Feasibility of Retrofitting Centralized HVAC Systems for Room-Level Zoning

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***Abstract*—Heating, ventilation, and cooling (HVAC) accounts for 38% of building energy usage, and over 15% of all US energy usage, making it one of the nation's largest energy consumers. Many attempts have been made to optimize the control of HVAC systems by minimizing the energy wasted in conditioning buildings that are unoccupied. Systems have been proposed that turn off HVAC systems when a house is unoccupied, or put the system into an energy saving deep-setback mode when the occupants are asleep. An area that has not been as well explored is the retrofitting of centralized HVAC systems to save energy when the residents are at home and awake. In this paper, we demonstrate how to use cheap, off-the-shelf sensors and actuators to retrofit a centralized HVAC system and enable rooms to be heated or cooled individually, in order to reduce waste caused by conditioning unoccupied rooms. We call this approach *room-level zoning*. Sensors are used to detect occupancy in rooms which allows the learning of occupancy patterns and prediction of room occupancy. Unoccupied rooms can be allowed to drift away from a user defined comfortable temperature if they are less likely to be used in the near future while occupied rooms are maintained at a comfortable temperature. We implement room-level zoning in a 1400 square foot house by retrofitting an existing centralized HVAC system with wireless temperature sensors to monitor room-level temperature, motion sensors to monitor occupancy, and wirelessly actuatable dampers to control the flow of conditioned air through the house. Initial analysis indicates that this method has a 20.5% energy savings over the existing single-zoned thermostat.**

***Keywords*-Building energy; wireless sensor networks; sensing**

I. Introduction

The HVAC system is the single largest energy consumer in residential buildings, accounting for 43% of the residential energy consumption in the US [7], and over 60% in Canada [8] and the UK [16], which have colder climates. Much of this energy is used to heat or cool unoccupied spaces during long periods when people use only a small fraction of the house. Zoning systems have attempted to exploit this fact by dividing a building into two or more zones that are controlled by separate thermostats, so that the occupants can schedule each zone to be heated or cooled separately. However, zoning systems are expensive, and are, therefore, typically only used for very course-grained zoning of the house: a typical configuration can condition the first floor living spaces separately from the second floor sleeping quarters for example. Such systems are both spatially and temporally course grained allowing large areas, in this case floors of a building, to be zoned separately and scheduled with a low frequency, for example switching between the living and sleeping areas only twice a day.

In this paper, we explore the effectiveness of using cheap and simple wireless embedded sensors and actuators to produce a fine-grained, room-level zoning system by retrofitting a centralized HVAC system and controlling the airflow into each room. Such a system could reduce wasted energy that is used to heat and cool unoccupied rooms. However, the energy savings of such a system is not a foregone conclusion due to three key challenges. First, the size of the HVAC system is typically chosen based on the size of the entire house, and so heating or cooling only a fraction of the house would result in an oversized system, which is typically inefficient. Second, restricting airflow into some rooms will create backpressure in the ducts, which can further reduce the efficiency of the HVAC system by causing leaks in the ducts and at the dampers. Third, most houses do not have insulated interior walls, and the lack of thermal insulation between rooms can lead to heat transfer between the conditioned and unconditioned zones. Several previous studies have explored the possibility of room-level zoning, but the conclusions of these studies have been mixed and inconclusive [22], [24], [25]. To our knowledge, the only long term study of room-level zoning in actual residences was carried out by Scott et al. [20] who demonstrate energy savings when room occupancy predictions are used to control the heating of rooms. Yet, their room-level systems were implemented in British homes using radiators that can be controlled independently for each room. Their implementation in the United States, where houses traditionally have centralized HVAC systems, resorted to centralized control where the occupancy of the whole house, rather than each room, is considered in controlling the system.

We demonstrate the feasibility of saving energy by retrofitting a centralized HVAC system to be controlled at the room-level. We implement a wireless sensor/actuator system that can be cheaply and easily deployed in existing homes. The system includes 21 temperature sensors and a wireless thermostat that controls the HVAC hardware and mechanically opens and closes dampers in order to control airflow through the home. The components used cost less

978-1-4673-2154-9/12/$31.00 © 2012 IEEE

than $500, and a production version is expected to cost considerably less. In contrast, traditional zoning systems often cost more that $5000. We deployed our system in a 7-room, single-story, 1400 square foot house and measured the energy consumption of heating and cooling. Our results indicate that the system consumed 20.5% less energy than if the HVAC system were controlled by the existing thermostat over a 20-day experimental period. These results indicate that retrofitting an existing centralized HVAC system for room-level zoning has a potential for substantial energy savings, and warrants further investigation into this approach.

II. Background and Related Work

Traditional HVAC zoning systems for homes typically separate a house into floors, each of which can be controlled individually. These systems are often installed more for comfort than for energy savings, because a single un-zoned system that operates on multiple floors will often result in a warm top floor and/or a cold bottom floor. Floor-level zoning also makes sense in many homes that have bedrooms on the top floor and living areas on the bottom floor. Floor-level systems have resulted in homeowners saving as much as 20-30% as compared to single zoned systems [25]. However, these systems are expensive and the energy savings can take years or even decades to produce a positive return on investment. Furthermore, it can be difficult to retrofit an existing home with a zoning system.

Commercial buildings often use zoning systems that divide a single floor into multiple rooms. This is especially common in hotels, banquet halls, and office buildings. For example, the discharge-air-regulation technique (DART) uses temperature sensors to control the HVAC fan speed [9]. Other systems include the Millennial Net [15] and Siemens APOGEE [10]. Just like the residential zoning systems, these solutions are expensive and are much easier to add to a new installation. Similarly, micro-environment systems (also called task-ambient conditioning) allow a worker in an office building to have fine-grained control over the ambient conditions around his or her working space, typically a desk. Several systems, including Personal Environments from Johnson Controls [4] and Habistat from Interface Architectural Resources, are currently commercially available. The individually controlled spaces are not insulated from each other and operate within a single thermal zone. These systems are designed for occupant comfort over energy efficiency. The systems can produce some energy savings by not conditioning desks that are not occupied, and several studies have shown substantial savings of micro-environment systems [2], [18], [19]. However, the cost of these systems is between $20,000 and $100,000 per desk, which is too large to produce a positive return on investment. Furthermore, this approach is designed for offices and would be difficult to transfer to homes, where usable space can be more difficult to instrument than a desk or cubicle.

Numerous studies have explored the effect of providing individual temperature control in rooms, but the results have been mixed and inconclusive. One experiment tested the energy used to heat a single-room with 10 registers and leaky ducts while closing an increasing number of vent registers [22]. The results indicate that closing registers increases the pressure within ducts causing greater duct leakage and reduced system efficiency. However, since all registers were within the same room, this study did not determine whether the reduced efficiency outweights the savings produced by conditioning a smaller area; all register configurations were conditioning the same sized area.

A subsequent study developed an automated vent louver design for room-level zoning [24], similar to the one developed for our system and other similar systems [17]. The authors evaluate the system by dividing a house in Danville, CA into four zones and increase the temperature in each zone by 2-5° F. They also increased the temperature in the entire house by the same amount. The results indicate that it takes less energy to increase the zone temperature per degree than it takes to increase the whole house temperature per degree, since the smaller zones heat up faster than the whole house, allowing the system to turn off sooner. However, this study only measured the transitional time and energy of a room-level zoning system, and it did not measure the steady state energy. In other words, it does not show the difference in energy required to *maintain* a particular temperature in a zone versus the whole house. This distinction is profound, because thermal leakage between adjacent rooms could cause system to also turn back on more quickly, nullifying the energy savings of turning off more quickly. This is often called *short cycling*, and is known to decrease system efficiency as well as reduce the overall lifetime of the equipment.

The latest attempt at occupancy-based room-level heating control is a system called PreHeat [20]. The authors implement occupancy-based heating control in houses in the United States and United Kingdom. In the United Kingdom, the authors exploited the radiators that are used to heat rooms in order to implement a room-level controlled heating system. In the United States, since the houses used a centralized HVAC system for heating, the authors used occupancy-based whole-house control similar to that proposed by Lu et al. [14]. The main weakness of PreHeat that we attempt to address is the lack of interaction between rooms in any of the models used for prediction. For instance, the authors predict the occupancy of each room based on the history of occupancy of that particular room without considering the occupancy of any other rooms. We demonstrate that taking into consideration occupancy patterns across a house would lead to higher accuracies in predicting the occupancy of a particular room. The authors also use a very simple thermal model to predict when a room should be preheated. The model is simply the average amount of time it took to in-

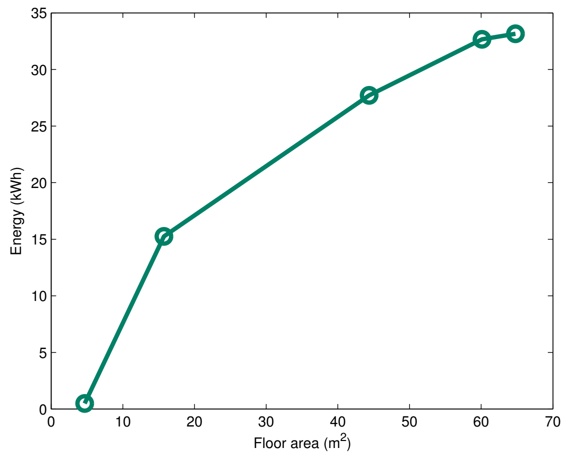


Figure 1. With an ideal system, the amount of energy used for conditioning a building is almost proportional to the floorspace being conditioned.

crease the room temperature by a degree based on historical data. We present a model, which we are currently working on, that takes into consideration the thermal interactions between rooms.

Finally, there have been patents filed for occupancy-based zoning of HVAC systems using security systems [3] or motion sensors [21] to detect occupancy. While these systems attempt to solve the problem we are addressing, the effectiveness of their approach is not evaluated. Also, these systems fail to address hardware safety concerns that arise with implementing room-level zoning using a centralized HVAC system. Our approach is cognizant of the short-cycling and back-pressure that could reduce the lifespan of HVAC hardware and attempts to minimize the potential damage to hardware.

III. Intuition and Preliminary Studies

Before implementing our room-level zoning system, we performed two simulation studies to better understand whether such a system should be expected to reduce energy savings, and why. These two studies are explained in the following subsections.

A. *Effect of an Oversized HVAC System*

In houses with a typical non-zoned central heating and air conditioning system, the size of the system is chosen based on the expected load of the entire house. Therefore, using the same system to heat or cool only a fraction of the house would mean that the system is oversized for the conditioned space. It is well known that oversizing an HVAC system results in reduced efficiency of the system. Our first study was designed to determine how much this oversizing would reduce the potential for energy savings of a room-level zoning system.

We used the EnergyPlus building energy simulation framework [5] to heat multiple buildings in simulation, with increasing size from $5\mathrm{m}^2$ to $65\mathrm{m}^2$. The model buildings had idealized insulation and leakage properties. All buildings were heated with the same sized HVAC system, which was sized for a $65\mathrm{m}^2$ building. The results are shown in Figure 1, which indicate that the amount of energy required to heat a smaller building does indeed decrease, even if the size of the HVAC system remains the same. The sub-linear curve indicates that some efficiency is lost for smaller buildings due to the oversizing of the system. However, this loss in efficiency does not outweigh the gains from heating a smaller space. From these results, we postulate that room-level zoning can be effective, even when applied by retrofitting a home with an existing HVAC system that was sized for the entire house.

B. *Inter-room Leakage*

Homes often have thin non-insulated walls and even doors between adjacents rooms, which can reduce the effectiveness of room-level zoning because of thermal leakage between rooms. Our second study was designed to explore how much this leakage would reduce the energy savings of a room-level zoning system. We used the EnergyPlus simulation framework to heat a single room in a two-room building. We used five variations of the floor plan of the house, and the conditioned room had a different number of exterior walls in each variation. The five variations are shown along the x-axis of Figure 2, and the energy required to heat the shaded room for each floor plan is shown as a bar graph above each variation. These results indicate that the energy required to condition a room is dramatically reduced as the number of exterior walls of the room decreases. In other words, a neighboring room is a better thermal insulator than an exterior wall, even if the wall between the conditioned room and the neighboring room is not insulated. This result indicates that leakage between conditioned and unconditioned zones will not eliminate the energy-saving potential of room-level zoning.

C. *Room Occupancy*

Finally, our preliminary analysis showed that, even when a home is occupied, the occupants use only a fraction of the house. For example, empirical analysis of one home is shown in Figure 3, showing that primarily only one room is used at night, three rooms are used in the evening, and four rooms are used in the morning.

IV. Challenges

Implementing a room-level zoned centralized HVAC system poses many practical challenges. These include, maintaining a minimum airflow and preventing short cycling for HVAC hardware safety, predicting room occupancy with no history, and coordinating the conditioning of zones. We describe these issues below.

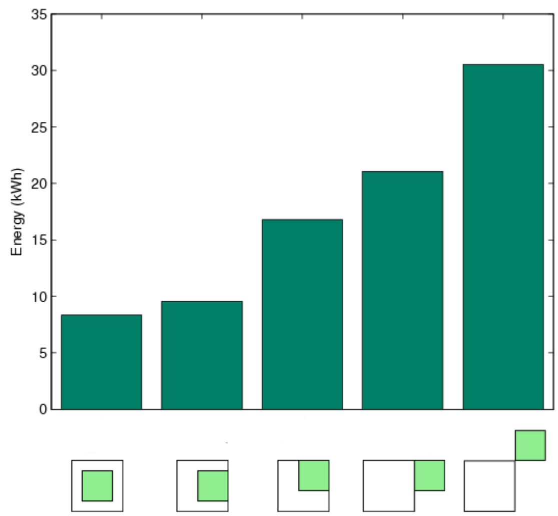


Figure 2. The energy required to condition a room decreases as its number of exterior walls is decreased. The x-axis depicts the position of the conditioned room (shaded) with respect to the unconditioned room (unshaded).

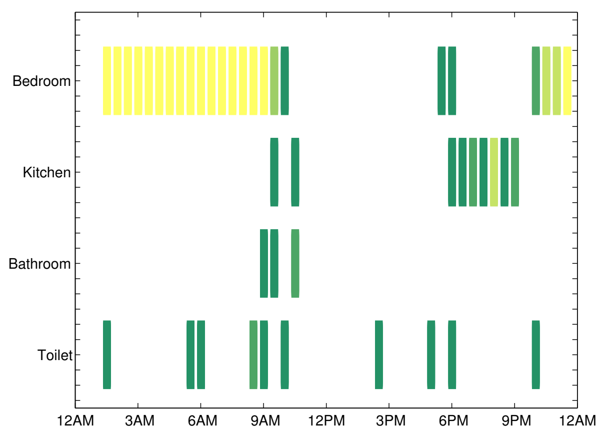


Figure 3. The frequency of room usage throughout a day changes. Darker colors indicate lower frequency while brighter colors indicate higher frequency usage with yellow being the highest frequency.

A. Minimum Airflow

HVAC systems are rated for a certain output airflow depending on the operating stage. For instance, the HVAC system in the house where our experiments were carried out produces 830 ft^3/min (CFM) of conditioned air when cooling in stage 1, 1200 CFM of air when cooling in stage 2, etc. The ductwork for HVAC systems are carefully designed so as to allow most of this air to leave through registers. This prevents pressure buildup in ducts, *back-pressure*, which can increase leakage through cracks in ducts and improperly insulated connections. Back-pressure can also damage HVAC equipment by reducing the rate at which air flows over the coils that carry the refrigerant. The lower airflow would result in insufficient heat transferred to the refrigerant causing it to return to the compressor in liquid form, without fully evaporating, which can damage the compressor.

Zoning a centralized HVAC system involves closing ducts so that air only flows to a subset of a house. If too many ducts are closed, or ducts are closed in a wrong configuration, back-pressure could build up resulting in energy wastage due to leakage and equipment damage. In order to enable room-level zoning of a centralized HVAC system the buildup of back-pressure has to be taken into consideration when making actuation decisions.

B. Short Cycling

Manufacturers recommend a minimum time for which an HVAC system should operate at a particular stage before transitioning to a lower stage, for instance transitioning from stage 2 to stage 1 or turning off from stage 1. Transitioning before this minimum threshold increases the wear and tear on the equipment due to it cycling more frequently and doesn't allow the pressure to equalize between cycles. Therefore, in implementing a system that controls the HVAC equipment at a fine granularity, it is essential that we ensure the compressor is not short cycled. This adds another factor to be considered when making actuation decisions.

C. Occupancy Prediction

Occupancy-based HVAC systems can be classified as either *reactive* or *predictive*. Reactive systems use room-level controllable HVAC equipment such as radiators or window air-conditioner units that can be turned on and off independently. These systems then monitor rooms for occupancy and turn on or off the occupied room's conditioning unit in response to detected occupancy. Coordination between zones is not an issue for such systems since the heating or cooling units are independent. Reactive systems with centralized HVAC systems have been implemented, but they either focus on whole house conditioning so that the system turns on when the house is occupied and off when the house is unoccupied, or rely on customized ducts with bypass ducts that prevent back-pressure. While bypass ducts can prevent the problems associated with back-pressure, a purely reactive centralized zoned system fails to exploit a lot of the energy savings possible due to being zoned because it has to turn on whenever a room that is not at the setpoint is occupied. In a house with a lot of activity, such a control scheme could result in a zoned system being no more efficient than a centralized HVAC system because it is always on. Another drawback to reactive systems, both whole-house and room-level, is the need to quickly heat or cool a space when occupancy is detected. This rapid conditioning can be less efficient than maintaining the space at a setpoint.

Predictive systems attempt to predict when a house or rooms are going to be occupied and start pre-heating or cooling the space so that it can be conditioned over a longer period of time using a more efficient HVAC stage than the rapid conditioning required during reaction. Yet, prediction is difficult due to the large amount of historical data that has to be collected in order to make an accurate prediction. This difficulty increases with the temporal granularity with which a prediction has to be made. For instance, it is much easier to predict which rooms would be used within the next six hours based on history, but much harder to accurately predict which rooms would be used within the next five or ten minutes. The accuracy of prediction increases as historical data is collected, but the amount of data necessary increases as the size of the prediction window decreases.

D. Zone Coordination

The biggest challenge to implementing room-level zoning using a centralized HVAC system is coordinating the conditioning of zones so that energy is not wasted by the compressor constantly being in operation or air leaking between conditioned and unconditioned zones. We attempt to minimize the inefficiency by conditioning thermally homogeneous zones together so that the temperature gradient within such zones is relatively small. This would reduce the amount of leakage out of conditioned rooms and minimize the amount of time the HVAC system has to be turned on when an unoccupied room is occupied because it would be close, in temperature, to the neighboring rooms and, thus can quickly be brought to the setpoint after which the compressor can be turned off.

V. Implementation

We implemented a room-level zoning system in order to empirically test the ability to save energy with this approach. Our implementation involves: (1) sensing temperature at the room-level, (2) controlling air-flow into rooms, and (3) controlling the HVAC system.

A. Sensing House Temperature

We monitor the home's temperature at a fine granularity by instrumenting the house with wireless temperature sensors placed at various points on the walls. For the deployment discussed in this paper, we used 21 off-the-shelf temperature sensors manufactured by La Crosse Technology [13]. Because the temperature across the house is not uniform, one challenge in designing a room-level zoning system is to choose how to process the temperature readings to approximate the true average air temperature in each room. This problem can also be addressed for whole-house conditioning when more than a single temperature sensor is available [12].

Figure 4 shows the temporal variations of several temperature sensors placed throughout the house. One sensor is placed in the center of the house, directly in front of the only return register, and therefore is exposed to a mix of air from all rooms. Another sensor is placed on an internal wall of the house, and a third sensor is placed on an external wall. The figure shows that the temperature sensor on the internal wall varies with the temperature of the individual room, which is slightly more than the variation of the centrally placed sensor. However, the sensor on the external wall is subject to wild temperature swings. On the left side of the graph, it is clear that the sensor has much greater downward swings than the internal sensors. This is because is it subject to direct air flow from the ducts, which are typically placed on external walls. It is also subject to heat that concentrates around the window mid-day. Because of these large temperature fluctuations, we decided to use only sensors on the internal walls of each room: the temperature in a zone was calculated as the average of the temperatures of each of the internal sensors in the rooms comprising the zone.

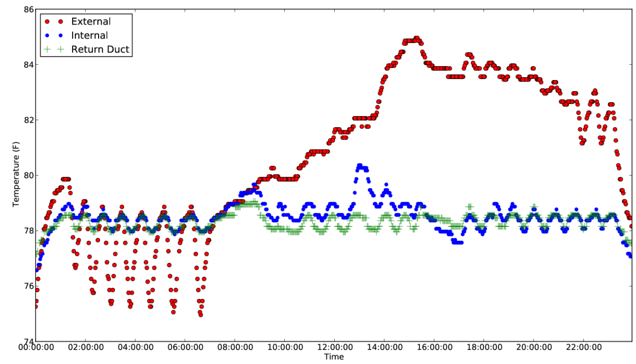


Figure 4. The variation of temperature on a sensor placed on an internal wall, an external wall, and near the return duct.

B. Controlling Air-flow into Rooms

In order to control the airflow into individual rooms, we designed and built *active registers and dampers* that can be wirelessly opened or closed. While controllable registers are commercially available, they actuate based on either preset temperatures or temporal schedules. Commercial active registers that are controllable through a remote control would be hard to integrate with our wireless control system and such registers are expensive, costing over $50 each. By designing our own registers by retrofitting passive registers with servo motors, we were able to build active registers for under $20 each, excluding the cost of the radio and microcontroller, that integrated wirelessly with the rest of our infrastructure. Our design improved through three generations as shown in Figure 5. We implement the registers using cheap, off-the-shelf (COTS) components including an operable register, a servo motor, and a small amount of custom circuitry. These components resulted in a cost of less than $20 per register excluding the cost of the TelosB mote, which was used for wireless communication. We built upon several prototypes

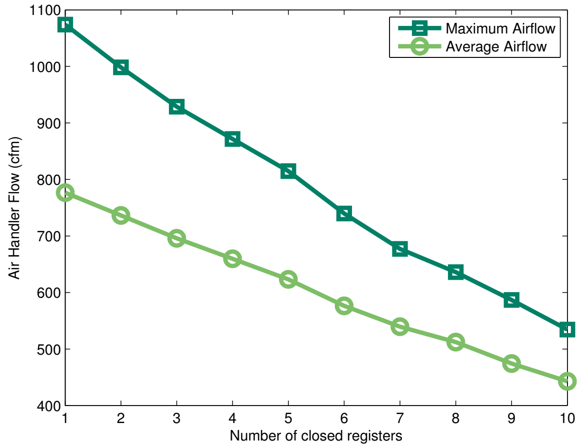


Figure 6. As more registers are closed, some efficiency is lost and the total total air volume output by the system decreases.

and even commercial versions of similar hardware that are currently available [22], [23], [24],but go beyond these devices by integrating them into a cooperative, wireless system.

We measured the effectiveness of the registers using the bench-top testing framework shown in Figure 5(d). The first generation registers were not very efficient at blocking air when closed. The second generation registers improved this aspect by blocking nearly 100% of airflow but was noisy when opening and closing. Due to these reasons we resorted to dampers used in commercially implemented zoned systems as our third generation of airflow controllers.

We measured how effective these registers are at directing airflow into different rooms using a Kestrel 4100 Pocket Air Flow Tracker manufactured by Nielsen-Kellerman [11]. This sensor is placed above the register and provides a measure of airflow in terms of cubic feet per minute (CFM) that is coming out of the register. This measurement is based on the known size of the register and the speed of the air. Figure 6 shows that the total airflow coming from all registers is reduced as an increasing number of registers are closed. When all registers are open, the average airflow is approximately 800 CFM, which matches the specification of the air handler in this house. However, as more registers are closed, the average airflow approaches 450 CFM, which is almost half. Total airflow does not approach zero because some air escapes even from the closed registers. This result verifies that closing registers does decrease the overall efficiency of the system because it reduces the total airflow output, as suggested by [22]. Therefore, actively cooling only half the house would not cause double the amount of air to be available to the cooled zone, because some air is lost due to backpressure, increased duct friction, duct leakage, and leakage from the closed registers.

C. Controlling the HVAC System

Our system uses a simple state machine (Figure 7) to control the HVAC system through four possible stages: *Float*, *Hold*, *Cool 1*, and *Cool 2*. Cool 1 and Cool 2 are intended to represent different stages of the HVAC system in which the compressor and hair handler operate at different cooling capacities. Hold causes the HVAC system to maintain the current temperature at the thermostat, and Float causes the HVAC system to turn off.

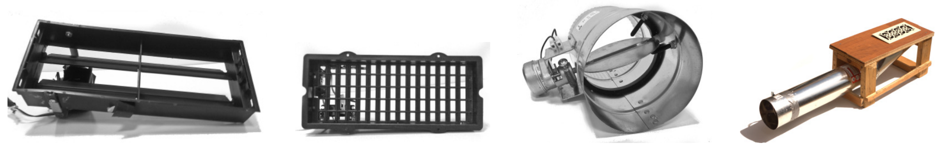
State	Action
Float	ThermSP = ThermTemp + 1
Hold	ThermSP = ThermTemp
Cool1	ThermSP = ThermTemp - 1
Cool2	ThermSP = ThermTemp - 2

Table I
THE OPERATING STAGE OF THE HVAC EQUIPMENT WAS CONTROLLED BY ADJUSTING THE THERMOSTATIC SETPOINT *ThermSP* WITH RESPECT TO THE TEMPERATURE THAT WAS SENSED BY THE THERMOSTAT *ThermTemp*.

In order to control the HVAC equipment, our system must interface through an Internet-controllable thermostat manufactured by BAYweb [1]. However, the BAYweb thermostat only allows its setpoint to be changed; it does not allow direct control over the equipment. In order to control the equipment, therefore, we modify the setpoint of the thermostat $ThermSP$ to be higher, lower, or equal to the temperature measured at the thermostat $ThermTemp$. When we want to put the equipment into the *float* state, we use a setpoint that is higher than the current temperature. This causes the thermostat to turn off the equipment. Similarly, when we want to hold or lower the temperature, we use a setpoint that is the same as or lower than the current temperature, respectively. To lower the temperature quickly, i.e. to use stage *Cool 2*, we use a setpoint that is two degrees lower than the setpoint. This exploits the PI controller that is built into the thermostat, which causes the equipment to go into high stage cooling when the temperature is two degrees from the setpoint for more than 5 minutes. The operation of the system is summarized in Table I. This coarse-grained control over the equipment is not ideal and could have caused some loss of efficiency and energy waste. In future work, we expect an improved control system to produce better results.

VI. Evaluation

We deployed our room-level zoning system in an 8-room, single story, 1200 square foot residential building shown in Figure 8. For simplicity, we divided the house into two zones. The red zone composed of the living room, dining room, and kitchen is actively conditioned between 8:00 AM and 9:30 PM while the blue zone composed of the bedroom, nursery, toilet, and mudroom is conditioned between midnight and 8:00 AM. Between 9:30 PM and



(a) 1st Generation (b) 2nd Generation (c) 3rd Generation (d) Bench-Top Test Rig

Figure 5. Three generations of active registers. (a) The first generation uses servo motors and a rotating louver design, but exhibited too much leakage. (b) The second generation uses a sliding gate design to solve the leakage problems, but causes too much noise. (c) The third generation is a commercial in-line damper with a servo motor used for traditional zoning applications. (d) The bench-top test rig used to verify that the second generation wirelessly controlled active registers have almost no air leakage.

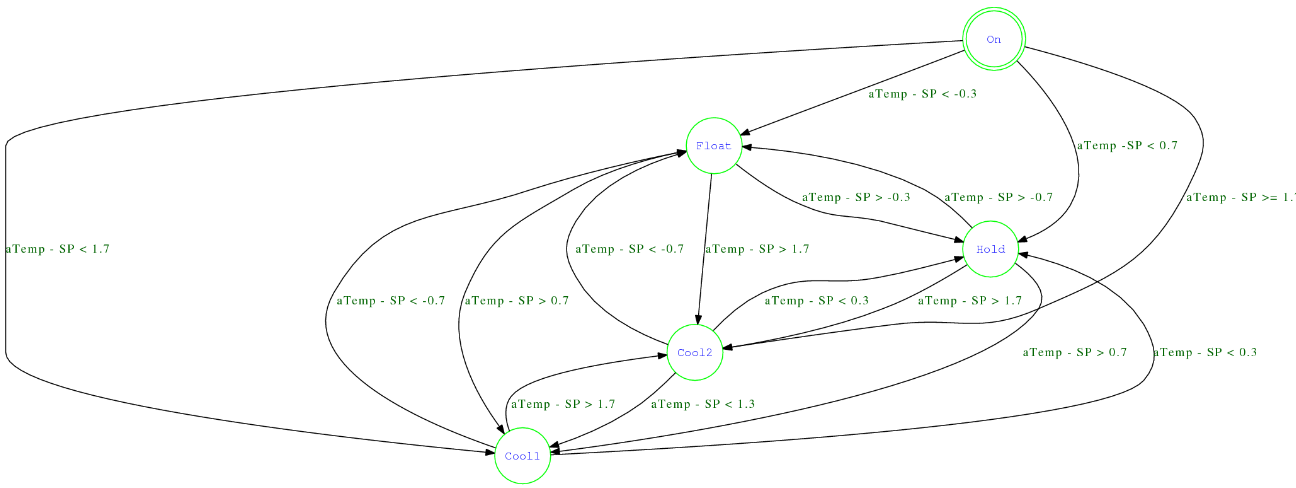


Figure 7. The zoning controller attempts to maintain the average temperature of the active zone (aTemp) at the desired setpoint (SP) by transitioning the system between five states.

midnight the whole house is conditioned. We compare this approach to conditioning of the whole house using an off-the shelf programmable thermostat manufactured by *BAYweb* [1]. In both cases, the setpoint temperature of the house is controlled by the occupants. This means that the experiments measure the energy required to keep the occupants comfortable with both systems, as opposed to keeping the space at a particular setpoint.

In order to minimize the effect of changing whether patterns on energy consumption, we alternated control of the HVAC system between the single-zoned whole house control and the sub-zoned controller over a twenty day period, such that each system ran every second daty. Both systems executed for a total of 10 days. The energy consumed by all systems in the house was monitored using The Energy Detective (TED) [6] real-time in-home energy management system and the amount of energy used by the HVAC system was deduced using the operation logs generated by the BAYweb thermostat.

Figure 9 shows the energy consumed in conditioning a house using sub-zoning and whole house conditioning. This graph indicates that whole-house conditioning consumed 20.5% more energy than our prototype implementation of room-level zoning, on average. The actual energy consumption for each day is also shown as a scatter plot, with the average temperature of for that day on the x-axis, the energy

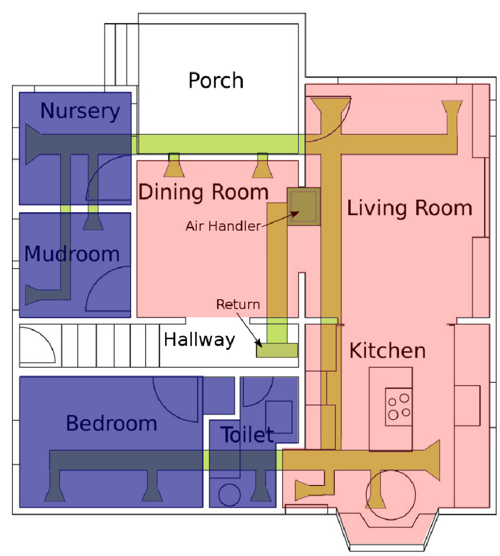


Figure 8. The residence in which Sub-zoning is evaluated. The rooms that compose Zone 1 are shaded in light red and the rooms that compose Zone 2 are shaded in dark blue.

consumed on the y-axis, and the control algorithm shown as the color of the scatter point.

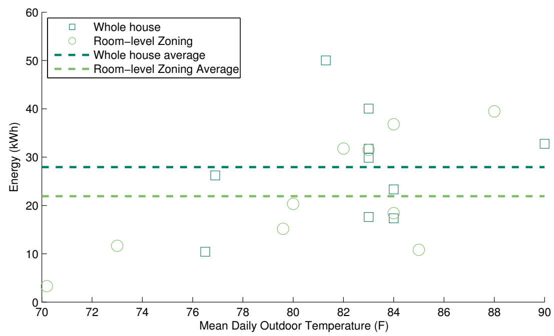


Figure 9. Our implementation of room-level zoning uses 20.5% less energy than whole house cooling on average. The dotted lines indicate the average energy used over the experimental period.

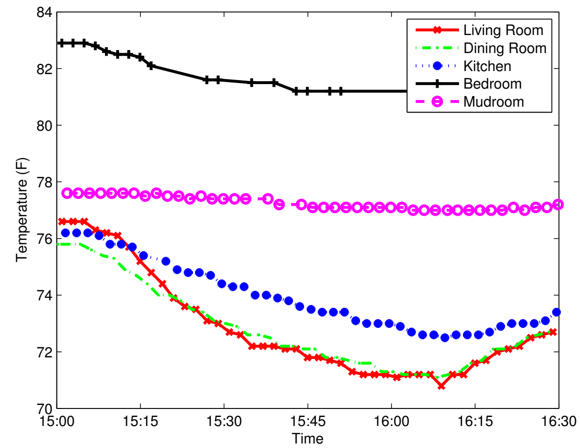


Figure 10. Temperature response of both conditioned and unconditioned rooms as the active zone temperature is dropped from 76 to 72.

Figure 10 shows how the temperature of several rooms in different zones vary as the temperature in the active zone was dropped from 76 to 72 degrees. In this graph, the bottom three lines shown the temperature of conditioned rooms over time while the top two lines show the temperature of unconditioned rooms. Although some leakage is evident, particularly into the top line, the temperatures of the unconditioned rooms remains substantially higher than the conditioned rooms. These temperature traces explains how room-level zoning is able to save energy by reducing the size of the space that must be conditioned.

In order to better understand these results, Figure 11 illustrates how effective the active registers were at activating and de-activating the red and blue zones. It is clear from this figure that the greatest airflow in a zone is obtained when the registers in the other zone are closed. However, air flow to the inactive zone does not stop, nor does it all get directed to the active zone. In future work, we expect an improved active register system to produce better energy saving and thermal insulation results.

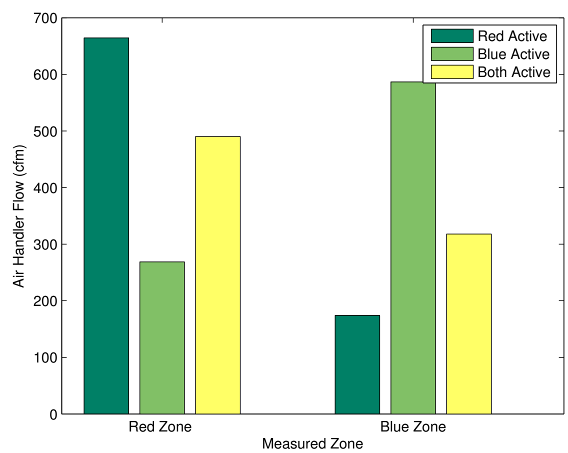


Figure 11. Activating different zones does not redirect all air flow from one zone to another, but does affect air flow substantially.

VII. Work In Progress

In this paper we present a prototype system that can be used to retrofit a residential centralized HVAC system to be zoned at the room-level and use this prototype to carry out the first long term experiments to demonstrate the feasibility of saving energy through such a retrofit. This project is a work in progress and there are two directions in which we have, and in the process of, improving it. The first is a transition from statically defined zones to dynamically changing zones, and the second is a more sophisticated controller than the simple state machine presented in this paper.

The system presented in this paper involved switching between pre-defined static zones temporally. That is, the active zone is decided based on time of day with knowledge of occupant activity used to manually define the zones. The ultimate goal of this project is to dynamically activate sub-zones based on occupancy. This would involve the controller using historical information on occupancy to pre-condition sets of rooms with the highest probability of being occupied while reacting to the actual locations of occupants. We are moving towards achieving dynamic predictive occupancy-based HVAC control through a two phased approach. The first phase involved implementing a reactive system that does not predict occupancy, but instead reacted to the real-time readings from occupancy sensors to define zones dynamically. We briefly describe this approach and some of the pitfalls we encountered below.

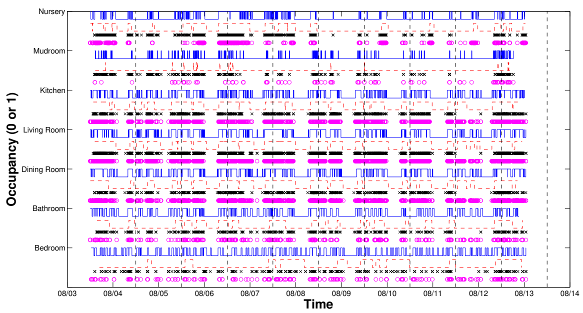


Figure 12. Transitional and Stable Occupancy Detected Using the Occupancy Model. The solid line represents transitional occupancy, the dashed line represents stable occupancy, the X's depict the firings of the X10 motion sensors in rooms, and the O's depict the firings of the PIR sensors on doorways.

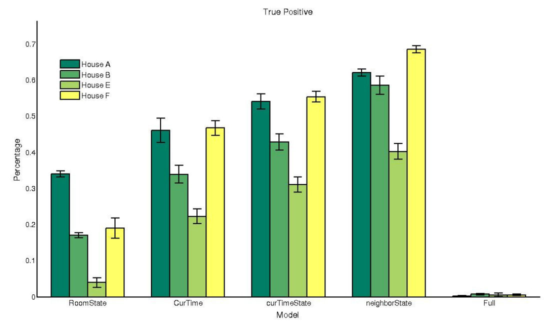


Figure 13. True positive percentages for five models of occupancy analyzed using data collected from four houses over three months.

A. Reactive Control

In a room-level zoned system that reacts to occupancy, rather than predicts occupancy, a room that is sensed to be occupied is added to the active zone and a room in which no occupancy has been sensed for more than a certain period of time is added to the inactive zone. Adopting such an approach naively results in two problems. The first is fluctuations between active and inactive zones as residents move through the house and the second is rooms being uncomfortable when entered after a long period of being vacant due to the time it takes to heat up or cool down. We attempted to overcome the first issue by classifying rooms into two types of occupancy: *transitional* and *stable*. Transitionally occupied rooms, such as passageways, bathrooms, or wardrobes, change their occupancy state frequently or are used for very short durations of time and therefore, we ignore their occupied states when making HVAC control decisions, yet leave their dampers open so that conditioned air would be delivered to them ensuring their temperature is not far from the setpoint. A room that goes from being transitionally occupied to being stably occupied is considered when making HVAC control decisions.

We defined a room to be transitionally or stably occupied based on the frequency of sensor firings. These frequencies are obtained by processing historical occupancy data for each room and attempting to minimize the total duration a room is assessed as being occupied while minimizing either the number of false negatives (for transitional occupancy) or number of transitions between occupied and unoccupied states (for stable occupancy). Figure 12 shows the occupancy patterns obtained by processing ten days worth of data. It it clear that transitional occupancy captures frequent occupancy changes as detected by aggregated sensor firings, while stable occupancy captures long-term room usage. The zone controller constantly monitors the occupancy sensor firings and classifies a room as being either vacant, transitionally occupied, or stably occupied by comparing the observed frequencies to the threshold frequencies obtained by processing the historical data.

B. Predictive Control

As mentioned above, reactive control results in warm up and cool down periods when a room is occupied after a long period of vacancy. During this time, the occupant might be uncomfortable as the room's temperature has drifted away from the setpoint. In order to overcome this, our current version of the system attempts to predict occupancy and condition a room when the expected cost of leaving the room unconditioned outweighs the cost of conditioning the room in terms of energy used and duration of time an occupant would be uncomfortable.

We analyze a number of occupancy prediction models using ten-fold cross-validation in order to identify the model that maximizes the accuracy with which the state of a room in the future can be predicted while minimizing the amount of data required to make a large percentage of predictions. Figure 13 shows the accuracy of five different occupancy prediction models. The first model uses just the current state of a room (whether it is occupied or not) in order to predict the occupancy of that room at various times in the future; the second model uses only the current time in order to predict future states; the third model uses the state of a room and the time; the fourth model uses the states of a room and its neighbors to predict the future state of a particular room; and the fifth model uses all of these features. As the graph shows, using all of the features drastically decreases the accuracy with which predictions are made because the three months of data was insufficient to build such a detailed model. We are currently in the process of building a model that allows us to achieve the accuracy of the full model without the need of a long training period.

VIII. Conclusions

In this paper, we present an implementation of a room-level zoning system to minimize the energy consumed for heating and cooling homes by conditioning only occupied spaces. Our preliminary analysis shows that such a system can be used to cheaply and easily retrofit an existing single-zoned residential HVAC system. Even with leakage from the registers and imperfect isolation between rooms, whole house zoning consumed 20.5% more energy than this system over the course of a 20-day study. While longer-term studies are necessary to eliminate potential effects of weather during the study, these results are promising and warrant further investigation into this approach, especially in light of the shortcomings of our prototype, as described in Section V, and that we only evaluated multi-room zones instead of individual-room zones.

ACKNOWLEDGMENT

This work is based on work supported by the National Science Foundation under Grant No. 1038271.

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