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APPLICATION OF MULTIZONE HVAC CONTROL USING WIRELESS SENSOR NETWORKS AND ACTUATING VENT REGISTERS

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ABSTRACT

Most residential heating, ventilating, and air conditioning (HVAC) systems are designed to treat the home as a single zone. Single zone control consists of one thermostat, in a central area of the house that controls the HVAC operation. In a single zone system all of the vent registers are open, distributing air into all areas of the house at once. Single zone control leads to wasted energy for two reasons – all rooms being conditioned when they are not occupied, and conditioning occupied rooms, without maintaining them at a comfortable temperature for the occupants. Improved control of residential cooling and heating can be attained with a variable HVAC fan, duct, and vent system.

Existing single zone systems are expensive to retrofit with the above mentioned features. Current techniques require replacing major components in the HVAC system which are both costly and time consuming, invading the user's home. An alternative to the extensive retrofit is detailed in this work.

The experiments in this paper implement an automated vent louver system to solve two problems in heating homes: the problem of temperature stratification between floors and zonification between rooms, and the energy wasted to heat in unoccupied areas of the home.

This paper considers the application of replacing the standard vents in each room with wireless controlled louvered vents. These vents allow for simpler, more cost effective retrofits which are also less invasive to the end user's home. The experiments in this paper implement an automated vent louver system to reduce the energy wasted to heat unoccupied areas of the home.

The test house in these experiments was a two story home. Wireless sensor-actuator networks were used to automate the task of closing off vent registers while maintaining the appropriate temperature set point in a control zone. A control zone consists of the house area where the vents are fully open. Controlling the vent registers allowed for reduced zonification between rooms on the same floor, and reduced stratification between the upstairs and downstairs. Energy savings were shown when vents were closed to heat the control zones containing the bedrooms, or the office.

INTRODUCTION

Most residential heating, ventilating, and air conditioning (HVAC) systems treat the house as a single zone. The standard residential system is constant air volume (CAV). This means that the conditioned air is delivered to all vent registers in the house at a fixed proportion. The lack of finer control over where conditioned air enters the house leads to zonification due to large temperature differences between rooms on the same floor, and stratification due to large temperature differences between rooms on different floors.

Energy is often wasted conditioning a zone of the house that is not occupied. Energy is also wasted when an occupied room is conditioned to a temperature that is not comfortable. Multi-zone control over which areas are heated and cooled is needed to solve this problem. A variable air volume (VAV) system would allow for increased air flow into some areas of the house while decreasing air flow to others.

State of the art multiple zone wireless HVAC control systems are available for commercial buildings. Discharge-air-regulation-technique (DART), implements wireless mesh networking to measure temperature and control HVAC fan speed [1]. Millennial Net, and Siemens APOGEE offer wireless solutions to building controls and measurement [2,3]. The latter systems utilize wireless temperature nodes but the VAV controls are wired to the thermostat control system.

Multiple zone solutions often require expensive retrofits. This paper focuses on a more cost effective alternative by automating vent registers rather than altering the entire HVAC system. With wirelessly controlled louvers, a low cost software based home controller would be able to enable increased comfort and energy savings by closing off vents to areas where conditioning is not needed [4].

Most gains for energy management in residential buildings will come from smarter use of HVAC systems. HVAC systems comprise over 50% of the total residential energy demand. Reductions in residential energy demand due to optimized automation of HVAC systems would reduce both peak and base energy load, in most regions [5,6].

While this paper focuses on the application of the multizone solutions for residential systems, the technology is also applicable to commercial buildings as well. As with residential systems, it is common to control several rooms of a building with a single thermostat sensor. Previous researchers have investigated the simulation of applying multiple temperature sensors in the building environment [7]. Simulations show an increase in user comfort by using targeted comfort control strategies.

A two story house in Danville, CA was retrofitted to test and verify the proposed multi-zone retrofit. All of the vents in the house were replaced with wirelessly controlled vent louvers. The thermostat disaggregated into several pieces: an actuator switching on an off the heating, cooling, or fan, a software controller that was running on an embedded server, and temperature sensors that were distributed throughout the house.

The residence is divided into four Control Zones. Zone 1 contains the downstairs living, dining, and kitchen area. Zone 2 contains the bathrooms and laundry room. Zone 3 is all of the bedrooms, and Zone 4 is the office.

In this paper a Control Zone is defined as the area of the house where all vents are open, while all other vents in the house are closed. The temperature of a Control Zone is determined by the average temperature of the temperature sensors within the open vent area. The HVAC controller determines if a Control Zone has reached the set point based on the average temperature. Building simulations in literature show that optimal HVAC energy savings are achieved when taking the average of distributed temperature sensors within the area being conditioned [7].

Wirelessly controlled vent louvers are a component of an automated multiple sensor, and multiple actuator system that can be controlled locally within the residence, or remotely over the internet [7]. An embedded server is outfitted with a wireless base station that is able to interact with the wireless network by receiving and sending message. The server contains a database that receives and stores sensor data, and actuator state data that is accessible by a Java controller operates in the server unit. The Java controller is able to send out messages to the vent and HVAC actuators. The message for the vent actuators in open or close and the message for the HVAC actuator is heat, cool, fan, or off.

The following Section describes the system hardware and software setup. A description is given of the automated vent louvers, the wireless HVAC actuator, the wireless temperature sensors, and the embedded server-controller unit. Within that section the system software is described including the software that drives the sensors and actuators, the software that controls the actuators, and the database software setup. The subsequent Section describes the reliability tests of the hardware and software system.

Section 4 describes air handler fan energy demand measurements for each vent configuration, and the variable air flow measurements in each zone for each vent configuration. Accurate measurement of air flow for each vent configuration was needed to prove the effectiveness of the vent retrofit and to better understand the energy demand measurements.

Section 5 describes the procedure used to measure energy demand for heating a particular zone. Section 6 shows the preliminary results from zone control with the automated vent registers. Trends in the experiments indicate that closing registers can lead to less system on-time which will yield energy savings.

EXPERIMENTAL PLATFORM

The experiments were automated with the use of wireless sensors and actuators. An embedded server-controller unit allowed remote monitoring and scheduling of experiments. There were four key pieces of hardware used in the experiments: the Tmote wireless platform, the NSLU2 embedded server unit, the wirelessly controlled vent louver, and the wirelessly controlled HVAC actuator. The software is divided into three components: the user interface, controller, and TinyOS sensor-actuator network software.

Hardware

The sensor and actuator wireless devices used in these experiments were the Tmote (Telosb) platform from the company Moteiv, shown in Figure 1. The Telos mote operates from a TI MSP430 microprocessor that features eight 12 bit analog to digital converters (ADC) and four digital input output converters. The mote communicates wirelessly with a Chipcon CC2420 transceiver that operates on 2.4GHz and is 802.15.4 compliant [8].

The Tmote onboard sensor suite has two components: a digital based, self- calibrating CMOS temperature and humidity sensor, and an analog based light sensor capable of detecting visible and infrared radiation. The temperature and humidity sensors are manufactured by Sensirion, models SH11 and SH15. The light sensors consist of a thermally sensitive radiation sensor (TSR) and a photosynthetic active radiation sensor, manufactured by Hamamatsu. The light sensors connect to two ADC ports.

The Tmote is also equipped with an extensible header that allows for interface into ADC ports and Digital Input-Output pins. Figure 1 shows an example of how the Tmote could be interfaced with a board that allows for additional sensors. The furnace system on time (SOT) was determined by a current sensor attached to a similar interface board. These header pins allowed a voltage signal to be input into one of the additional 12-bit ADC ports of the Tmote. The current sensor was a current transducer that measured the current flowing to the furnace air handler fan. The current transducer was in the form of a clamp with an integrated AC rectifier. An interface board fitted with a RC low pass filter removed any high frequency noise from the rectified voltage measurement.

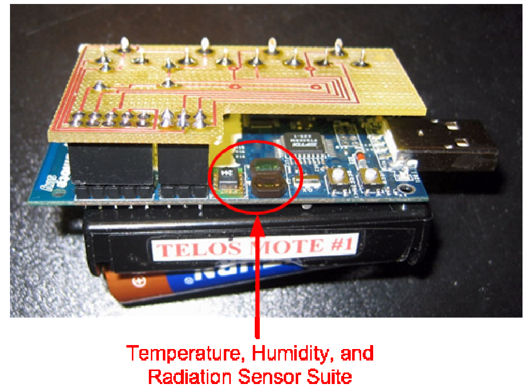

Figure 1: Tmote with full sensor suite: temperature, humidity, photosynthetically active radiation, and total solar radiation.

The backbone of the system is the NSLU2 Linksys storage link USB server. NSLU2-Linux (SLUG) is installed on the device in place of the Linksys operating system configuration. A picture of the NSLU2 is shown in Figure 2. The controller unit had enough processing power to control the vent and HVAC actuators. The unit was also able to store and serve sensor data and actuator state data.

Figure 2: NSLU2 used as the server-controller unit. On the left side is a front view of the device. Two USB ports and one Ethernet port are shown on the right side.

The residential HVAC system was retrofitted for control by a Tmote. The thermostat was rewired to interface with the Tmote based HVAC actuator, or run in normal mode. A manual switch was available next to the thermostat so that the resident could switch into normal mode in the event that the retrofit failed. A diagram of the interface can be seen in Figure 3 [9]. An interface circuit was connected to the ADC ports of the Tmote. Voltage signals from the ADC ports enabled a set of 24V, 1 amp relays to actuate the heater, AC, or fan. Wireless signals from the controller caused the mote to turn the unit to heat, cool, or off.

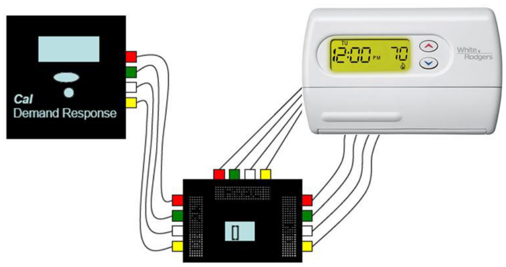

Figure 3: Wireless HVAC actuator and thermostat interface.

Off the shelf louvered vents were retrofitted with a Tmote, low power servo motor, and a battery pack [4]. Figure 4 shows the hardware layout of a vent. Interface circuitry between the Tmote ADC ports and the servo inputs enabled wireless actuation of the vents. The ADC ports sent out a pulse width modulation signal controlled by TinyOS to actuate the vents open or closed. The NSLU2 controller unit was able to wirelessly actuate the vents by sending a signal to the onboard Tmote.

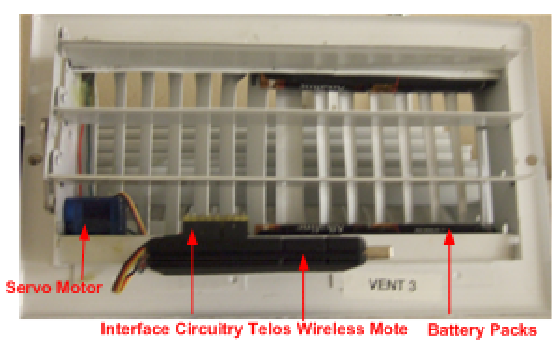

Figure 4: Vent louver design with Tmote controlling Servo, both the Tmote and Servo are powered from separate battery packs.

Figure 5 shows a diagram of the entire hardware system. The NSLU2 server controller unit receives data from, and sends data to, the wireless sensor network. The unit also acts as a server for users to access the wireless network. A webpage interface allows the user to automate vent and HVAC experiments over a local area network, or more remotely over a wide area network.

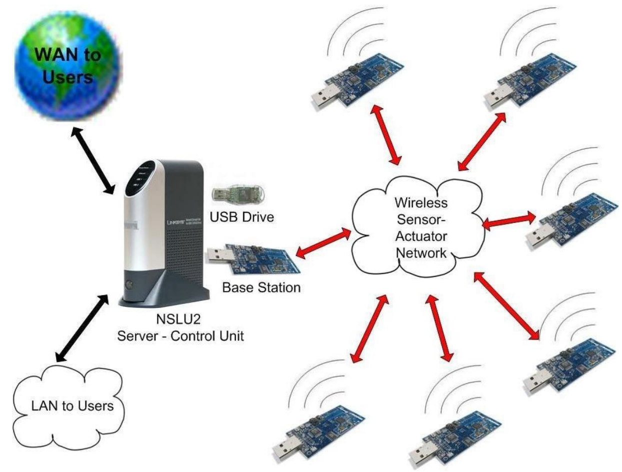

Figure 5: Embedded server - embedded wireless client - internet based client architecture.

Software

This section will describe the software used to implement the intelligent vent louver experiments. The NSLU2 unit was installed with a version of Linux called OpenSlug. OpenSlug provided many easy to install software packages useful for the vent louver experiments, including Java, mySQL, PHP, and server software. The Tmote sensors, actuators, and base station all ran TinyOS [8]. A C version of serial forwarder is used as a server and client to receive and send all packets to the Tmotes. Serial forwarder is provided with the TinyOS software suite. It acts as software based server and client that delivers and receives Tmote packets. These packets are delivered from the physical world by a Tmote base station that is shown above in Figure 5.

A Java based controller software receives all sensor data and actuator state data via serial forwarder. The controller software stores all sensor-actuator data into the mySQL database tables. The database consists of 5 tables: sensors, vent actuator, hvac actuator, scheduled tests, and completed tests. Vent motes and the HVAC mote alert the Java controller with an ‘awake’ message. An ‘awake’ message is sent by the HVAC or vent Tmotes to inform that Java controller that the actuator’s radio has come out of sleep mode. The Java controller responds by looking up scheduled tests or user defined temperature set points. If the actuator state in the table does not match the state sent by the HVAC or vent actuator, the Java controller sends out a wireless message commanding the actuator to switch to the appropriate state.

PHP enabled web pages allows experimenters to view and graph sensor data and actuator state data. Experimenters can also schedule tests and view completed tests stored in the database. Tests scheduled via the interface are read out of the database by the Java controller in a last-in, first-out order. Figure 6 shows the layout of the software architecture.

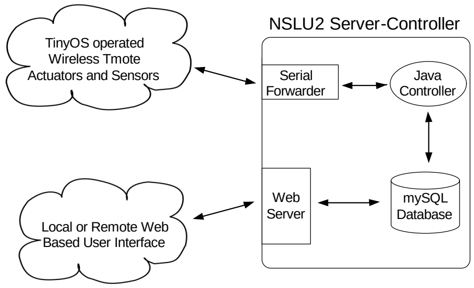

Figure 6: Server-client software system architecture.

HARDWARE AND SOFTWARE RELIABILITY TESTS

The reliability of the server, control software, and wireless sensor actuator network system was tested offsite in a simulated laboratory environment for one month. The full system was installed and tested onsite in the residence for two weeks before conducting the experiments. Previous residential experiments wireless sensor networks [10] shows that a star Telos wireless sensor network with the CC2420 radio has acceptable performance for our experiments.

The offsite tests consisted of doubling the frequency of sensor readings to once every 30 seconds, and increasing the frequency of the actuator state data to every 30 seconds. The set point was altered every hour to ensure that the NSLU2 controller and server software integration were stable. Offsite tests in a simulated residential environment showed that the controller, server, and wireless sensor network worked reliably for one month.

vents upon receiving the signal from the controller unit. The mySQL database successfully stored all sensor readings and actuator state data. This was verified by recording the sensor or actuator mote id number and packet sequence number.

Low power radio management and low power MSP430 power management allowed for increased battery life along with a reliable wireless network. The sensor and actuator motes without failure went into sleep mode and woke up to send data and receive control commands. The sensor motes with a low duty cycle of sending packets to the controller unit every minute can operate on a pair of AA batteries for 6 months.

HVAC ENERGY DEMAND AND VENT FLOW MEASUREMENTS

Closing off vents to direct heated air into different zones leads to varying flow out of the open vents and varying air handler fan power demand. Vent air flow was measured before experiments with a portable flow hood device.

Simultaneously, the air handler power was measured while the vent configurations were being measured for air flow. It is interesting to note that the air handler fan power decreased when air flow was redirected by closing off vents. Figure 7 shows a correlation between increased air flow and increased fan power demand.

The data from Table 1 is a summary of most possible vent configurations along with the resulting air flow through open vents and the corresponding power demand of the air handler fan. The fan power demand decreases as the vent flow is reduced.

Control Zone	Power Demand(W)	Flow Rate (CFM)	Vent Config (table 2)
whole house	672.75	400 + 306.4 + 507.7 + 124	1
1	622.15	535.5	14
2	618.7	438.7	13
3	639.4	651	12

Table 1: Whole house and Zone 1-3 power and flow measurements taken before automated vent experiments.

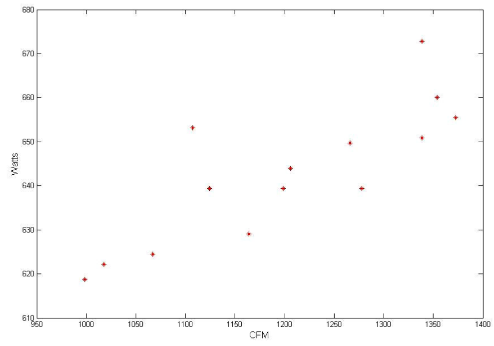

Figure 7: Power (Watts) as function of Vent Flow (CFM) data for various test configurations. _The power versus flow data suggests that fan power increases as vent flow increases.

This shows that constricted air flow in this case leads to less power demand. Fan inefficiencies may exist, but those loses do not lead to an increase in fan power demand. Closing vents to force heated air into desired zones will lead to energy savings based on these fan power and vent flow results.

PRELIMINARY SYSTEM TEST USING WIRELESSLY CONTROLLED VENT REGISTERS

This section describes a series of tests of the vent control system in a retrofitted home in Danville CA. The experiments were performed over three days (December 18th-December 21st, 2006).

Considerations

One complication for measuring energy expenditure is that the outside temperature as well as adjacent zone temperatures will influence the amount of energy used by the system. Additionally, previous heating runs will have a large affect on the energy use as the thermal mass of the home absorbs the directed air. Therefore it would be extremely difficult to show the same energy expenditure values over different days and different tests due to the variation of the outside temperature during the day and the amount of energy absorbed inside the home. Rather than showing the absolute amount of energy saved in the home for all cases (as it will vary as discussed earlier), this work intends to show trends in the system using the different control zones.

Vent actuation can also help reduce zonification and stratification by forcing air only into the rooms which show large temperature differentials as shown by the temperature sensors. However, the temperature stratification is also a function of the outside temperature and amount of incident light or outside weather conditions. It is difficult to show decreased stratification with the system without long term testing to test in a variety of outside conditions. To that end, temperature stratification testing has been left out of the scope of this testing.

There are also questions of duct performance and safety when closing and opening vent registers. It is feared that closing too many registers will lead to an increased back pressure on the fan which may lower the lifetime of the fan, cause frozen coils, or blow open the ductwork. Residential literature on duct leakiness has shown that closing less than 60% of the registers will not pose a significant threat to the system [11,12]. The order in which vent registers are closed can possibly alter the duct pressure, which would lead to varying fan energy demand for each zonal configuration. These experiments were not conducted considering the order of closing vent registers. Some inconsistencies in energy used to heat zonal configurations to a temperature may be explained by this vent closing inconsistency.

System Description

The following section details the procedure of experiments. The experiments were performed before noon in order to reduce the effects of outdoor temperature increases on heating energy demand. The house was divided into four Control Zones: Zone 1 bounded the kitchen, living, and dining areas, Zone 2 bounded, the least occupied areas, the bathrooms, and laundry room, Zone 3 bounded all bedrooms, and Zone 4 bounded the upstairs home office. Table 2 lists the volumes of each zone and the sensor mote Ids associated with each zone.

A Control Zone is the area where all vents are open. A Control Zone temperature is determined by the average of all temperature sensor readings in the heated zone, and the controller actuates based on the temperature of a Control Zone. The average of all temperature sensors in a zone was chosen as the method for heating control based on building literature. Two other potential methods are mentioned for determining the set point in a control zone. One is to actuate the HVAC on the worst sensor in the zone, in this case the coldest one. The other method is to actuate by the average of the worst and best sensors in the zone, both the coldest and warmest sensors [6].

Danville House			
Zone	Description	Vol. (ft^3)	MoteID
1	Kitchen/Living	13000	1, 2, 3
2	Bathrooms/Laundry room	3800	4, 7, 11
3	Bedrooms	6840	6, 9, 10
4	Home Office	1500	8

Table 2: Tmote temperature moteIDs, volume, and rooms contained within Control Zones 1, 2, 3, & 4.

An energy saving test consisted of heating a Control Zone to a temperature set point. The system on time (SOT) was measured by the amount of time the air handler fan was turned on. The amount of time that the air handler fan was on closely corresponded to the time that the furnace was on. The energy used to heat a Control Zone to a set point was calculated from the SOT with the following equation:

Energy Use = (Fan Power + Furnace Power) * SOT

SOT is determined by a UNIX timestamp applied to each wireless packet received by the controller unit from the CT mote.

Each experiment began with heating the whole house, with all vents open. First, energy use to heat the whole house was measured Second, the measurement of temperature for all vents open was recorded. Third, the temperature decay times were recorded for each zone and the whole house while all vents were open.

The dead band was set to one degree above the set point in order to closely follow the behavior of a standard residential thermostat. A temperature sensing Tmote was placed directly on top of the preinstalled residential thermostat unit. It was noticed that the temperature of the thermostat mote was 2-3 ^{o}F warmer than the standard unit temperature measurement. The testing procedure consisted of heating a Control Zone 2-5 ^{o}F above the current temperature of the zone.

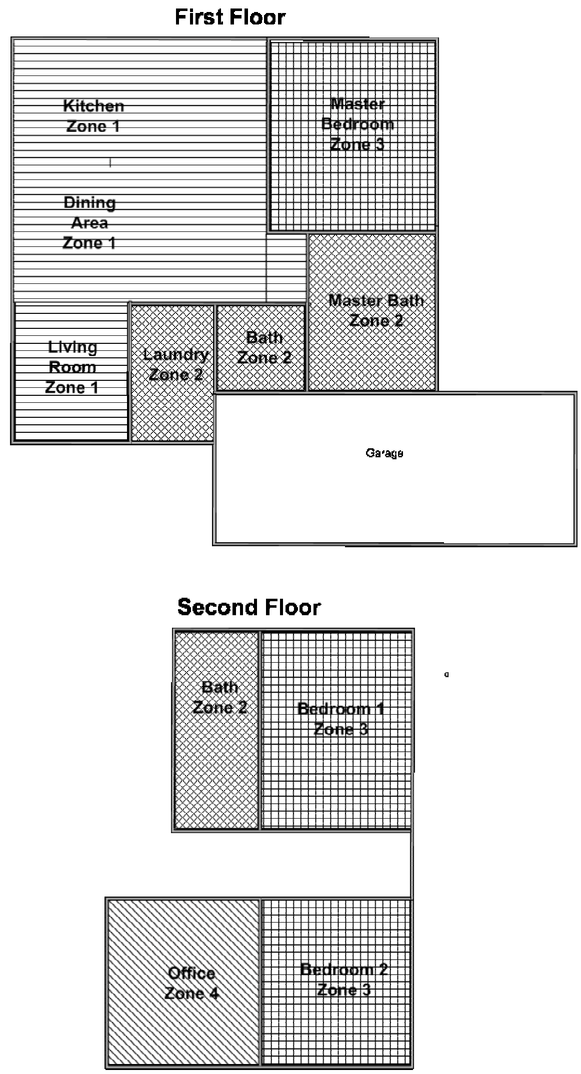

Figure 8: Map of Control Zones in the test house

Placement of the temperature sensor on which the set point is actuated could be a factor that affects the length of system on time. If the HVAC conditions longer due to poor placement of a temperature sensor, the results could be misrepresented. In an attempt to alleviate this affect, I placed all sensors at approximately the same height as the thermostat and on wall locations away from areas where they could be affected by outside forcing factors such as sunlight and drafts from windows or doors.

Day 1 Run Procedure

Run 1 started with heating the whole house (Tmote ID 19, placed directly on the normal thermostat unit) to a set point of 68 ^{o}F. Run 2 heated Zone 1 (Tmote ID 1, 2, 3), with the set point at 70 ^{o}F. The house was already at a stable 69 ^{o}F as measured on the wall thermostat (Tmote 19). Run 3 heated Control Zone 2 (Tmote ID 4,7,11) to a set point of 83 ^{o}F, because the average temperature of the motes was on average 10 ^{o}F higher than the temperature of Zone 1. This was due to the temperature differences between Zone 1, and the Master Bathroom in Zone 2, next to Control Zone 3. Run 4 heated Control Zone 3 (Mote ID 6,9,10) to a set point of 82 ^{o}F. The high set point for this Control Zone was caused by heating the adjacent Zone 1 and Zone 2 in the previous runs. Lastly, during Run 5 Control Zone 4 (Mote ID 8) was set to 82 ^{o}F. The recorded energy results and outdoor temperature during the experiments are shown in Figure 9.

Day 2 Run Procedure

Run 1 of Day 2 began with heating the whole house to 67 ^{o}F. Run 2 heated Control Zone 4 to 79 ^{o}F. Run 3 heated Control Zone 3 to a set point of 78 ^{o}F. Run 4 heated Control Zone 2 to a set point of 79 ^{o}F. Run 5 heated Control Zone 1 to a set point of 70 ^{o}F. Lastly, four runs were conducted with the whole house heated to varying set points in order to collect data for better characterization of the house energy demands and thermal behavior. The energy results and outdoor temperature during the experiments are recorded in Figure 10.

Day 3 Run Procedure

Run 1 of Day 3 began with heating the whole house to a set point of 67 ^{o}F. Run 2 heated Control Zone 3 to a set point of 77 ^{o}F. Run 3 heated Control Zone 2 to a set point of 77 ^{o}F. Run 4 heated Zone 4 to a set point of 82 ^{o}F. One hour was allowed for the house to decay thermally. Then, Run 5 heated Zone 4 to a set point of 82 ^{o}F. Run 5 heated Zone 3 to a set point of 79 ^{o}F. Run 6 heated Zone 2 to a set point of 78 ^{o}F. Run 7 heated Zone 1 to a set point of 70 ^{o}F. The energy results and outdoor temperature during the experiments are recorded in Figure 11.

TRENDS IN SYSTEM PERFORMANCE

The following section will present the results of the zonal heating experiments. The experiments show that closing registers and forcing air into the different control zones leads to less system on-time and energy savings.

A comparison is shown between the energy demand for heating the whole house and zones 1-4. Zones 1,2,3 and 4 required less energy to heat per 1 ^{o}F than the energy required to heat the whole house 1 ^{o}F. Zone 2 has a 3000 ft^{3} smaller volume than Zone 3, but requires 4 kW-h/ ^{o}F more energy to heat. This is due to a 35% lower flow rate (refer to Table 1 CFM measurements for the comparison), and thermal properties that allow for a faster rate of heat loss.

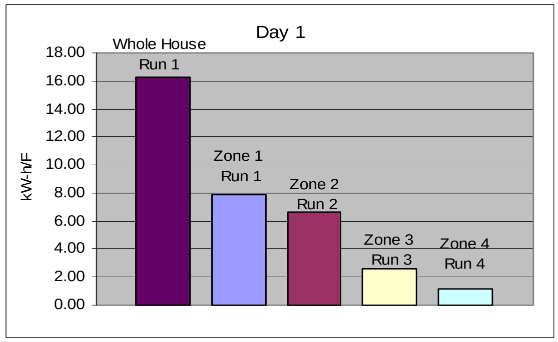

Figure 9: Day 1 comparison of furnace and fan energy required to heat zones 1-4 to the energy to heat the whole house.

Figure 10 shows the results from the day 2 experiments. A similar comparison between zones 1-4 and the whole house is made as in day 1. Notice that the order of Control Zone heating was reversed to heat zones 4, 3, 2, and 1, with a repeated measurement of the whole house energy demand at the end of the day 2 experiment. Zones 1-4 required less energy to heat than the whole house. The whole house required less energy to heat to a setpoint because the temperature outside was 2 ^{o}F warmer. Day 1 required more energy to heat the whole house and in some zones because the temperature dropped from 34 ^{o}F to 29 ^{o}F during that day's experiments.

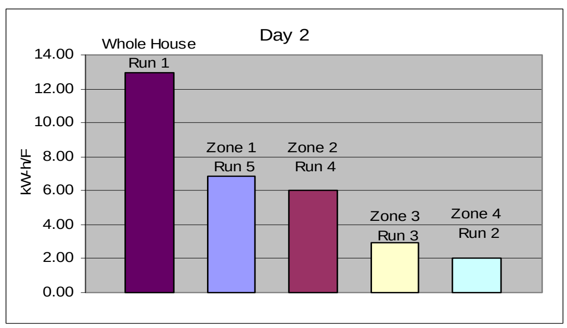

Figure 10: Day 2 comparison of furnace and fan energy required to heat zones 1-4 compared to the energy required to heat the whole house.

Figure 11 shows the results of the day 3 experiments. Notice that the order of Control Zone heating was reversed to heat the whole house, then zones 3, 2 and cycling back through zones 4, 3, 2, and 1. In the day 3 experiments, Zones 1-4 required less energy to heat than the whole house. The whole house required less energy to heat to a set point because the temperature outside was 39 ^{o}F.

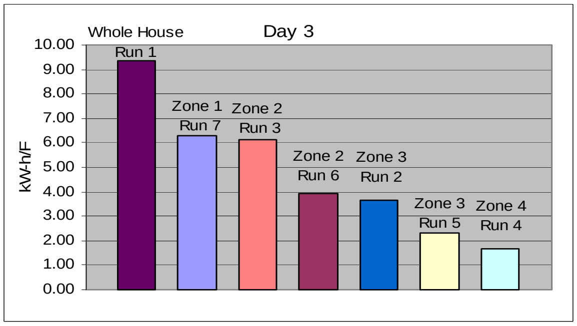

Figure 11: Day 3 comparison of the furnace and fan energy required to heat zones 1-4 compared to the energy required to heat the whole house.

CONCLUSIONS

This work has shown the application of wireless sensor networks and actuating vents in the residential environment. The hardware platform consisted of a Tmote wireless node, a low cost embedded server, a wireless controlled actuating vent register, and a wirelessly controlled HVAC actuator. The experiments show that energy savings is possible by directed air into localized zones.

ACKNOWLEDGEMENTS

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