RoomZoner: Occupancy-based Room-Level Zoning of a Centralized HVAC System

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ABSTRACT

Cyber-Physical Systems (CPSs) combine low-power radios with embedded processors in order to provide high-resolution sensing and actuation over a geographic area. This revolution has begun to deliver a new generation of engineering systems and scientific breakthroughs. One area in which CPSs can have a significant impact is in energy conservation through the intelligent control of systems. In this paper we present a CPS that enables a centralized Heating, Ventilation, and Air Conditioning (HVAC) system to be retrofitted to enable room-level conditioning of a residence. This is a compelling application due to residential HVAC systems accounting for over 15% of all U.S. energy usage, making it one of the nation's largest energy consumers. Also, it has all the aspects of a complex CPS: it uses sensors to detect room occupancy and indoor climate, it actuates hardware, and it requires complex control algorithms in order to maximize energy savings without damaging the HVAC equipment or discomforting the occupants. With an implementation using commercial off-the-shelf (COTS) components and a simple control algorithm we demonstrate an almost 15% energy saving in a residence over its existing centralized thermostat. With this demonstration, we pose a challenge to control theorists with the CPS community to refine our approach which could lead to even greater energy savings.

Categories and Subject Descriptors

C.3 [**Special-Purpose and Application-Based Systems**]: Real-time and Embedded Systems; H.1.2 [**Models and Principles**]: User/Machine Systems—*Human Information Processing*

General Terms

Design, Experimentation, Economics, Human Factors, Measurement

Keywords

Building Energy, Cyber-Physical Systems, Energy, Environment, Sensing, Home Monitoring, Programmable Thermostats, Wireless Sensor Networks

1. INTRODUCTION

Cyber-Physical Systems (CPSs) combine low-power radios with embedded processors in order to provide high-resolution sensing and actuation over a geographic area. This revolutionary technology has begun to deliver a new generation of engineering systems and scientific breakthroughs. One domain where CPSs can have an immidiate impact is in home automation, an area computer scientists have been researching for over three decades. CPSs provide the technology to finally enable the smart home of the future.

Automation can improve two aspects of a home: decrease its energy usage and increase the comfort of its occupants. It can make a large and immidiate impact in both of these aspects by optimizing the control of the Heating, Ventilation, and Air Conditioning (HVAC) system of a house because it is the largest energy consumer in a home [9] and it controls the climate of the house in order to maintain a comfortable temperature for the occupants. Researchers have focused a considerable effort on optimizing this system and even commercial CPSs which intelligently control the HVAC system by sensing occupancy and actuating the HVAC hardware are available, yet there is still plenty of room for further improving the efficiency of this system. In this paper, we demonstrate the usage of a CPS to retrofit a centralized HVAC system to condition rooms individually based on occupancy. We use a simple control algorithm in the implementation evaluated in this paper in order to demonstrate that room-level zoning of a centralized HVAC system is feasible, yet the control problem is a challenging one in this domain due to the number of inputs and outputs that have to be considered, the real-time nature of the system, and the constraints the controller has to meet in order to ensure the safety of a centralized HVAC system which is not designed for room-level control. While demonstrating the applicability of room-level zoning control as a means of improving the energy efficiency of homes, we pose a challenge to control theorists within the CPS community to refine our approach which could lead to even greater savings for homeowners.

RoomZoner is a room-level HVAC zoning system where each room is individually conditioned based on its occupancy and temperature. RoomZoner dynamically changes zones in response to occupancy and temperature changes within rooms. It uses an occupancy assessment technique that relies on simple motion sensors to decide when rooms become occupied or vacant and a simple thermal model of the house to predict the effect of control decisions. Using this information RoomZoner responds to changes in occupancy by redirecting conditioned air thorugh the house. We base this approach on the concept of Micro-zonign which allows the customization of an HVAC schedule for individual rooms [5]. Rose and Dozier observed that micro-zoned systems report energy savings of up to 43% compared to conventional HVAC systems with larger zones [21] when applied to an office environment.

We implement RoomZoner as a residential Cyber-Physical System application. RoomZoner involves a novel occupancy assessment technique and a zone control algorithm that ensures the safety of a centralized HVAC system not designed for zoned usage. The goal of RoomZoner is to minimize energy wastage without compromising occupant comfort.

The occupancy assessment technique enables the inference of room occupancy and distinguishing when a room is in use from when a resident is walking through a room using simple motion sensors like those found in most residential security systems. The zone controller attempts to maintain occupied rooms at a comfortable setpoint while ensuring the safety of the HVAC equipment. Hardware safety considerations include ensuring the compressor is not turned on and off too frequently and the pressure within the ducts does not build up due to the closing of a large number of registers. A study carried out over a two month period indicates that room-level zoning, with RoomZoner, consumes 14.4% less energy than whole house conditioning.

2. BACKGROUND AND RELATED WORK

Previous studies have explored the possibility of room-level zoning, but produced mixed and inconclusive results [30, 31, 33]. RoomZoner addresses this shortcoming with a long-term deployment in an instrumented residence which enables the monitoring of occupancy and the control of the HVAC system in response to the occupancy. RoomZoner responds to changes in occupancy using an occupancy assessment technique that relies on simple occupancy sensors. Researchers have proposed different techniques for tracking occupants through a home, identifying them, and understanding what activities they are doing. Until recently, however, existing technologies have all been too expensive or intrusive for use in energy conservation applications. For example, some systems require the user to wear a tag [25], or to actively trigger a biometric sensor such as a thumbprint or retina scanner. Other systems require cameras in the home [17] and identify people, locations, and activities using gait analysis, form matching, or face recognition. However, cameras are often perceived to be invasive to personal privacy. Other systems require structural changes to the home such as the installation of smart floors, which incur a high initial cost and effort that are too prohibitive for most homeowners. Finally, some systems detect user activities by requiring a large set of training data that must be laboriously collected for weeks or even months after the original sensor deployment [32].

Unlike other smart home applications that rely on fine-grained activity recognition, RoomZoner does not require cameras or wearable tags that could be intrusive to the user; in contrast to other smart home applications such as medical monitoring and security, this domain can tolerate a small loss in accuracy in favor of cost and ease of use. Therefore, RoomZoner utilizes commercial off the shelf (COTS) motion sensors, which cost approximately $5 each. These sensors are wireless and are installable in minutes using double-sided tape. Evaluations of a similar system in eight homes have been able to identify occupancy and sleep activities with over 90% accuracy [27, 28]. We evaluate the raw sensor readings with a novel occupancy assessment approach to distinguish rooms that are actively in use from those that are transiently occupied as residents pass through them.

RoomZoner uses a reactive thermostatic control scheme. Reactive control is one of the three common types of HVAC thermostatic control mechanisms, the other two being manual and programmable thermostats [3]. While thermostats differ in the way they operate depending on what category they fall into, they all attempt to trade off energy savings for occupant comfort.

Manual thermostats maintain the temperature of the house, or zone, it is monitoring at a temperature to which it is currently configured, the setpoint. With conscientious users, who setback the temperature when they leave the house and go to bed and return the temperature to a comfortable level only when they are active around the house, manual thermostats can be the most energy efficient type of thermostat. Yet, they place a tremendous burden on the user to constantly set the temperature based on his/her current activity. Also, the fact that manual thermostats only start heating or cooling a house after the residents return, or wake up, results in the resident having to endure periods of discomfort while the house is warming up or cooling down. These reasons result in over 65% of residents with manual thermostats not switching to a setback temperature when they vacate their houses [2].

Programmable thermostats operate on a pre-defined *setback schedule*: the house is conditioned to a setpoint temperature when the occupants are typically active, and floats to a more energy efficient setback temperature when the occupants are typically away or asleep. Over 50% of households that have programmable thermostats are reported to not use setback periods at night or during the day [4]. In contrast, households with the simpler dial-type thermostats can easily adjust temperature settings before going to sleep or leaving the house, and as a result actually save more energy on average than households with programmable thermostats[4, 23].

Reactive thermostats use motion sensors, door sensors, or card key access systems to turn the HVAC equipment on and off based on occupancy. However, preliminary studies of such systems in residential buildings have demonstrated less energy savings than programmable thermostat and even increased energy usage by up to 10% [11]. Some commercial buildings are beginning to use occupancy sensors to create a tighter link between occupancy and HVAC control with reactive thermostats that use motion, window, and/or door sensors to turn the HVAC system on or off after detecting that the occupants have left or returned to a space. For example, the Telkonet SmartEnergy [1] control system allows the user to define a maximum recovery time parameter, which is set by the user. When the space is unoccupied, the system maintains a setback temperature from which it can return to the setpoint within the specified recovery time, once the occupants return. The system estimates the response time based on building and system parameters as well as current weather conditions. Other similar commercial systems include the Verdant [20], Viconics [29], and PECO [19] systems. While reactive thermostats are a step in the right direction, they are almost always applied to hotel rooms because they rely on the simplicity of hotel rooms and the keyed entrance to identify occupants; more complex spaces with multiple rooms, entrances, and occupants require more advanced sensing technology, such as the techniques discussed in this proposal.

Thermostatic control wastes energy due to occupancy patterns varying from the pre-defined schedule, and the system having to maintain a setback temperature close to the setpoint temperature so as to minimize discomfort if the occupants become active unexpectedly. In order to remove the burden of having the program a thermostat based on occupancy patterns, the *self-programming thermostat* which automatically chooses the optimal setback schedule was proposed [11]. This system does not fully solve the problems because occupancy patterns change every day, and so *any* static schedule must either waste energy or sacrifice occupant comfort.

Smart Thermostat is an extension to the self-programming thermostat. It incorporated dynamic actuation in order to minimize the energy wastage and loss of comfort due to variations in occupancy patterns [15].The researchers use data collected from eight homes over a period of two weeks, using leave-one-out cross-validation, to train a Hidden Markov Model (HMM). Smart Thermostat uses this model to predict occupancy and control a multi-stage HVAC system. While this approach goes a long way in minimizing the energy consumed by not conditioning an unoccupied house, there is still a lot of savings to be had by not conditioning unoccupied spaces of an occupied house.

Gupta et al. [12] add GPS-control to traditional thermostats by using information from location aware mobile phones to augment thermostats with the ability to control HVAC systems using travel time. By estimating how long it takes for the residents to return to an unoccupied home, the thermostat can transition to a "just-in-time" travel-to-home-time mode so that it starts conditioning the house in time for the residents' arrival, thus staying in a lower-power setback mode for longer. Through simulations, the authors demonstrate energy savings of up-to 7% in certain households. While this system is one solution to the problem of efficiently using programmable thermostats, it generally results in lower savings than programmable or manual thermostats and does not provide any energy savings in heating or cooling occupied houses.

Mozer et al. present the *Neurothermostat* which uses daily occupancy schedules and a neural network trained on five months of occupancy data in order to control an HVAC system [16]. The authors demonstrate that the Neurothermostat results in a lower unified cost, defined as a combination of energy usage and occupant discomfort.

Previous researchers have also investigated using multiple temperature sensors in a building with a single thermostat [14]. This work, done in simulation, demonstrated an increase in user comfort by using targeted comfort control strategies. Others retrofitted a house in Danville, CA with wirelessly controllable registers and demonstrated that energy savings is possible by directed air into localized zones [31]. This work did not use occupant information to control the HVAC 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 [10]. Other systems include the Millennial Net [18] and Siemens APOGEE [13]. 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. A number of systems, including Personal Environments from Johnson Controls [7] 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 prioritize occupant comfort over energy efficiency. The systems can produce some energy savings by not conditioning desks that are not occupied, and other studies have shown substantial savings of micro-environment systems [5, 21, 22]. 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 targets offices and would be difficult to transfer to homes, where usable space can be more difficult to instrument than a desk or cubicle.

Finally, there have been patents filed for occupancy-based zoning of HVAC systems using security systems [6] or motion sensors [24] to detect occupancy. While these systems attempt to solve the problem addressed by RoomZoner, 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. RoomZoner 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.

3. PRELIMINARY IMPLEMENTATIONS

The initial implementation of occupancy assessment involved a simple threshold based approach. For a room with N sensors, if $N/2$ sensor firings were recorded within a one minute interval, the room was considered to be occupied. This was based on the assumption that if at least half the sensors in a room fired within a short period, an actual occupancy should have been detected within the room.

While this approach proved sufficiently reliable to detect room occupancies, it could not differentiate between rooms being actually occupied or sensors being triggered as people passed through rooms. This causes the occupancy assessment algorithm to classify occupancy as either stable or transitional based on sensor firing characteristics.

A number of HVAC stage selection and dump zone selection algorithms were implemented before settling on the algorithms described in Section 4. In the following subsections some of these approaches are described.

3.0.1 HVAC Stage Selection

RoomZoner uses the average temperature to select an HVAC stage. Before settling on this implementation, two alternative HVAC stage selection strategies, as described below, were considered.

Majority room request. In this scheme, each room is given a vote to decide on an optimal HVAC stage depending on its temperature and occupancy. Hysteresis is used on a per-room basis. Once all the rooms cast their votes, the majority from among the votes is used to control the HVAC system. For instance, if five of the seven rooms requested stage 1 cooling while the other two rooms requested stage 2 cooling, the HVAC would be actuated in stage 1.

In most instances most of the rooms are not far enough from the setpoint to request stage 2 and, therefore, the HVAC system operates in stage 1 almost exclusively when it is turned on. This results in rooms that require stage 2 heating or cooling to not receive the appropriate volume of conditioned air and, thus, take a long time to reach the setpoint or not be able to achieve that temperature.

Max room request. Due to the shortcomings of the majority room request HVAC stage selection approach, the stage selector was modified to use the maximum stage request. With this approach, if any room requires stage 2 this stage would be used to condition all the rooms. Such an approach is based on the assumption that rooms requiring a higher stage could reach the setpoint within a reasonable time while rooms requiring a lower stage would reach the setpoint faster than with the lower stage, thus saving energy.

What was observed when executing the system with the max stage request HVAC stage selection policy was a majority of the rooms overshooting the setpoint temperature due to them requiring less conditioned air than that provided with stage 2 heating or cooling. This results in discomfort for residents due to rooms being too cold or too hot.

3.0.2 Dump Zone Selection

RoomZoner selects dump zones based on their estimated influence on the active rooms using a simple model of thermal flow through the house. Before implementing this dump zone selection technique, three dump zone selection algorithms were considered. The first one was based on room temperatures, the second was based on a pre-defined selection priority, and the third was based on room connectivity,.

Temperature-based dump zone selection. In this approach, for each room that was not occupied RoomZoner calculates the difference between the temperature in the room and the setpoint. It then sorts these dump candidates based on temperature difference so that rooms further away from the setpoint get a higher priority of being selected as dump rooms than rooms closer to the setpoint. This approach was based on the intuition that maintaining the average temperature of the unoccupied rooms at close to the setpoint as possible would minimize the time required to heat, or cool, these rooms when they were occupied.

Execution of RoomZoner using this dump zone selection approach caused dump zones to constantly fluctuate. For instance, in a particular iteration of RoomZoner if the bathroom and a bedroom were dump candidates with only one of the two required for the dump zone and the bathroom was further from the setpoint than the bedroom, the bathroom would be conditioned and the bedroom left unconditioned. In the next iteration, due to being conditioned the bathroom would be closer to the setpoint than the bedroom causing the bedroom to be selected as the dump room and the bathroom to be left unconditioned. Such an approach has two drawbacks. The first is the constant alternating between rooms could result in a room never being sufficiently heated or cooled to approach the setpoint. Each time a room alternates from being a dump room to being left unconditioned, the energy expended in heating or cooling that room could be lost due to leakage. The second shortcoming of this approach is the constant opening and closing of active registers or dampers as rooms are added and removed from the dump zone. This could reduce the lifetime of these dampers, both in terms of energy if they are operating on batteries, as well as the number of mechanical actuations they are capable of sustaining.

Priority-based dump zone selection. In the next attempt at dump room selection, a pre-defined priority scheme with which rooms are added to the dump zone was tried. The following priority scheme was utilized:

- Transitionally occupied rooms have a higher priority than occupied rooms.
- Rooms with open dampers have a higher priority than rooms with closed dampers.
- Rooms further from the setpoint have a higher priority than rooms closer to the setpoint.

This approach to dump zone selection was aimed at minimizing thrashing without compromising occupant comfort. By preferring transitionally occupied rooms to unoccupied rooms, rooms that are occupied, even temporarily, are kept at a comfortable temperature. Transitionally occupied rooms are also more likely to be stably occupied than rooms that are unoccupied for long periods of time. Thus by maintaining them at close to the setpoint, they can be quickly and efficiently conditioned to the setpoint in the event that residents begin using them. By preferring rooms with dampers already opened to rooms with closed dampers, the number of transitions between opening and closing dampers is minimized, increasing system stability. Finally, selecting rooms further from the setpoint than those closer to the setpoint ensures no room will drift far from the setpoint before it is conditioned.

Priority-based dump zone selection resulted in stable dump zones with minimal thrashing, yet it also caused certain rooms to not be conditioned for long periods of time due to being low on the priority list. When such rooms were occupied, a large amount of energy and time was required to condition it back to the setpoint, and occupants were uncomfortable for long durations of time while the room warmed up or cooled down.

Connectivity-based dump zone selection. In the third attempt at a dump zone selection algorithm, it was decided to prioritize neighboring rooms when selecting dump zones. This approach was based on the intuition that neighboring rooms would have the greatest influence on occupied rooms. For instance, if a neighboring room is not conditioned, the temperature difference between it and its occupied neighbor would be large resulting in a greater thermal transfer between the occupied room and the neighboring room. By conditioning neighboring rooms, this thermal gradient could be minimized reducing the leakage. Also, leakage from a neighboring room into an occupied room could benefit the occupied room.

Connectivity-based dump zone selection minimized fluctuations between dump rooms since occupied rooms do not change as frequently. Due to the fact that rooms neighboring occupied rooms are more likely to be occupied in the near future, and these rooms are selected as dump rooms, the problem of a person entering an unoccupied room and it being far from the setpoint was mitigated. Yet, it was observed that this approach resulted in less conditioned air being provided to occupied rooms. Airflow measurement experiments indicated that closing dampers and registers within a branch of the duct system increased the pressure within that branch and thus forced more air out of the open dampers in that branch. Since neighboring rooms are more likely to share a common branch of the HVAC ducts, opening neighboring rooms resulted in a lower volume of conditioned air entering occupied rooms. The model of thermal flow attempted to capture this phenomenon and suggest rooms that would have the greatest positive impact on occupied rooms.

4. IMPLEMENTATION

We implemented RoomZoner in order to identify some of the challenges associated with implementing such a Cyber-Physical System. The following subsections describe the challenges faced in assessing room occupancy and controlling the hardware, and our approaches to overcoming these challenges.

4.1 Challenges

In [26] we describe a number of challenges to retrofitting a centralized HVAC system for room-level zoning. We described challenges such as preventing the short cycling of the HVAC by not turning it on and off faster than its specified rate and coordinating zones to prevent a large temperature gradient causing leakage from conditioned rooms to unconditioned rooms. In this section we describe additional challenges to implementing such a system, in particular in terms of assessing room occupancy. The challenges in assessing occupancy in most houses arise from room usage durations not matching equipment operation periods and errors inherent in sensing hardware. The mismatch in room usage durations and equipment operation periods can manifest itself in *passageway rooms*, *multi-room usage*, and *short-term room usage*. Inadequacies of hardware usually manifest themselves as false positives or negatives. In terms of hardware control, the major challenge arises in safely using a centralized HVAC system in a manner for which it was not designed. This section described these challenges to implementing RoomZoner.

4.1.1 Passageway Rooms

Passageway rooms are rooms, such as hallways, which connect two or more other rooms. These could be central rooms in a house that are surrounded by other rooms. Passageway rooms pose a challenge because they are constantly in use throughout the day, yet for short durations of time. Therefore, trading off between saving energy and ensuring resident comfort becomes difficult. If comfort was of utmost importance, RoomZoner would consider passageway rooms as occupied for most of the day so that whenever a resident passes through them they would be at the comfortable setpoint temperature. Yet, because the amount of time a resident spends in this rooms is a small fraction of a complete day, RoomZoner would waste energy by maintaining the room at the setpoint. Thus, a successful occupancy assessment algorithm has to identify a room as a passageway room so as not to waste energy conditioning when it is not occupied, yet attempt to maintain it at close to the setpoint so that when occupants pass through the room, as they are likely to do frequently throughout the day, they are not discomforted.

4.1.2 Short-term Room Usage

In addition to passageway rooms, there are rooms that are usually not used for long periods of time. For instance residents enter storage rooms, bathrooms, kitchens, and wardrobes for short periods of time throughout the day. RoomZoner cannot condition these rooms in response to usage because, in most instances, the rooms are not occupied for a sufficient period of time for conditioning to be effective. Differentiating short-term room usage from regular usage is a challenge RoomZoner has to addressed in order to prevent the wastage of energy.

4.1.3 Multi-Room Usage

There are instances when residents use rooms in groups. For example a resident may watch the news on television while preparing dinner, so that s/he alternates between the kitchen and the living room, or set the dining table while keeping an eye on a dish on the stove, alternating between the dining room and kitchen. RoomZoner cannot identify and exploit such usage patterns if the occupancy assessment algorithm defines room usage based on a resident entering and leaving a room. In other words, a resident does not necessarily start using a room the moment s/he enters it and stop using it the moment the s/he leaves. The occupancy assessment algorithm has to detect residents using multiple rooms concurrently so that they maybe conditioned as a group, increasing the efficiency with which the HVAC system operates.

4.1.4 False Positives/Negatives

False positives and negatives are common errors associated with simple binary occupancy sensors. Shadows or the changes in light levels, due to the movement of the sun for instance, can trigger PIR and X10 sensors resulting in false positive sensor readings. These sensors also have a limited sensing radius. Moving through blind spots within a room can result in false negatives sensor readings. We can overcome false positives by filtering out spurious sensor firings while minimizing false negatives by increasing the number of sensors in a room so as to reduce the blind spots. A room-level zoning system has to consider these limitations of binary sensors.

4.1.5 Interdependence Between Zones

The interdependence between zones is caused by all the rooms sharing the same network of HVAC ducts. Thus, opening and closing certain ducts, using registers, has an effect on the airflow through other ducts. For instance, if two rooms are services by branching ducts off a common trunk duct, closing off one of the rooms would increase the airflow rate into the other room. Thus, knowing the effect of closing different combinations of registers is essential in deciding on dynamic zones. A simple solution would be to know the layout of ducts in the house being retrofitted, but this may not always be known by the homeowners. Therefore, a method based on airflow measurements from the registers, which can be easily taken using a handheld airflow meter, is presented.

4.1.6 Minimum Airflow

The centralized HVAC system poses a challenge to room-level zoning and one of the major reasons for this is the minimum airflow requirement for forced-air HVAC systems. These systems rely on forcing air over a condensation coil, transferring heat between the refrigerant and the air, and then delivering the air through a series of ducts to the rooms of a house. HVAC systems are rated for a certain output airflow depending on the operating stage. Ducts are usually properly sized so that most of the air delivered by the fan exits the ducts, which prevents pressure buildup within the ducts, and enables a constant flow of air over the coil. Ducts are also sized to distribute air to rooms depending on the size of the room, with larger rooms having more registers and wider ducts than smaller rooms.

Room-level zoning requires these ducts to be closed which decreases the amount of air that can leave the ducts through the registers. This causes leakage through openings such as insufficiently insulated joints and could even cause pressure buildup within the ducts that slows down the flow of air over the coil. This *back-pressure* could damage the compressor due to insufficient thermal flow between the refrigerant and air causing the refrigerant to not fully vaporize before flowing back into the compressor. Thus, ensuring a minimum airflow out of the registers when deciding on which registers to close is a challenge that has to be overcome to ensure equipment safety.

4.1.7 Thermal Transfer

Thermal transfer between rooms has to be taken into consideration when deciding on rooms to be conditioned at any given time. For instance, in a house with an open floor-plan with the kitchen and living room sharing a large opening between them, attempting to condition the living room and not the kitchen, or vice versa, would cause a wastage in energy due to the large amount of leakage of conditioned air from the conditioned room to the unconditioned room. In such a situation maintaining dependent rooms at a temperature close to the rooms being conditioned would reduce the energy wastage by decreasing the temperature gradient between the rooms. Thus, identifying these inter-dependencies is a challenge that has to be addressed for zone control.

4.2 Approach

RoomZoner attempts to maximize the stability of the system by minimizing the number of system changes. Thus, at any decision point RoomZoner attempts to maintain the register and HVAC equipment at their current state unless changing their state would greatly decrease the estimated energy used, or leaving the system at its current state would considerably affect resident comfort.

The implementation of occupancy assessment for RoomZoner involves learning room usage patterns using historical data and constantly evaluating the sensor firings to identify the occupancy patterns exhibited by occupied rooms. In order to overcome the challenges described above RoomZoner filters the raw sensor firings and attempt to categorize occupied rooms as being either *transitionally occupied* or *stably occupied*. Ideally, passageway rooms, short-term room usage, and initial room occupancy would be categorized as transitionally occupied while rooms that are being used for longer periods of time, including multi-room usage scenarios would be identified as stably occupied.

The occupancy model used by RoomZoner defines room usage based on rates of sensor firings for transitional occupancy of stable occupancy to start or end. Since the number of sensors differ per room, these rates of firing take the sensor counts into consideration. Thus, for each room of the house, four sets of parameters are defined in order to detect transitional occupancy or stable occupancy starting or ending. Each set of parameters is composed of a firing count, C and a timeout, T. For instance, for the living room to start being transitionally occupied, the number of sensor fired within the timeout defined for starting transitional occupancy divided by the number of sensors in the room has to be greater than the firing count for the starting of transitional occupancy. For transitional occupancy to end the number of sensors fired within the timeout for transitional occupancy ending, normalized by the number of sensors, should be less than the firing count for transitional occupancy ending. Similarly, RoomZoner uses parameters to detect stable occupancy. Transitional occupancies are usually based on shorter timeouts while stable occupancies are based on longer timeouts.

The RoomZoner implementation involves five steps: (i) false positive minimization, (ii) search space generation, (iii) parameter selection, (iv) temperature estimation, and (v) register actuation which will be described below

4.2.1 False Positive Minimization

False positives occur when sensors fire in a room that is not occupied. In order to minimize these occurrences, which could lead to unoccupied rooms being assessed as occupied, RoomZoner aggregates sensor readings from multiple sensors in a room to filter out false firings from any one sensor. As more sensors are aggregated, the possibility of false positives occurring decreases.

Algorithm 1 False Positive Minimization

$aggregateData = []$
$windowStartIndex = 1$
while $windowStartIndex < length(sensorFirings)$ **do**
  $windowEndTime = sensorFirings(windowStartIndex) + oneMin$
  $firingsBeforeEnd = sensorFirings < windowEndTime$
  $firingsInWindow = firingsBeforeEnd(windowStartindex : end)$
  if $length(firingsInWindow) \geq numSensors/2$ **then**
    $aggregateData.append(firingsInWindow(end))$
    $windowStartInterval = windowEndInterval + 1$
  else
    $windowStartInterval = windowStartInterval + 1$
  end if
end while

The RoomZoner false positive filtering algorithm (Algorithm 1) takes in raw motion sensor firings, F_R, and outputs aggregated firings, F_A. The filtering algorithm searches for one minute intervals when the number of sensor firings for a particular room is at least half the number of sensors in that room. Each time it finds such an interval, all the sensor firings within that interval are aggregated into a single sensor firings. By enforcing the requirement for at least half the sensors in a room to fire, or a particular sensor to fire at least $n/2$ times for a room with n sensors, the filtering algorithm attempts to minimize instances when a single spurious sensor firing is considered an indication of occupancy. This technique also helps minimize false negatives because for any one minute interval only $n/2$ sensors have to fire for that whole interval to be considered as having a sensor firing. Thus, residents don't have to constantly keep triggering sensors in order for them to be detected as being present in a room.

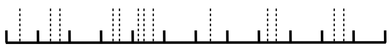

Figure 1: The solid lines indicate one minute intervals and the dotted lines indicate when sensor data was collected from a room with two motion sensors.

Figure 1 illustrates an example of data collected from a room with two motion sensors. In this example, the sensor firings in intervals with a single sensor firing would be eliminated while the firings in intervals with multiple sensor firings would be aggregated into a single firing as shows in Figure 2.

Figure 2: For a room with two motion sensors, false positive minimization removes the firings from intervals with fewer than two sensor firings and aggregates the firings in intervals with multiple sensor firings.

4.2.2 Search Space Generation

F_A is scanned using moving windows and the number of aggregated firings within the window is compared to thresholds to identify if occupancy began or ended. The following four occupancy parameters are used to define the beginning and ending of occupancy:

1. Occupancy start window size, W_S
2. Occupancy start firing threshold, FT_S
3. Occupancy end window size, W_E
4. Occupancy end firing threshold, FT_E

W_S and FT_S define a frequency, f_o, with which the aggregated sensor firings should occur for the room to be considered as having become occupied and W_E and FT_E define a frequency, f_v with which the sensors have to fire for the room to be considered as having become vacant. If the observed frequency of sensor firings in F_A is greater than or equal to f_o, meaning there are at least FT_S sensor firings within a window of size W_S, the room is considered to have started becoming occupied at the end of the window with size W_S. If the frequency of sensor firings drops to below f_v, the room will be considered to have become vacant at the end of the window with size W_E. Figure 3 shows an example of occupancy start and end being identified with $W_S = 2$ min, $FT_S = 2$, $W_E = 3$ min, $FT_E = 2$.

Multiple values for W_S, FT_S, W_E, and FT_E are tried, and the following statistics collected for each set of parameters:

1. False Negative count, FN: number of sensor firings that are ignored

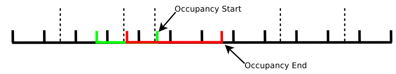

Figure 3: The occupancy start window, W_S is shown in green while the occupancy end window, W_E, is shown in red. The times when occupancy would be considered to have started and ended are labeled.

2. Occupancy period, T_O: total amount of time a room is considered occupied
3. Occupancy transitions, OT: number of times a room transitions between being occupied and unoccupied
4. 25th percentile period $T25$: the minimum T_O for at least 25% of all occupancy durations in the data set

The output of the search space generation process is a set of occupancy parameters, OP, and corresponding statistics. The parameter selection function searches over the statistics to identify parameters that can distinguish stable occupancy from transitional occupancy.

4.2.3 Parameter Selection

In order to identify optimal parameters for occupancy assessment, the parameter selection algorithm first prunes the search space of statistics using the following three thresholds:

1. Maximum number of false negatives, FN_{max}
2. Maximum number of occupancy transitions, OT_{max}
3. Maximum 25th percentile period, $T25_{max}$

Two sets of these three parameters are defined, one for stable occupancy and one for transitional occupancy as shown in Table 1. These parameters were selected to address the issues described in Section 4.1. In order to minimize short cycling, a longer $T25_{max}$ for stable occupancy was defined and OT_{max} was defined to be small. With these restrictions, FN_{max} was increased to allow the algorithm some flexibility in selecting parameters. For transitional occupancy, false negatives were a concern since the aim of transitional occupancy is to capture occupancy in passageway rooms and during short-term room usage. Thus, the threshold for FN_{max} was set to be low and the threshold for OT_{max} was made high since there would be a large number of transitional occupancy events during a day. Finally, a short duration for $T25_{max}$ was defined in order to capture the short periods of time when passageway and short-term rooms are in use.

	FN_{max}	OT_{max}	$T25_{max}$ (min)
Stable	30	4	30
Transitional	4	30	3

Table 1: Parameters selected for search space pruning reflect the characteristics of stable and transitional occupancy.

Once the search space is pruned, the remaining parameters in OP form the set of $candidateParameters$. This set is searched for the parameters that have the minimum total occupancy time, T_O. This stage of the algorithm outputs two sets of occupancy parameters, one to identify stable occupancy and one to identify transitional occupancy.

4.2.4 Temperature Estimation

A number of temperature averages that could be used to control a room-level zoned HVAC system such as the following:

1. Occupied room average, t_O: the average temperature of all rooms in use
2. Conditioned room average, t_C: The average temperature of rooms with open registers
3. Whole house average, t_H: the average temperature of all rooms in the house

Yet, controlling a room-level zoned HVAC system using each of these averages individually is not ideal due to the following reasons. The occupied room average, t_O can change every time a resident enters a room or leaves a room. This could cause a high variability in the average temperature used for making control decisions, which could result in *thrashing*: the system state changing frequently. If the newly occupied room hasn't been used recently, it could have drifted far from the setpoint. Adding that room to the set of rooms for which the average is calculated could cause the average temperature to shift drastically resulting in a higher HVAC stage being requested. If the resident leaves the room and enters a room at the setpoint, the average temperature could again change by a large amount causing a lower HVAC stage to be requested or the system to be turned off. Such fluctuations in HVAC control is inefficient in terms of energy usage and could be damaging to the HVAC hardware. Using only conditioned rooms could result in unconditioned rooms drifting far from the setpoint so that when they become occupied a large amount of energy would have to be expended to condition them to the setpoint. This could be more inefficient than maintaining their temperature closer to the setpoint even when they are unoccupied. Also, bringing these rooms towards the setpoint could take longer, discomforting the residents. Finally, using the average temperature of the whole house would result in the greatest stability in terms of temperature, but this could affect the responsiveness of the system. For instance, the average temperature of the house could be at the setpoint if most rooms are at, or above, the setpoint. But, a particular room could still be below the setpoint. This could be because the room is small and has fewer air vents causing it to receive less conditioned air, it being less well insulated than the other rooms, or it receiving a large amount of sunlight due to its location. A resident entering such a room could be discomforted and the system would be unable to detect it due to the other rooms skewing the average temperature towards the setpoint.

In order to minimize the shortcoming of each of the average temperature calculation methods, RoomZoner uses a hybrid of all three averages to make control decisions. When heating, RoomZoner uses the maximum of the three temperatures while when cooling it uses the minimum of the three. This approach reduces temperature variance and increases system stability.

4.2.5 Register Actuation

Register actuation involves selecting the registers to be opened and closed and sending the appropriate commands to the register control circuitry. Since the zone controller does not use room-level temperature control all rooms that are occupied have their registers open. The HVAC stage selected by RoomZoner determines the minimum airflow into the rooms in order to ensure equipment safety. The register actuation module attempts to ensure this minimum airflow by strategically opening additional rooms as needed so that there is minimum impact to the efficiency with which the occupied rooms are conditioned. The decision that has to be made is on what additional rooms, called *dump rooms*, that comprise the *dump zone* have to be opened, if they are closed. This decision is based on ensuring the safety of the HVAC equipment by minimizing the chance of back-pressure buildup due to a large number of registers being closed.

A dump zone selection algorithm is used during zone control to select the rooms that comprise the dump zone. Whenever there are insufficient rooms occupied in order to ensure sufficient airflow out of the ducts, the dump zone selection algorithm is called. This algorithm selects dump zones based on the estimated benefit, in terms of thermal transfer, to the occupied rooms rather than the actual temperatures of the potential dump rooms. Also, the algorithm prefers rooms that have been occupied in the near past as dump rooms. These approaches to dump zone selection ensures the zone controller is able to achieve its goal of maximizing system stability by minimizing state changes.

The first phase of dump zone selection is separating the rooms into active rooms, those room that require conditioning due to either being stably or transitionally occupied or being beyond the setback temperature, and dump candidates. Next, all combinations of dump candidates are evaluated in order to identify the set of rooms that have the greatest positive impact on the goals of zone control.

The first step in dump candidate evaluation is estimating the total airflow out of the ducts with a particular set of dump rooms. The airflow calculator provides a conservative estimate of the expected airflow when a particular set of registers is closed. This estimation is based on empirical values of airflow collected with a airflow meter. Two values of airflow are collected for each register: openAirflow and closedAirflow. *openAirflow* is the volume of air output from a register when all registers are open, while *closedAirflow* is the volume of air output from a register when it is closed while all other registers are open. these values are used as approximations of the airflow out of a register when it is opened or closed. They are lower bounds since the closing of any other register concurrently, should cause these values to increase. RoomZoner calculates the total airflow by adding together either a closedAirflow or an openAirflow value for each register in the house depending on the state of the register. This sum provides a lower bound for the amount of air expected to leave the ducts. This value being beyond the safety limit of the HVAC system would ensure the safety of the hardware. We use a lower bound calculation instead of an accurate measurement of the airflow due to the large number of measurements necessary to build such a model. The residence where the system was implemented had 13 registers, therefore $2^{13} = 8192$ measurements are necessary to build a complete model. Using the lower bound allows us to build the model within a few hours.

We use the estimated airflow to eliminate dump candidates that would not help with ensuring a safe volume of airflow out of the system. RoomZoner, in addition to ensuring that this safety limit is met, verifies that no room can be removed from the set and still have a safe airflow out of the system using the minimum airflow change which is the minimum difference in airflow from a room in the set being opened and closed. RoomZoner compares this minimum airflow change to the difference between the airflow estimate and the safe airflow to ensure that the change is greater than the difference. If so, it opens the registers.

The final step of register actuation is optimizing over the search space of dump candidates that passed the airflow check. RoomZoner performs this optimization over two parameters: *zone energy* and *register changes*. Zone energy is an estimate of the thermal impact on occupied rooms by a particular dump zone and register changes is the number of rooms that toggle the state of their registers from open to closed, or closed to open. Zone energy is calculated using voltage values obtained from a circuit model of airflow in a house that we describe in the next subsection. This model assume rooms are wires with resistors between them and the air coming out of the registers are current sources. Give a set of current sources, as estimated airflows from the registers, the model provides voltages for each room. These voltages describe temperature changes in rooms with higher voltages indicating a greater temperature change. Thus, the optimization function attempts to search for dump zones that have the greatest impact on the voltage of the occupied rooms, indicating the possibility of the greatest positive impact on those rooms in terms of thermal transfer. With this approach we address the thermal transfer challenge described in Section 4.1.7. In addition to the zone energy, we also attempt to minimize the number of register changes necessary to configure the dump zone. This ensures that RoomZoner prefers rooms that were recently occupied as dump candidates since their registers are more likely to be open and also minimizes the number of state changes necessary, as the zoning controller is trying to achieve. Preferring recently occupied rooms helps ensure that rooms that residents use in multi-room occupancy scenarios remain close to the setpoint. This also helps ensure that the temperature of rooms that are more likely for residents to occupy in the future, due to temporal locality, are not allowed to drift far from the setpoint.

5. EVALUATION

To evaluate RoomZoner, we alternate the control of the HVAC system between room-level zoning and whole house conditioning over a 42 day period. We selected this protocol to minimize the effect of changing weather patterns on energy statistics. These experiments occured out over a period of four months during the winter. For this evaluation we excluded the data from days when the HVAC did not turn on due to the temperature never being below the setpoint and days when their were clear data loss due to unusually low energy consumption values. From the remaining days we extracted 21 days worth of data for each system so that for each month RoomZoner and whole-house control had the same amount of data. We did this to ensure fairness by minimizing the effect of weather when the data for one system is from the coldest part of the winter while the other system's data is from milder days. We use the E-Monitor total home energy management system [8] to monitor the energy consumed by the HVAC system. Figure 4 shows the energy consumed in conditioning a house using RoomZoner and whole house conditioning. This graph indicates that whole-house conditioning consumed 14.4% more energy than the prototype implementation of room-level zoning, on average.

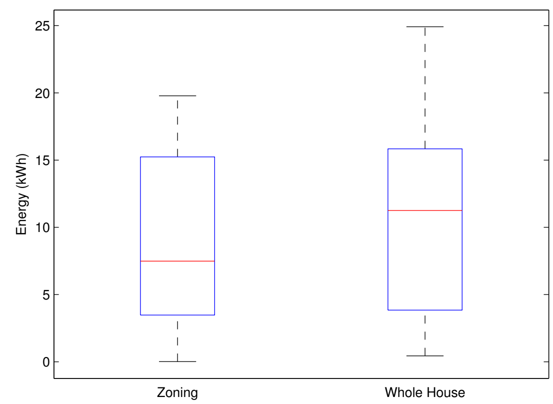

Figure 4: The implementation of room-level zoning uses 14.4% less energy than whole house heating on average.

Figure 5 shows the actual energy consumption for each day as a scatter plot, with the average temperature of for that day on the x-axis, the energy consumed on the y-axis, and the control algorithm shown as the color of the scatter point.

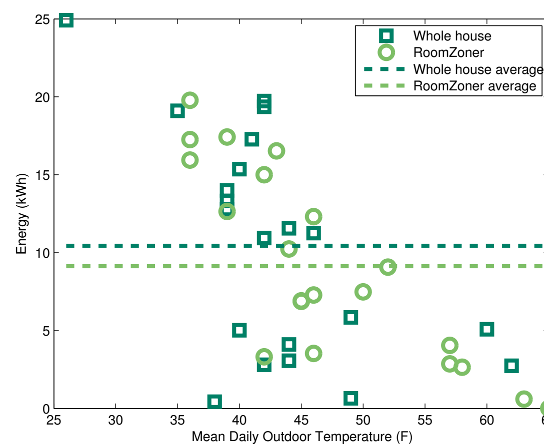

Figure 5: The dotted lines indicate the average energy used over the experimental period.

6. CONCLUSIONS

RoomZoner is a preliminary proof-of-concept demonstrating the benefit of cyber-physical systems in residences. Even with its simplifications, it demonstrated a 14.4% energy savings as compared to the existing centralized thermostat. We are working on improving RoomZoner in a number of ways. In particular, we are attempting to transition it from the reactive system described in this paper to a predictive system where it attempts to predict room occupancies and effects of actuations before making a control decision. In order to achieve such a system, we are working on ways to model the effects of damper openings and closing with different combinations of HVAC stage selections on the temperatures within rooms. We are also looking into alternative approaches to enable highly accurate predictions of room occupancie with the off-the-shelf motion sensors used for the implementation of RoomZoner described in this paper and without necessitating a long training period. With these components, we could design a sophisticated control algorithm that pushes the efficiency of a centralized HVAC system towards its potential. Thus, this paper sets out a challenge to the control theorists within the CPS community to join in this effort to develop such a model predictive controller.

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