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Occupancy Detection Chair Sensor: An Energy Conservation Tool

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Dr. Shehadi is an Assistant Professor of MET in the School of Engineering Technology at Purdue University. His academic experience have focused on learning and discovery in areas related to HVAC, indoor air quality, human thermal comfort, and energy conservation. While working in industry, he oversaw maintenance and management programs for various facilities including industrial plants, high rise residential and commercial buildings, energy audits and condition surveys for various mechanical and electrical and systems. He has conducted several projects to reduce CO2 fingerprint of buildings by evaluating and improving the energy practices through the integration of sustainable systems with existing systems. Professor Shehadi also has an interest in air pollution reduction and in providing healthier environment by analyzing the various pollutants that are present in outdoor and indoor air. His current research focuses on sustainable and green buildings and energy conservation. He is currently investigating various ways to reduce energy consumption in office buildings.

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Abstract

Occupants' behavior inside buildings is a vital parameter in determining the building energy consumption. Occupancy density distribution is a wide uncertain parameter due to the difficulty in predicting the attendants' behavior. Currently, occupancy detection tools and technologies have been insufficient of determining the exact number of occupants and, thus, the space ventilation requirements are not set at its optimized values.

This capstone project was part of a bigger project conducted at Purdue Polytechnic Kokomo to better improve the energy consumption used for ventilation and AC in buildings. The objective of this capstone project was testing potential energy savings in an office space by using an occupancy seat sensor. An experimental and parametric approach were followed. The project was led by one MET student (Mechanical Engineering Technology). The project built and tested a seat occupancy chair sensor that detects a seated occupant of 40 lb_f and above. The chair was tested inside a controlled office room. The transmitter of the sensor was connected to a programmable logic controller (PLC) unit that detected and recorded the chair status along with changes in temperature. To investigate potential savings due to the usage of occupancy detection sensors in an office, a parametric case study was conducted. The study compared the cooling load required based on actual number of occupants present versus the peak load when no chair sensors were used. It was found that the case with chair sensors that detects the variable occupancy level can save 15% every month (May through September) of the required cooling load and of the power consumed. This figure can significantly double to higher values when considering higher occupancy density spaces such as theaters, class rooms, and large meeting rooms.

The project revealed high impact on the level of understanding for students. Students performance and project outcomes were assessed against ABET learning outcomes: (a) apply knowledge, techniques and skills to engineering technology activities, (b) apply knowledge of mathematics, science, and engineering to engineering technology programs, (c) Conduct tests, measurements, calibration and improve processes, (e) Problem Solving: ability to identify, formulate, and solve engineering problems, and (f) Effective Communication: ability to communicate effectively.

Introduction

Many commercial building spaces are designed for high occupancy usage such as theaters, meeting rooms, and classrooms. The ventilation of these spaces are designed for a high peak occupancy that is usually not met and are thus over supplied. Ventilation and air-conditioning power consumption can be reduced during the many hours of operation when these spaces are less occupied or even vacant. Currently, there are different means to detect humans inside buildings, such as monitoring the change in CO_2 concentration, using passive infrared (PIR) sensors, network of motion sensors, image recording and tracking, occupant counting turnstiles for shopping centers or buildings, and even counting ticket sales for theaters. However, each of these has its own cons and pros.

Several energy audit reports for buildings indicated that occupancy sensors can significantly reduce energy consumption. The equipment demand for heating, ventilation and air-conditioning has increased in the USA from $11 billion in 2004 to $19 billion in 2014 [1]. Having an efficient air-conditioning supply and control system can reduce energy consumption in buildings.

Many techniques and technologies were used to detect and count occupants inside buildings. Some of the studies investigated the change in the level of CO_2 inside rooms and buildings to identify the number of occupants and their activity level, such as such as by [2], [3], [4], and [5]. Carbon-dioxide is a direct indicative parameter for the required ventilation inside a closed environment space. CO_2 monitoring parameter can be through a direct measure for the ventilated space or by monitoring the difference between inlet and exhaust levels. However, a challenging issue with CO_2 sensors is the feedback delay. The sampling unit in the CO_2 sensor will need time to detect the new level of carbon dioxide in the space. This delay might create a buffer zone where occupants might feel uncomfortable. Other studies investigated the applicability of passive infrared sensors (PIR), as a single unit or when used in a series of networked sensors, for detecting occupants and tracking them, such as by [3], [6], and [7]. Other techniques used to detect occupants' presence and motion inside buildings is radio frequency with tracking tags by [8] or even a network of cameras throughout the building. Tracking occupants through digital imaging can create privacy issues when it comes to installation licenses. Infrared (IR) sensors and motion detectors can be used as supportive systems for human detection as previous studies showed some inaccuracies in their detection capabilities. For example, a cat presence or if a paper is remotely printed from another office, the system might be trigger ON although there is no human presence in the room.

Purdue Polytechnic has the main campus located in West Lafayette and nine other remote locations distributed across the state of Indiana. Purdue Polytechnic Kokomo started offering BS degree in MET recently which limited the number of senior students available at this time. For that reason, this project was done by one MET student but it is the department's interest to start assigning teams for capstone projects in the coming semesters. This capstone project was part of a bigger project conducted at Purdue Polytechnic Kokomo to improve energy consumption in buildings. This specific capstone project investigated the impact of human density in an office on its cooling load requirements and actual energy consumption. The project was conducted by one senior MET student and was supervised by the author of the paper. Other capstone projects investigate thermostat reliability and accuracy, condenser every saving, and other energy saving techniques. The results of all projects would be merged together, at a later stage, to reveal the overall energy consummation and savings in office buildings through the different sustainable techniques followed. The learning outcomes that the student gained by the end of this capstone project:

- Energy consumption evaluation
- Energy consumption simulation (analytically and using commercial software)
- Cooling load estimation
- Improving the student's controls and measurements skills

Experimental setup

An office space located at Purdue Polytechnic in Kokomo was utilized as a testing room. The office floor area is 3.7 m × 2.7 m with a height of 3 meters. Figure 1 and Figure 2 show a plan layout and the interior of the office, respectively. The office had a desk, chair, computer, printer, and filing cabinets similar to a standard office. In addition to that, the office had a round meeting table with four chairs around it. Two of the office walls are adjacent to other offices, the third contains a large 1.8 m×1.2 m double pane window, and the fourth wall has the entrance door that leads to the building hallway. The hallway was generally kept at a higher temperature than the testing office and the adjacent offices. The room ceiling is made up of squared acoustic tiles with 0.6 m on each side and has two triple-bulb fluorescent light fixtures.

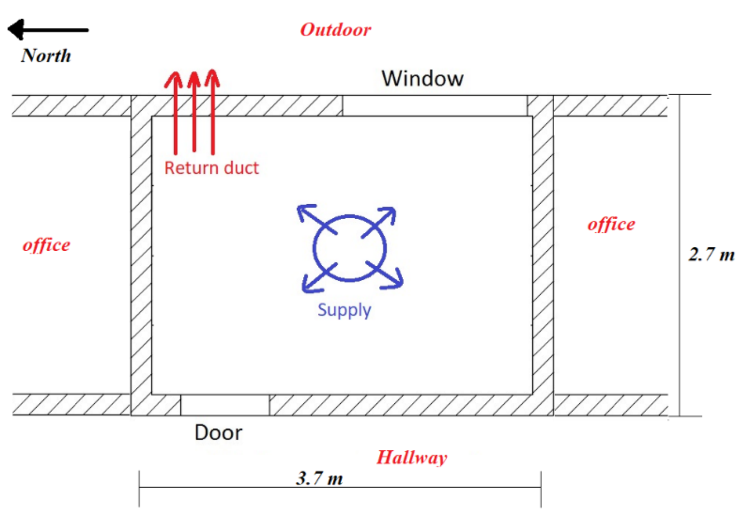

Figure 1. Office plan layout

Figure 2. Office used for experimental data collection

Detection sensors were equipped to four chairs in the office for experimental testing. A Programmable Logic Controller (PLC) unit was used to store and control data collection.

Chair sensors

The chair sensors were each built using an infrared (IR) emitter and receiver mounted onto each of the testing chairs as shown in Figure 3(c and d). Multiple switches were used under the chair cushion (Figure 3a and b). An inexpensive IR emitting diode and an IR receiver that is capable of receiving an IR signal at 38 kHz were used. The details for all parts used are summarized in Table 1 including the suppliers, part model number, and associated costs. When the receiver detected a signal, the output was switched to the low or OFF state, therefore resulting in a sinking or NPN signal. The receiver requires a 5 volts DC power supply. This was provided using a simple 120-volts-AC to 5-volts-DC outlet plug. Finally a single LED was added to the bread board so that the user could easily identify the low state of the built circuit. The emitter part of the system required a 5-volts-DC power supply. However, it won't be feasible to use a direct electric plug and a converter as for the receiver, since the emitter is attached to the chair and it won't be the best idea to use an electric wire and a plug with the chair. A wired chair is generally not well accepted by users and hence a battery pack was used to power the receiver. The pack contained four 1.5-volts-DC AA type batteries. An ATTIN85 microcontroller was used to control the operation of the system. The chip was initially programmed to cause the IR emitter to pulse at the required 38 kHz constantly whenever the system is active upon the closing of one of the chair switches. However, this would limit the life of the batteries to 8 hours only since it would be continuously used whenever the seat was occupied and the circuit is ON. To overcome this limitation, the controller was programmed to only pulse for a period of 1 second per minute. This effectively extended battery's life by a multiple of 60. Under this scenario, if the seat is occupied for approximately 8 hours a day, the battery will need to be changed every 2 months.

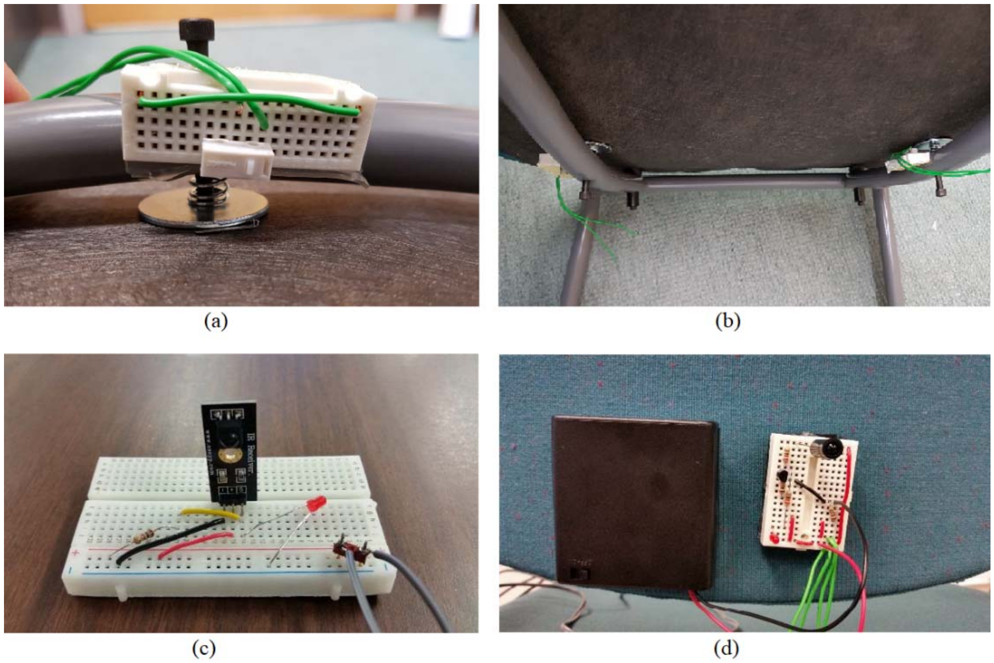

Figure 3. Chair sensor (a) & (b): switch between chair frame and cushion, (c) & (d): IR emitter, receiver, diodes mounted on chair

The sensor threshold detection weight was tested by adding weights increments of 10 pounds till a signal was triggered and the PLC system status was switched to ON. The system status was triggered when 40 pounds and more were on the cushion of the seat. This would ensure that no wrong detection was done such as when office equipment are placed on the chair such as a book, stapler, or a calculator.

PLC system setup and programing

An Automation Direct brand programmable logic controller (PLC) (model H2-DM1E) was used to store the signal. The PLC unit was resourced from EET labs and has three modules that allowed the unit to interact to different measuring sensors. The PLC was equipped with GUI (Graphical User Interface) input screen. The PLC unit is shown in Figure 4(a). The display was designed as shown in Figure 4(b) giving the status of the room whether occupied or not and indicating the number of occupied seats based on the signals received by the PLC. If the room is unoccupied, then the minimum allowable ventilation would be supplied to the room to maintain a healthy environment but then excessive and circulation requirements will be limited by the number of occupants present. This was not an option for the experimental part since it would require access to the building AC system and was not a viable option. This was analyzed in the parametric case study presented later in this paper.

Table 1. Chair sensor details

Part	Supplier	Part #	Unit Cost	Quantity	Total Cost
IR Emitting Diode	Frye's Electronic	NTE3017	$ 3.49	1	$ 3.49
Bread Board	Frye's Electronic	170TP	$ 6.49	1	$ 6.49
Momentary Switch	Frye's Electronic	LS-00002	$ 4.99	4	$ 19.96
Battery Box	Frye's Electronic	7726858	$ 3.29	1	$ 3.29
IR Receiver	Frye's Electronic	IRREC-01	$ 9.95	1	$ 9.95
Resistors (various)	Frye's Electronic	6349891	$ 6.49	1	$ 6.49
Transistor	Newark	2N3904	$ 0.24	1	$ 0.24
Microcontroller	Newark	ATTINY85	$ 2.15	1	$ 2.15
Subtotal					**$ 52.06**
Tax (7%)					**$ 3.64**
Total Cost					**$ 56**

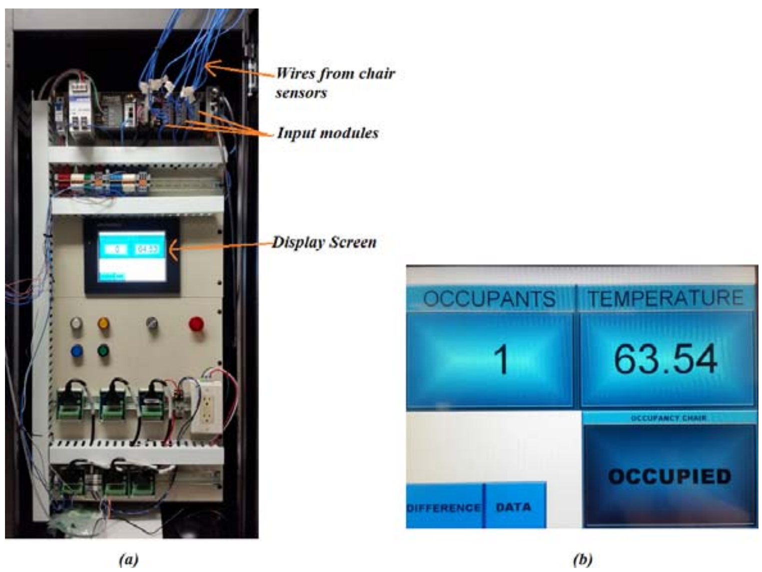

Figure 4. (a) PLC unit, (b) Output screen from the PLC unit

Results and Discussion

Four chairs were used in the office for experimental testing. The first step was done by comparing the signals detected by the PLC unit to a manual registry used to record the number of occupants present in the office during three days. The manual registry for the number of occupants present in the room is shown in Table 2. Since the number of occupants were recorded and reported every 15 minutes, the output signal detected by the PLC system was averaged over 15 minutes and is shown in Figure 5 along with the data in Table 2. The averaging of the captured signals over 15 minutes period would filter out any error due to occupants' standing or moving within the office for few seconds.

Table 2. Occupancy presence manual record

Time	Day 1	Day 2	Day 3	Time	Day 1	Day 2	Day 3
8:00 - 9:30	0	0	0	12:00 - 12:15	0	0	0
9:30 - 9:45	4	3	3	12:15 - 12:30	0	0	0
9:45 - 10:00	3	2	4	12:30 - 12:45	0	0	0
10:00 - 10:15	4	2	4	12:45 - 13:00	0	0	0
10:15 - 10:30	4	4	4	13:00 - 13:15	3	3	2
10:30 - 10:45	2	4	3	13:15 - 13:30	3	3	2
10:45 - 11:00	2	3	2	13:30 - 13:45	4	3	2
11:00 - 11:15	0	0	0	13:45 - 14:00	2	4	4
11:15 - 11:30	0	0	0	14:00 - 14:15	0	2	4
11:30 - 11:45	0	0	0	14:15 - 14:30	0	2	4
11:45 - 12:00	0	0	0	14:30 - 15:00	0	0	0

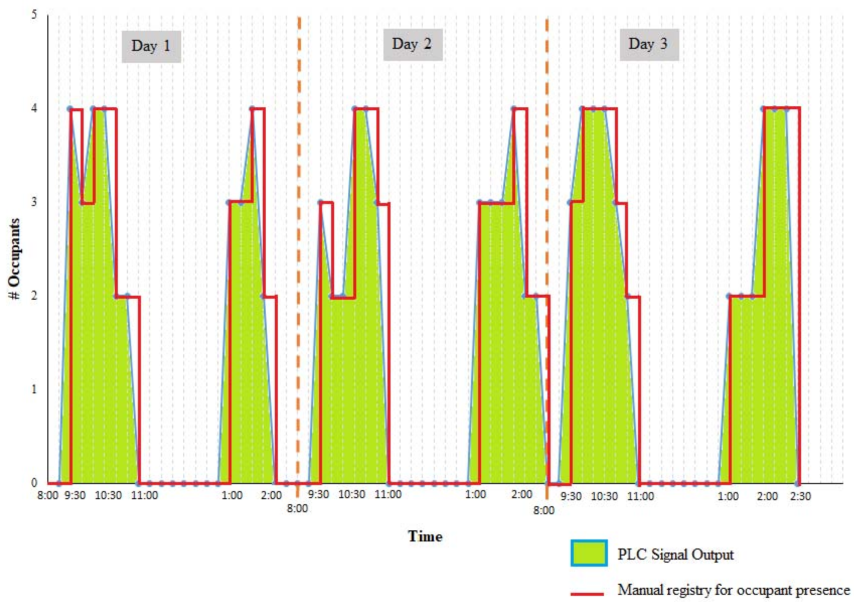

Figure 5. Occupancy registry shown in Table 2 versus PLC output signal

It was observed from Figure 5 that the signal captured by the PLC matched the number of occupants registered in Table 2. The cost of the built chair sensor was around $56 as reported in Table 1. This gives the design of this project a big advantage over other commercially available sensors that cost $500 to $1,000.

Case study – Evaluation of the performance of chair sensors

The office room used for testing the chair sensor is part of Purdue Polytechnic Kokomo building. Hence the air-conditioning system for the room is connected to the whole building system, and it was not possible to control and report the savings in the cooling load when using a variable supply air system that responds to changes in the office room occupancy level. To investigate the savings in cooling load requirements due to the use of chair sensors, a parametric case study was done investigating the cooling load for the office room for May through September. Two scenarios were followed to calculate the cooling load savings for the office room: the first one was based on maximum occupancy presence which is the case when no occupancy detection was used. The second one was based on variable occupancy level and it used occupancy records shown in Table 2 or as recorded by the PLC unit. The design parameters used for calculating the cooling load were based on ASHRAE codes [10] and are reported in Table 3. Both cases considered the same variables/parameters except for the occupancy level. The cooling load calculations were done using the commercially based software from Carrier - Hourly Analysis Program (HAP) [9]. Full and partial occupancy schedules were considered for Monday through Friday from 8:00 am to 5:00 pm and no occupancy afterwards from 5:00 pm till 8:00 am. Office equipment such as desktop PC and printers were considered ON from 8:00 am to 5:00 pm, Monday through Friday, as well. Lighting was assumed ON for 24 hours during all days of the week. Since this was a comparison case study to show savings due to occupancy level, no detailed reasoning was provided to the followed schedules for lights, PC, and printers. These parameters along with indoor thermostat temperature, building wall materials, glass, were all fixed during both cases. The only difference between both cases was the occupancy level.

Table 3. Design variables for cooling load calculations

Location	Kokomo, IN
Indoor Conditions	22.2 ˚C (72 ˚F) dry bulb and 50% relative humidity
External Walls	16 mm gypsum + 203 mm brick + air space + 102 mm face brick *
Internal/Partition walls	16 mm plywood + air space + 19 mm plywood (Light Wall) *
Lighting	12 W/m^2
Entrance door	2.5 m × 0.9 m wooden door
Window	1.8 m × 1.2 m double pane with 13 mm air space + 10 mm setback and roller shades
Door	2.2 m × 0.9 m wooden door
Floor area	3.7 m × 2.7 m tile with lower room at 22 ˚C
Ceiling Height	3 m
Hallway Temperature	25 ˚C (77 ˚F)
Adjacent rooms Temperature	23.3 ˚C (74 F)
Equipment	Office with desktop, 2 screens, and printer (14.35 W/m^2) **
Occupancy	**4 for case 1 and Table 2 for case 2**

* [9]
** [10]

The monthly peak demand cooling loads for both the full and partial occupancy levels were extracted from HAP and are reported in Table 4. The cooling load savings ranged between 14-16%.

Table 4. Cooling load comparisons for full and partial occupancy

Month	Cooling Load (kW)		% Cooling Load Savings
	Full Occupancy	Partial Occupancy	
May	1,286	1,118	15%
June	1,411	1,236	14%
July	1,452	1,276	14%
August	1,416	1,240	14%
September	1,262	1,087	16%

Project assessment

Through the implementation of the project, the involved student gained extensive experience in the field of HVAC, energy and cooling load calculations, controls and measurements, statistical analysis, and commercial software utilization that can help in future career placing. Project outcomes were evaluated against ABET learning outcomes summarized in Table 6. Performance assessment and feedback were done through the evaluation of biweekly submitted reports by the student. There were four main categories toward the final GPA of the student: biweekly reports (15%), draft report (10%), final report (50%), and presentation (25%). The details of the four categories are as follows:

1) Biweekly reports: constituted 15% of the final GPA. These reports summarized the work of the previous two weeks. Each report was recorded on a log-book that included the following activities:
    i. Agendas and minutes of meetings identifying decisions and action items taken.
    ii. A weekly prioritized to-do list.
    iii. A weekly list summarizing goals achieved during the previous two weeks including the time spent (in hours) working (how much of the to do list was completed?)
    iv. Notes from outside research.
    v. Notes of how to accomplish a task.
    vi. Calculations, graphs (hand made and/or computer generated), drawings.
    vii. Drawings and schematic diagrams, including changes or updated versions, with detailed explanations of what was changed or updated.
    viii. Test plans, collected data, analyses, and conclusions regarding testing.

Each of the biweekly reports had a general theme as follows:

Report 1 Proposal
Report 2 Conceptual Design
Report 3 Preliminary Design
Report 4 Critical Design
Report 5 Proceed to Test
Each report was evaluated based on rubrics given in Table 5.

Table 5. Rubrics used for evaluating biweekly reports

Points	4	3	2	1	0
Weekly notes from supervisor and other parties	Notes exceeded expectations	Notes were appropriately relative to meeting content	Notes qty & quality were missing some meeting contents	Some evidence of notes	No evidence of notes
Legibility	Exceeded expectations	All entries clear & legible	75% or less clear & legible	50% or less clear & legible	25% or less clear & legible
Readability	Exceeded expectations, cross-referenced	Well identified entries	< 75% are identified, erratic flow in places	50% are identified, erratic flow in most places	< 25% identified, erratic flow
Completeness	Well documented, flow and content of entries demonstrated forethought, connections, and results, in and between process phases	75% of flow and content of entries demonstrated forethought, connection, and results	50% of flow and content of entries demonstrated forethought, connection, and results	Flow and content were spotty and unconnected	No evidence of forethought, connections, or results in and between process phases
Lab Notebook Guidelines (items i-viii above)	Followed all criteria	Criteria followed about 75% of the time	Criteria followed about 50% of the time	Criteria followed about 25% of the time	No evidence of following guidelines

2) Draft report (10% of final GPA): submitted 1-week before project presentation to allow any final feedback from the supervisor.
3) Presentation (25% of final GPA): The student presented results of the project to interested MET faculty members and guests.
4) Final report (50% of final GPA): submitted by the end of the semester after getting feedback from the project supervisor, guests and other faculty members, who served as external evaluators, and then embedding their comments, suggestions and corrections in the final report.

Table 6 shows the relation between the ABET learning outcomes and the category/ies that were used to meet these expectations.

Table 6. ABET ETAC students learning outcomes rubrics used for project assessment and the respective means used to meet these outcomes

ABET ETAC Rubric/Learning Outcomes		Means used to meet the rubrics
(a)	Apply knowledge, techniques and skills to engineering technology activities	Final Report and biweekly reports
(b)	Apply knowledge of mathematics, science, engineering, and technology to engineering technology problems	Final report and biweekly reports
(c)	Conduct tests, measurements, calibration and improve processes	Biweekly reports, draft report, and final report
(e)	Problem Solving: ability to identify, formulate, and solve engineering problems	Project proposal and biweekly reports
(f)	Effective Communication: ability to communicate effectively	Presentation and biweekly reports

Conclusions

By the end of this project, the students were able to: (1) build a system that detects a seated person in an office room, (2) tested and validated the accuracy of the system against a manual registry record, and (3) conducted a parametric study calculating and comparing the cooling load for maximum versus partial occupancy level.

Initial consideration of the obtained energy savings due to the usage of chair sensors clearly demonstrates this system as a viable and low cost tool that can help building operators to lower the building energy consumption. A simple and low cost system was able to accurately detect all occupants present in an office room. Results shown in Table 4 reflects an average of 15% savings in cooling loads. However, these savings were based on a predetermined occupancy schedules for a small office containing four chairs only. Savings can be much higher for bigger rooms such as movie theaters or school auditoriums. Having more chairs means that a more complicated data loggers are needed, but the complexity of the system and signal transfer and detection can be easily justified with numbers from energy savings as reflected in this study.

The chair sensor sensitivity was tested and proved that mistaken detection is minimized. The system threshold limit was found to be approximately 40 pounds. This would ensure that a book or a laptop left on the chair overnight won't trigger the sensor to an occupied state.

A major drawback or limitation of this system is its inability to detect standing occupants and, thus, applications of this system are limited mainly to places when occupants are mostly seated. To overcome the false-detection resulting from the standing of occupants, either to get a paper from the printer or to adjust their seat location, the chair sensor state should not be checked momentarily but rather should be averaged as was done in the above analysis. This would minimize system delivery fluctuations that can be harmful to the life time of the fan and other components of the ventilation system.

Assessment rubrics reflected students expectations from ABET learning outcomes. Some outcomes were not met due to inapplicability such as team work. Team projects shall be assigned in the future to help the students meet more of the ABET learning outcomes.

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