power module for onboard sensing (see Fig. 2 for a schematic of the system's circuit). It was then integrated with a temperature and humidity module for subsequent real-time calibration. Next, a Bluetooth Low Energy (BLE) module was used to allow for real-time streaming to the users smart phone, and from the smart phone to a cloud server (Amazon Web Services, Seattle, CA). The sensor system was housed in a small black box that prevented errors associated with light interference in the optical scattering of the dust sensor. A cost breakdown of the completed system for one prototype sensor is shown in Table I. Finally, the onboard advanced encryption standard (AES) encryption provided by the BLE module allowed for Health Insurance Portability and Accountability Act (HIPAA) compliant privacy and security necessary for remote health monitoring applications.

B. Calibration

Since previous studies have shown that the Sharp sensor does not provide accurate results under increasing temperature and humidity conditions [8, 9], the wireless dust density system was calibrated and smoothed for accurate readings under various real-world conditions. To this end, the raw data were filtered using Grubb's test for statistical outliers as dropped packets were consistently observed. Then, the following equation [9] was used to determine the dust concentration (ρ, in mg/m^3) from the raw voltage values, x:

$$\rho=5.4\times10^{-4}x-0.15 \quad (1)$$

Once the dust concentration for the wireless sensor was determined, the data was smoothed using a simple six-point moving average filter. Then, the effects of temperature and humidity were mitigated using the following linear compensation modified from Budde et al. [8] to include the effects from humidity changes:

$$\rho_c = \begin{cases} \rho(x); \Delta H = 0, \Delta T = 0 \\ \alpha_H H + \beta_H - (\alpha_{T1} T + \beta_{T1}); \Delta H > 0, \Delta T > 0 \\ \alpha_H H + \beta_H - (\alpha_{T2} T + \beta_{T2}); \Delta H > 0, \Delta T < 0 \\ \rho(x) - (\alpha_{T1} + \beta_{T1}); \Delta H < 0, \Delta T > 0 \\ \rho(x) - (\alpha_{T2} + \beta_{T2}); \Delta H < 0, \Delta T < 0 \end{cases} \quad (2)$$

where α_H is 2.8×10^{-3} α_{T1} is 0.0005, α_{T2} is 0.0002, β_H is 0.1647, β_{T1} is 0.0133, and β_{T2} is 0.0329. This formula is based on prior work used for temperature calibration [9, 10], and was modified to include humidity variations as well. The constants were determined by performing several controlled experiments described below where the Dylos and wireless dust density system were exposed to increasing temperature and humidity.

C. Accuracy and Reliability Testing

To assess the calibration coefficients for the wireless dust density system, the wireless dust sensor and Dylos Pro 1100 were first compared under controlled increasing and decreasing temperature and humidity conditions. In addition, the resulting calibrated sensor was tested under a real-world burning oil condition to mimic a cooking situation in which a user of a remote health monitoring system is exposed to smoke for 15 to 20 minutes. The resulting calibration coefficients were used to calibrate the sensor, which was then tested further for reliability and accuracy under real-world conditions for several hours.

In order to test the wireless dust sensor's reliability among different copies of the device, a second sensor with the exact same hardware and software specifications was developed. Both wireless sensors were then tested against the Dylos Pro 1100 and Alphasense OPC-N2. In addition, to assess the accuracy of these sensors, they were tested both in indoor and outdoor conditions for several hours to replicate real-world conditions. Under the indoor conditions, the sensors were exposed to dusty conditions such as cooking and walking on the carpet for several hours. For the outdoor test condition, the sensors were exposed to natural changes in wind, humidity, and temperature throughout the day.

D. Post-Processing and Analyses

Since all sensors tested collected data at different sampling rates, several preprocessing steps were taken to compare the sensors under each condition. Analysis included resampling to the highest sampling rate (0.5 Hz) using interpolation, band-pass filtering at 60 Hz to remove the noise due to local power lines from the sensors, and performing cross-correlation analyses on the dust sensors against each other for accuracy and reliability by assessing the similarity across measurements under the above different conditions.

In addition to the above preprocessing steps, the Dylos sensor required conversion from particle count to dust density concentration. This was done using the following equation:

$$\mathrm{PM}_{2.5} = (\mathrm{PC}_{2.5\mu m} - \mathrm{PC}_{0.5\mu m})/100000 \quad (3)$$

where $\mathrm{PM}_{2.5}$ is the particulate matter of particles 2.5 μm in size (in mg/m^3), and $\mathrm{PC}_{2.5\mu m}$ and $\mathrm{PC}_{0.5\mu m}$ are the particle counts greater than 2.5 μm and 0.5 μm, respectively. Finally, the Alphasense OPC-N2 sensor provides 16 bins of data, which includes the particles count for the following particle sizes: 0.38 μm, 0.54 μm, 0.78 μm, 1.0 μm, 1.3 μm, 1.6 μm, 2.1 μm, 3.0 μm, 4.0 μm, 5.0 μm, 6.5 μm, 8.0 μm, 10 μm, 12 μm, 14 μm, and 16 μm. Based on these counts, it provides three different particle densities of $\mathrm{PM}_{1\mu m}$ $\mathrm{PM}_{2.5\mu m}$ and $\mathrm{PM}_{0.5\mu m}$. Since the dust sensors developed in this study measured dust density particles of 2.5 μm in size, the density of particles in the 2.1–3.0 μm bin was used in the above cross-correlation analyses.

IV. Results

The wearable wireless dust density systems were measured under several indoor and outdoor real-world conditions to test their accuracy and reliability by comparing them to the Dylos DC1100 Pro and Alphasense OPC-N2 sensors. Prior to this, to determine whether temperature and humidity had any effect on the calibrated sensor and to assess the calibration coefficients, the system was first exposed to increasing humid and temperature conditions while all other variables remained constant both with and without calibration turned on. Then, the calibrated sensor were exposed to a burning oil condition for a short duration to mimic a similar indoor dust situation in which a user of a remote health monitoring system is cooking and exposed to smoke and determine the accuracy of the calibration. The correlation between the sensor and Dylos under these conditions was assessed, along with the time delay for future real-time air-quality alerts in remote health monitoring systems.

A. Dust Concentrations without Calibration

The dust density system was first compared to the Dylos DC1100 Pro sensor under a burning oil condition. This was performed over a short duration (15–20 min) in order to mimic real-time detection of a typical indoor condition when using a remote health monitoring system. As seen in Fig. 3 below, both the Dylos and dust density system increased very quickly under a burning oil condition, however, only the Dylos showed a significant increase in dust concentrations for several minutes after the oil had stopped burning.

a) No Humidity, Varying Temperature—Prior to calibration, the dust density system and Dylos were subjected to increasing and decreasing temperatures by exposing the units to a portable heater (Fig. 4). This was performed to mimic another type of real-world indoor condition the dust sensor system could be exposed to during remote health monitoring use. The temperature was measured using the DHT22 temperature and humidity sensor (Aosong Electronics Co., Ltd., Guangzhou, China) under a constant relative humidity of 44.1 ± 19.5%. Note that the dust concentration of the system increased with temperature, and vice versa, while the Dylos concentration remained the same.

b) Humid Condition—In addition to varying temperature under constant dust conditions, the wireless dust density and Dylos systems were exposed to increasing and decreasing humidity by exposing them to a humidifier (Fig. 5). The humidity was also measured using the DHT22 temperature and humidity sensor under a constant temperature of 25.6 ± 0.9 °C. It can be seen in Fig. 4 that decreasing the humidity did not cause any change in dust concentration, while an increase in humidity caused an increase in dust concentration in both the Dylos and dust density systems.

B. Comparison with Temperature & Humidity Calibration

The temperature and humidity were calibrated in real-time using equation (2) and the coefficients were determined using the above controlled experimental conditions. The calibrated wireless dust density system was then tested twice. First, the two sensors were tested against the Dylos for several hours under varying conditions performed indoors and outdoors to ensure that the two wireless sensors' outputs are correlated in addition to their high correlation with the Dylos (Figs. 6 and 7). Second, the two wireless sensors were tested against the Alphasense OPC-N2 and Dylos sensors under real-world varying temperature and humidity conditions for several hours under both indoor and outdoor conditions to approve the validity and accuracy of the wireless sensor designed (Figs. 8 and 9). These two experiments provided the means to test these wireless sensors under realistic conditions that are likely to be seen in health applications. The tests also proved that these sensors are accurately calibrated to represent all real-world situations for air quality monitoring.

C. Accurracy and Reliability Testing

According to the results from the indoor and outdoor experiments described in the previous section, high correlations of 0.858 ± 0.026 for outdoor testing, and 0.667 ± 0.002 for indoor testing were found when both sensors were compared against the Dylos. Furthermore, the sensors had a 0.969 correlation when compared to the Alphasense during the full day indoor experiment, and 0.972 during the full day outdoor experiment. Not only were the wireless sensors highly correlated with the Dylos and Alphasense sensors, but these sensors were also perfectly correlated when compared to each other, achieving correlation coefficients of 0.963 ± 0.05.

V. Discussion

As seen from the results of the experiments described above, it was found that the wireless dust sensors produced similar outputs to the high-cost and wired Dylos air quality and Alphasense OPC-N2 monitors under different and controlled conditions, such as changing humidity, temperature, or particle concentration. To ensure that the wireless dust sensor can represent the real time dust concentration in the air in future real-world conditions, calibration was performed and tested under these changing conditions. Additionally, because the particle sizes and velocities of the particles change under varying temperature and humidity conditions according to the Ideal Gas Law, it is important for the system to be examined separately under each variable condition in a controlled manner. For instance, under changing humidity, the water particles can interfere with the dust particles, and as a result, increase the sampled particle density. In addition, when the temperature in the air increases, the velocity of the particles of the dust particles increase, which also causes inaccurate readings. Consequently, the wireless sensor was calibrated by observing the results of the professional Dylos and the wireless dust sensor separately under these varying conditions. After calibration was performed, we conducted two different tests to verify that the calibration allows for accurate estimation of dust particle density under real-world conditions. The first test was conducted for several hours under varying particle concentration, where humidity and temperature both indoors and outdoors was varied to ensure that the wireless sensor is able to detect real time variations typically seen in real-world remote health monitoring applications. The second test was performed for a day both indoors and outdoors to test the reliability and accuracy of the wireless dust sensors against the Dylos air quality monitoring.

As presented in the Figs. 6 through 9 after calibration was performed, we were able to develop and validate a wireless, wearable, and secure dust sensor suitable for remote health monitoring applications. The comparison between both prototype sensors also validated the reliability of the sensor. The resulting correlations from initial testing, as well as from the accuracy and reliability testing, demonstrated that these systems were able to achieve the necessary accurate measurements required for a wireless wearable environmental sensing device in remote health monitoring applications under real-world conditions. Specifically, the output of the sensor was first compared with the Dylos air quality monitoring system for a short amount of time (15–20 min) to enable real time analysis of the sensors under different conditions with varying humidity, particle concentration and temperature. Then, the system was tested for reliability by developing a second copy of itself, and comparing these sensors to professional sensors for a longer time (i.e. several hours) under indoor and outdoor real-world conditions. After these experiments were performed, to test the wireless sensors for a long time interval (i.e. a full day), they were tested under varying indoor and outdoor conditions. For the indoor condition, the sensors were exposed to changing temperatures that were due to a heater being used over night with changes in humidity due to cooking in the evening and people breathing in the room overnight, along with natural changes in particle concentration due to dust from walking on a rug and oil particles from cooking. For outdoor testing, the sensors were exposed to the overnight humidity before a rainy day along with a decrease in temperature and increase in particle concentration from burning wood in the neighborhood. During the day, the sensors were exposed to temperature increases, which caused a decrease in humidity. This created a unique real-world condition for reliability and accuracy testing of the wireless sensors against the professional sensors. The results from these tests proved that this system is reliable under all types of conditions typically seen in remote health monitoring applications, as well as accurate when compared to professional non-wearable environmental sensors.

It can be seen in Figs. 6 through 9 that there were inaccurate readings observed by the Dylos air quality monitoring. This is likely because the monitor was not calibrated for increasing humidity changes. However, our wireless dust sensor was able to successfully detect these particles and correctly calculate true particle concentration under increasing humidity. Furthermore, as seen in Figs. 6 and 7, a slight lag was observed between the wireless dust sensors and the Dylos monitor. This was likely due to the sensors being located further apart from the Dylos sensor due to the large size of the professional monitor, so it took a longer period of time for particles to travel from one sensor to the other in high humidity conditions.

In the future, in order to make the wireless dust sensor system more reliable for multiple versions of itself, as well as more wearable for remote health monitoring applications, we plan to perform printed circuit board (PCB) design for the internal circuitry. Furthermore, we plan to design a replacement for the Sharp dust sensor that uses a laser beam dependent system to improve the system's accuracy. However, the most important obstacle in making the system more wearable is the battery size given those that are available in the market. Currently, this sensor is able to collect data for 21 hours, but the size of the battery is too large in comparison to the Sharp sensor, which makes the design more inconvenient to be worn on clothing while collecting data for this duration. However, the sensor could easily be attached to the carrying bag, belt, or the individual's bicycle. Consequently, by reducing the sampling rate and simplifying the calibration calculation, we were able to optimize power consumption to some extent. We plan to further optimize the energy consumption from the BLE device to increase the duration of sensor use beyond 21 hours. In addition, we plan to further study the chip design to determine how to optimize the firmware for power optimization so that a smaller battery can be implemented and the device can become more applicable for future remote health monitoring systems. Finally, once optimized by implementing the above features, we can include this firmware in different health monitoring devices (e.g. during use of a medical vest for critical medical monitoring [13], or a smartcane system [14] in those who suffer from respiratory illnesses). If this system is found to be widely useful in different areas of remote health monitoring, the collected data can improve healthcare through advanced health analytics, such as through participatory user centered design techniques for large scale ad-hoc health information [15] or decentralized electronic triage [16].

VI. Conclusion

The results of this study show that a low-cost wireless dust density system for real-time remote air quality and health monitoring applications is achievable. Furthermore, it is clear that temperature and humidity affect current low cost dust sensors, so calibration under these conditions is necessary for accurate measurements. It can also be noted from the results that humidity caused an increase in inaccurate dust concentration readings among all sensors only when increasing and not when it was decreased. This is likely due to interference of water particles in the light trap of the sensors [8]. Finally, the accurate and reliable measurements obtained from both wireless sensors under real-world indoor and outdoor conditions for several hours and over the course of a full day demonstrate the feasibility of using these low cost dust sensor systems instead of commercially available ones for real-time remote health monitoring applications.

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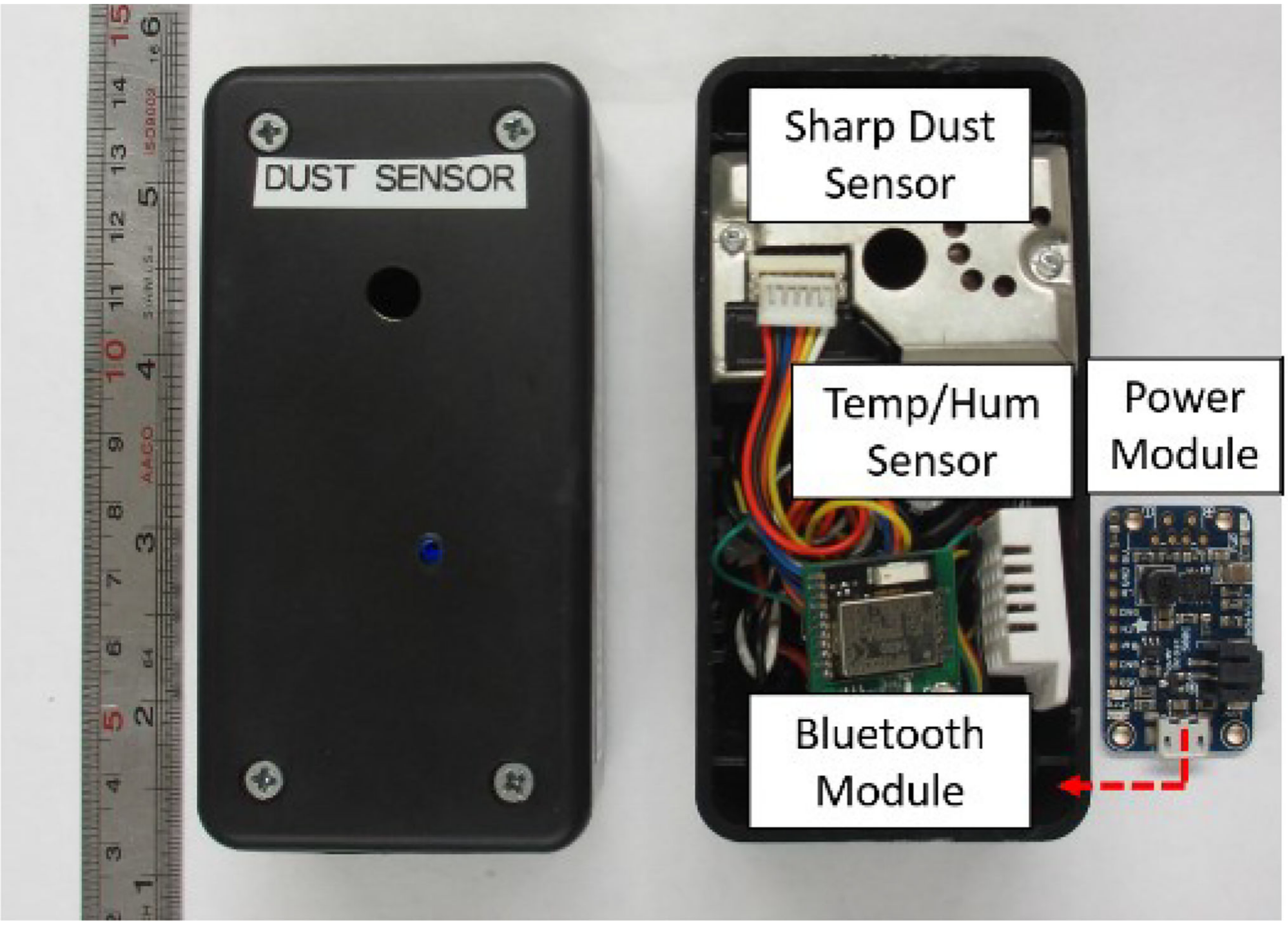

Fig. 1.

Design of the wireless dust sensor.

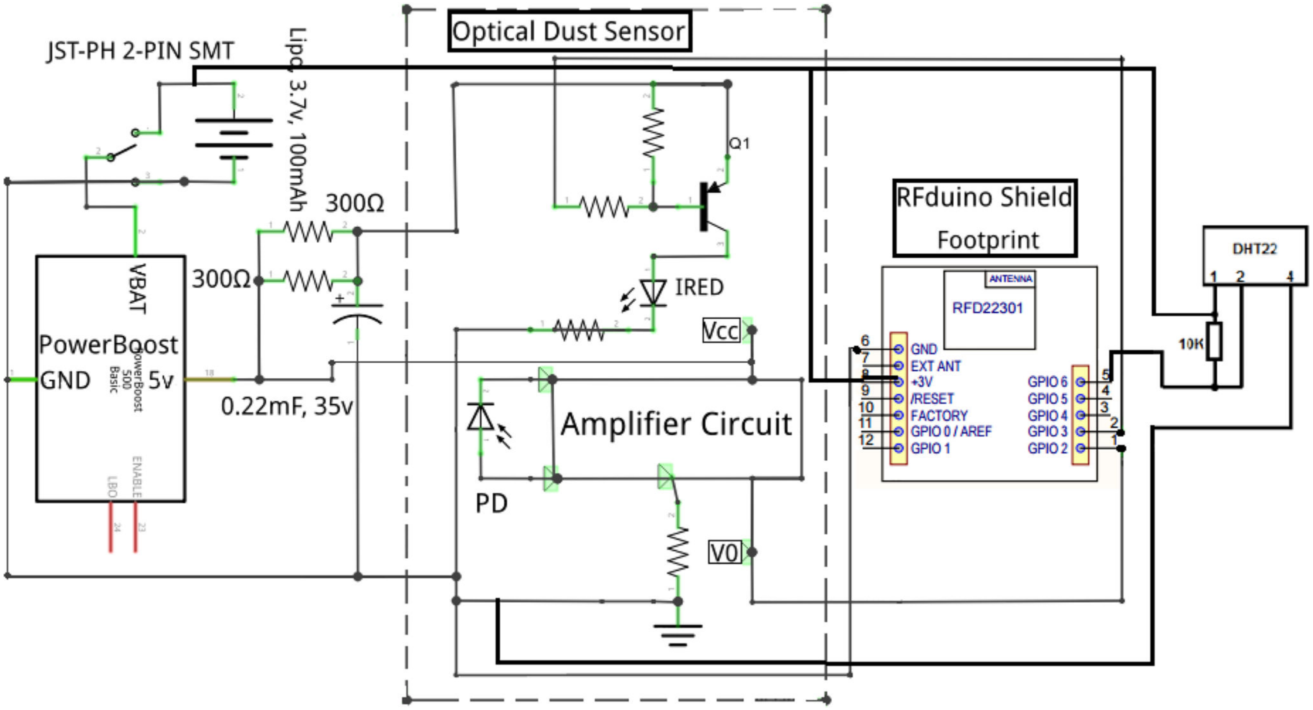

Fig. 2.

Schematic of the wireless dust sensor.

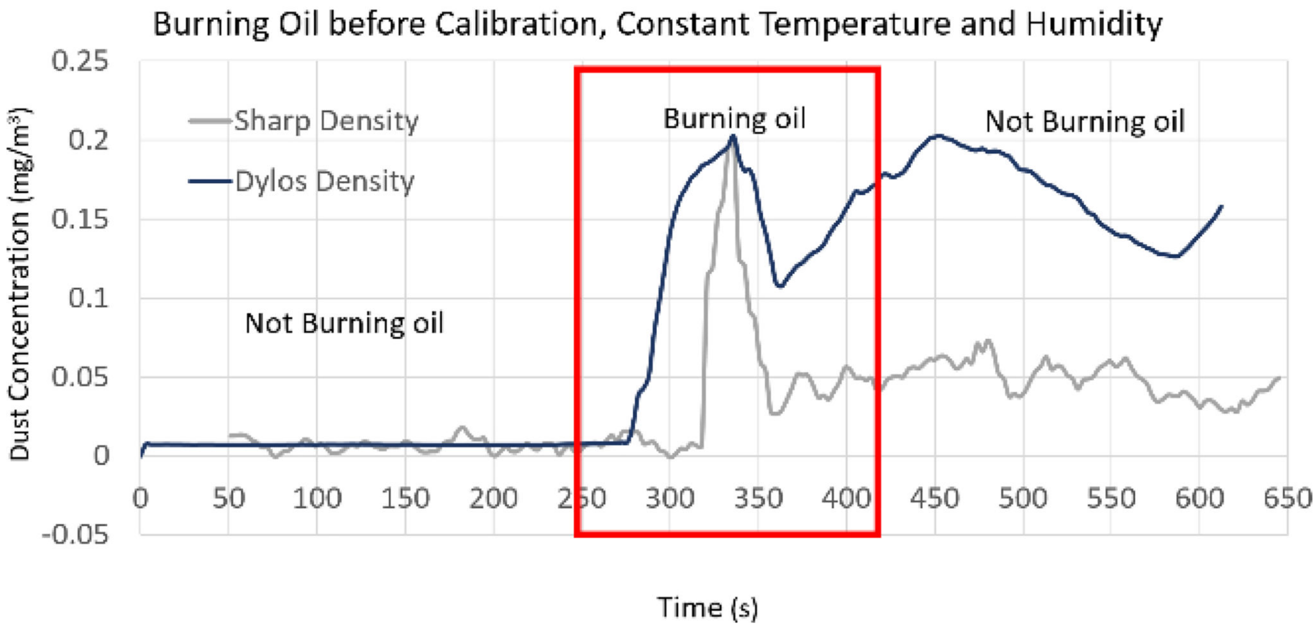

Fig. 3.

Dylos and dust density system exposed to burning oil prior to temperature and humidity calibration.

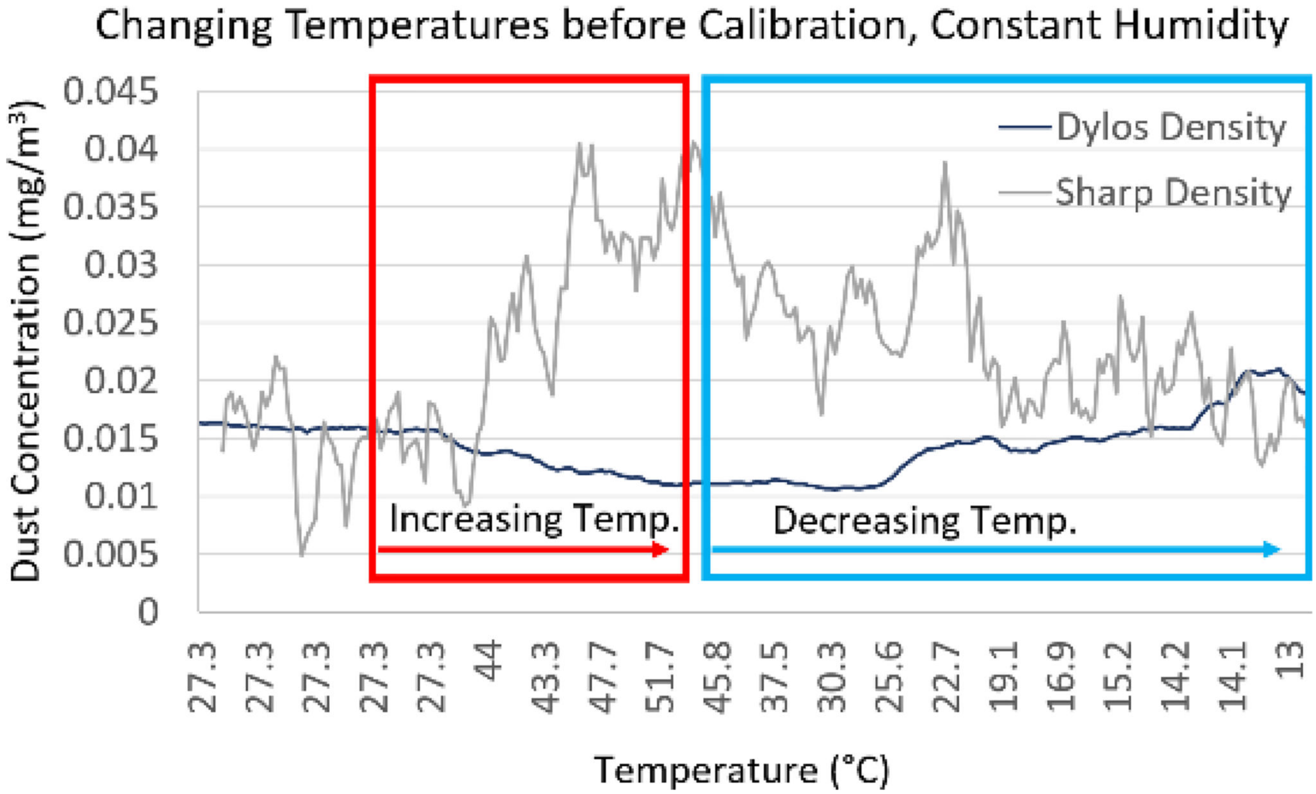

Fig. 4.

Dylos and dust density system exposed to increasing and decreasing temperatures while humidity and dust concentrations are kept constant.

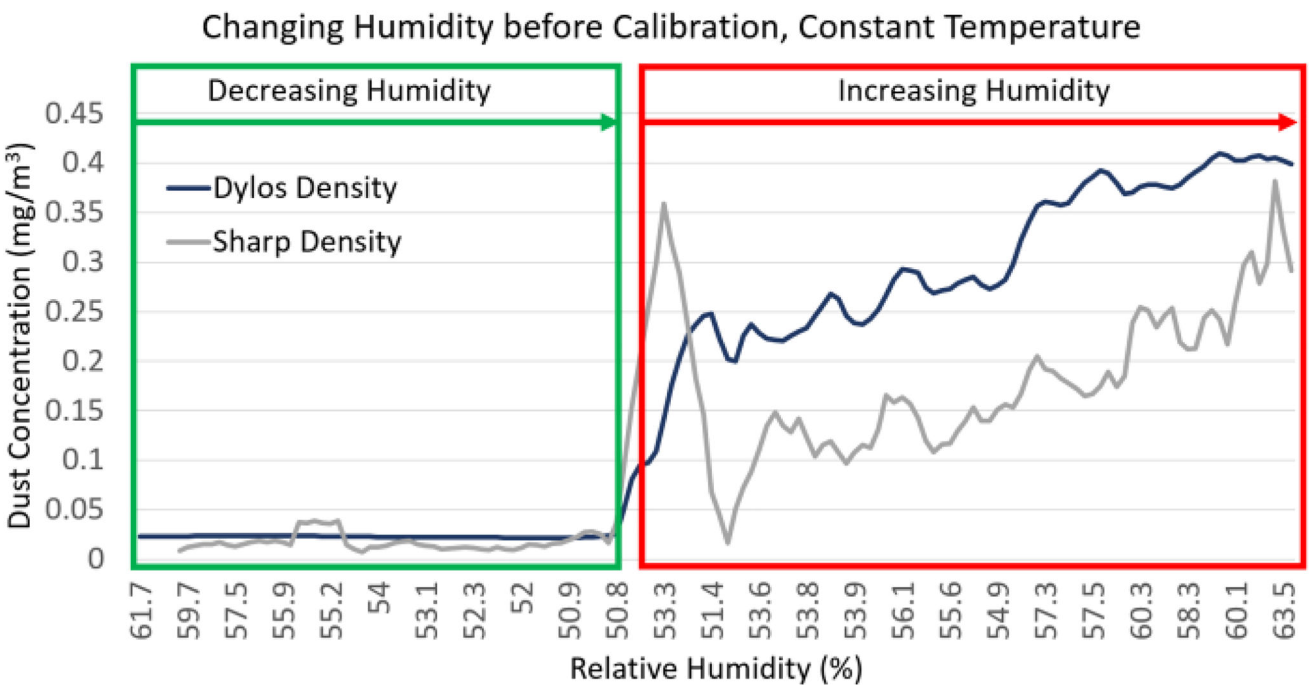

Fig. 5.

Dylos and dust density system exposed to decreasing and increasing humidities while temperature and dust concentrations are kept constant.

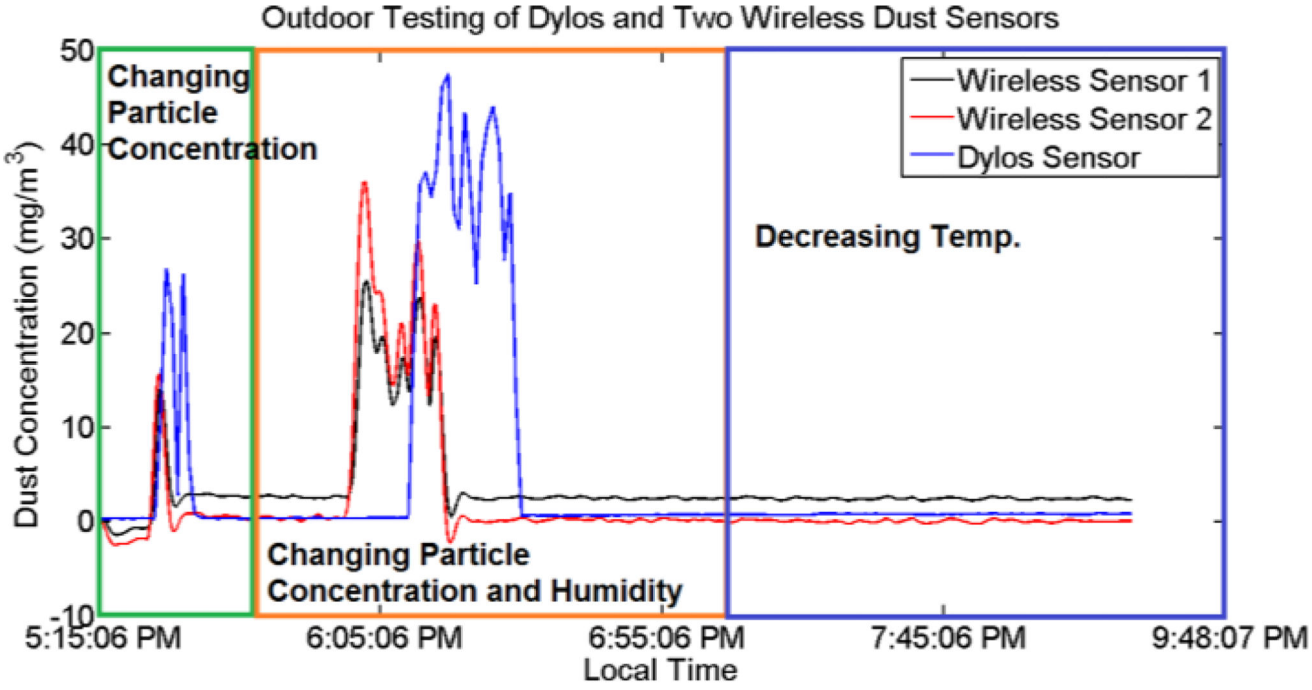

Fig. 6.

Dylos and calibrated dust density systems exposed to burning wood under varying humidity and temperature conditions for 4–5 hours in an outdoor condition.

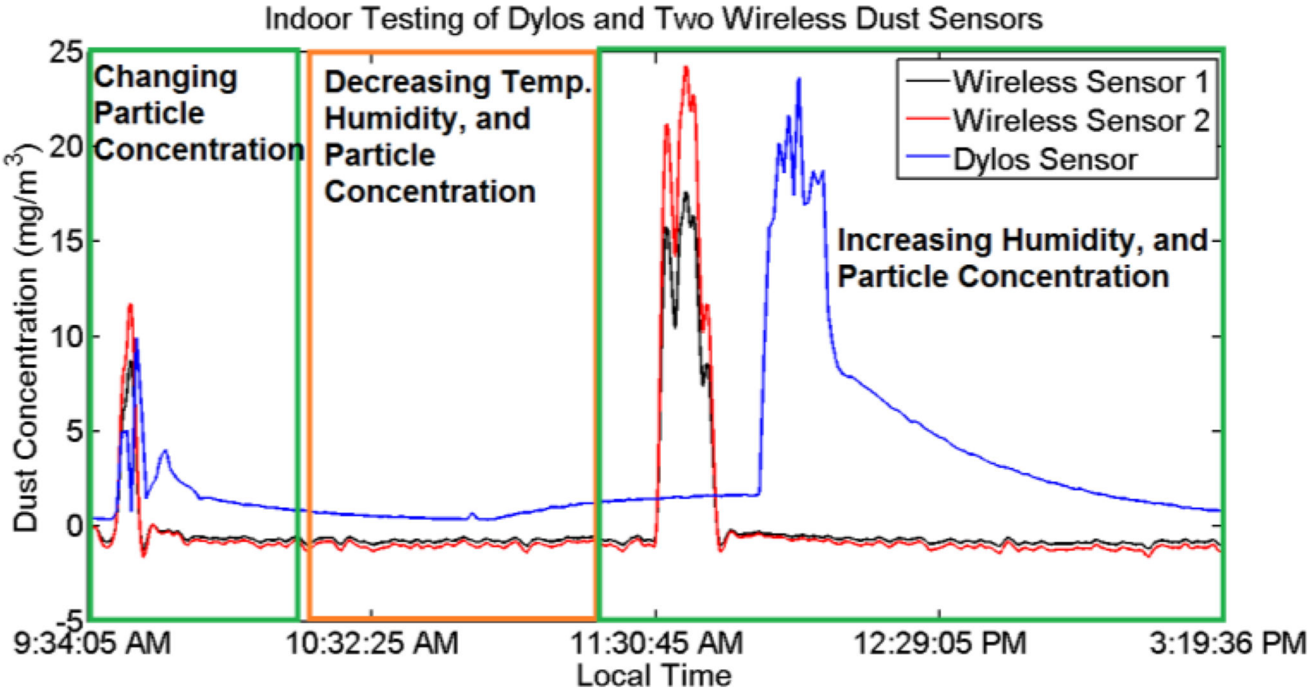

Fig. 7.

Dylos and calibrated dust density systems exposed to burning oil under varying humidity and temperature conditions for 4–5 hours in an indoor condition.

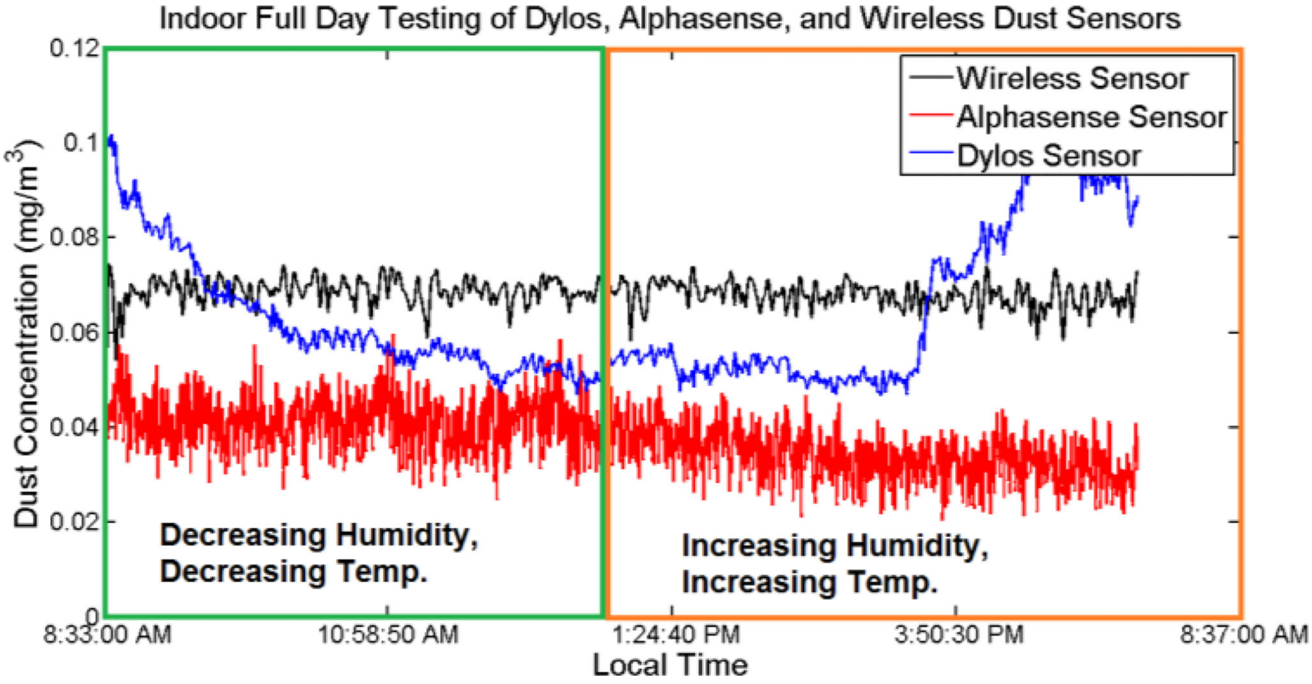

Fig. 8.

Dylos, calibrated dust density systems, and Alphasense exposed to dust and cooking particles under varying humidity and temperature conditions for a full day in indoor condition.

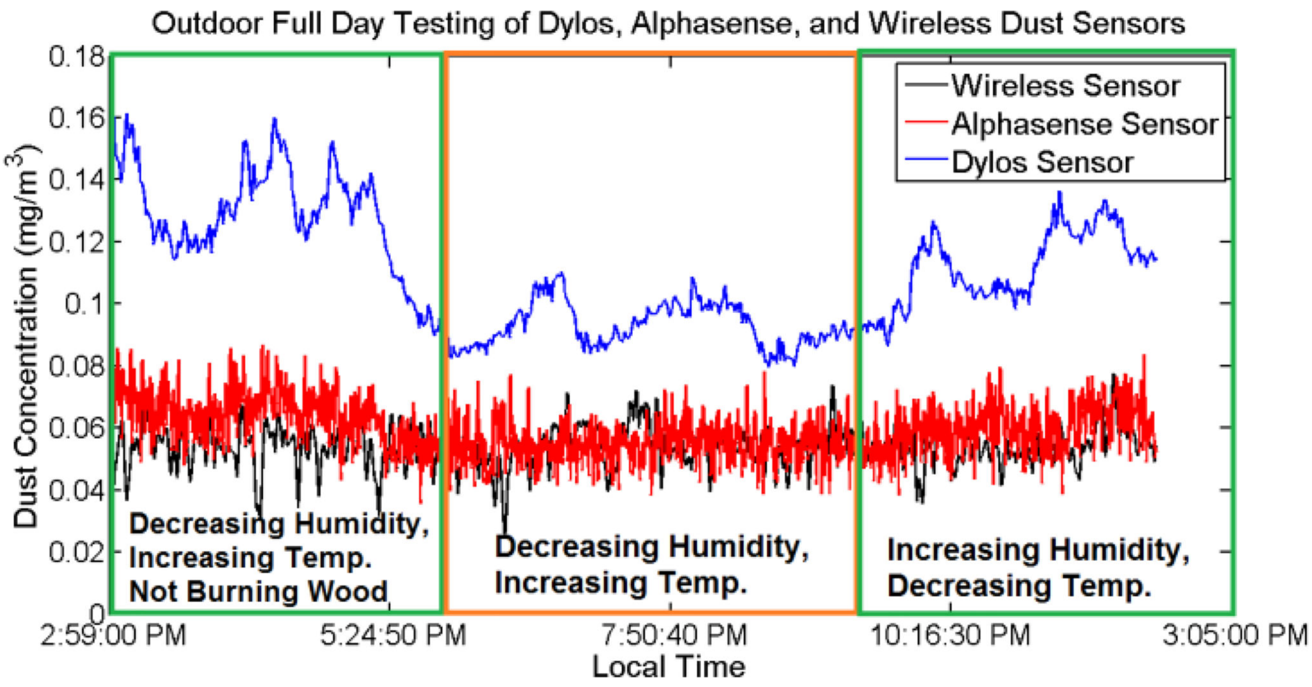

Fig. 9.

Dylos, calibrated dust density systems, and Alphasense exposed to burning wood from the night before under varying humidity and temperature conditions for a full day in outdoor condition.

TABLE I

Cost breakdown of the wireless dust sensor.

Item	**Unit Cost**	**No.**	**Total Cost**
Bluetooth Module (RFDuino)	$19	1	$19
Optical Dust Sensor (Sharp)	$12	1	$12
Power Supply Module (Adafruit)	$15	1	$15
Temp. & Humidity Sensor (DHT22)	$10	1	$10
Housing (RadioShack)	$4	1	$4
Resistors, Capacitors, Wires	$1	1, 2	$3
Total:	**$63**		