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New Low-Cost Sensing Network for Indoor Environmental Monitoring and Control in Buildings

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ABSTRACT

New types of low-cost sensors have the potential to replace existing sensor networks in buildings, which have high cost and low flexibility in terms of monitoring local indoor environmental quality (IEQ) close to the occupants. The objective of this study is to (i) investigate the reliability, accuracy, robustness, and communication capabilities of low-cost sensor networks and (ii) develop and implement an overall framework of monitoring and control of indoor environmental conditions, embedded in existing control infrastructures or using new system typologies. Different low-cost temperature, humidity, and light sensors, wired and wireless, were tested. The sensors can communicate with a single-board computer, and with the building monitoring and control system, providing flexibility in monitoring IEQ (local sensing), communication (networking) with other devices, as well as in developing new control frameworks. We present results for monitoring and control of indoor thermal conditions using low-cost local sensing with a flexible scheme embedded in existing thermal control infrastructures.

INTRODUCTION

New types of low-sensors that have become available in the last decade may replace the existing sensor network in buildings, with a cheaper cost, smaller form factor, and higher flexibility thanks to the recent advancements in wireless network technologies. Such sensors can cover almost every aspect of indoor environmental quality (IEQ) focused on human-oriented building operations. Recent studies have reviewed and analyzed the current disconnection between personal comfort studies and building thermal control research (Zhang and Tzempelikos 2021). Wireless communication capability and lower price of the new generation of low-cost sensors enable sensing and control of local environment close to the occupants –which could not be achieved with common controls based on conventional wall thermostats. Such features lead to the potential application of human-centered, personalized control of local environments based on highly sophisticated algorithms –such as machine learning-based approaches or model predictive controls –seamlessly integrated into existing building control frameworks (Shibata et al. 2016; McLeod et al.2020), as well as monitoring and adopting advanced comfort metrics that include time constancy and spatial uniformity, for ensuring long-term indoor environmental comfort (Atzeri et al. 2016).

In such context, the objectives of this study are to (i) investigate the reliability, accuracy, robustness, and communication capabilities of low-cost sensor network; (ii) develop and implement an overall framework of monitoring and control of indoor environmental conditions (temperature, relative humidity, illuminance, etc.) embedded in existing building control frameworks or using new system typologies; and (iii) implement a wireless-sensing based local temperature control in a real private office

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and compare its performance to a typical deadband temperature control based on a wall thermostat reading.

Different types of low-cost sensors, wired and wireless, were examined and compared against calibrated, scientific-grade ones. The sensors can communicate with a single-board computer, and with the building management system, allowing higher flexibility and local sensing, processing, and communication with other devices.

TEMPERATURE AND HUMIDITY SENSORS

Five different types of temperature and relative humidity (RH) sensors were tested (Figure 1). Sensors (a) and (b) were also embedded in an integrated microcontroller unit board with a wireless communication capability –referred to as wireless MCU board in this paper. Sensor names and brand names have been removed due to commercialization restrictions in this paper.

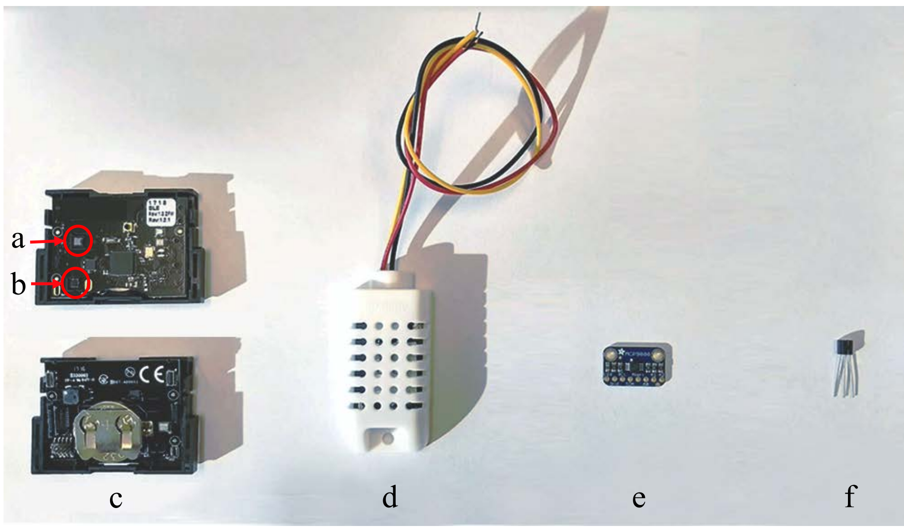


Figure 1 Low-cost temperature and humidity sensors studied: sensors (a) and (b) are embedded in MCU (c). Sensor (b) measures both temperature and relative humidity.

All the sensors have measurable range of temperature and humidity suitable for indoor monitoring purpose. The accuracy of temperature sensors ranges from 0.25°C (0.45°F) to 1.0°C (1.8°F), while that of humidity sensors range from 2% to 3%. The price range of the individual sensors is $1.5~$5, except for the MCU board (c) that includes multiple sensors with wireless communication capability, in the order of $30. The specifications of temperature and humidity sensors are presented in Table 1.

Table 1. Thermal environment sensors used

Sensor	Range	Resolution	Accuracy	Precision
(f)	-40°C - 80°C/-104°F-176°F	0.0625°C/0.1125°F	0.5°C/0.9°F	-
(e)	-40°C - 125°C/-104°F-257°F	0.0625°C/0.1125°F	0.25°C/0.45°F	0.2°C/0.36°F
(a)	-40°C - 125°C/-104°F-257°F	0.03125°C/0.05625°F	1.0°C/1.8°F	-
(b)	-40°C - 125°C/-104°F-257°F 0% - 100%	-	T: 0.4°C/0.72°F RH: 3%	0.1°C/0.18°F

(d)	0% - 100%	0.1%	2%	-

The sensors were installed in private tested offices and measurements were taken every minute for seven days. Simultaneous temperature and relative humidity measurements were collected with reference sensors (calibrated Type-T thermocouple and RH sensors) placed right next to the low-cost sensors (Figure 2). The temperature of the room was intentionally controlled through a scheduler in the building management system (BMS) during the experiments.

(a) (b)

Figure 2 Temperature & RH measurement setup in testbed office. (a) Testbed office (b) Sensor placement (sample).

A total of 9,362 points were collected from the experiment. The measured range of temperature and RH were 19.7°C – 31.4°C (67.46°F -88.5°F) and 19.6% - 53.6%. Root mean squared error (RMSE) and R^2 between the calibrated sensors and each of the low-cost sensors were computed before and after calibration of low-cost sensors (Table 2). The RMSE of temperature sensors before calibration ranged from 0.28°C to 0.43°C (0.50°F - 0.78°F), while it ranged from 0.5% to 6.24% for RH sensors. For all of the low-cost thermal sensors, a strong linear correlation (R^2>0.99) was observed between their readings and the reference sensor readings. Thus, the sensors were calibrated via simple linear regression by fitting their measurement to the reference measurement. As shown in Table 2, the RMSE resulting from calibration was reduced to 0.18°C (0.32°F) at maximum, showing reasonable accuracy.

Table 2. Validation of temperature and RH sensors

Sensor	RMSE	$RMSE_{calibrated}$	R^2
(f)	0.30°C/0.54°F	0.15°C/0.27°F	0.995
(e)	0.28°C/0.50°F	0.17°C/0.31°F	0.994
(a)	0.31°C/0.56°F	0.18°C/0.32°F	0.993
(b)	T: 0.43°C/0.78°F RH: 6.24%	T: 0.18°C/0.32°F RH: 0.51%	T: 0.993 RH: 0.993
(d)	1.2%	0.5%	0.993

LIGHT SENSOR

A light sensor – labelled (g) - was also tested, able to measure incident illuminance (Figure 3a). The normalized spectral sensitivity of the sensor is presented in Figure 4. For validation and calibration similar to the thermal sensors, a calibrated photosensor that closely follows the CIE (International Commission on Illumination) human photopic sensitivity function $V(\lambda)$ (CIE 1932) was used to compare the measurements (Figure 3b). Both sensors were placed in the same testbed room where the thermal sensors were tested, continuously measuring the illuminance with 1-minute-intervals. Electric lights were set to off during daytime, to focus on daylight measurements, while at night electric lights were dimmed using a ramp function to cover several light levels. Three days of full measurements were adequate to collect 3,394 data points. The maximum illuminance measured was 2,652 lux (246.4 fc) during the experiment. As shown in Table 3, the RMSE of the readings before the calibration was 123 lux (11.4 fc) showing a strong R^2 of 0.973. The calibration via linear fitting reduced the RMSE to 37 lux (3.4 fc), showing a reasonable accuracy for building indoor applications.

(a) (b)

Figure 3 Light sensors tested. (a) Sensor g embedded in wireless MCU board (outlined in yellow) (b) Scientific-grade photosensor used for validation.

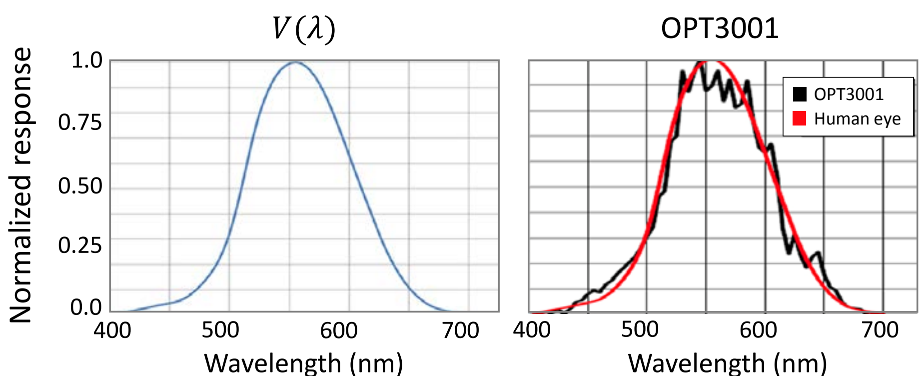


Figure 4 CIE human eye photopic sensitivity function V(λ) and spectral sensitivity functios of low-cost light sensors.

Table 3. Light sensor validation & calibration

Sensor	RMSE	$RMSE_{calibrated}$	R^2
g	123 lux/11.4 fc	37 lux/3.4 fc	0.973

LOW-COST WIRELESS MCU BOARD

A commercially available MCU board that contains 7 different sensors – including infrared (IR) temperature sensor, temperature & humidity sensor, and ambient light sensor– was tested in this study, integrated with the building management system, and used for temperature control as described next. As shown in Figure 5, the MCU board has a small form factor and runs with a coin-cell battery with a life span up to 1 year depending on the type of wireless module. The MCU board supports various types of wireless communication protocols. Its long life span, small form factor, and wireless capability are essential features required for local environmental monitoring and control. The potential application of the wireless, integrated sensor module for indoor local temperature control was the focus of the current study, although as shown above, relative humidity control is also straightforward.

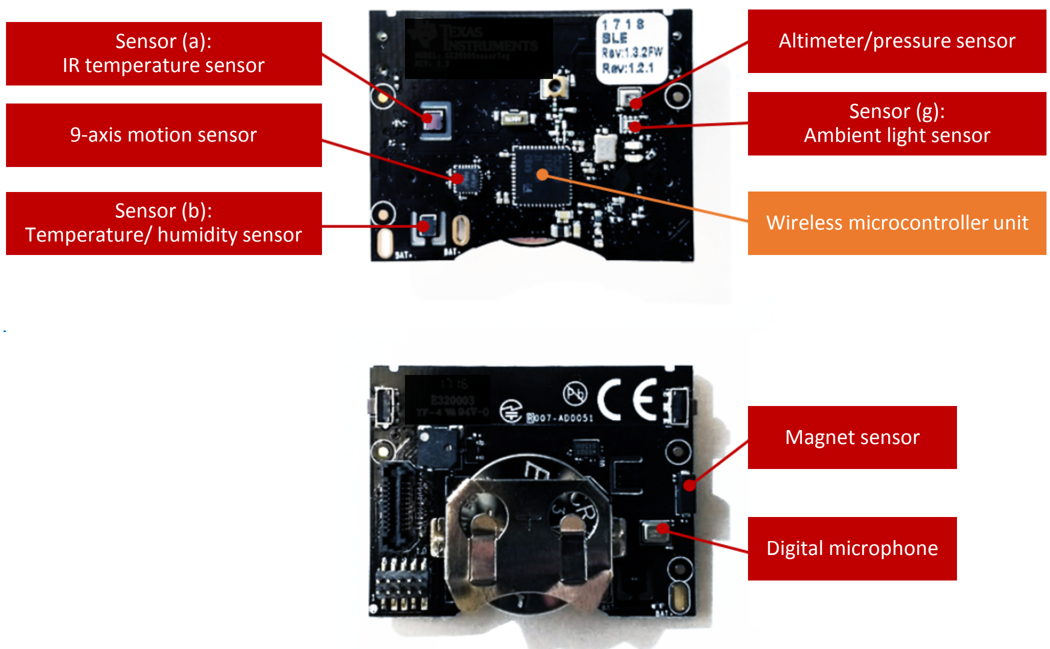


Figure 5 Wireless MCU board with 7 different sensors.

COMMUNICATION WITH BUILDING MANAGEMENT SYSTEM

Reliable communication is essential to seamlessly integrate low-cost sensors into existing building management systems (BMS). Sensors can be either directly wired to a single-board computer or a microcontroller unit, or connected through wireless communication protocols (such as *ZigBee, Bluetooth*, and *WiFi*). In this study, we integrated the custom low-cost sensors to a single-board computer that communicates with the BMS through Modbus TCP/IP protocol. The sensor measurements and Modbus communication can be fully implemented via custom Python scripts. Through Python, it is possible to implement highly flexible and sophisticated algorithms, such as model-predictive controls (MPC) or even machine-learning-based control algorithms that are generally not supported by typical building control frameworks with limited flexibility (Joe et al. 2018). Modbus communication through Python is possible through a Python package named *PyModbus* (Petrak n.d.). The proposed framework was successfully implemented in real testbed offices in the Center for High Performance Buildings at Purdue University campus (Figure 6).

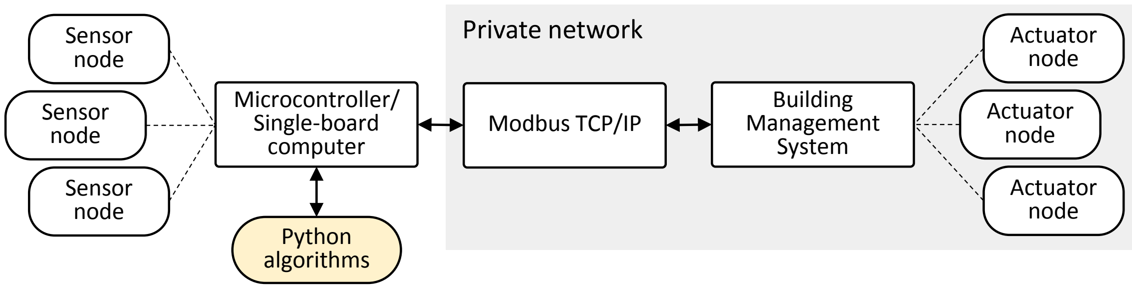


Figure 6 Sensor-BMS integration and dual-channel communication.

LOW-COST SENSOR-BASED TEMPERATURE CONTROL

Monitoring and control of local environments can be achieved through the low-cost sensor network. In this work, the real-time temperature control can either use a wall thermostat or local wireless sensor for temperature sensing in the office, run a control algorithm that determines temperature setpoints, and communicate with BMS back and forth (Figure 7). The low-cost sensor network allows embedding control algorithms with different complexities into an existing BMS to always provide updated temperature setpoints according to the current environments. In addition, the monitoring data from low-cost sensor or thermostat can be transferred and stored in BMS through single-board computer to achieve real-time sensing of local environments.

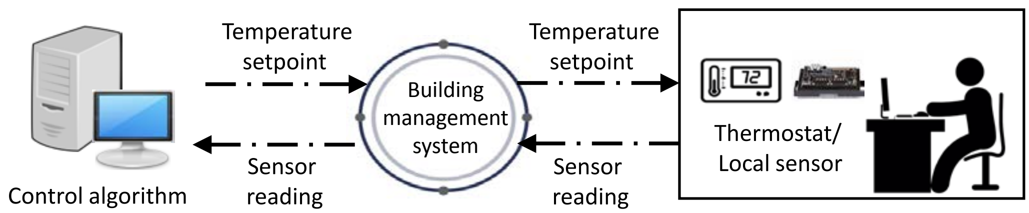
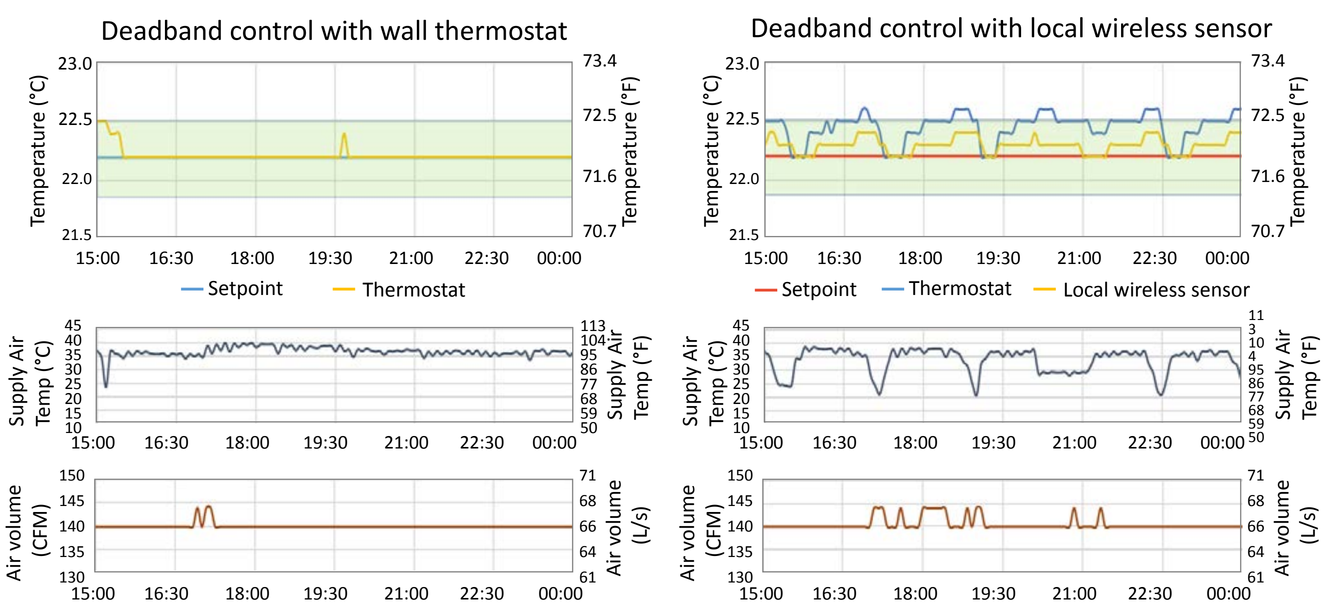


Figure 7 Implementation of temperature control with wall thermostat / local wireless sensor.

With the low-cost sensor network, this study tested the real-time temperature controls with both wall thermostat sensing and wireless local sensing in two adjacent, identical south-facing private offices (Figure 8), and examined the thermal control performances of both options. Each of the offices was conditioned with an individual VAV box from a centralized air conditioning system. During the experiment, the temperature in one of the offices was controlled with a conventional wall thermostat and the other office was controlled with a local wireless sensor on the desk (1m or 3.3 ft away from wall thermostat). The local wireless sensor was shielded to reduce the influence of solar radiation on sensor temperature readings. Temperature sensor (a) of Figure 1, embedded in the wireless MCU board (c), was used for local temperature sensing during thermal controls. The two controls were implemented simultaneously with a simple deadband control strategy: a deadband control of 0.56°C (1°F) with the setpoint of 22.2°C (72°F), determined by a built-in PID control logic in the BMS, to maintain reasonable thermal comfort for occupants (ASHRAE 2013).

Sample comparative results of the thermal control performance are presented in Figure 9. Using the same deadband control strategy in the two offices, temperature readings from the wall thermostat and the wireless local sensor, as well as the supply air temperatures and volume from VAV boxes were monitored. During the thermostat-based control operation, when a near-constant amount of over 35°C (95°F) supply air was consistently supplied to the office, the temperature reading from the wall thermostat barely changed across the time. However, during the local-sensor-based control during the same test period, the temperature readings fluctuated within deadband due to the heating from supply air. Temperature differences appeared between wall thermostat readings and local temperatures measured by the low-cost local sensor, and the heating rates kept changing with the fluctuations of local temperatures. Overall, the results showed that the local wireless sensor is more responsive to the local temperature variation than the wall thermostat, and that local temperature sensing allows to maintain the air temperature close to the occupants within a comfortable range, while potentially reducing energy use for air-conditioning.

Figure 8 Experimental setup in two adjacent, identical private offices for comparing the performance of temperature control using a local sensor vs a wall thermostat.



(a) (b)

Figure 9 (a) Deadband control with wall thermostat and (b) Deadband control with local temperature sensor in the identical private offices. Temperature range (top), supply air temperature (middle) and VAV system air volume (bottom) were monitored.

CONCLUSION

The potential of the new types of low-cost sensors for advanced building controls was investigated. IEQ sensors, focused on the thermal and visual environment, were compared against the scientific-grade sensors and showed strong linearity and reasonable accuracy with simple linear fittings. Also, a communication scheme for the seamless integration of the low-cost sensors to the existing BMS was suggested and implemented in real offices. The integrated framework enables high-level and flexible control algorithms through open-source Python language. Through the framework, a local temperature control based on a wireless low-cost temperature sensor was implemented and compared with a conventional, thermostat-based control in identical private offices, controlled with the same deadband temperature control logic. The results showed that the local low-cost sensors are reliable, can maintain thermal comfort better than wall-mounted sensors, and have a high potential to replace conventional, less flexible sensors, allowing more occupant-centered and energy-efficient controls in buildings. Further research is required to investigate the efficiency of IEQ controls using various degrees of complexity with wireless low-cost localized sensors. Also, the ability of such control frameworks to predict advanced comfort metrics (including time constancy and spatial uniformity) needs examination, focused on long-term indoor environmental comfort.

ACKNOWLEDGEMENTS

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REFERENCES

ASHRAE. 2013. *ANSI/ASHRAE Standard 55-2013, Thermal Comfort Conditions for Human Occupancy*. Atlana: ASHRAE.

Atzeri, Anna Maria, Francesca Cappelletti, Athanasios Tzempelikos, and Andrea Gasparella. 2016. "Comfort Metrics for an Integrated Evaluation of Buildings Performance." *Energy and Buildings* 127 (September): 411–24. https://doi.org/10.1016/j.enbuild.2016.06.007.

CIE. 1932. *Commission Internationale de l'Eclairage*. *Commission Internationale de l'Éclairage Proceedings*. Cambridge: Cambridge University Press.

Joe, Jaewan, Panagiota Karava, Xiaodong Hou, Yingying Xiao, and Jianghai Hu. 2018. "A Distributed Approach to Model-Predictive Control of Radiant Comfort Delivery Systems in Office Spaces with Localized Thermal Environments." *Energy and Buildings* 175: 173–88. https://doi.org/10.1016/j.enbuild.2018.06.068.

McLeod, Katherine, Petros Spachos, and Konstantinos N. Plataniotis. 2020. "An Experimental Framework for Wellness Assessment Using the Internet of Things." *IEEE Internet Computing* 24 (2): 8–17. https://doi.org/10.1109/MIC.2020.2972817.

Petrak, Hynek. n.d. "PyModbus." Accessed December 5, 2020. https://github.com/riptideio/pymodbus/.

Shibata, Tiago, Roberto Azevedo, Bruno Albertini, and Cíntia Margi. 2016. "Energy Consumption and Execution Time Characterization for the SensorTag IoT Platform." In *XXXIV Simpsio Brasileiro de Telecomunicaes e Processamento de Sinais (SBrT 2016)*, 55–59. https://doi.org/10.14209/sbrt.2016.167.

Zhang, Hejia, and Athanasios Tzempelikos. 2021. "Thermal Preference-Based Control Studies: Review and Detailed Classification." *Science and Technology for the Built Environment* 27 (8): 1031–39. https://doi.org/10.1080/23744731.2021.1877041.