An open-source platform for indoor environment monitoring with participatory comfort sensing

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Abstract

We present an open-source wireless network and data management system for collecting and storing indoor environmental measurements and perceived comfort via participatory sensing in commercial buildings. The platform, called a Personal Comfort and Indoor Environment Measurement (PCIEM) platform, consists of a number of devices on office occupants's work areas, a wireless network, and a remote database to store the data. Each device - called a PCFN (Personal Comfort Feedback Node) - contains a touchscreen through which the occupant can provide feedback on their perceived comfort when they wish, and a number of sensors to collect environmental data. The platform is so designed that it can be part of an indoor climate control system that can enable personalized comfort control in real-time. Apart from describing the design and its prototype, we also report on an initial deployment of a small number of PCFNs in a commercial building. The lessons learned during design/prototyping, and from the deployment, are described in this paper. Application of the data collected from the PCFNs for modeling and real-time control will be reported in future work. The hardware components are of commercial-off-the-shelf variety and the software design is based on open source tools that are freely available, so that it is possible to replicate the system by others. The design, including the software, is made publicly available.

Keywords: Participatory sensing, Comfort perception, Open source, Arduino, Sensors, Data collection, Indoor environment

1. Introduction

The primary purpose of an HVAC control system is to provide a healthy and thermally comfortable indoor climate for all occupants. Thermal comfort is defined as "that state of mind which expresses satisfaction with the thermal environment" [1]. A key challenge in providing thermal comfort to occupants of a building is the lack of a thermal comfort sensor. A host of factors affect a person's perception of comfort [2]. For instance, the well known Fanger's comfort index depends on variables such as metabolic rate and clothing insulation [3]. These variables are impossible to measure with current technology in a manner that does not disrupt an occupant's normal activity.

Since an individual is the best sensor for what is comfortable to her, a climate control system should ideally involve the occupant in the climate control loop. This is the notion behind *participatory sensing*; see e.g., [4, 5]. The key challenge is to get useful information and yet not be disruptive to the occupants. There is an increased interest in recent years in participatory sensing, and some of the relevant work is discussed in Section 1.1. However, there is a dearth of work on developing a indoor monitoring system for office buildings that (1) can collect data from which individual office workers' thermal comfort perception can be predicted based on environmental data, and (2) can be part of an intelligent HVAC control system. The requirement that it can be part of a real-time control system means that it must not be disruptive to occupants, and the building operator must be able to keep it running for long periods of time with little maintenance.

The *Personal Comfort and Indoor Environment Measurement (PCIEM)* platform described in this paper is motivated by this state of affairs, and is designed to meet the two requirements mentioned above. The platform consists of a network of devices connected via a wireless network to a base station which in turn pushes the data from the devices to a database via the Internet; see Figure 1. Each device is called a *Personal Comfort Feedback Node* (PCFN). Every PCFN has a number of sensors that measure environmental variables continuously. Every PCFN also has a touch screen through which a user can provide feedback on her perceived comfort any time she wishes, but otherwise the PCFN does not disrupt the occupant in any way; see Figure 1a. The envisioned goal of the PCFN is to use both the regularly measured environmental variables and the comfort perception feedback provided by the user - though the latter is likely to be far less frequent than the

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former - to learn a *personalized comfort model* of the specific user that interacts with that PCFN. Eventually, an HVAC control algorithm will be able to use this model to predict what combination of environmental conditions will keep that particular individual comfortable, which can be used as part of an optimal control algorithm to, say, minimize energy use while keeping comfort within a certain range.

In this paper we describe the design of the *PCIEM platform*, which includes the PCFN devices, the network backbone (base station and the database structure), and the lessons learned during its prototyping and deployment in an office building. The details of how the data from the PCFNs will be used to compute personalized comfort models, and how the models can be used for real-time control of a HVAC system, are beyond the scope of this paper.

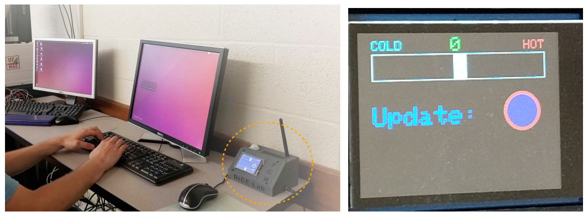
All information needed to recreate the platform (including the software and hardware design files, server side scripts, etc.) are made publicly available [6]. Our aim is to enable others to reproduce and refine the system. In this aspect our goal is similar to Ali *et. al* [7]. There are many similarities between the system described in [7] and ours. The main differences are that in our system, each device has a touch screen that enables a user to provide comfort perception feedback while that in [7] did not, and communication from PCFNs to the base station occurs through wireless communication in our system while that in [7] did not.

The choice of environmental sensors in the PCFN is dictated by the envisioned use of this data to identify a "comfort model" from the data, i.e., a mapping between the environmental sensor data and the recorded occupant discomfort level, without use of disruptive sensors such as heart rate monitors or skin patches, or in fact any wearable sensors. Since it is not clear at present what environmental measurements are needed to identify personalized comfort models, the PCFN is designed so that additional sensors can be easily added to it.

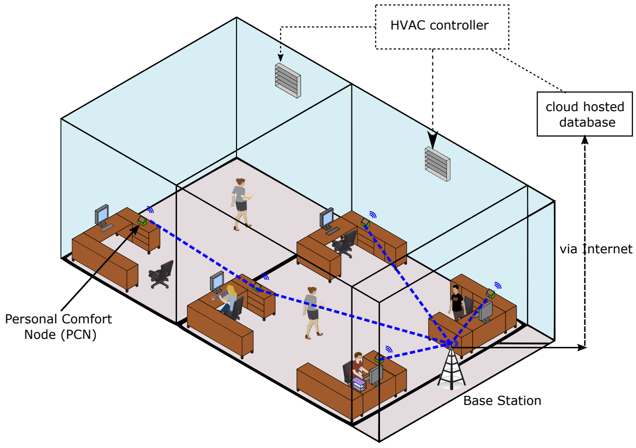
The rest of the paper is organized as follows. Section 1.1 details related work and clarifies the difference with our work. Section 2 described the prototype of the system and its production version, while Section 3.2 reports on a preliminary deployment in a large office building. Section 4 describes the lesson learned during the development. The paper concludes with Section 5.

1.1. Related work

A number of platforms have been developed for participatory sensing enabled HVAC control. A commercial system is the Comfy App^{TM} (www.comfyapp.com), which uses smartphone apps for seeking comfort feedback from occupants. Since smartphones do not have the ability to measure relevant environmental variables such as ambient temperature and humidity, determining individual users' comfort from feedback provided through a smartphone is challenging. This weakness is partially ameliorated in



(a) A PCFN prototype (left) and its user interface for comfort perception feedback.



(b) An artist's view of the PCIEM platform.

Figure 1: A prototype of a single PCFN and an illustration of the PCIEM platform deployed in an office building.

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[8] and [5] by an additional network of sensors to measure space temperatures. The many advantages of using a smartphone to get users' feedback comes with a number of significant challenges, such as ensuring that a particular person's smartphone is mapped to the temperature sensor in the room that the person is occupying in a given time instant. A network of wearable sensors through which users could provide feedback on comfort, and which was part of a HVAC control system, is described in [9]. An occupant can provide three levels of comfort feedback (hot, cold, or fine) through an interface on the wearable device. The devices also recorded temperature, humidity, light level, and movement of the person wearing it via an inertial sensor.

There are many works on comfort modeling that include some form of participatory sensing; see e.g., [10, 11]. There is also a plethora of work describing wireless sensor networks for collecting indoor environment data; see [12] and references therein, and [13] a review of such systems with low-cost sensors. The systems described in these works focus only on collecting passive environmental data. They do not enable collection of comfort perception data from the occupants. The opposite end of the spectrum are the participatory sensing work described above, some of which are too disruptive to the users normal routine and/or privacy invasive, or do not provide environmental data at all.

The proposed system strives to strike a balance between the two extremes. Apart from collecting environmental data that can impact comfort, the main design intents behind the system are: non-disruption to occupants, scalability to a large number of occupants, ability to be part of a closed loop HVAC control system, and ease of reproducibility by others.

2. The PCIEM Platform: Prototype

The PCIEM platform refers to a collection of PCFNs, a base station and a database server. A high level illustration of this system is shown in Figure 1. The individual PCFNs collect indoor environment measurements from sensors and perceived comfort feedback from the occupants. The base station is responsible for collecting the data from all the PCFNs and exporting to the database server. The database server can in principle reside in the base station itself, but it is more likely to be hosted in a remote computer, perhaps in the cloud. The system described in this paper adopts this architecture.

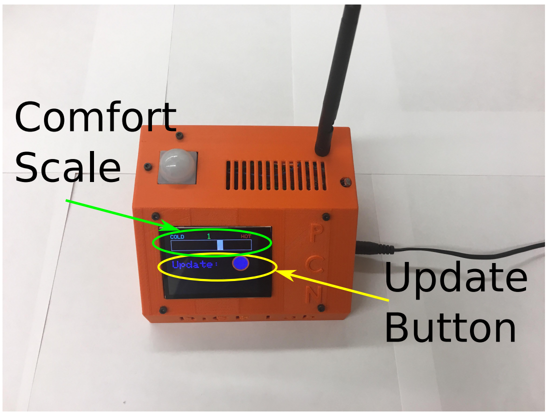
The components of the PCIEM platform are described in greater detail next.

2.1. The PCFN

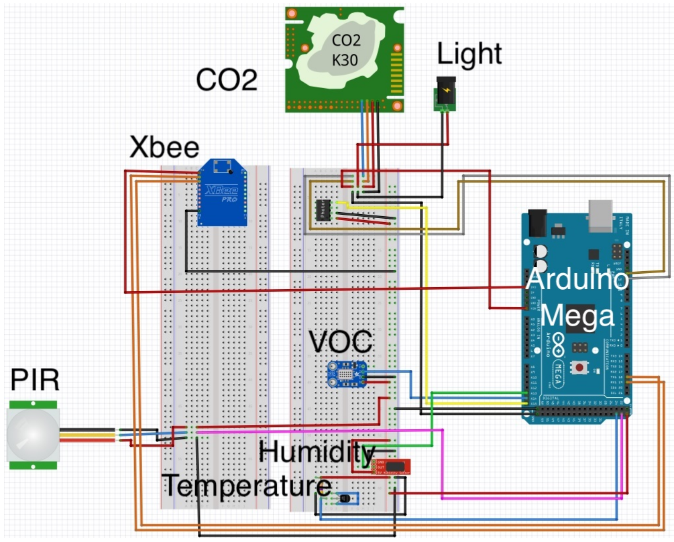
An early prototype of the PCFN is shown in Figure 2a, and its breadboard design in which the internal components are readily visible, is shown in Figure 2b. The PCFN is equipped with a capacitive touchscreen, a number of environmental sensors, a microprocessor, a radio and a power supply. The radio transmits the data from the PCFN to the base station every 10 seconds, with an exception when the user interacts with the PCFN, which will be described below.

The capacitive touchscreen is the key component that allows an office occupant to provide comfort feedback. The touchscreen is programmed to display a comfort perception scale, -3 to 3, with -3 being extreme cold and 3 being extremely hot. The numerical value corresponding to the slider is indicated on the touchscreen. The user can move the bar in the middle of this scale to indicate their perceived comfort within the -3 to 3 range. As the user moves bar the display of the corresponding numerical value on the touchscreen is updated. A software defined “update” button is placed on the capacitive touch screen. When the user presses the “update” button on the touchscreen, the sensor data and the comfort feedback is immediately polled and transmitted to the base station.

Note that how to measure perceived thermal comfort, and how to design an user interface to collect such feedback, is a highly complex question. A number of distinct thermal comfort sensation scales have been proposed in the literature for assessing occupants’ perceptions; see [5, Sec 3.1] for a detailed discussion. Our choice of the comfort scale and the user interface is made based on a trade-off between ease of use and fidelity of the feedback.



(a) An early prototype of the PCFN.



(b) A Fritzing© circuit diagram of a PCFN prototype.

Figure 2: PCFN: early breadboard prototype.

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Recall that the choice of environmental sensors is dictated by the eventual goal of identifying a comfort model from the data, i.e., a mapping between the environmental measurements and an occupant’s perceived thermal comfort. Since it is not clear, apart from temperature and humidity, what other environmental variables may affect comfort, we decided to add the following sensors, though it is easy to add more sensors in future iterations: (i) air temperature sensor, (ii) air humidity sensor, (iii) CO_2 concentration sensor, (iv) VOC (volatile organic compound) concentration sensor, (v) light level sensor, and a (vi) PIR motion detector (to measure occupant presence).

A DS18B20 digital thermometer was used as the ambient temperature sensor. It is supposed to have a $\pm 0.5^0$ C resolution, and does not require a separate power supply but can draw the necessary power from the data line. Humidity is measured with the HIH-4030 sensor, which has an accuracy of $\pm$(5 to 8)%. It needs a 4-6 Volt power supply, which is within the range of feasible voltages for the overall PCFN. A SenseAir K-30 1% sensor was chosen for CO_2 concentration measurement due to its widespread use in environmental monitoring. A Parallax PIR sensor was used for motion detection. We refer the interested reader to [7] for a detailed description of these two sensors and their underlying technology. A PDV-P8103 photocell was used for measuring light intensity. Since it was not clear how much effect light intensity will have on an occupant's thermal comfort perception -if at all - light intensity sensing was not considered critical. The PDV-P8103 is an inexpensive and extremely simple sensor: it is simply a photosensitive resistor. So the sensor has to be calibrated by the user if its reading is to be translated to lumens. Similarly, a VOC sensor (MiCS-5524 from SGX Sensortech) was added to the PCFN to enable measurement of pollutants other than CO_2 that might be correlated with poor indoor air quality and thus perception of comfort. This sensor can detect many types of volatile organic compounds such as CO and Ammonia, but as with the case of light, the scalar reading of the sensor does not provide high resolution information about any specific gas. As with light, VOC concentration measurement was considered non-critical and thus more expensive options were not considered.

The brain of each PCFN is an Arduino Mega 2560, which was chosen so as to adequately support the devices attached to it (sensors and touchscreen). Due to the libraries required to support the capacitive touchscreen, lighter and cheaper options such as the Arduino Uno were eliminated due to memory capacity issues. The Arduino Mega also has more I/O pins, so the design is robust to future demands of more sensors.

The components of the PCFN are powered by a 9V DC power supply that takes input power from 110V single phase AC wall outlet. It is rated for 1A DC supply, and is needed because of the high power demand of the touchscreen. Note that the the high power and energy demand of the touchscreen that eliminates battery as a possible source of power. An Xbee Pro 2.4 GHz radio was used, together with an RP-SMA antenna for extending the range of wireless transmission.

2.1.1. Sensor Characterization

Most of the sensors used in the PCFN were low-cost hobby-grade sensors except the CO_2 sensor, which makes their accuracy and reliability a concern. The K-30 CO_2 sensor is widely used, and a comparison of its measurements with another CO_2 sensor is provided in [7]. Similarly, a comparison of the measurements from the Parallax PIR motion detector was provided in [7] as well. So we do not characterize the K-30 and the PIR motion sensors here.

Among the remaining measured variables, temperature and relative humidity are expected to be critical for comfort modeling, so we characterized the sensors for accuracy and consistency before integrating them to the PCFN. Data was collected from ten distinct temperature and RH sensors (with the same part number and purchased together) that were placed on a desk in physical proximity, before being integrated into PCFN s. The ground truth for the temperature and humidity sensors is a Vaisala HM70 humidity and temperature sensor that is accurate up to ±1% relative humidity. The measurements collected are shown in Figure 3. These figure shows that the temperature sensors are quite accurate and consistent across sensors. However, the humidity sensors are less accurate, and there is a bias among the sensors.

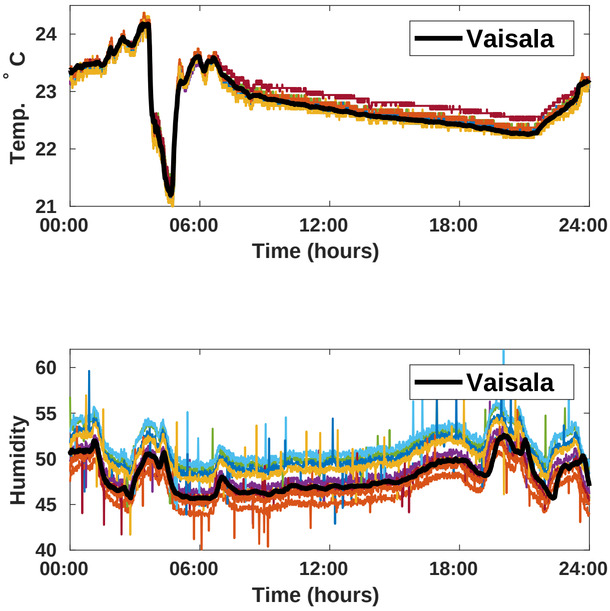


Figure 3: Pre-integration sensor characterization with ten sensors: (top): temperature, (bottom): humidity. The legend "Vaisala" indicates measurements from the Vaisala^{TM} HM70 sensor considered to be the ground truth.

Each PCFN is assigned a unique identifier, called the UID (or `uid`) in the sequel. This information is embedded into the Arduino code while programming the PCFN. Each data packet has the UID of the transmitting PCFN in it, which is forwarded by the base station (discussed next) to the database server (discussed in Section 2.3).

2.2. The Base Station

The base station has two functions: (i) receive data packets from the PCFNs, and (ii) push these data packets, after time-stamping them, into a remote database server. The base station consists of two main pieces of hardware: a wireless receiver, and a general purpose computer with Internet connection; see Figure 5.

ZigBEE was chosen as the wireless communication protocol. The communication transfer requirement (in bytes) is low and the envisioned number of devices is at most a few hundred for a single building, typically less. These requirements make ZigBEE more favorable as compared to bluetooth or wifi [14]. Another critical advantage of ZigBEE is that is an open protocol and capable of automatic mesh networking, so that data from a PCFN device that is not in direct range of the base station is automatically routed to the base station via other PCFNs.

The PCIEM network here is comprised of two types of members: (i) the transmitters, PCFN's ("Router" in ZigBEE mesh terminology) and (ii) a single receiver in the Base Station ("Coordinator" in ZigBEE mesh terminology). This is illustrated in Figure 4. Just as the PCFN transmitters, the receiver in the base station also uses an Xbee radio.

The pipeline for data flow from PCFN s to the remote database server through the base station is illustrated in Figure 4. The details of the software in the base station that enables the data transfer is described in the next section.

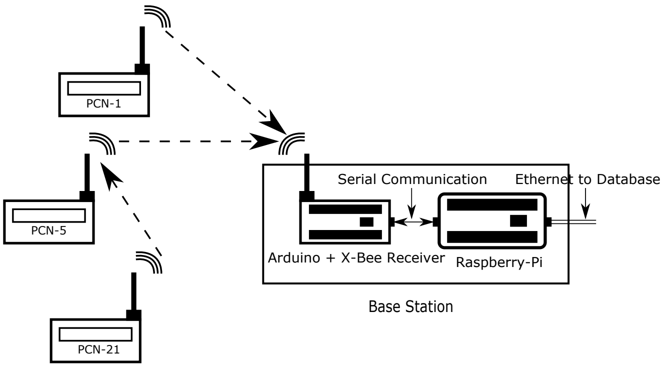
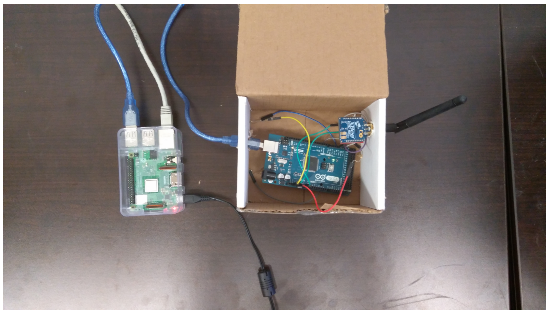


Figure 4: A schematic of the data transfer chain over the PCIEM network.

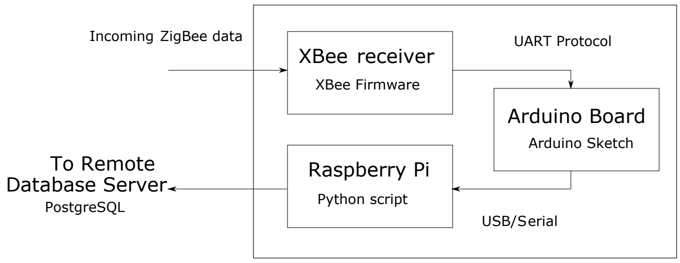
The wireless receiver in the base station is an Arduino Mega with an Xbee Pro© radio, the same as that in PCFN s. A Raspberry Pi model 3B+ was selected as the computer, which runs a Linux based operating system. The Pi has Internet connectivity via both Ethernet and Wi-Fi.

The Xbee Pro© is connected as the only peripheral to the Arduino, and it is powered from the 3.3V Power Pin on the Arduino. The UART (Universal Asynchronous Receiver/Transmitter) interface is utilized for data transfer from the Xbee Pro© to the Arduino. The Arduino board is connected to the Raspberry Pi through a USB cable, which simultaneously powers the Arduino board and facilitates serial communication between the Raspberry Pi and the Arduino board using an FTDI chip. The Raspberry Pi is powered by its own power supply.

The entirety of the software utilized in the base station and database server is developed using open source tools. A Python script running on the Raspberry Pi pulls data received from the Xbee Pro© radio (receiver) through the Arduino microprocessor (vis the USB/serial connection) to the Raspberry-Pi; see Figure 5b. The same Python script also time-stamps the data and pushes it to the remote database through the Internet. Since the base station (rather, the Raspberry-Pi) is connected to the Inter-



(a) A prototype of the base station. (Left): Raspberry Pi, (Right): Arduino and Xbee Pro© receiver.



(b) Data flow inside the base station.

Figure 5: The base station (prototype version).

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net and its clock is synchronized to a global clock, time stamps made at the base station are considered accurate. The only time inaccuracy comes from the delay between transmission from a PCFN and reception by the receiver Xbee Pro© at the base station, which is small. It should be emphasized that a small timing error, smaller than a second, is negligible because of the intended application: HVAC control and occupant thermal perception, which are dominated by processes with much slower time scales.

As with the PCFN, all the software and description of the hardware used at the base station, are available publicly [6].

2.3. Database server

PostgreSQL was chosen as the relational database management system since it is free and open-source, is widely used, and has proved useful in our past work in managing large volumes of time-series data related to HVAC monitoring and control [15]. The database was designed to have only one table, with columns for `uid`, `date-time`, `temperature`, `humidity`, `voc`, `co2`, `light`, `motion`, and `comfort`. Each row of the table corresponds to the data collected from one PCFN at one time instant, with the column `uid` indicating which PCFN it is, and `date-time` indicating the time instant the data was received by the base station, and the rest being the sensor measurements. The Python library `psycopg2` makes connecting to a PostgreSQL database server and pushing data into a database quite easy.

The database can in principle be hosted anywhere, for instance, in the cloud using a myriad of cloud hosting services that are available currently. In our development, a desktop Linux machine, located in the MAE-B building in the University of Florida campus, running a postgreSQL database server hosted the database.

2.4. Automatic restart on power cycle

Ensuring automatic restart of the data collection and transfer in the event of a power cycle is essential in achieving the goal of low maintenance. A power cycle refers to the loss of electricity supply to one or many of the hardware components, followed by restoration. When power is restored, the end-to-end data transer should resume without requiring any human intervention, especially on the PCFNs or the base station. Otherwise the maintenance cost of the network will be extremely high. This lesson was learned the hard way in a previous project, in which a wireless sensor network was developed and deployed in a building that did not have an automatic restart capability [16, 17]. Though the network was successfully used for closed loop HVAC control (see [15]), maintaining the network required manual labor due to the occasional and temporary loss of power supply to the base station that occurred.

The receiver Xbee Pro© in the base station was robust to such a power cycle since the Arduino processor restarts executing its embedded code whenever a power cycle occurs. The same is true for the PCFNs. But some care is needed to ensure the Python script in the Raspberry-Pi of the base station restarts after a power cycle and successfully reestablishes the data transfer process. Because Raspberry-Pi runs on a linux stack, many methods are available for such automation. We tested several methods; more than one worked. But some were less reliable and more complex than others. The method we finally chose requires adding a single line to the `autostart` file that is already part of the base Raspbian installation (or any other standard Linux distribution). Location of the file may vary depending on the distribution, but in the Raspberry Pi we used, the file was located in `/etc/xdg/lxsession/LXDE-pi`. The following line has to be added to the end of the autostart file in that folder:

```
/usr/bin/python2.7 <path to python script>
```

where "python script" refers to the one that pulls data from the Xbee receiver and pushes to the remote database.

We found that no special design is needed on the database server side to enable automatic restart of data collection. Even if the database connection is lost due to powering down of the base station, once the python script at the base station restarts, it is able to reconnect to the database server and push data.

3. The PCIEM platform: Production Version and Deployment

3.1. Production version of PCFNs

In the prototype described in the previous section, the various components in both the PCFN and the base station, such as the Arduino Mega, sensors, and radios were connected with jumper wires. Such a design has a high probability of failure over long time periods with wires getting loose. Moreover, many of the sensors came with additional peripherals when purchased that were not only unnecessary but also added bulk and power consumption. Therefore, once the prototype of the platform was tested and verified, we redesigned and fabricated the PCFN and the base station for greater reliability through an electronic design and fabrication company: Out Of The Box Robotics (`oobrobotics.com`), in Gainesville, Florida, USA, who will be referred to as the vendor in the sequel. The resulting system is termed the *production version*, to distinguish it from the prototype version.

A production version PCFN device is shown in Figure 6. Instead of using the entire Arduino Mega board and the sensors with their breakout boards, the main processor of the Arduino and the main components of the sensors were used in a printed circuit board (PCB) that was custom designed by the vendor. This version was also more convenient for assembly and disassembly. In case of the base station, only the receiver node (radio and microprocessor) changed, the computer stayed the same: a Raspberry-Pi.

Except for the professional re-design of the circuit boards and assembly of the PCFNs, everything else was the same between the prototype version and the production versions with the exception of the location of the temperature sensor. The heat radiated by the touchscreen is sufficient to raise the interior temperature of the PCFN case to create a biased temperature measurement, should the sensor be placed in the case without any special protection. Initially we attempted to negate this effect by designing the plastic case of the PCFN to include a plastic separator between the touchscreen and the temperature sensor, and adding as many slots as possible in the case for airflow. Some of these slots are visible in Figure 2a. While this design appeared to be successful initially, subsequent testing created doubt about the reliability of the temperature measurement. So finally the PCFN and the circuitboard was redesigned so that the temperature and humidity sensor sticks out of the back of the case, exposed to the environment it is supposed to measure; see Figure 6. This is a suboptimal design since the temperature sensor can be inadvertently damaged by the user; it no longer benefits from the protection provided by the case. Still, we proceeded with this design for the production version in the interest of measurement accuracy.

A cost breakdown of the components of the PCFN (production version), including the assembly cost charged by the vendor, is provided in Table 1.

3.2. Deployment in an office building

University of Florida's *Innovation Hub* (iHub for short, located at SE 2nd Ave, Gainesville, FL, USA) was chosen as the demonstration site. A PCFN platform, with the production version of the PCFNs and the base station,

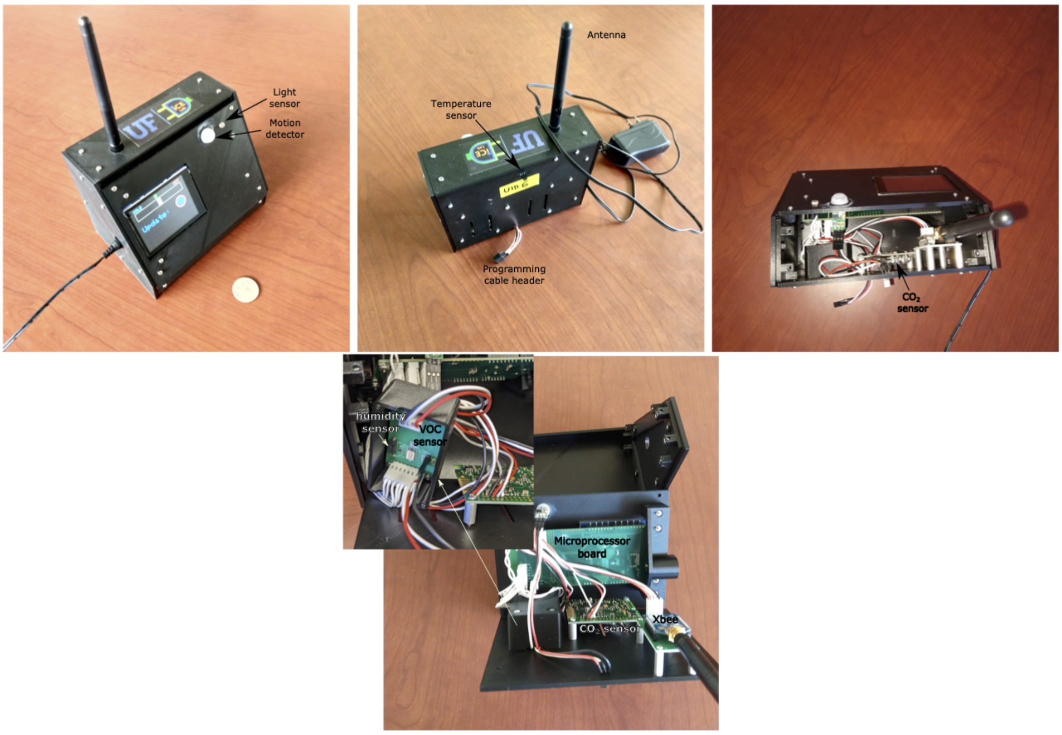


Figure 6: A production version of a PCFN with the internals exposed. The slots on the back cover and the gap on the front cover are to ensure adequate airflow through the case for the VOC and humidity sensors.

was deployed in iHub in April 2021. The database was still hosted on the same Linux machine (located in another building in the University of Florida campus) that was used during prototyping.

Due to COVID-19 induced delays and preference for remote work that reduced the number of regular office occupants in the building, we were able to recruit only a small number of volunteers to be part of the study. So we stared with a much smaller deployment than planned, consisting of only five PCFNs. Analysis of the data from this small network still provides useful information on the functioning and performance of the platform in a realistic setting since the nodes of the network spanned three floors and a floor space of approximately 50,000 sq. ft.

Figure 7 shows the building. The location of the PCFNs in the building are shown in Figure 8. Photographs of a few PCFNs installed in office occupant's workstations are shown in Figure 10. The base station is shown in Figure 9, which was installed in a telecom room that allows access to an Ethernet port without disruption or raising concerns about visual clutter.

3.3. Analysis of data

Data collection from the PCNs was stopped in October 2021 due to lack of funding to continue the project, especially since a larger PCN deployment is necessary for the next phase of the project: modeling user comfort from environmental measurements. Still, the deployment from April to September provided a useful window into the performance and reliability of the platform.

The histogram of the inter-sample time of the data collected from all the PCFNs installed in iHub are shown in Figure 11. The PCFNs transmit data every 10 seconds, except for those instants when the user presses the "update" button. The histograms shows that more than 99% of the samples were received with a inter-sample interval of 10 seconds, showing highly successful data transmission and reception even though the devices were located far apart from one another and from the base station.

A time series of four environmental variables collected from the PCFNs - for a month - is shown in Figure 12. The month (June) is chosen arbitrarily.

The comfort perception feedback provided by the corresponding users are shown in Figure 13. Recall that a positive comfort number means the user is saying they are feeling warm/hot while a negative number indicates they are feeling cold; zero means comfortable. As expected, the office occupants only intermittently interacted with the PCFNs. The user of PCFN 5 has provided the most amount of feedback during the period shown in the figure, and this user's comfort has varied and fluctuated over time, between quite hot to quite cold. That is consistent with the environmental measurements shown in Figure 12: this PCFN has seen some of the largest and most variations in the indoor climate among those recorded. Similar fluctuations in temperature is also present for PCFN 7, but the user of that device provided feedback much less.

Table 1: Cost of PCFN (production version).

Parts	Description	
Sensors	Part name/description	Price in $
VOC Sensor	MICS-5524	11.96
CO_2 Sensor	K-30	85
Motion detector	Parallax PIR	4.86
Light Sensor	DigiKey PDV-P8103	0.65
Humidity Sensor	HIH-4030-003	5.9
Temperature Sensor	DS18B20+	3.98
Hardware		
Capacitive Touch Screen	Adafruit 2.8" TFT	40.46
Microprocessor	ATMEGA2560-16AU	14.28
XBEE-Pro Radio 2.4 GHz	XBP24CZ7SIT-004	32.56
Duck Antenna	A24-HASM-450	5.5
Voltage Supply	DigiKey L6R12H-090	6.3
PCBs	–	15
Miscellaneous	screws, jumpers, housing	20
Assembly cost	-	100
Total		331.4

Prices in USD, in 2019-2020 dollars.

This difference may be attributed to the difference among users personalities, or difference among thermal comfort perceptions. Due to the small sample size not much more can be said at this stage. Since PCFN 12 was installed in an unoccupied room, there is no occupant interaction; so its comfort value always remained at 0.

4. Lessons learned

A few lessons learned during the development process are listed below.

1. Overall, getting a functioning prototype of a single PCFN was straightforward and required much less effort compared to that needed to get the wireless communication aspect of the PCIEM platform working reliably. The main reason is that programming the Xbee Pro© radios is not trivial. One needs to be ready to spend many hours in Internet help forums, and trying multiple radios and programming boards to make sure the problem is not faulty hardware (sometimes it is). There are many radios with lower cost, and perhaps even easier to use, but we chose Xbee Pro© for the simple reason that these radios have been consistently available for many years and unlikely to disappear in the near future. In the do-it-yourself (DIY) ecosystem of development boards, sensors and radios, obsolescence is common and frequent. In fact, the company that made one of the radios we tested in the beginning of the project went out of business during the course of the project, making it impossible to buy more radios of that type.

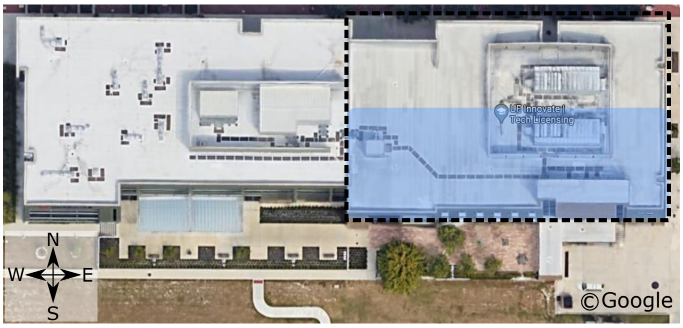
2. As discussed in Section 3.1, the heat generated by the touchscreen was a concern for the temperature sensor. This was resolved by putting the sensor outside the case, but in the future a more elegant solution will be preferable. In any case, design of the housing is important to ensure high degree of airflow into the case, since otherwise the VOC and CO_2 sensors' readings will be different from what they are meant to measure: concentrations in the ambient near the PCFN.

3. The current rating of the power supply is important. Because the touchscreen draws considerable power when its display was on, and together with the power draw of the other components, the combined demand can be higher than what a lower rated 9V power supplies can deliver. In such a scenario, the sensors will produce biased readings. This issue was discovered early in the prototyping stage when a lower rated power supply was used.

4. The software for the PCFN was initially written to send the same data packet up to ten times until a acknowledgment (ACK) was received from the receiver at the base station. It was discovered during a network test with many PCFN s that after a few days, the PCFNs stopped sending data. When the "repeat until ACK received feature" was removed from the transmitters, the problem vanished. Although the reason is not quite clear, data transfer was highly reliable even without this feature as reported in Section 3.2, so the feature was removed in the production version.

5. Cyber-security is a potential issue due to the fact that a general purpose computer (the Raspberry-Pi) is part of the base station and is connected to the

(a) Picture of the Innovation Hub building (view from south to north). Phase-1 is enclosed in the dashed lines.



(b) Top view of the Innovation Hub building. All - except one - of the PCFNs are deployed in the southern half of Phase-1 (region shaded in blue), which is served by an air handling unit (AHU-2). Imagery ©2021 Maxar technologies, U.S. geological survey, Map data ©2021 Google, maps.google.com (January 22, 2021).

Figure 7: Innovation Hub building located at the University of Florida campus.

Internet constantly, while being unattended. These concerns were ameliorated by not keeping a monitor/keyboard/mouse connected to the base station (see Figure 9), and by setting up screen lock and password for the Raspberry Pi.

6. Another lesson learned from the project was the value of ZigBEE mesh networking. A wireless sensor network was developed by our team in a past project for real-time indoor climate control that did not use ZigBEE. The details of the network are described in the two MS theses [16, 17]. The network was developed to enable closed loop HVAC control; and the resulting closed loop experiments are described in [15]. Two important lessons were learned in this earlier project, namely, (i) it is important to avoid any proprietary tools in the development, and that (ii) ad-hoc mesh networking is critical for scalable deployment of a large indoor sensor network. The earlier design used a radio with a proprietary communication protocol (SimpliciTI$^{\text{TM}}$ [18]) that used a star communication topology, meaning that each transmitter had to be in direct range of a receiver. However, indoor spaces are challenging for radio communication, and sometimes two points that are close in Euclidean distance may still be out of range. As a result, range-extenders had to be established after an initial deployment indicated the presence of wireless dark spots [17]. Use of mesh networking in

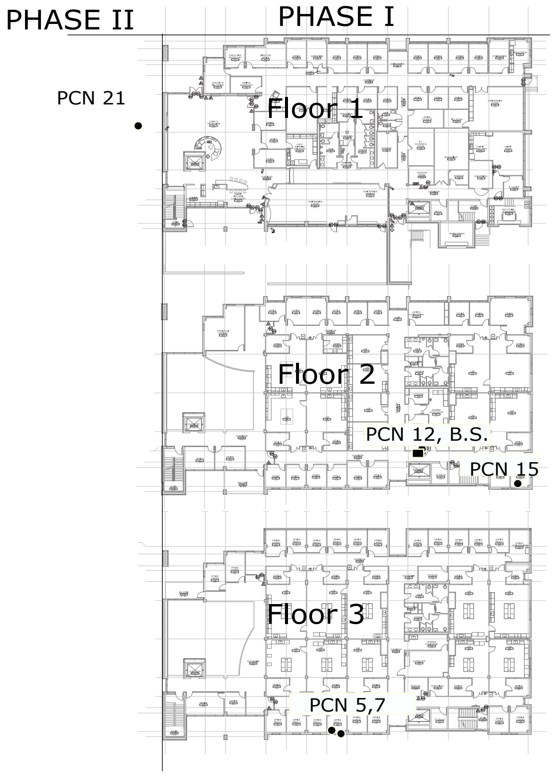


Figure 8: Locations of the PCFNs deployed in iHub and that of the base station (marked as B.S.).

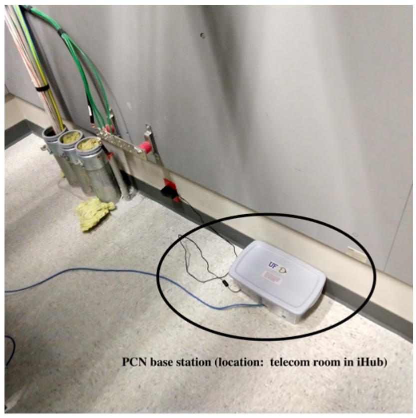


Figure 9: Base station installed in iHub, in an unoccupied room that houses communication equipment. The base station hardware, including the radio and antenna, is inside the plastic box for protection from the environment. PCFN 21 is in a room in Phase II - a recent extension - to the building.

Figure 10: A few PCFNs, as installed in offices in iHub.

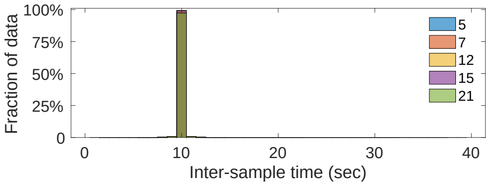


Figure 11: Histogram of inter-sample durations of data received by the base station from the PCFNs in iHub.

this project eliminated that issue and reduced the time needed for deployment tremendously. In fact, the system described here had only one base station in a large building. Yet, it was still able to collect data from all of the PCFNs in the building due to multi-hopping, perhaps aided by the RP-SMA antenna that increased range. Additionally, with an open protocol with a large user base, there are many resources that are freely available to the developer. That was not the case for the proprietary SimpliciTI^{TM} protocol, which too made development in the earlier project challenging.

7. Need for automatic restart of the entire system after a power cycle cannot be overemphasized; see Section 2.4.

5. Conclusion

We presented the design and preliminary deployment of a Personal Comfort and Indoor Environment Measurement (PCIEM) platform, which collects indoor environmental measurements and enables office occupants to provide feedback on their perceived comfort without any disruption to their normal routine. Building occupants interact with the PCIEM platform through an individual PCFN that is meant to remain in their work areas. The PCFN is equipped with a capacitive touch screen, so interacting with one is similar to that with a smart phone. Wireless networking with open protocols enables ease of deployment and maintenance.

All the software, hardware design files, and installation instructions of the PCIEM platform are made publicly available in [6] so that other researchers can reproduce the system and refine it. The platform is designed with free and open-source tools and commercial off-the-shelf components to aid in such efforts.

The platform is envisioned to aid in identifying personalized comfort models for individual office occupants, keep those models updated, and eventually be a part of a closed loop HVAC control system. This paper only describes the development and deployment experience of the platform; modeling and control is part of future work.

Actual deployment in an occupied office building was hampered by the COVID-19 pandemic. We hope to perform a larger scale deployment in the future. It will be particularly interesting to see how often users interact with the PCFNs to provide comfort feedback and how challenging it is to identify comfort models for partipants from the data. There are many additional avenues for future research on the platform itself, such as reducing cost and size.

Acknowledgment

We thank Lucas Murphy for his help with the first PCFN prototype, Roshan Raisoni and Ninad Gaikwad for their help with writing the server side scripts and testing. The research reported here is supported partially by a grant from the Florida Department of Agricultural and Consumer Services and NSF awards 1646229 (CPS/ECCS) and 1934322 (CMMI).

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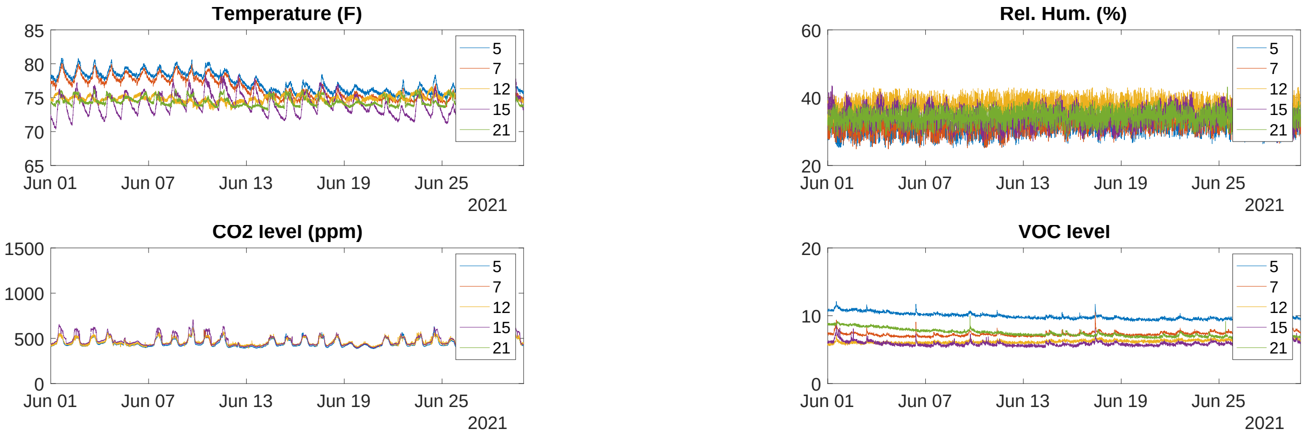

Figure 12: Data on four environmental variables collected by sensors in the PCFNs deployed in iHub. Legends correspond to UIDs of PCFNs.

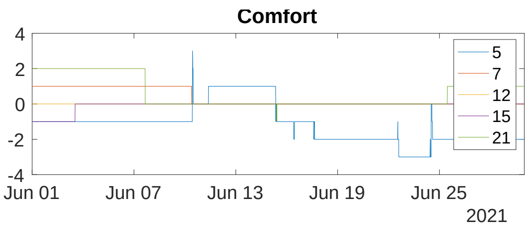

Figure 13: Comfort feedback recorded by PCFNs deployed in iHub over a month.

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