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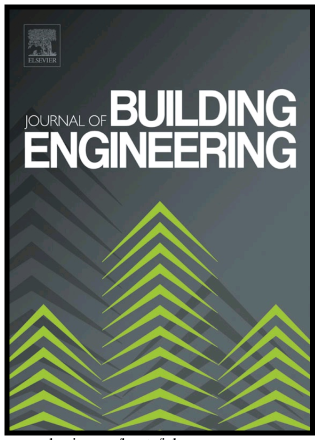

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Continuous Monitoring of Indoor Environmental Quality using an Arduino-based Data Acquisition System

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Abstract

Building performance monitoring could be limited due to the cost and inflexibility of hardware and software platforms for data acquisition. This paper describes a portable continuous measurement toolbox which provides a robust, easily extendable, and low-cost setup for indoor environmental quality (IEQ) monitoring and performance assessment. Various sensors—temperature, relative humidity, illuminance, CO_2, VOC, $PM_{2.5}$, and occupancy—for IEQ performance measurement are included within this toolbox. Arduino Uno boards were connected to the sensors for data acquisition. ZigBee communication protocol was established between an XBee device for each Arduino board and an XBee receiver connected to a computer. The toolbox utilized the open source, agent-based software platform VOLTTRON for data communication and analysis. The data collection system was calibrated against an accurate data acquisition card. Experiments have been conducted using the toolbox for assessing IEQ performance in an open computer lab within a commercial building. Thermal comfort, indoor air quality, and lighting performance have been analyzed based on collected data. The study demonstrated reliability and robustness of the toolbox for continuous monitoring of indoor environmental quality.

Keywords: Indoor environmental quality, ZigBee, VOLTTRON, Wireless communication

1. Introduction

Indoor environmental quality (IEQ) covers the performance of thermal comfort, indoor air quality, lighting and acoustics for indoor environments. IEQ greatly influences an occupant's comfort, health, productivity and living quality [1]–[3]. Poor thermal comfort was identified as the main source of occupant dissatisfaction in commercial buildings [4]. Insufficient indoor air quality has a direct effect on building-related health symptoms, known as sick building syndrome (SBS), which impacts the worker's performance and productivity [5]. Heinzerling et al. [6] conducted a comprehensive review of IEQ performance assessment including both subjective and objective measurement methods and tools. Continuous IEQ measurement devices, integrating various sensors and/or meters, have been created for different studies because no integrated, continuous measurement IEQ toolkit is commercially available.

Various important studies involve the development of IEQ monitoring devices. Chiang et al. [7] conducted continuous measurement of indoor environment quality for senior centers. The monitoring parameters include carbon monoxide, carbon dioxide, airborne dust, air velocity, air temperature, relative humidity, noise, and illuminance. Choi et al. [8] developed an instrument cart for IEQ assessment in 20 commercial office buildings. The instrument cart continuously monitored carbon monoxide, carbon dioxide, total particulates, volatile organic compounds (VOCs), and relative humidity. Kim and Haberl [9] developed an IEQ monitoring cart and conducted a field test to evaluate IEQ environments in an office building located in College Station, Texas. The IEQ monitoring cart was able to continuously monitor air temperature, globe temperature, relative humidity, air speed, CO_2 concentration, VOCs, illuminance, and sound pressure level. There is a wide range of sensors and data loggers used in the created monitoring devices for IEQ assessment.

The cost of measurement devices can be prohibitive with the need of a data logger and a variety of sensors. A low-cost device for data collection and analysis is important to make IEQ assessment affordable and to use comprehensive assessment of IEQ for better control of the built environment. Ali et al. [10] created a low-cost Arduino-based IEQ sensing system including an Arduino Uno board, an SD memory card for data storage, and a series of low-cost sensors for temperature, relative humidity, occupancy, lighting intensity and CO_2 concentration.

Wireless capability increases the flexibility of the IEQ devices when various sensors are installed in different locations. Wireless communication also reduces the setup time and labor cost by avoiding the need for using additional wires for connecting the sensors to central data acquisition system. Furthermore, incorporating wireless data transmission relies on the ability to collect all the data in one node and store them in the computer. Wireless data communication can be established through a mesh network. Data loggers may have a limited number of analog inputs which may restrain the number of connected sensors. Increasing the number of sensors requires incorporating more data loggers, which end up increasing the cost of data collection system. Using wireless communication eliminates this constraint and provides a flexibility in the number of sensors. Wireless data transmission has been used in building monitoring systems for indoor air quality monitoring [11] [12], thermal comfort measurement [13] [14], and indoor environmental quality evaluation [4]. Heinzerling [4] developed a wireless indoor climate monitor (ICM) for IEQ assessment of an office building located in San Francisco. The ICM device can continuously monitor temperature, globe temperature, relative humidity, air velocity, illuminance, and CO_2 concentration. Data communication of ICM devices used a wireless mesh network with a web-based data collection and analysis software [4]. The wireless network was established using a NeoMote hardware [15]. sMAP [16] was employed for data exchange, data collection, and data retrieval through web-based enabled applications. A JavaScript program also handles real-time analysis of time series data [15].

In this study, we present a newly developed Arduino-based IEQ toolbox, integrated with ZigBee communication protocol. Also incorporated is the software platform, VOLTTRON, which enables real-time monitoring and analysis of indoor environmental parameters. VOLTTRON [17] is an open-source platform developed by Pacific Northwest National Laboratory (PNNL) for control of distributed systems. VOLTTRON platform also enables the quick development of other applications which provides the toolbox with the possibility to be used for control and fault detection purposes.

In comparison with the toolkits presented in [7-10, 15], the toolkit presented in this paper offers advantages in reducing the cost by replacing commercial data loggers with Arduino device, increasing the flexibility and simplicity of integrating multiple sensors using wireless data transmission, and enabling online monitoring and cloud based data storing using VOLTTRON software platform. However, the various sensors presented with current indoor environmental toolkit are selected based on the requirements of the scientific study and some of the sensors are expensive.

Provided contributions in this paper are emphasized as follows.

- Using open source platforms in both hardware (Arduino device) and software layers (VOLTTRON software);

- Enabling online monitoring and cloud-based data storage by integrating the VOLTTRON software
- Calibrating Arduino devices and constructing a low-cost monitoring system for building performance with good accuracy;
- Developing an Xbee agent for VOLTTRON software enabling robust wireless data collection;
- Demonstrating the application of toolbox in real building IEQ evaluation.

The paper is presented in the structure as follows. First, we present the hardware and software platforms of the IEQ toolbox. After that, we discuss calibration of the Arduino-based data logger using an accurate National Instrument data acquisition card. Then, we conducted a case study using the IEQ toolbox in a commercial building for data collection and IEQ data assessment. Finally, we discuss the results of the IEQ assessment for the building and provide future recommendations for IEQ toolbox development and application.

2. Prototype description

2.1 Toolbox architecture

Toolbox system architecture, demonstrated in Figure 1, is composed of hardware and software layers. The core of the hardware layer is based upon a wireless mesh network communication, which enables connection of sensors in different locations and collection and storing of data in one location. Different sensors used include dry bulb temperature, elevation temperature, relative humidity, horizontal illuminance, vertical illuminance, CO_2, VOC, $PM_{2.5}$, and human occupancy. Operation of the wireless mesh network in Application Programming Interface (API) mode provides the flexibility of adding new sensors and new meshes to the system with no need to change the current system configuration. XBee modules in the hardware layer of the toolbox enable wireless data transmission based on ZigBee communication protocol. XBee modules are connected to Arduino Uno boards to collect the data from the sensors. Data is received through an XBee module as a coordinator, which is then connected to a computer and data is sent to the software layer using serial protocol.

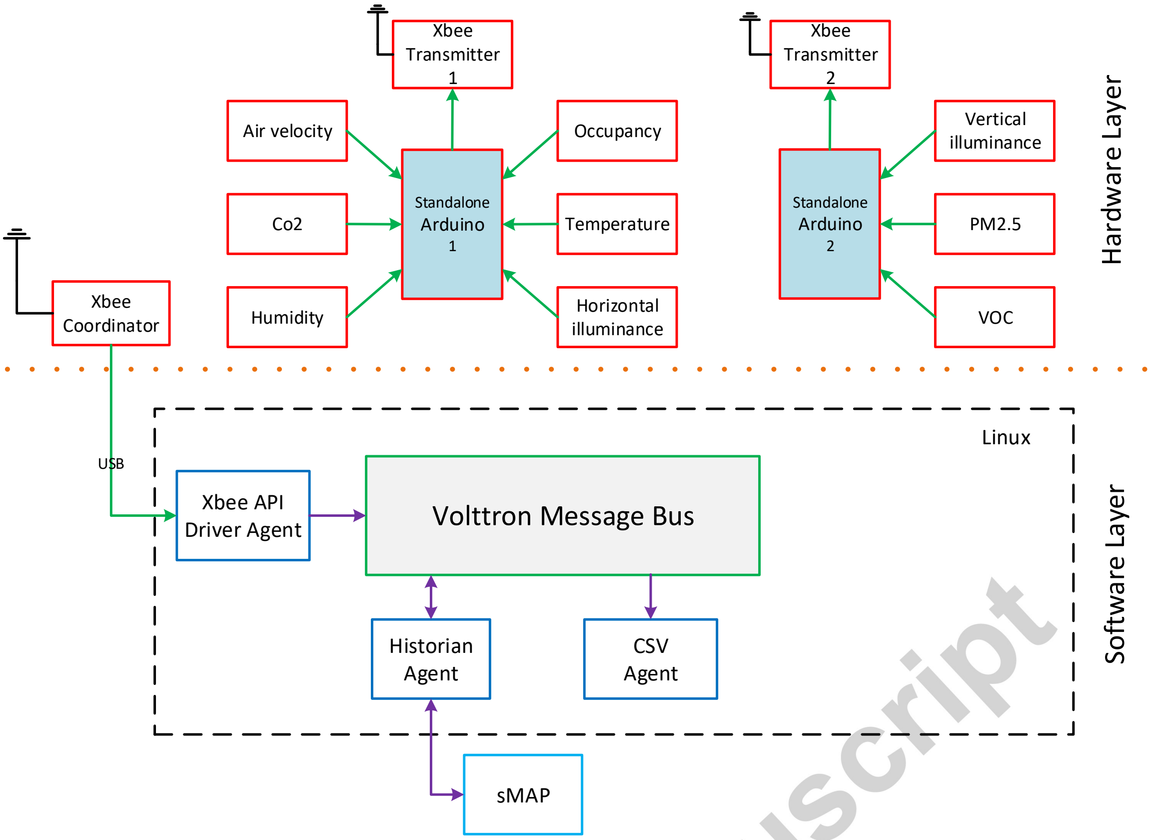

Figure 1: Toolbox system Architecture

The core of the software layer is a VOLTTRON platform which is constructed on top of a Linux operating system and written in Python language to enable data acquisition, data analysis and monitoring [17]. The VOLTTRON platform is composed of different agents, which are supposed to perform a specific process on data and can be executed in parallel. We developed an agent as a driver for XBee coordinator in the VOLTTRON platform to import data from the serial port. The VOLTTRON platform supports a logging service which enables archiving and retrieving the message bus data. sMAP historian has been integrated to the VOLTTRON platform as a big data archiver platform [16]. Data in the format of time series can be submitted to the sMAP through the message bus. Each data point is given a unique identifier and a tag, which makes storing and retrieving of the data easy and quick. Based on the sMAP architecture, which uses HTTP server to store the data, it is possible to connect the VOLTTRON to cloud base applications, enabling VOLTTRON to be used as an Internet of Things (IoT) platform. Figure 2 shows different parts of final IEQ toolbox. A portable cart is utilized to assemble the instruments. A vertical bar is attached to the cart to install temperature sensors at various elevations and a vertical illuminance sensor.

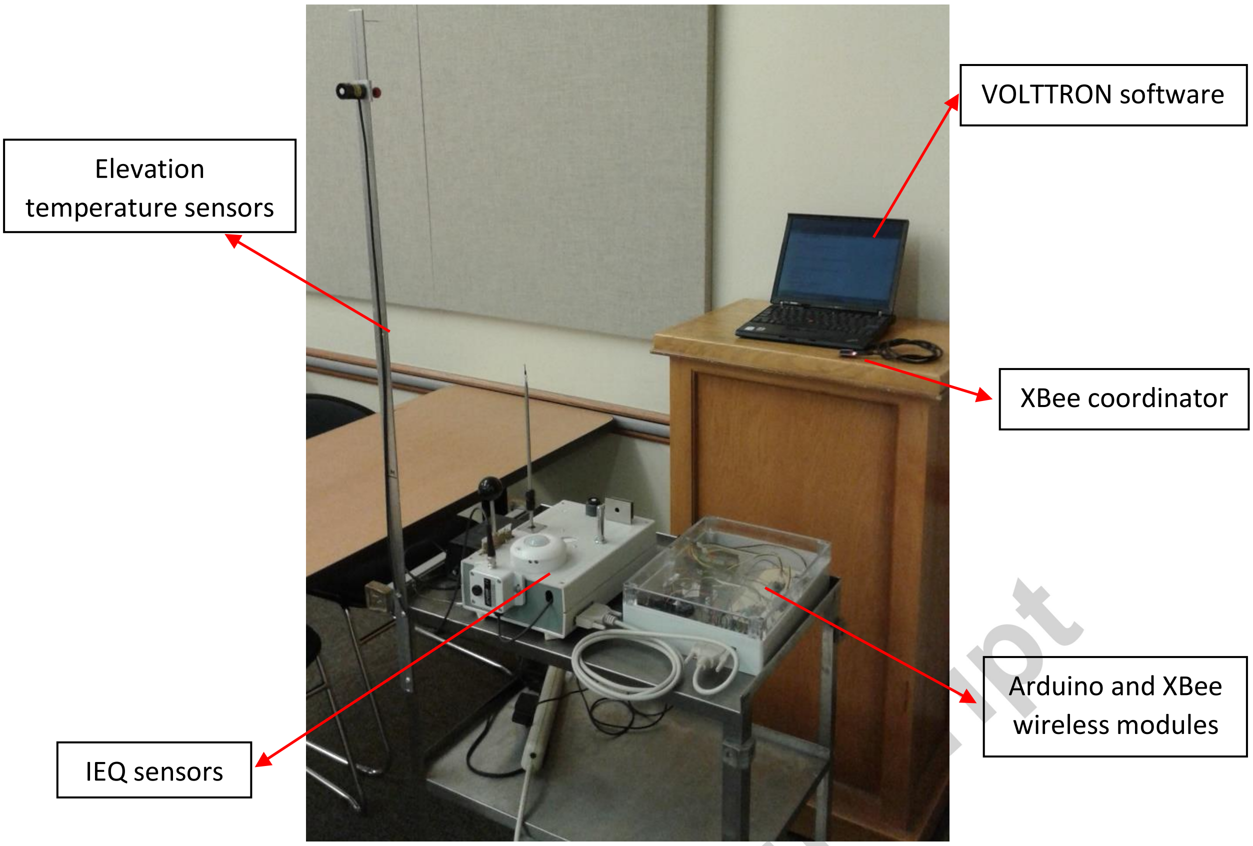

Figure 2: Portable IEQ toolbox

2.2 Toolbox hardware

Toolbox hardware includes Arduino hardware, a ZigBee wireless network instrument, and various sensors to evaluate IEQ.

2.2.1 Toolbox sensors

Various sensors are implemented in the toolbox to evaluate the IEQ. One set of sensors are aimed at computing the PMV and PPD indices and evaluating the thermal comfort. The sensors corresponding to the thermal comfort evaluation measure the dry bulb temperature, relative humidity, air velocity, globe temperature and vertical air temperature gradient in the selected space. A Vaisala INTERCAP HMP60 sensor is used to measure both temperature and relative humidity levels. To conduct the air velocity measurement, an omnidirectional air velocity transducer TSI 8475 was installed in the toolbox. The globe temperature is defined as the equilibrium temperature resulting from the net heat exchange due to convection and radiation in and surrounding the globe. In order to measure the globe temperature in our toolbox, we use a black painted table tennis ball [18]. The internal temperature of the tennis ball indicates the globe temperature. A type K thermocouple, manufactured by ONSET, is inserted into the table tennis ball to measure the globe temperature. This thermocouple has a header compatible with a HOBO data logger which automatically converts the voltage generated by the thermocouple to the equivalent temperature value. In addition to temperature sensor installed in desk level, three type K thermocouple sensors are installed in 0.1 m, 0.8 m, and 1.7 m height. Analysis of vertical air temperature gradient can show how well the air is circulated in the area.

The other set of sensors are used to evaluate the IAQ by providing measurements for carbon dioxide (CO_2), volatile organic compounds (VOC), and $PM_{2.5}$ fine particles. A K-30 sensor module, which uses non-dispersive infrared (NDIR) waveguide technology for CO_2 measurement, was installed in the toolbox. The K-30 sensor is maintenance-free and has the capability to perform self-diagnostic and auto-calibration. The CO_2 sensor has no sensitivity to change in volatile organic compounds (VOC) such as cooking odors, bio-effluence, and outdoor pollutants. In locations which are exposed to VOC sources, indoor air quality evaluation requires installing VOC sensors. Our toolbox is equipped with an IAQ-2000 indoor air quality module to measure a broad range of VOC gases. This sensor responds to change in the level of VOC substances including CO, CH_4, alcohols, ketones, organic, acids, amines, aliphatic hydrocarbons, and aromatic hydrocarbons.

Monitoring the concentration of fine particles with diameters less than 2.5 micrometers, known as $PM_{2.5}$, is important in assessing indoor air quality. A Sharp dust sensor GP2Y1010AU0F was installed on the toolbox to measure $PM_{2.5}$ concentration. This sensor employs an optical sensing system to detect dust and cigarette smoke. It has an infrared emitting diode and a phototransistor which generates a voltage in proportion to received light reflected from dust particles. Driving the emitting diode requires a pulse input with pulse cycle of 10 ms and pulse width of 0.32 ms. The sampling time of the output signal is 0.28 ms after sensing light emitting diode pulse. Configuring the input condition and sampling time requires logic programing. Arduino Uno board was used for both driving the sensor and capturing the output signal.

The toolbox uses Licor Photometric (LI-210SA) sensors to measure light level or illuminance in both horizontal and vertical directions. In this sensor, a filtered silicon photodiode has been utilized to respond to radiation at various angles of incidence with the reported response time of 2 µS and accuracy of ± 5 % of measurement. This sensor has a cosine correction ability to avoid measurement error when the light source is not directly overhead of the sensor. An amplifier is used to convert the output of sensor from current in the µA unit to the µV unit and then amplifies the data to provide a suitable signal for acquisition hardware.

An occupancy sensor provides information about the presence of an occupant in the location where the toolbox is installed. In our toolbox, a Sensky infrared motion sensor was used to detect the proximity of occupants. There is a time delay in sensor operation, which can be adjusted between 30 to 300 seconds. Time delay represents the time period in which sensor keeps providing high voltage after detecting the occupant. Table 1 provides a summary of IEQ sensors installed in the toolbox.

Table 1. Sensors in IEQ toolbox

Sensor type	Manufacturer	Model	Measurement range	Output signal	Accuracy	Power
Temperature	Vaisala	HMP60	-40°C to 60°C	0-2.5 V	± 0.5°C(10-30°C) ± 0.6°C(-40-10;30-60°C)	5-28 VDC
Relative humidity	Vaisala	HMP60	0-100%	0-2.5 V	± 3%RH (0-90%RH)	5-28 VDC
Air velocity	TSI	TSI 8475	0.05-2.54 m/s	0-10 V	±3% of reading value or ±1% of full scale range	11-30 VDC
Globe temperature	ONSET	type K thermocouple	0-285 °C	-	0.0075 of the measured temperature	-
CO_2	CO_2Meter	K-30	0 – 10,000 ppm	0-10 V	± 30 ppm ± 3 % of measured value	4.5-14 VDC
Illuminance	Licor Photometric	LI-210SA + 2420 amplifier	0-46.168 klux	0-5 V	± 5 % of measurement	3.8-28 VDC
Occupancy sensor	Sensky	PIR sensor	10-2000 lux	0-12 V	-	12 VDC
$PM_{2.5}$	Sharp	GP2Y1010A U0F	0-0.5 mg/m^3	0-3.4 V	-	5-7 VDC
VOCs	CO_2Meter	IAQ-2000	350-2000 ppm CO_2 equivalents	0-5 V	-	5 VDC

2.2.2 Arduino hardware

Arduino Uno, an open source platform, accounts for the data acquisition hardware in our toolbox. Different types of connection ports, including digital input/output, PWM output, UART TTL (5V) serial communication, and analog input, make the Arduino Uno board a powerful and cost-effective hardware for data collection purposes. The Arduino Uno board has an Atmel ATmega328 microcontroller which can be programmed in C/C++ language through an integrated development environment (IDE). Regulated 5 V and 3.3 V outputs can be obtained from the Arduino board to provide the supply voltage for particular sensors. The Arduino Uno supports 6 analog input pins which read data in the range of 0-5 V with the resolution of 10 bits.

2.2.3 ZigBee wireless network

Wireless network communication provides a flexible and cost-effective platform to transmit the information in control and monitoring applications. In this project, the ZigBee protocol is employed to establish wireless network communication. The XBee Series 2 module is used as a reliable hardware to enable wireless communication based on the ZigBee protocol.

The wireless mesh network in our toolbox includes an XBee module as a coordinator and two XBee modules as routers in a star configuration. The coordinator is connected to a computer and receives data from routers in the network. Although routers can communicate to each other, in our application they only send collected data to the coordinator.

XBee modules can be embedded in the data collection circuit with no need to incorporate external microcontroller. In this case, sensors are directly connected to the XBee module through the digital and analog input pins. Employing the XBee module alone has advantages in saving space in boards, reducing the board's weight, cost savings, and reduction of power consumption, which is highly crucial in battery-powered circuits. The standalone application of the XBee module faces some restrictions in more complex projects. A limited number of input and output pins are available in the XBee module. Moreover, it does not support both analog and pulse width modulation (PWM) outputs which are required to control a variety of devices. Another limitation of XBee module includes not supporting logic programming. Logic programming is required for local control of devices as well as collecting data from specific instruments such as a particulate matter sensor. The maximum allowable analog input is limited to 1.2 V, which provides low reading resolution, and consequently, reduces the data collection accuracy. The aforementioned limitations led to an incorporation of an external microcontroller as an auxiliary component to boost the performance of the XBee module. In our toolbox, we employ Arduino Uno since it provides a convenient environment for logic programming and supports several available shields to integrate the XBee module.

The XBee module supports a maximum of 4 analog inputs. Arduino extends the number of analog inputs in each wireless node up to 6 pins. The maximum allowable analog input voltage in Arduino is 5 V which serves better data acquisition resolution compared to that of obtained from using the XBee module alone. The data exchange between the XBee module and the Arduino board occurs in a serial format and through a UART interface.

2.3 Toolbox software

2.3.1 VOLTTRON platform

VOLTTRON has been developed as an open-source, agent-based software which provides an ideal platform to collect data and establish control algorithms in distributed systems. Agents are components of the platform, each of which is designed to perform a specific function. Agents are developed independently, making it easy to add or modify the agents. One group of agents, known as platform agents, enable interfacing with external devices to collect and share the data required by other agents and transmit control commands to actuators. BACnet and Modbus are two main interface protocols supported by VOLTTRON to communicate with industrial devices. BACPypes and PyModbus are python libraries utilized in VOLTTRON platform to provide BACnet and Modbus drivers, respectively.

The archiver agent is developed in VOLTTRON platform, allowing other agents to store and query time series data. Various cloud-based storage frameworks, such as sMap, SQLite, MySQL, and MongoDB, are integrated into VOLTTRON platform to make a history of data. In this study's toolbox, sMap was used as a cloud-based data archiver. In addition to data storage, sMap provides a graphical user interface to monitor the trend of observed data.

All agents in VOLTTRON platform can communicate with each other to exchange the data through a Message Bus. VOLTTRON Message Bus follows Publish/subscribe pattern to share data among different agents. According to this pattern, Message Bus provides an environment for agents to indirectly exchange their data. An agent can publish the result of its function to Message Bus and other agents can subscribe to data of interest from Message Bus. The VOLTTRON platform employs ZeroMQ software to establish Message Bus. The Publish/subscribe pattern in Message Bus provides the agents with the flexibility to be written in any programming language.

3.3.2 Xbee agent

Standard VOLTTRON software does not provide a driver agent to communicate with XBee devices. We developed a VOLTTRON agent, named as XbeeAgent, to collect data from the toolbox. XbeeAgent receives data from the XBee coordinator through the serial communication protocol. XbeeAgent periodically scans the serial port with the user-defined sampling rate. In order to avoid accumulating data in the serial buffer, sampling rate used to scan the serial port should be chosen at least twice as Arduino nodes sampling rate. Due to employing Zigbee communication protocol in API mode, data from each node is received in serial port as a package identified by a unique address corresponding to each node. XbeeAgent separates packages based on the attached address to perform a further process of the data. For each package, XbeeAgent extracts the data associated with each sensor and imposes a mapping function to convert received sensor voltage to the sensor's physical data. XbeeAgent is enabled to window the received data and generate the average of data. The size of the window can be adjusted by the user.

In XbeeAgent, information is converted to JavaScript Object Notation (JSON) format and published to VOLTTRON message bus. Published data includes time, the data unit, and the data type. VOLTTRON message is labeled with a topic name and several subtopics. Consumer agents can subscribe to the message of interest by referring to message labels. In XbeeAgent, "datalogger/log1/" and "datalogger/log2/" are labels for two distinct VOLTTRON messages which carry the data collected from two Arduino nodes.

Robustness is crucial to have a continuous data collection system. Since the XBee coordinator is connected to a laptop via Universal Serial Bus (USB) port, it is possible to lose the connection in a short period of time. USB short disconnection can likely occur due to electrostatic discharge (ESD). XbeeAgent is robust to USB disconnection and it continues collecting data once the USB is connected again.

4. Toolbox calibration

Most important errors in measurement systems consist of sensor error, transducer error, converter error, and signal transmission error [19]. In this paper, since it is assumed that sensors are factory-calibrated, no sensor error and transducer error is considered. So the main source of error in the toolbox was found in Arduino board as an analog to digital (ADC) converter. Quantization error, gain error, offset error, and nonlinearities contribute to the performance error in ADC converter [20]. Each ADC has a characteristic curve which maps the input voltage to the associated digitized output. The ideal N-bit ADC with a full scale analog input V_f, has a linear characteristic curve which passes the origin with the slope of $2^N/V_f$ codes per volt. Quantization error results from the finite resolution of ADC converter. Offset error is the deviation of digital output at zero input. Gain error is the deviation of the slope of the characteristic curve from the ideal line. Nonlinearity causes different digitization errors for different input voltages. Signal transmission error is associated with the noise imposed by the environment and can reduce the accuracy of measurement. To reduce the impact of noise, data is collected with the frequency of one sample per second then the average of data in every minute is computed and monitored.

Selection of Arduino boards for data acquisition was a result of compromising between cost and accuracy of the toolbox. Calibration of the analog input pin of Arduino can enhance the accuracy of data acquisition. One error source in data acquisition with Arduino is the relatively low resolution of the board. The magnitude of Arduino Uno's resolution is 10 bits while some industrial data acquisition (DAQ) cards can provide 16 bits of resolution.

In the calibration process, a National Instrument (NI) DAQ card, equipped with 16 bits analog to digital converter, plays the role of the reference data acquisition system. Both Arduino and NI DAQ card analog inputs are fed with same voltage using a regulated DC power supply. The approach is to increase the excitation voltage by 0.2 V increment in each step and collect measured data with the NI DAQ card and Arduino board with the frequency of 1 sample/second for a period of around 4 minutes. Then, data collected from Arduino board is compared to that of collected from NI DAQ card to calibrate the Arduino analog input pin using a correction function. Transient data collected during the change the input signal was eliminated so that we can make the calibration based on steady-state data in each step. The calibration process has been conducted for the two Arduino boards used in the toolbox. Figure 3 shows measured data using NI DAQ card and Arduino1 board after cleaning transient data.

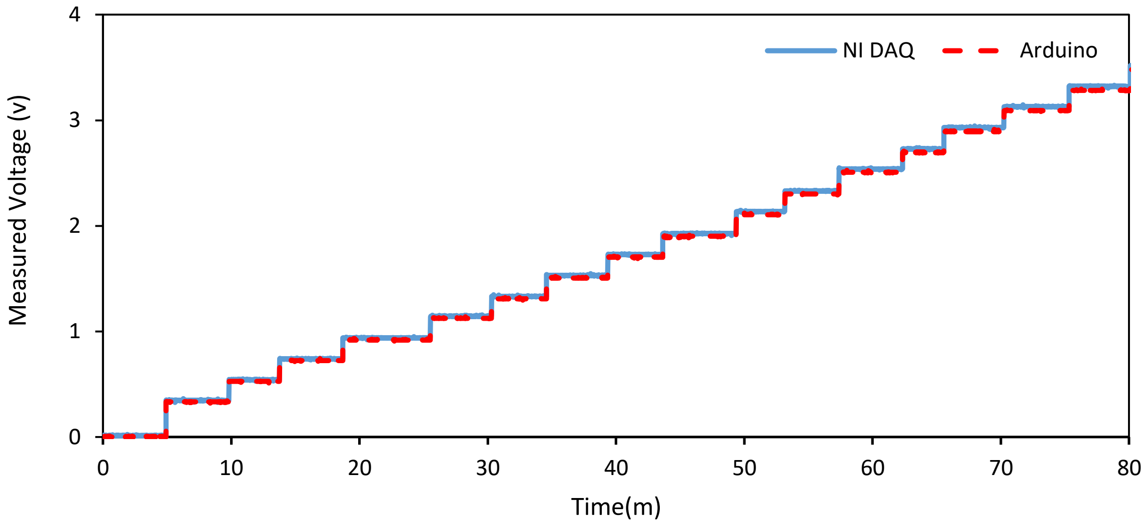

Figure 3: DC power supply voltage measurement using NI DAQ and Arduino1

For each steady-state segment of the measured voltage shown in Figure 3, the average value of collected data from NI DAQ card and the Arduino1 board is computed. Difference between these two values constitutes the Arduino1 measurement error since the NI DAQ card is supposed to be reference DAQ system. As shown in Figure 4, measurement error in the Arduino1 board increases with the analog input signal.

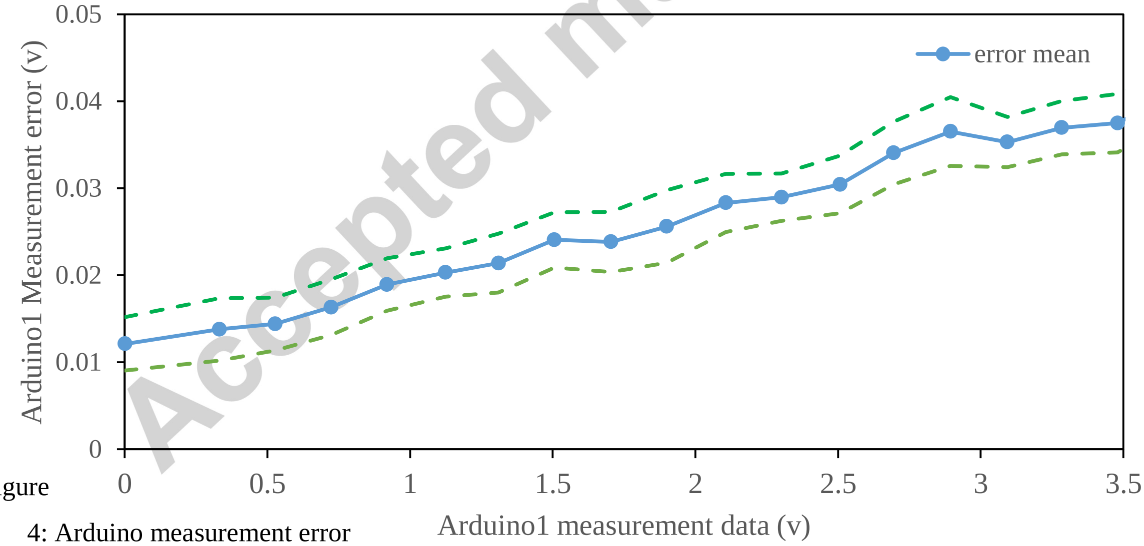

Figure 4: Arduino measurement error

Using a linear curve fitting approach, we can provide a calibration function to compensate measurement error in the Arduino1 analog input pin. Figure 5 shows the calibration function which correlates the data captured by NI DAQ to Arduino1 data.

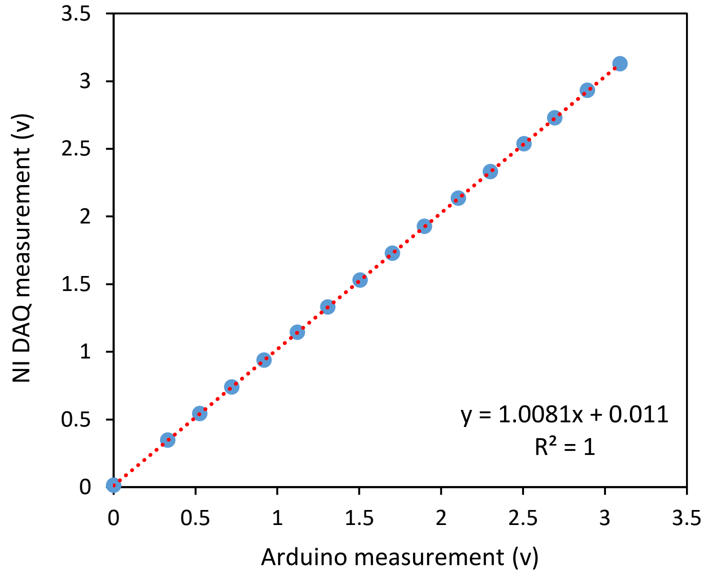

Figure 5: Correlation between NI DAQ measurement and Arduino1 measurement

To investigate the amelioration of Arduino1 data acquisition accuracy provided by the implementation of the calibration function, a temperature sensor is connected to both NI DAQ analog input as a reference and the Arduino1 analog input pin. Figure 6 compares the performance of the calibrated Arduino1 and the uncalibrated Arduino1 in the acquisition of temperature sensor data. Table 2 shows improvement in the average of measurement error and maximum error when calibration function is implemented in Arduino1.

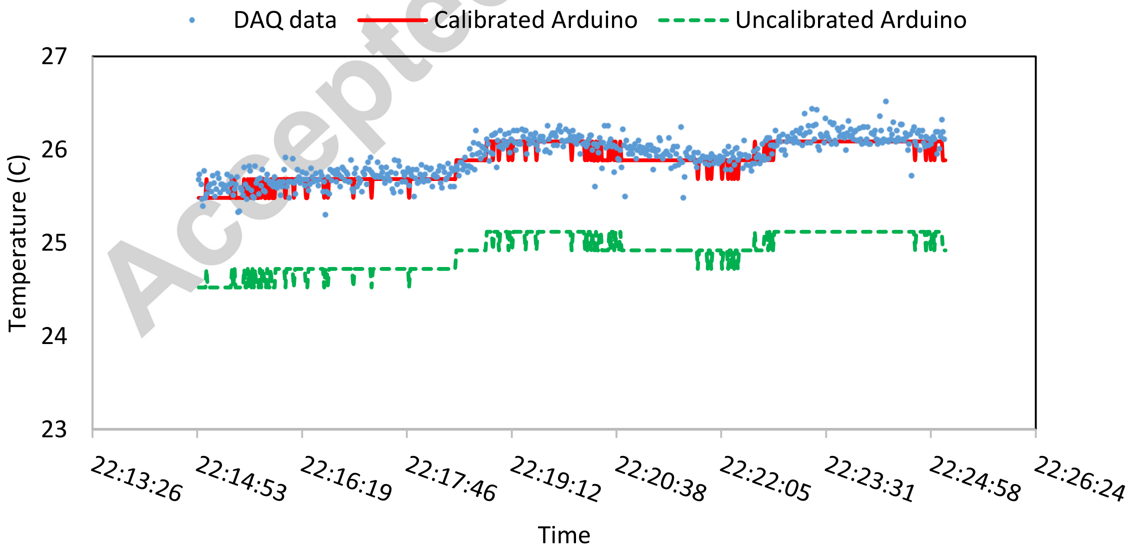

Figure 6: Effect of Arduino1 calibration on temperature measurement accuracy

Table 2. Temperature measurement accuracy improvement in calibrated Arduino1

	Temperature sensor	
	Error average (°C)	Maximum error (°C)
Uncalibrated Arduino1	1.07	1.40
Calibrated Arduino1	0.05	0.43

Testing of another Arduino used in the toolbox shows a different correlation function between NI DAQ and Arduino2, which means it is necessary to extract a distinct calibration function for each Arduino board. A similar process is used to calibrate the Arduino2. Figure 7 shows how the Arduino2 measurement error is related to the magnitude of the measured signal. The calibration function for the Arduino2 is shown in Figure 8.

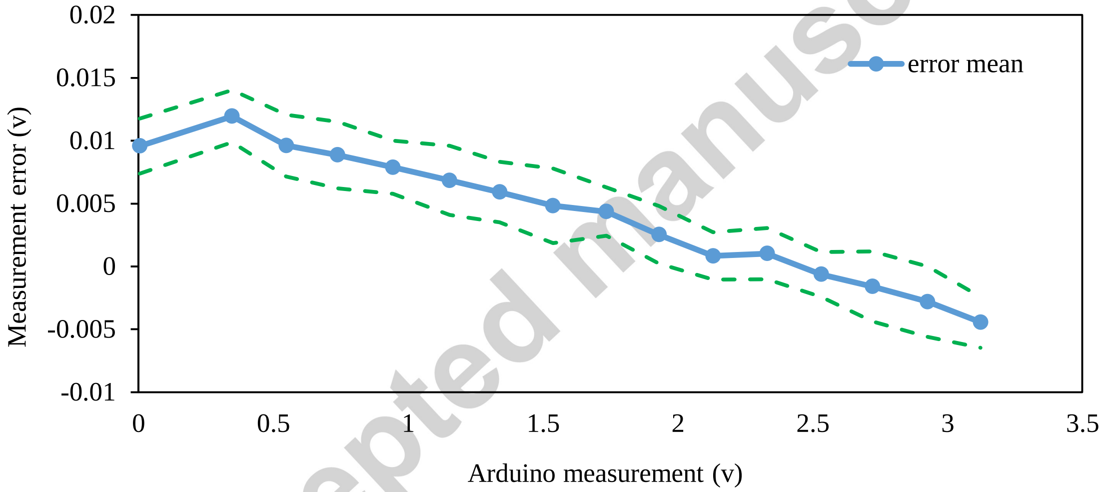

Figure 7: Arduino2 measurement error

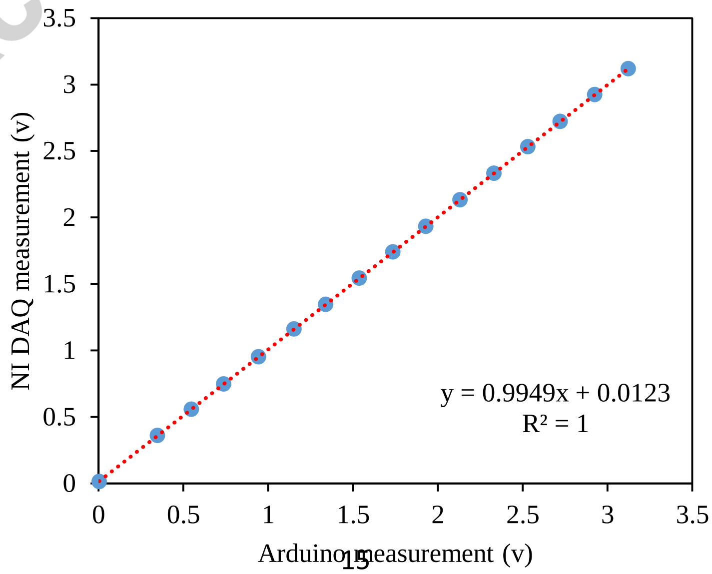

Figure 8: Correlation between NI DAQ measurement and Arduino2 measurement

5. Case study

In order to study the applicability of this toolbox in evaluating IEQ performance, an open computer laboratory was chosen for installation of the toolbox. Continuous monitoring of different IEQ parameters is conducted for 10 days. Data collected by the toolbox was then used to evaluate thermal comfort, IAQ, and lighting performance in the selected region.

5.1 Thermal comfort

This section explains the application of the toolbox in thermal comfort analysis of a computer lab. Measurement parameters corresponding to thermal comfort include dry bulb temperature, globe temperature, vertical gradient temperature, relative humidity, and air velocity.

Along with monitoring the sensor data, ASHRAE standard 55 suggests predictive mean vote (PMV) and predicted percentage of dissatisfied (PPD) as combinatorial indexes to evaluate thermal comfort in occupied spaces. The application of PMV and PPD monitoring can be extended to the control of HVAC systems. For example, one can satisfy thermal comfort with reduced energy consumption by developing a PMV-based model predictive control which adjusts fan speed and heating/cooling equipment such that the PMV setpoint is met within the acceptable range [21], [22].

Calculation of PMV and PPD depends on six factors including metabolic rate, clothing insulation, air speed, relative humidity, radiant temperature, and air temperature. Metabolic rate and clothing insulation are occupant-related parameters. Air speed, relative humidity, and air temperature are measured directly using sensors installed in the toolbox. Mean radiant temperature is calculated using equation (1).

$$T_{mrt}^4 = T_g^4 + C\bar{V}(T_g - T_a) \tag{1}$$

Where T_{mrt} is mean radiant temperature (K), T_g is globe temperature (K), T_a is ambient air temperature (K), $\bar{V}$ air speed (m/s), and C is a constant equal to 0.247×10^9. Based on the procedure explained in ASHRAE Standard 55, a program, written in Matlab, was developed to calculate PMV and PPD indexes in offline mode using the data collected from the toolbox. In future studies, the program will be integrated into the VOLTTRON platform as an agent to enable real-time monitoring and evaluation of PMV and PPD indexes.

A simple method which provides an insight into the thermal comfort is monitoring the gradient temperature to see how well it is controlled within the recommended range. Results for the open computer lab's temperature distribution measurements can be found in Figure 9. Temperatures in the open computer lab vary between 19 C° and 23 C° which are less than the minimum recommended setpoint for nearly the entire measurement period, suggesting an overcooling problem in this space.

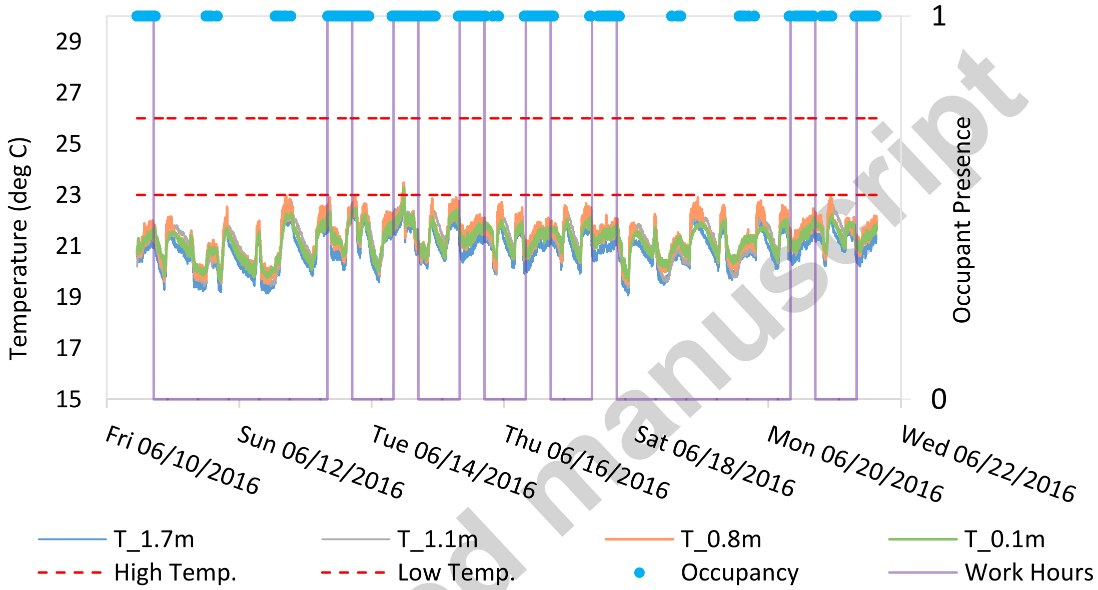

Figure 9. Open computer lab temperature distribution

As shown in Figure 10, PMV remains negative and outside the recommended limits during the entire measurement period in the open computer lab. Furthermore, Figure 11 shows that PPD varies widely from 12% to 75% violating the 10% limit during the entire measurement period. The PMV and PPD calculations indicate that thermal comfort expectations are not met in the computer lab during the summer time. According to the PPD calculations, it is predicted that on average around 45 % of occupants are predicted to be dissatisfied in the computer lab. The level of dissatisfaction is less in the morning and evening when the working hours start and end.

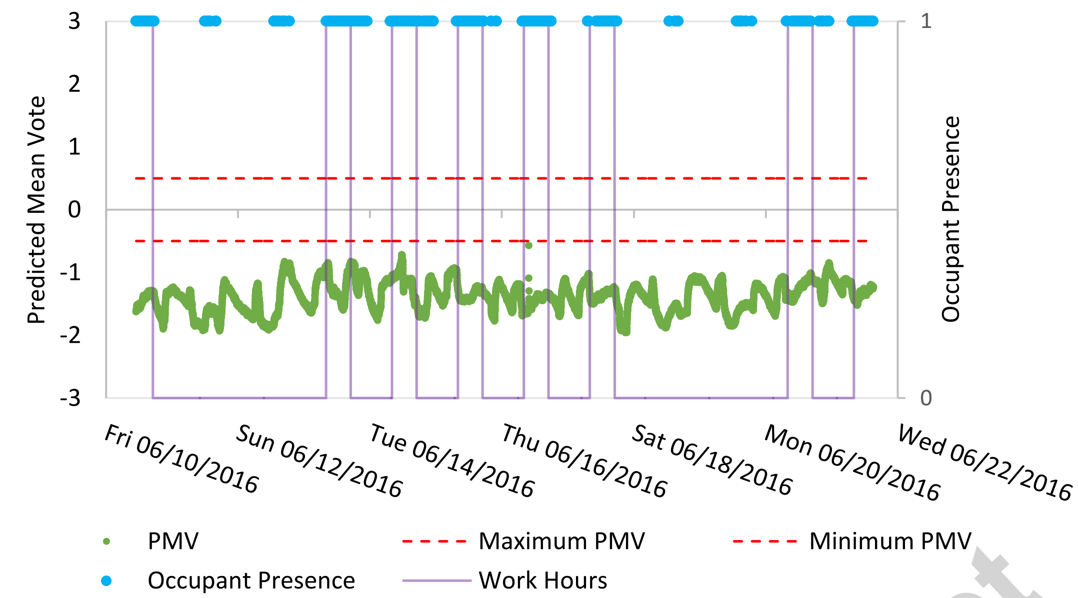

Figure 10. PMV in the computer lab

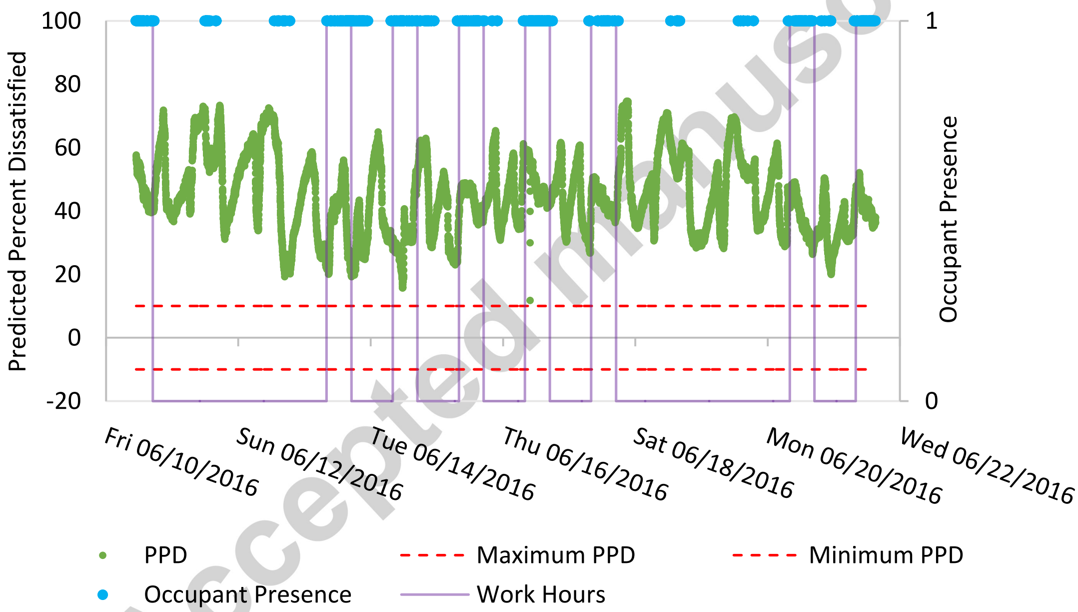

Figure 11. PPD in the computer lab

Further investigation of the measurements provided by the toolkit revealed that temporal variations of the relative humidity and air movement speed were within the acceptable range. However, the temperature in the measured area was lower than the minimum recommended setpoint for the summer season. This indicates an overcooling issue which contributes to the thermal discomfort. Increasing the temperature setpoint and investigating the HVAC system for possible faults in temperature sensors are suggested to better control of temperature in this area which can lead to thermal comfort satisfaction as well as an energy saving.

5.2 Indoor air quality

The toolbox was used for continuous monitoring of CO_2, $PM_{2.5}$ (fine particles), and VOC to evaluate indoor air quality. In this section, we demonstrated the measurements on indoor air quality in an open computer lab for 10 days. Measurement of the outdoor air CO_2 and $PM_{2.5}$ levels may assist in identifying the source of indoor IAQ dissatisfaction. Since the building was located in the low polluted area, we did not perform outdoor condition monitoring.

According to ASHRAE Standard 62.1[23], CO_2 concentration in the indoor environment should be kept less than 700 ppm above the outdoor air CO_2 concentration. 1000 ppm was recommended as the upper limit for the indoor CO_2 level. The CO_2 measurement in computer lab exhibited a maximum value of 390 PPM during the summer time. Since the CO_2 concentration was pretty low, another measurement was performed during the winter time to make sure that the CO_2 concentration varies within the standard range. Measurement results during winter time are shown in Figure 12.

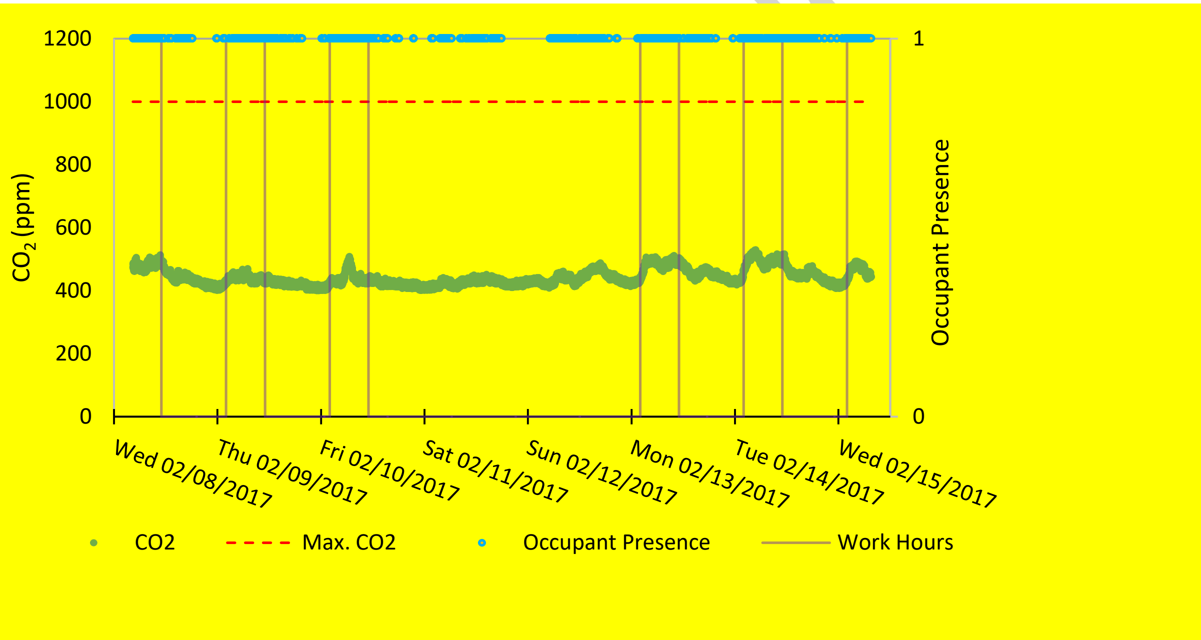

Figure 12. CO_2 concentration

The CO_2 level in computer lab varies between 400 PPM to 530 PPM which does not exceed the limit throughout the entire measurement period. Presence of occupants, as well as airside economizer operation, are important factors corresponding to change in CO_2 level. As shown in Figure 12, in the mornings, due to the presence of occupants the CO_2 concentration starts to increase. During the weekend, less variations have been observed in CO_2 level since the area is less crowded. A considerable margin of CO_2 level from maximum allowable value shows proper ventilation rate in this building.

The vertical temperature measurement exhibited relatively consistent temperatures in various heights which are an indicator of uniform air distribution in the area. Uniform air circulation corresponds to spreading the fresh air and reducing IAQ discomfort in the area [9]. Complementary analysis for IAQ evaluation was performed by measuring the outdoor air flow rate in the ventilation system. Measurement confirmed satisfaction of minimum required ventilation rate in compliance with the ASHRAE Standard 62.1 [23].

Continuous measurement of Volatile Organic Compounds (VOC) can be used as an indicator to help to evaluate the indoor air quality. However, analysis based on absolute value of VOC is not suggested since there is no standard definition, measurement method, or defined allowable ranges. Therefore, relative variations of the VOC level should be considered for indoor air quality analysis. Figure 13 shows the results of the VOC concentration measurement. There are some sudden sharp increases in the VOC level when occupants exist in the area. These short-time increase of VOC occurs after working hours, which can be the result of the temporary existence of a contaminant source such as cleaning materials.

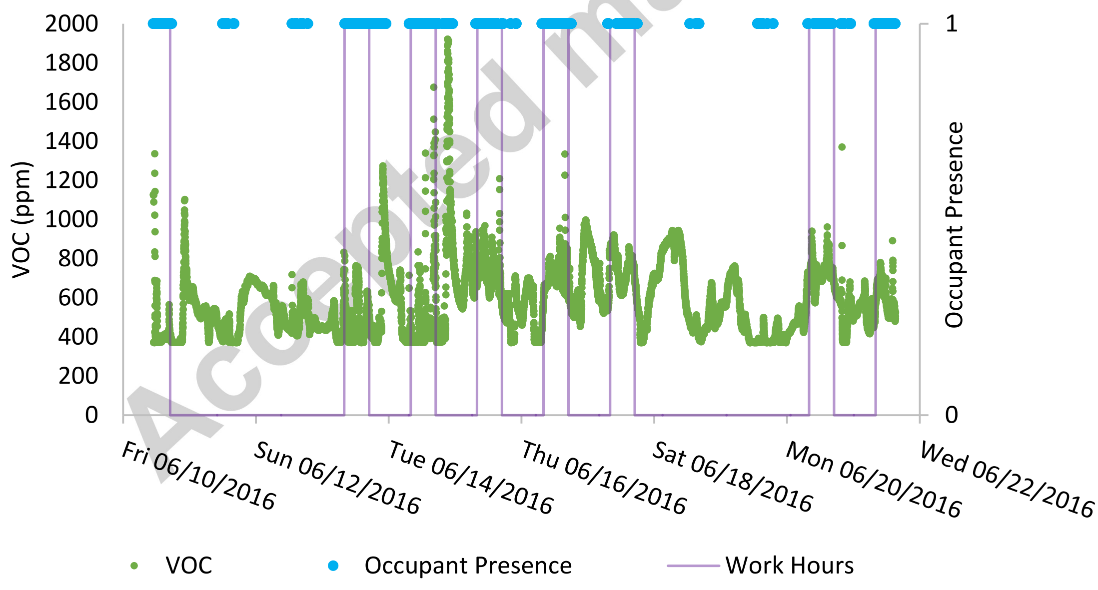

Figure 13. VOC concentrations

A recorded trend of $PM_{2.5}$ measurement in open computer lab is shown in Figure 14. Measurement shows that $PM_{2.5}$ levels vary slightly, but remain below the recommended criteria. The maximum value of PM2.5 particulates reaches to 0.007 mg/m^3, mostly after the working hours. Since the building is located in a clean area, it was expected to have a low particulate concentration inside the building.

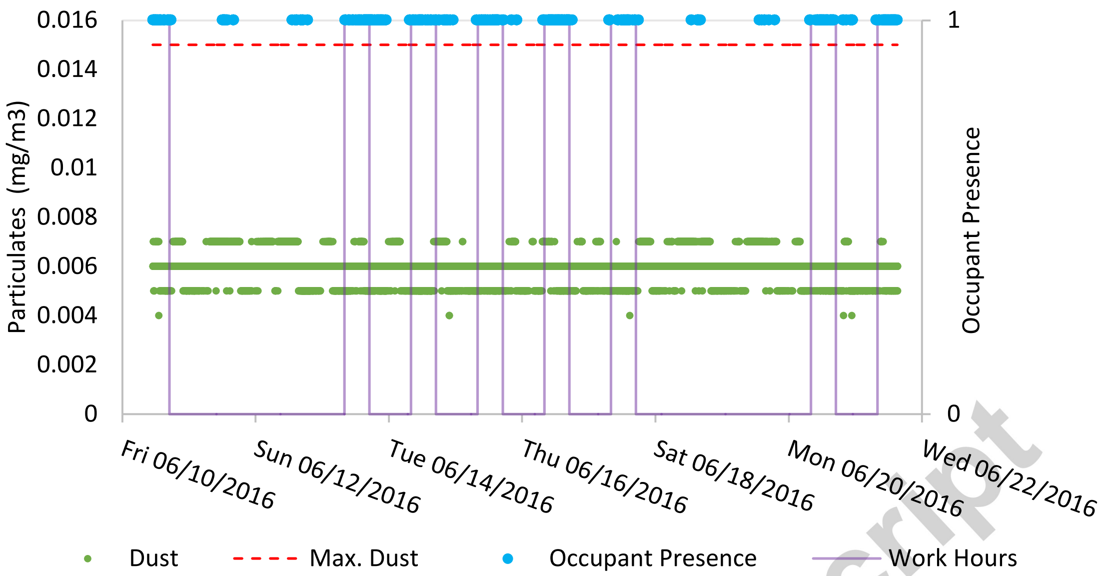

Figure 14. Particulate concentrations

5.3 Lighting

Recorded measurement of vertical surface illuminance level in the open computer lab is shown in Figure 15. Illuminance levels rise throughout working hours in computer lab due to the effect of daylight. Measurement shows that vertical illuminance levels during occupied hours reach to 0.27 klux which are much higher than the 0.05 klux as the minimum recommended value. The light emitted from the computers screens can also contribute to the high vertical illuminance levels in the computer lab.

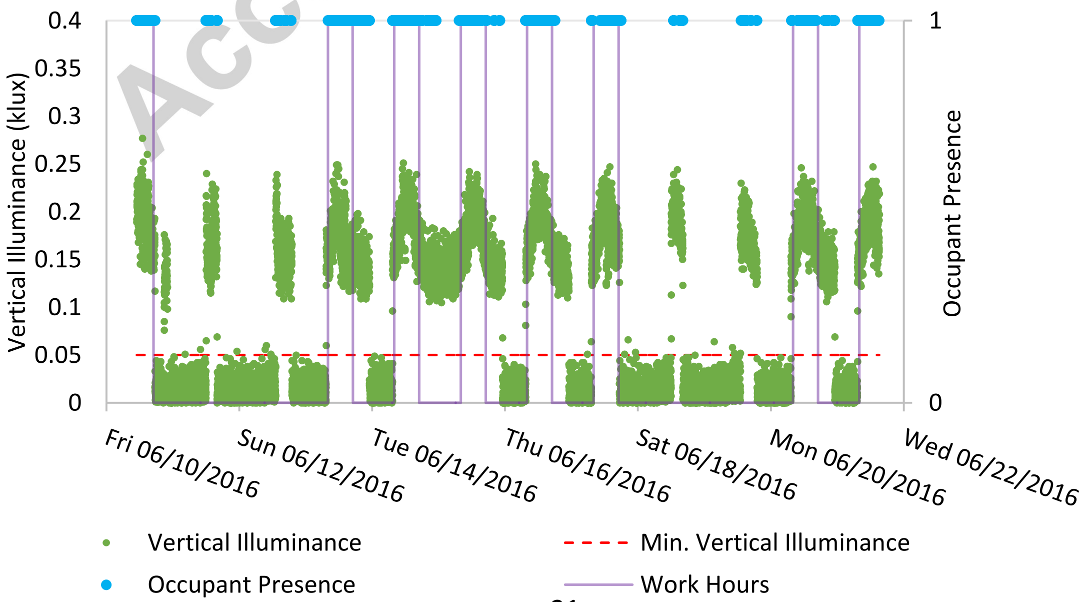

Figure 15. Vertical illuminance

Figure 16 shows the recorded values for horizontal illuminance level in the open computer lab.

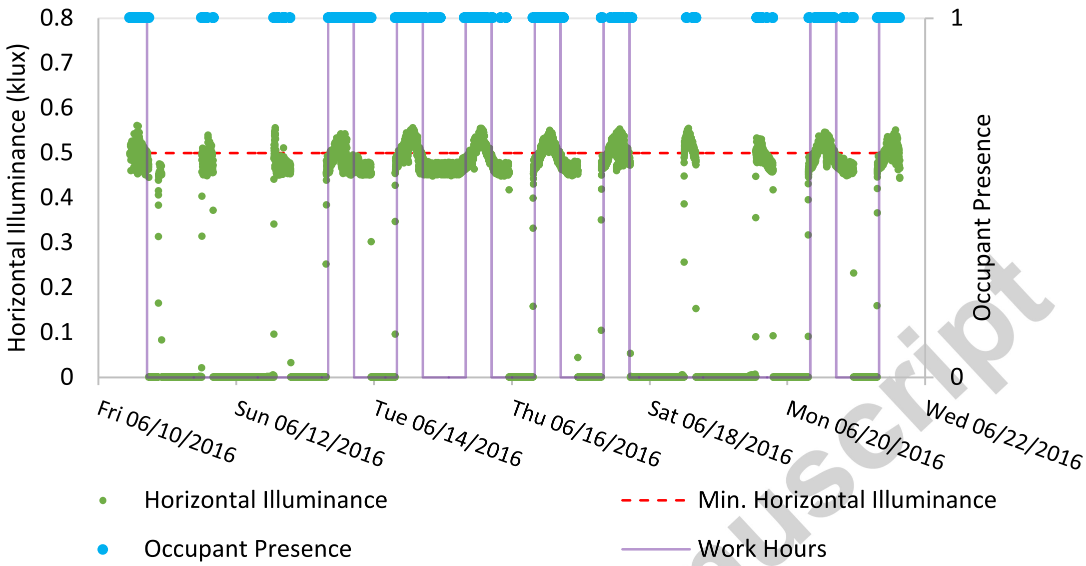

Figure 16. Horizontal illuminance

As shown in Figure 16, due to daylighting effects, the horizontal illuminance level varies from 0.44 klux to 0.56 klux during the occupied hours. Since the computer lab is exposed to the natural light, the horizontal illuminance level varies as the daylight level changes. Therefore, the minimum recommended lighting level is met during the most of working hours. However, during occupied night hours, horizontal illuminance level falls below the acceptable level.

Further improvement in lighting quality assessment could be obtained using high dynamic range (HDR) photography. HDR photography enables analysis of luminance in the built environment.

6. Conclusion

We have presented and tested an IEQ toolbox for evaluation of a building's indoor environmental quality. The toolbox platform was designed based on open source technology, both in hardware and software elements. The IEQ toolbox is cost-effective and is flexible for further incorporation of new sensors. A wireless mesh network was employed to collect data from various sensors. VOLTTRON software was used as an open source platform to receive data in real time, enabling cloud-based data storage, and real-time data monitoring and analysis.

To ensure the accuracy of data collection in the IEQ toolbox, data transmission was calibrated using a National Instrument DAQ card. It was observed that calibration of the data collection system increased the accuracy of temperature monitoring by reducing the average of error from 1.07 °C to 0.05 °C.

A computer lab was selected to experimentally test the application of toolbox in IEQ assessment. The toolbox was installed in the selected area to continuously collect the data for 10 days. No missing data was found during the data collection, which implies the robustness of toolbox for long-term applications.

The current toolbox is limited to analyzing thermal comfort, IAQ, and lighting performance. In the hardware layer, future work will explore adding relevant sensors to evaluate acoustic performance. In the software layer, we are working on developing an agent in VOLTTRON to perform real-time data analysis and report an alarm if the IEQ criteria are not met. In addition, inexpensive single-board computers, such as Panda Board or Raspberry Pi, will be explored to reduce the cost of the monitoring toolkits. Further cost reduction is also achievable in our proposed system using low-cost sensors.

In future work, we will connect the IEQ toolkits with building control system for advanced HVAC system control. For example, PMV and PPD indices instead of room temperature only can be used to control HVAC systems for better thermal comfort. The toolkits can be extended further for the recognition of human behaviors, which can be integrated with HVAC system control for energy reduction.

References

[1] S. Kang, D. Ou, and C. Ming, “The impact of indoor environmental quality on work productivity in university open-plan research of fi ces,” *Build. Environ.*, vol. 124, pp. 78–89, 2017.

[2] J. Kim, T. Hong, J. Jeong, C. Koo, and M. Kong, “An integrated psychological response score of the occupants based on their activities and the indoor environmental quality condition changes,” *Build. Environ.*, vol. 123, pp. 66–77, 2017.

[3] A. Sadick and M. H. Issa, “Occupants’ indoor environmental quality satisfaction

factors as measures of school teachers' well-being," *Build. Environ.*, vol. 119, pp. 99–109, 2017.

[4] E. A. Arens, H. Zhang, and C. Huizenga, "Partial- and whole-body thermal sensation and comfort, Part I: Uniform environmental conditions," *J. Therm. Biol.*, vol. 31, pp. 53 – 59, 2006.

[5] W. J. Fisk, "Health and productivity gains from better indoor environments and their relationship with building energy efficiency," *Annu. Rev. Energy Env.*, vol. 25, pp. 537–566, 2000.

[6] D. Heinzerling, S. Schiavon, T. Webster, and E. Arens, "Indoor environmental quality assessment models : A literature review and a proposed weighting and classi fi cation scheme," *Build. Environ.*, vol. 70, pp. 210–222, 2013.

[7] C. M. Chiang, P. C. Chou, C. M. Lai, and Y. Y. Li, "A methodology to assess the indoor environment in care centers for senior citizens," *Build. Environ.*, vol. 36, pp. 561–568, 2001.

[8] J. Choi, V. Loftness, and A. Aziz, "Post-occupancy evaluation of 20 office buildings as basis for future IEQ standards and guidelines," *Energy Build. j*, vol. 46, pp. 167–175, 2012.

[9] H. Kim and J. S. Haberl, "Field-Test of the New ASHRAE / CIBSE / USGBC Performance Measurement Protocols : Intermediate and Advanced Level Indoor Environmental Quality Protocols," *ASHRAE Trans.*, pp. 58–66, 2012.

[10] A. S. Ali, Z. Zanzinger, D. Debose, and B. Stephens, "Open Source Building Science Sensors (OSBSS): A low-cost Arduino-based platform for long-term indoor environmental data collection," *Build. Environ.*, vol. 100, pp. 114–126, 2016.

[11] S. Abraham and X. Li, "A Cost-effective Wireless Sensor Network System for Indoor Air Quality Monitoring Applications," *Procedia Comput. Sci.*, vol. 34, pp. 165–171, 2014.

[12] S. M. Saad, A. Rahman, M. Saad, A. Muhamad, Y. Kamarudin, and A. Zakaria, "Indoor Air Quality Monitoring System using Wireless Sensor Network (WSN) with Web Interface," in *International Conference on Electrical, Electronics and System Engineering*, 2013, pp. 60–64.

[13] A. Ioannou and L. Itard, "In-situ and real time measurements of thermal comfort and its determinants in thirty residential dwellings in the Netherlands," *Energy Build.*, vol. 139, pp. 487–505, 2017.

[14] W. Torresani, N. Battisti, A. Maglione, D. Brunelli, and D. Macii, "A Multi-sensor Wireless Solution for Indoor Thermal Comfort Monitoring," *IEEE Work. Environ. Energy Struct. Monit. Syst.*, pp. 1–6, 2013.

[15] T. Webster, D. Heinzerling, G. Anwar, T. Hoyt, and D. Dickerhoff, "A prototype toolkit for evaluating indoor environmental quality in commercial buildings," Berkeley, 2013.

[16] S. Dawson-haggerty, X. Jiang, G. Tolle, J. Ortiz, and D. Culler, "sMAP – a Simple Measurement and Actuation Profile for Physical Information," in *SenSys'10*, 2010, pp. 197–210.

[17] B. S. Katipamula, J. Haack, B. Akyol, G. Hernandez, and J. Hagerman, "An open-source software platform of the future.," *IEEE Electrif. Mag. /,* no. December, pp. 15–22, 2016.

[18] M. A. HUMPHREYS, "The Optimum Diameter For A Globe Thermometer For Use Indoors," *Ann. occup. Hyg,* vol. 20, no. September, pp. 135–140, 1997.

[19] P. Sydenham and R. Thorn, *Handbook of Measuring System Design*. Wiley, 2005.

[20] K. H. Lundberg, *Analog-to-Digital Converter Testing*. lecture notes, MIT, 2002.

[21] Y. I. Alamin, M. Castilla, J. D. Álvarez, and A. Ruano, "An Economic Model-Based Predictive Control to Manage the Users ' Thermal Comfort in a Building," *Energies*, vol. 10, no. 321, pp. 1–18, 2017.

[22] R. Z. Freire, G. H. C. Oliveira, and N. Mendes, "Predictive controllers for thermal comfort optimization and energy savings," *Energy Build.*, vol. 40, pp. 1353–1365, 2008.

[23] *ANSI/ASHRAE Standard 62.1-2007, Ventilation for Acceptable Indoor Air Quality*. Atlanta, GA: American Society of Heating, Refrigerating and Air-Conditioning Engineers, Inc.

Highlights

- A portable Arduino-based IEQ toolbox, integrated with ZigBee communication protocol was developed.

- VOLTTRON platform was used for real time data collection and monitoring.

- Toolbox used for assessing IEQ performance in an open computer lab within a commercial building.