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Harvesting Built Environments for Accessible Energy Audit Training

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Abstract

The "Building-as-a-Learning Tool" (BLT) teaching approach provides energy engineering training by using existing academic facilities as living laboratories instrumented to provide human comfort and energy consumption data. Typically, BLT facilities are hard-wired with instruments, which are costly to purchase and maintain, prohibiting practical BLT training where resources are limited.

An alternative BLT instruction approach is being created using techniques borrowed from the building energy audit industry and inexpensive hand-held logging instruments. This approach simultaneously capitalizes on several attractive elements to provide accessible BLT training with dramatic cost reduction.

1) Public awareness of energy's global sustainability impact induces interest and applicability across all STEM disciplines.

2) Building audit skills are relevant for future energy professionals as legacy construction will make up the bulk of buildings in the US and abroad through the 21st Century; HVAC and lighting consume 40-60% of energy in commercial buildings.

3) Building energy audit techniques enable practical technical discourse with students about how instruments work via underlying fundamental principles of energy-thermal-fluids.

The overall goal of this project is to teach use of inexpensive auditing tools to produce building energy performance data of quality, utility, and fidelity equal to that obtained by costly professional auditing equipment.

Keywords: Building as a Learning Tool, Building Energy Audit, Energy Engineering Curriculum, Accessible Energy Audit Training

Introduction

Energy-focused education is critically needed to train today's engineers because 46% of energy industry jobs will be vacant by 2012 due to retirement and attrition.[i] According to ASHRAE, energy consumption in U.S buildings accounts for 40 percent of total domestic energy use,[ii] approximately 38.8×10^{15} BTU per year.[iii] Therefore, training engineers to indentify building energy conservation opportunities is critical to promoting sustainability in the built environment. To put the potential into perspective, thirty percent of operating costs in typical American office buildings arise from energy use, representing the largest category of controllable costs for this building type.[iv] In commercial buildings, HVAC accounts for 40 to 60 percent of energy used.[v] Thus, reducing HVAC-related energy consumption in these buildings by just 1% would yield an annual domestic energy savings of about 8.7×10^{13} BTU, the energy consumed by roughly 5.5 million New York City households in a year.[vi]

While energy-conscious design can be incorporated into new buildings, existing legacy buildings, completed when less attention was placed on efficiency due to the low cost of energy, will continue to represent the bulk of buildings in the United States and abroad through the 21st Century.

Enormous savings are attainable by providing building owners with high-quality data allowing them to make informed choices about retrofitting their buildings to improve energy efficiency. Legacy buildings often conceal many opportunities for simultaneous improvement in energy efficiency and human comfort; improvements that when properly identified and implemented pay themselves back through energy cost savings and are attractive investments for building owners. To provide building energy audit training, the Building-as-a-Learning Tool (BLT) approach is a best practice because existing academic buildings become living laboratories where students can learn and practice skills under realistic conditions.

A paragon example of BTL training in an academic environment occurs at the University of Colorado at Boulder, which completed its BLT facility, the Integrated Teaching and Learning Laboratory (ITLL), in 1997. This purpose-built facility is instrumented with over 300 sensors to monitor human comfort and energy consumption metrics.[vii] While it provides an unparalleled venue for training, the cost to create a similar facility is prohibitive for smaller universities, community colleges, high schools, and companies wishing to reproduce a BLT program. The instruments and computers enabling ITLL data collection cost $69,000 with annual upkeep of $10,000. By contrast, this paper introduces a different approach, "accessible building audit training", which refers to BLT training pedagogies that 1) can be reproduced with low initial and recurring cost and 2) can be spirally inserted into any Science, Technology, Engineering, and Mathematics [STEM] curriculum by relying upon fundamental concepts that underpin all STEM fields.

The BLT training exercises described in this paper have a total equipment cost of only about $2,000, a 40-fold cost reduction compared to Boulder's ITLL. However, these techniques empower any institution with even one academic building to reproduce a BLT training experience for students. The first exercise uses wireless sensors to illustrate which measured human comfort parameters are most relevant in the built environment. Incorporating wireless sensors for building monitoring is an emerging building technologies topic familiar to many students through the mainstream media. By allowing students to work with "new" technology, they learn hands-on voltage measurement techniques, the need for sensor calibration, data acquisition and analysis fundamentals, and elements of engineering economics. They also learn how to represent data on a plot. The second exercise expands use of wireless sensors to compare the quality and fidelity of different types of measurement devices. Data arising from this exercise lends itself to uncertainty analysis as a tool to compare different data streams. The second exercise also helps students to think about how environmental influences can impact the quality of experimental measurements. The third exercise builds upon sensor and data comparison skills by using two different temperature sensor types (thermocouples and an infrared [IR] thermometer) to measure temperature profiles on building walls. Probing building walls for hot/cold spots is an important building energy audit skill professionals use to locate air leaks, internal damage, and poorly insulated areas of a building's envelope. Here, students learn the physical phenomena underlying how different instruments take measurements (i.e., conduction in thermocouples versus radiation in IR thermometers). Also, uncertainty analysis is again addressed through graphic representation of experimental uncertainty on a plot using error bars.

Wireless Sensor Battery Life Evaluation

Background and Goals

Data-driven building evaluations, particularly with respect to occupant comfort and energy efficiency, offer critical feedback on envelope performance while providing a reference to quantify potential future improvements.[viii] In conventional BLT, building-integrated sensors distributed throughout the space provide real-time data and historical archives for evaluation. However, in non-BLT buildings, these data are not typically directly available to occupants. Thus, inexpensive building-scale data acquisition is enabled by allowing students to deploy a network of battery-powered, wireless environmental sensors.

The utility, multi-functionality, and potential cost savings over conventional monitoring afforded by wireless sensors in buildings is a major contemporary research topic, [ix],[x],[xi],[xii],[xiii] and students are generally aware of it through mainstream coverage. So, student-distributed wireless sensor networks in buildings motivate important teaching opportunities; including an experimental evaluation of the benefits and drawbacks of this “new” technology. Critical questions students can answer for themselves through experimental evaluation of wireless sensors in the built environment include the following:

1) What is the installed cost for wireless versus hard-wired sensors?
2) How much energy do wireless sensors consume, and where does this energy come from?
3) Do recurring costs to power wireless sensors exceed initial cost benefits from installation?
4) What techniques reduce wireless sensor energy consumption while providing high-quality data?

Equipment and Procedure

To empower students to obtain their own answers to these questions through experiment, they used three Crossbow wireless indoor environmental sensors (Model # MTS 400 CA) with a receiving station and data collection software (Figure 1). These sensors can measure temperature, barometric pressure, ambient light level, and relative humidity; all relevant parameters for building performance monitoring. Free sensor communication software, Mote View 2.0, was installed on a second-hand 2.4 GHz Pentium 4 personal computer.

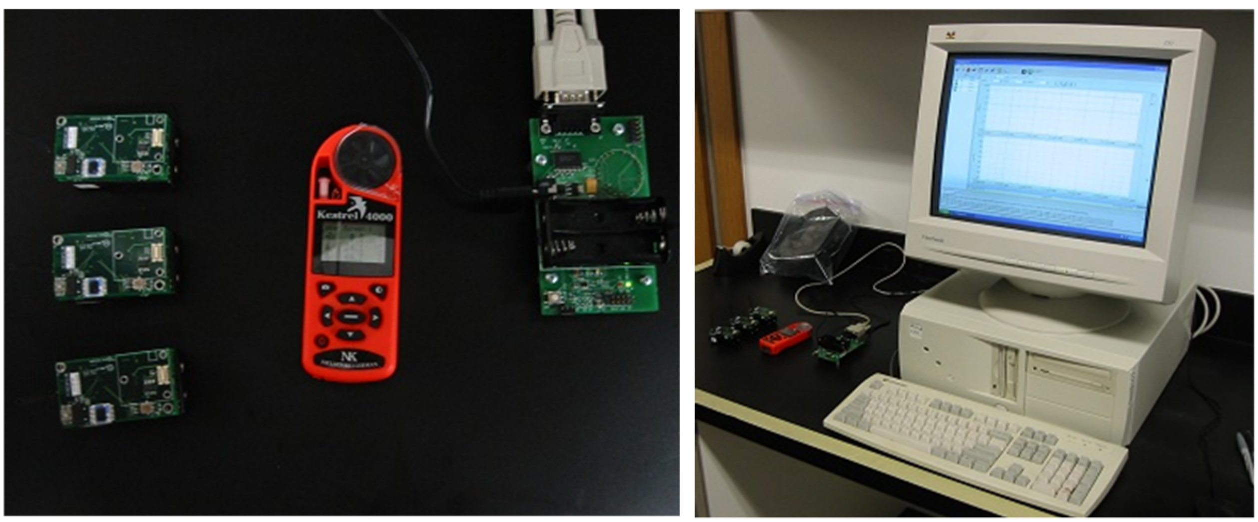


Figure 1: Three Crossbow wireless environmental sensors and a wireless receiving station were calibrated against a handheld, logging weather instrument (Left). All data was collected and analyzed using a second-hand PC (right).

To determine whether the sensors are viable self-powered units providing adequate economy and longevity to replace hard-wired sensors for building monitoring, students designed a battery voltage decay study to assess the lifespan of three battery types (lithium-ion, alkaline, and rechargeable).[xiv],[xv] The sensor sampling rate was set artificially high (0.0167 Hz in the first experiment and 0.0333 Hz in the second experiment) to speed battery voltage decay.

Three different AA battery types powered each respective sensor: lithium-ion (Energizer Model # 03-2022), alkaline (Energizer Model # 2013), and rechargeable (Energizer Model # CHDC-CA). Two batteries of the same type were installed in each Crossbow sensor in position A and B. Initial voltages of all batteries were verified and recorded using a Craftsman Digital Voltmeter (Model # 82082) set in 2000 mV mode. After installing the batteries, the data collection software was set to receive data at 60 second intervals (0.0167 Hz), and all three remote sensors were activated simultaneously. As a control and calibration measure, environmental conditions were logged throughout the experiment using a Kestrel 4000 handheld weather tracker (see Figure 1 – Left). Battery voltage and other comfort parameters (temperature, pressure, humidity, and light level) measured by each sensor were periodically captured via the data collection software. Through normal operation, battery voltage in each sensor eventually decreased to a level preventing data transmission. Essentially, the sensors ran until their batteries died. This procedure was repeated with the software set to receive data at 30 second intervals (0.0333 Hz). Both data sets were then compiled and processed using Microsoft Excel for comparison.

Results and Discussion

The initial sensors test run (0.0166 Hz sampling frequency) resulted in battery voltage decay to sensor shut-off in approximately 5.5 days. The rechargeable batteries were the first to shut off due to low voltage, followed by the alkaline and lithium-ion batteries, respectively. Initial and final voltages are given in Table 1. Figure 2 (left) illustrates the voltage decay patterns for each type of battery in the initial test run. The second sensor test run (0.0333 Hz sampling frequency) resulted in battery voltage decay (Figure 2, right) in approximately the same length of time as in the initial test run: 5.5 days. These similar repeated voltage decay times were an unexpected result for the students. They hypothesized that the second test would result in a voltage decay time approximately half as long as the initial test because the sampling rate was twice as fast. They concluded that the sensors must be sending out data at a fixed rate, which the receiver samples intermittently at the set sampling frequency.

Table 1: Initial and final voltages measured for each battery type reveal that Li-ion cells do not discharge uniformly while other batteries do.

	Voltage Decay Study #1 (0.01667 Hz Sampling Frequency)					
	Lithium-Ion		Alkaline		Rechargeable	
Position	A	B	A	B	A	B
Initial Voltage [mv]	**1790**	**1792**	**1617**	**1611**	**1383**	**1385**
Final Voltage [mv]	**1377**	**383**	**930**	**922**	**1013**	**948**

	Voltage Decay Study #2 (0.0333 Hz Sampling Frequency)					
	Lithium-Ion		Alkaline		Rechargeable	
Position	A	B	A	B	A	B
Initial Voltage [mv]	**1773**	**1773**	**1606**	**1605**	**1345**	**1350**
Final Voltage [mv]	**1217**	**412**	**894**	**923**	**1161**	**1158**

For most of the experiment, agreement in ambient temperature, barometric pressure, ambient light level, and relative humidity between the sensors and with respect to the calibration standard were excellent; better than ±5%, baring a few "events" in which spatial variations in the lab were induced by experimenter activity. However, below about 2.4 volts for the Li-ion batteries and below

2.2 volts for the alkaline batteries erroneous data began to be transmitted, likely owing directly to the low sensor voltage. This finding is consistent with low-battery-voltage induced error for environmental sensor networks reported in the literature.[xvi] The time elapsed between the error-prone low-voltage thresholds and complete sensor shut-off is about one hour. Thus, data collected during this period must be treated as not reliable.

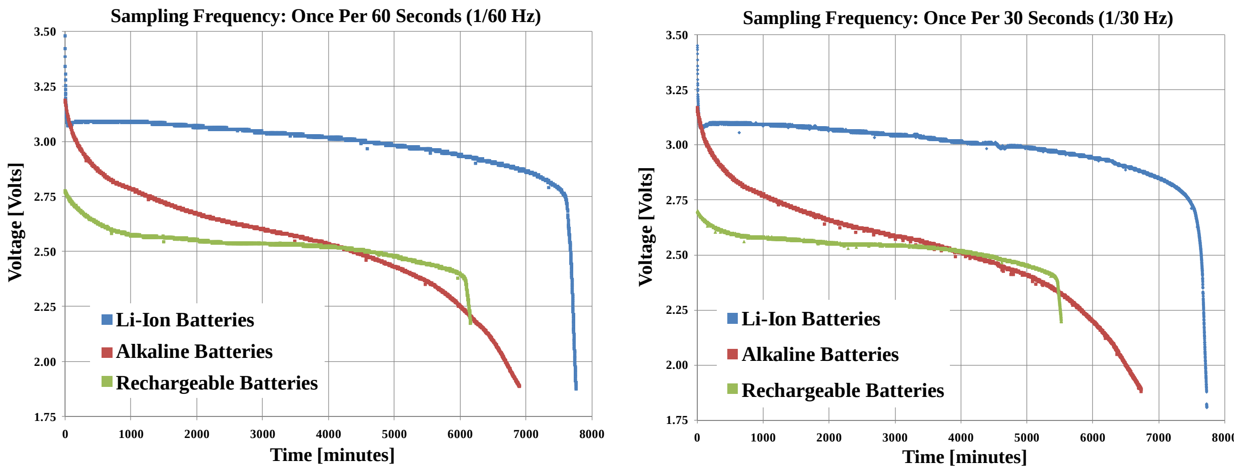


Figure 2: Replicate voltage decays for similar wireless sensors using three different battery types indicate that lithium-ion cells outlast alkaline and rechargeable batteries by over 1000 minutes (16.7 hours) for both 1/60 Hz and 1/30 Hz sampling rates.

From these initial experiments, the students concluded that Crossbow Model # MTS 400 CA environmental sensors cannot serve as true stand-alone, wireless, battery-powered units given the relatively short life of available battery types (5.5 days). Operating a large network of these sensors would require constant battery replacement to avoid voltage-decay-induced error or sensor shut down. Battery replacement and labor cost would quickly outstrip any initial savings realized by not paying installation costs to hard-wire conventional sensors.

Wireless Sensor Versus Hard-Wired Thermostat Comparison

Background and Goals

There is a second important teaching opportunity afforded by working with wireless sensors to measure building comfort parameters. Students, by placing the sensors themselves, begin to evaluate how sensor location and sampling rate impact the validity and relevance of the resulting data for building monitoring, automation, and control. This evaluation can be extended by assessing wireless sensor performance against existing hard-wired sensors (where available) to quantify and compare efficacy and accuracy. Critical questions students can answer for themselves through experiment include:

1) How does a sensor's location in a building impact the validity of its measurements?
2) What impacts might the built environment have on a sensor's validity and relevance (i.e., though changes in direct/indirect sunlight or room occupancy).
3) If the number of sensors is limited, what is the optimal placement distribution to maximize acquisition of useful data?
4) How well do legacy hard-wired sensors capture relevant human comfort parameters?

Procedure

To evaluate performance of a wireless sensor compared to a legacy hard-wired building thermostat, students designed a comparative study.[xvii] A wireless sensor was attached to an interior wall right next to a legacy thermostat (Figure 3). Temperature output of both sensors was logged for about four days. As mentioned above, non-BLT buildings typically are not equipped with occupant-accessible thermostat data logs. For these experiments, students coordinated with facilities managers to archive thermostat data every 30 minutes using a centralized building measurement and control computer. However, for buildings without this capability, temperature data for a room typically read out on the thermostat LCD display (see Figure 3) whether or not it is logged. These data can be hand-recorded periodically by students throughout a day. Alternatively, a digital camera set up to shoot an image every 15 or 30 minutes can be trained on the thermostat, or a video camera with time indexing can record the change in thermostat temperature with time.

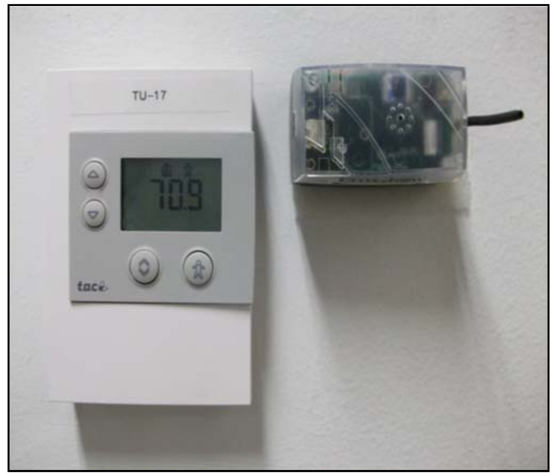


Figure 3: A wireless sensor wall-mounted next to a hard-wired thermostat enables comparison of room temperatures read using these two sensor types.

Results and Discussion

Representative data from the wireless and hard-wired temperature sensors are plotted in Figure 4. The lower sampling rate of the hard-wired sensor is apparent from the relative scarcity of points. Both sensors detect similar temperature deviation events. However, although the two data streams are time indexed to the same starting moment, the sensors differ on when events occurred.

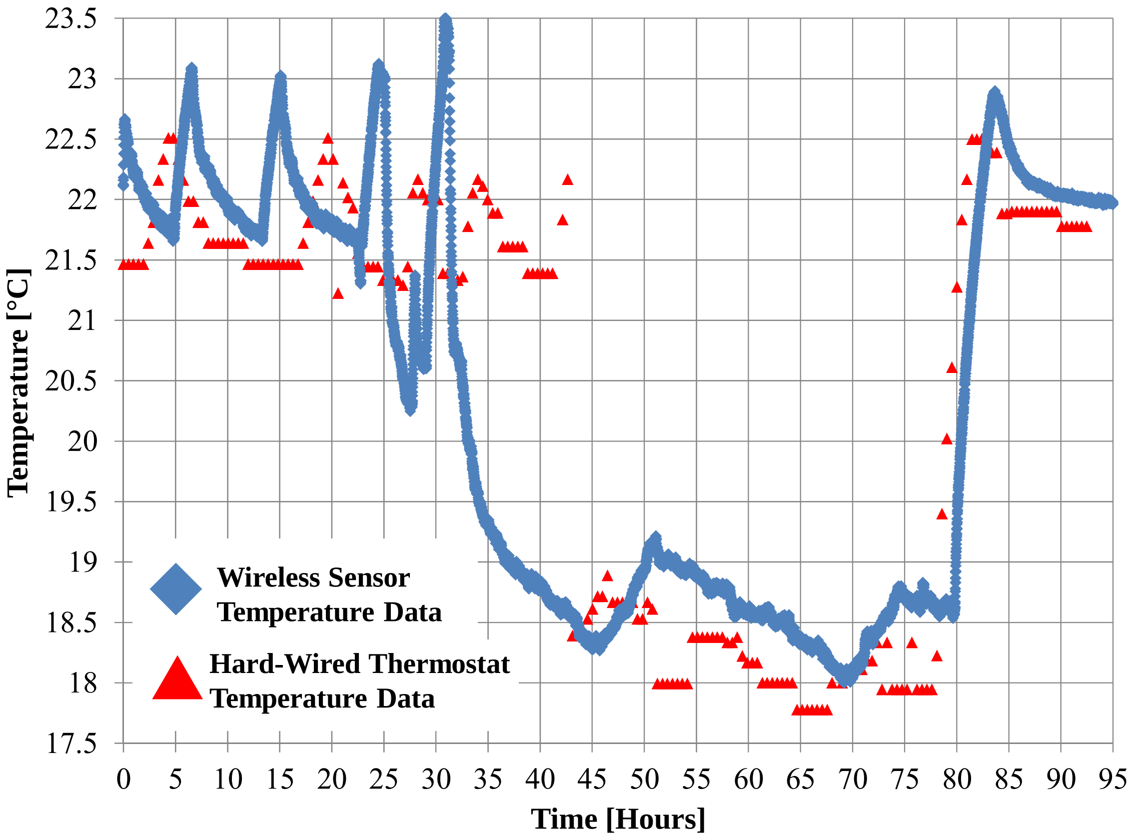


Figure 4: Direct comparison between wireless and hard-wired sensor temperature data from the same room reveal large-scale agreement for significant temperature shifts while the details of event magnitudes and times do not agree. This mismatch motivates analysis of environmental impacts of sensor fidelity.

Early in the data, the hard-wired thermostat appears to lag the wireless sensor, but by the experiment's end, the thermostat is leading. Most notably, the periodic temperature cycling ranging between about 20.5 °C to 23.5 °C and occurring from 0 to 35 hours is attributed to the building's HVAC system cycling on and off. Both sensors register five comparable on/off thermal cycles, but these events misalign in time by nearly 10 hours. By contrast, the large warm-up near 80 hours registered nearly coincidentally on both sensors. Numerous checks were made of the time indexing scheme, but ultimately these data aberrations in time could not be attributed to data processing errors. An interesting mystery concerning sensor placement and response time was thus established for students to work out.

They discovered that thermostats are manufactured with built-in time constants[xviii] that may cause the thermostat data to appear time-delayed. Another explanation posited by students for the data misalignment was that the thermal mass of the wall lagged the temperature change in the room. The hard-wired sensor with its secure attachment and wall penetrations to wire and conduit may be delayed owing to more thermal communication with the wall than the wireless sensor experiences.

Through their analysis, students learned that room temperatures measured by thermostats might be unapt for controlling room heating and air conditioning. Measured temperatures might not be spatially uniform within the room, especially if occupants are far away from the sensor. Wireless sensors have an advantage because they can be placed close to where occupants are clustered to provide the most relevant temperature data for heating and cooling control. Moreover, while it is typical to place only one thermostat in a room, multiple wireless sensors can be placed in one room to provide spatial temperature profile data.

An additional wireless sensor benefit is negligible installation cost because no signal wires, power wires, or conduit are needed. Also, since wireless sensors are instantly recognized by the data acquisition software, little time is invested in sensor set-up and testing. Moreover, if a room (or an entire building) is repurposed, wireless sensors can be easily relocated to accommodate new space usage patterns. Despite these benefits, high capital cost of wireless sensors relative to hard-wired sensors makes the newer technology unattractive for building monitoring and system control. Table 2, for example, shows the estimated difference in installed cost between the two sensor types; wireless technology is $274 more expensive per sensor. However, this dramatic cost difference may soon disappear; radio frequency modules are projected to drop to $4 per unit while integrated humidity and temperature are available for less than $3 per sensor at high volume.[xix]

Table 2a: Estimated installed cost per wireless sensor for building monitoring.

Item	Cost Each
MICAz 2.4GHz, IEEE/ZigBee 802.15.4 wireless sensor board	$99.00
Basic weather sensor board with temperature	$210.00
Injection-Molded housings for MICAz processor/radio board	$10.00
Installed Cost Per Sensor	$319.00

Table 2b: Estimated installed cost per hard-wired sensor for building monitoring.

Item	Cost Each
Non-Programmable digital wall-mounted thermostat	$20.00
Cost to run conduit and cable for hard-wired thermostat	$25.00
Installed Cost Per Sensor	$45.00

Comparison of Three Techniques to Measure Spatial Temperature Profile on an Internal Wall

Goals and Background

This study compared three different approaches to measuring a temperature gradient of a vertical wall in the built environment. The three evaluated instruments were 1) a FLIR Systems BCAM™ infrared camera, 2) an EXTECH® Instruments 42511 Infrared Thermometer, and 3) an array of bare-bead thermocouples adhered to the wall. Each instrument was selected to contrast their differences in measurement accuracy, ease of operator use, time investment in their function, and initial costs. The wall temperature profile for each of the three techniques was compared by evaluating the same spatial temperature gradient in a vertical wall. The existence of the wall temperature profile was known to exist by a simple qualitative assessment – touch, and it was verified by the IR camera before the comparative tests. By reporting and evaluating the accuracy, cost, and user time for each technique, this report draws important conclusions about the quality, expense, and utility of each technique.

The overarching goal of this project is to examine the validity of solely using an IR thermometer for building wall surface temperature measurements, in comparison to the results from a thermal imaging camera that provides an entire temperature field for a wall of interest in a short amount of time. Nonetheless, IR cameras are expensive pieces of professional energy audit equipment, costing a minimum of $3500. In addition, both the IR thermometer and IR camera are compared to placing a regularly spaced, linear array of thermocouples along the sample wall. If good thermal contact is maintained, the thermocouples provide the most precise measurements of temperature at the expense of an extremely time-consuming process of setting up the line of sensors.

Procedure and Equipment

Using the thermal imaging camera, numerous walls within an academic building were examined to locate a surface with a suitable temperature gradient for quantitative evaluation. This process led to the selection of an exterior wall that concealed a regular series of heated pipes. Their heat signatures provided a temperature-scale contrast easily detected by the thermal imaging camera. The spatially-repeating thermal signature of this wall enabled evaluation of the three measurement techniques of interest to this project.

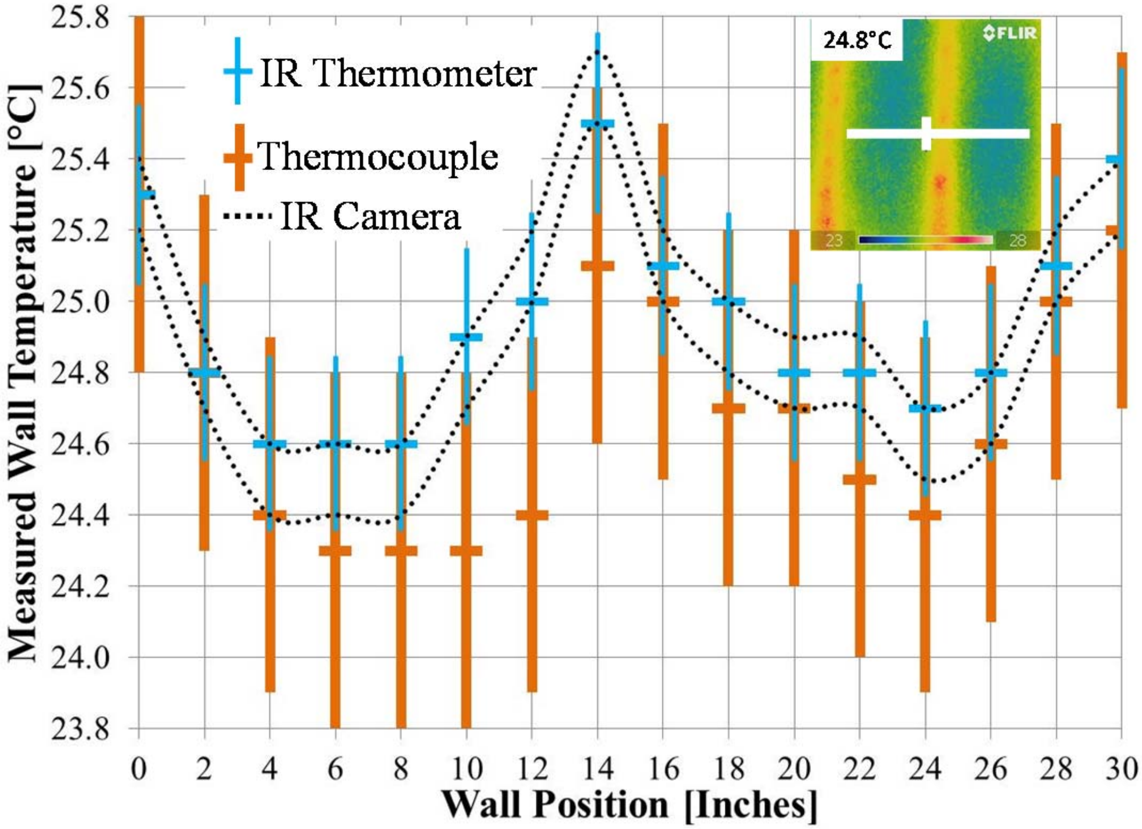
The experiment was deployed along a section of wall approximately 32 inches long where a strong temperature gradient, easy to detect, was observed using the IR camera. Sixteen K-Type thermocouples were placed at two inch intervals along a horizontal one dimensional line, passing right through a wall hot spot. The thermocouples were bare-bead and held in place with small pieces of masking tape. The thermocouple connectors were left hanging three feet below the beads to enable readings at a distance judged far enough away to impose minimal impact on the measured outcome created by the tester's own body heat influencing the readings.

The IR thermometer was used to take temperature readings co-located with the placement of the individual thermocouples along the wall. Results from both equipment types were recorded simultaneously to minimize the impact on any temperature change with time on evaluation of the IR thermometer's accuracy. A few moments later, a follow-up photo was taken with the thermal imaging camera of the area under scrutiny, creating a before-and-after comparison of the wall to help account for changes in temperature within the selected area with respect to time.

Results and Discussion

Temperatures measured ranged from approximately 24.4 °C to 25.2 °C, the hottest being at the location above the pipes within the wall. While only a single degree Celsius warmer, this hot spot is readily noticed by all three pieces of temperature measurement equipment and readily traceable once isolated.

As shown in Figure 5, the IR thermometer and thermocouples both displayed the same spatial gradient found by the thermal imaging camera. The IR thermometer consistently gave higher temperature readings than the thermocouples, and the amount of this overestimate varied by as much as 0.4°C. The discrepancy is likely caused by the two methods being out of calibration with each other. In other words, the IR thermometer enables the user to set the estimated irradiative emissivity of the surface whose temperature is being measured. For these experiments, the default ($\varepsilon = 0.95$) was used. However, a pre-measurement could have been taken by comparing a thermocouple temperature to the measured IR thermometer temperature of a wall surface, and the surface emissivity setting of the instrument could then have been adjusted to make the temperatures match.



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The resolution used to space the thermocouples along the wall and take IR thermometer measurements was only two inches, which was sufficient to notice the temperature gradient in the wall as seen by the infrared camera over a small temperature range. This result shows a promising opportunity that while the IR thermometer might not give as an accurate a temperature measurement at any single point as affixed thermocouples, it is nonetheless consistent enough to locate the same temperature gradients. For example with respect to the sample gradient used in these experiments, the IR thermometer alone could be used to discover the hot spot in the wall. Moreover, once the hot spot is discovered, the IR thermometer could be used to readily trace the path of the hot pipe within the wall.

An unexpected element that presented itself after the measurement process was completed was the measurement accuracy of the equipment. The thermocouples and IR thermometer have accuracies of ±1 °C, and the thermal imaging camera's accuracy is 2% of the measured value, which gives a functional margin of error of ±0.5 °C for these experiments. In each case, the range of experimental uncertainty exceeded the magnitude of the temperature gradient scrutinized. In other words, form the point of view of the instrument used, all the temperatures measured were the same value. While this realization raises concerns over the validity of the analysis, it cannot be denied that a temperature gradient was indicated by all three techniques, as well as tactile verification by placing one's hand on the wall. It is assumed, therefore that the measurement uncertainty given by the manufacturer for each instrument is an upper bound, and the actual temperature accuracy is fine enough to resolve the spatial changes in temperature observed.

As shown by the thermal imaging camera, the potential area for scrutiny for an energy audit can be significantly larger than the size of an irregular temperature gradient that could show up over an area no larger than five inches across. The time spent by a user to obtain a single reading with an IR thermometer is comparatively short, several data points per second with practice, which can allow for thoroughly measuring over a hundred square feet in less than half an hour. There also exist IR thermometers specifically designed to alert users of temperatures that differ from a point reference without appreciably increasing the cost, allowing for an even faster and more efficient measurement.

In conclusion, the IR thermometer shows real and practical promise as a low-cost alternative to thermal imaging for the purposes of finding temperature gradients in a constructed environment, for goals in both energy audits and education.

Conclusions and Future Work

Most contemporary BLT instruction arises from hands-on experience and data gathering within purpose-built heavily-instrumented facilities, which are prohibitively expensive for most institutions to construct and maintain. By contrast, this paper introduces "accessible building audit training", which uses inexpensive handheld tools and techniques borrowed from professional building energy auditing and monitoring practices to provide a rich, yet accessible, BLT training environment.

Three "accessible" BLT training exercises are described. The first uses wireless sensors to teach students basic experimental measurement of human comfort parameters while exploring viability of wireless sensors as replacements for legacy hard-wired sensors in building monitoring, automation, and control applications. The second expands use of wireless sensors to teach students how to compare the quality and fidelity of different sensors while exploring how environmental influences impact the quality of experimental measurements. The third exercise uses thermocouples and an IR thermometer to probe building walls for thermal anomalies. This exercise teaches physical phenomena underlying how the different instrument types take measurements.

Equipping STEM students with basic knowledge and skills from the energy field is critical to filling the many energy industry jobs that are expected to be vacated by 2012 due to retirement and attrition. Existing buildings provide a rich and realistic environment from which meaningful data streams can be harvested for training and education. Future development of the accessible energy audit training pedagogy will move beyond the predominantly temperature-measurement-focused approach of the current exercises by incorporating additional low-cost building energy audit equipment into the training tool kit. For example, a low-cost blower door has been designed, built, and tested to take infiltration measurements on a building's envelope. Energy engineering concepts related to mass flow and pressure difference will be taught through hands-on experimental lessons now under development by incorporating data acquired from the blower door.

About the Author

Matthew J. Traum is an experimentalist and expert in energy-thermal-fluids metrology. Traum received a Ph.D. in mechanical engineering from the Massachusetts Institute of Technology [2007] where he held a research assistantship at MIT's Institute for Soldier Nanotechnologies (ISN). In his dissertation, Traum described a new method for simultaneous thermal, mechanical, and biological protection for soldiers in harsh environments using raiment made from nano-porous barriers. Traum also holds a master's degree in mechanical engineering from MIT [2003] with a focus on cryogenics and two bachelor's degrees from the University of California, Irvine [2001]: one in mechanical engineering and the second in aerospace engineering. In addition, Traum attended the University of Bristol, UK as a non-matriculating scholar where he completed an M.Eng thesis in the Department of Aerospace Engineering [2000] on autogyro pitch stability in low-speed flight. Prior to his MSOE appointment, Dr. Traum co-founded the Mechanical and Energy Engineering Department at the University of North Texas where he introduced a hands-on, project-focused undergraduate energy engineering curriculum with integrated undergraduate research and industrial co-op programs.

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