Hot, Cold and In Between: Enabling Fine-Grained Environmental Control in Homes for Efficiency and Comfort

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ABSTRACT

Forced-air heating and cooling systems frequently perform poorly in multi-story homes. Long, leaky ducts running from the heater or air conditioner to the rooms of the house can impede airflow to second story rooms, creating dramatic temperature differentials between different spaces in the house. Such temperature discrepancies can lead not only to occupant discomfort, but also to energy waste since the thermostat would have to be set higher to achieve the desired temperature in some rooms. In this work, we propose a decentralized platform for heating and cooling systems in medium-sized homes that aims to independently control the temperature of each room. The goal of this approach is to provide heating and cooling necessary for poorly conditioned individual rooms to reach the required comfort level. By heating and cooling different rooms to different setpoints at different times, we can leverage our understanding about the way spaces in the home are actually used in order to fine-tune the environmental settings. We show that our techniques can both increase the residents' comfort and decrease the energy used by the house's heating and cooling system. In our primary test home, we estimate that our techniques could reduce natural gas consumption by roughly 18% during the coldest months of the heating season while increasing the temperature in the most-used living spaces by 2-5°F.

Categories and Subject Descriptors

C.3 [**Special-Purpose and Application-Based Systems**]: Real-time and embedded systems

Keywords

Smart Energy; Temperature Sensing; HVAC; Sensor Platforms

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1. INTRODUCTION

Residential heating and cooling systems frequently have trouble maintaining a constant temperature distribution throughout the building, particularly in multi-story homes. Homes heated by forced air systems are often the most difficult to control because conditioned air is not always distributed equally among all rooms in the house. In general, the farther away a room is from the furnace, the less conditioned air it will get. However, most residential furnaces have a single, centralized point of control – the thermostat – which controls delivery of conditioned air to the entire house. Thermostats are often located close to the furnace – generally on the first floor of a two story house – in rooms that receive a relatively high flow of conditioned air from the furnace or air conditioner.

Since there is generally only one point of sensing and control in most residential heating and cooling systems, the heating and cooling system can have an incomplete view of the temperature distribution in the house. Furthermore, residential HVAC[1] systems do not have the ability to fine-tune the temperatures on a room-by-room basis because there is no way to selectively heat or cool a subset of the rooms even if the thermostat knew that there were temperature disparities in some rooms. Because they do not have fine-grained control for multiple rooms, residential HVAC systems often spend a lot of energy to condition unoccupied areas of the home. For example, the bedrooms are frequently located on the second floor of a two-story house. These spaces are often too hot during the summer months and too cold during the winter months because they are not receiving enough conditioned air from the HVAC system. At night, the temperature in the bedrooms can be high or low by as much as ten degrees Fahrenheit, making it difficult to sleep, while the unoccupied areas such as the kitchen and living room are relatively comfortable.

To address this problem, some larger houses can be outfitted with multi-zone HVAC systems. In these systems, the home is divided into regions or zones that each have independent sensing and control. This is often done by outfitting each zone with an independent furnace, air conditioner, and duct system. For new construction, multi-zone HVAC systems are much more expensive to operate than single-zone systems because multiple furnaces and air conditioners may need to be installed and maintained. It is also extremely expensive and intrusive to retrofit an existing home with a

[1] Heating, ventilation, and air conditioning

multi-zone HVAC system because in addition to equipment costs, ductwork needs to be redone, requiring drywall to be torn out. The additional installation and maintenance costs put multi-zone systems out of reach for most homeowners.

Inefficiencies in residential heating and air conditioning systems can lead to discomfort in the home and excessive energy consumption. Since approximately 70% of US homes are conditioned by forced-air AC systems, and approximately 62 % of US homes feature some form of warm air furnace, these problems have broad reach across many people [5]. Furthermore, the US Department of Energy estimates that more than half of the energy consumed by buildings in the United States is used for space heating and cooling [6]. For this reason, small inefficiencies in a single type of system — the furnace or air conditioner — can have a massive effect on the country's energy consumption, while low energy prices insulate individual consumers.

To address these problems, we augment existing forced-air heating and cooling systems with a few additional components to provide localized control over the temperature of individual rooms. The relevant system components are depicted in Figure 1.

1. **Network-connected temperature sensors** located in every room of the home that measure environmental conditions and report to an off-site database server.

2. **Register booster fans** increase airflow from the heating and cooling systems to rooms that are too cold in the winter or too hot in the summer.

3. **Space heaters** locally augment the central heating system in rooms that are particularly cold.

4. **Network-connected smart power strips** with embedded relays that can control each register booster or space heater by switching its power on or off.

5. **Intelligent server-side control software** that analyses data reported by the environmental sensors and sends control messages to the smart power strips to regulate the temperatures of each room in the home.

Using these components, we can make residents more comfortable by individually controlling the temperature of small areas of the home. This is beneficial to homeowners and occupants in two ways. First, localized environmental control allows us to eliminate hot or cold regions of the home by selectively conditioning individual rooms. Second, we can avoid over-conditioning regions of the home that are not actively used.

Fortunately, heating and cooling systems lend themselves well to technological solutions for controlling energy consumption because users are accustomed to these systems being under automatic control. A reasonable approach to this problem would therefore be to develop control techniques that take energy consumption into consideration. By taking a global view of the temperature distribution in the home, we seek to control the temperature in a building on a per-room basis. This will allow building occupants to condition spaces in a way that is more closely aligned with the way the space is actually used.

The approach proposed in this paper allows homeowners to cheaply and easily retrofit an existing house that has single zone HVAC with fine-grained multi-zoned control. Our system is much easier to deploy than multi-zone HVAC because it can be installed by homeowners without the burden and expense of hiring a contractor. Furthermore, it can effect control of the HVAC system on a much finer granularity than multi-zone HVAC.

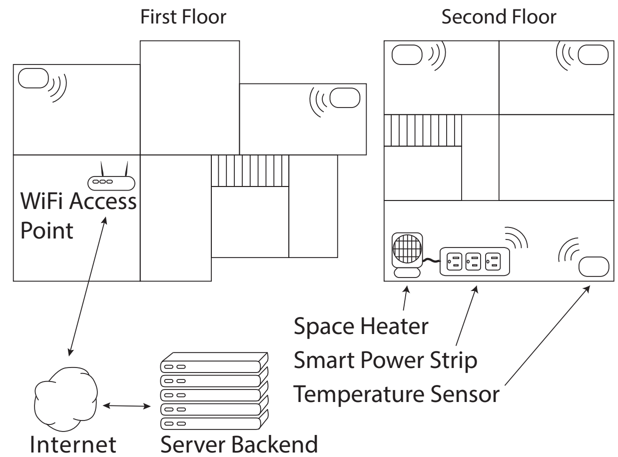

Figure 1: Floorplan of Home A in our study, showing the placement of temperature sensors throughout the building. Each sensor connects to the Internet through an existing WiFi access point. A remote server collects the data and controls local heating and cooling appliances through network-connected smart power strips.

We demonstrate that local temperature control is practical for average-sized two-story single family houses. To our knowledge, previous work in this area has focused primarily on small single-story houses, which generally do not have large temperature disparities between different areas of the building.

The goals of this work are to identify the sources of inefficiency in existing forced air heating and air conditioning systems and develop technical solutions to mitigate these problems. To this end, we have identified two related objectives. First, we need to make sure that the heating and air conditioning systems are correctly performing the tasks they set out to accomplish. If a user sets the thermostat to 70 degrees, we need to make sure that the temperature is actually 70 degrees. Using a decentralized sensing and control system, we are able to individually adjust the temperatures of the rooms in a building to ensure occupant comfort. This is important because we want to discourage residents from overcompensating for local temperature discrepancies (in a single room for example) with global corrections like turning the temperature setpoint up several degrees in the entire house.

Second, we wish to reduce the energy consumed by HVAC systems by intelligently conditioning spaces in the home based on the occupants' needs. For example, rooms that are heavily used should be tightly controlled at a comfortable temperature, while rooms that are not as frequently used may be allowed to drift. By combining these two techniques, we expect that it would be possible to set back the global thermostat settings while selectively conditioning rooms that are heavily used. In doing so, we can save energy and make the residents more comfortable.

The primary contributions of this work are as follows:

- We develop and deploy a distributed environmental sensing platform that can monitor the temperatures of each room in a home and report those measurements to a central controller.
- We use measurements taken by this system in *several homes over the course of six months* to identify sources of inefficiency in the HVAC systems. We observe consistent variations on the order of 5-10°F in second-story rooms among the houses we studied.
- Using feedback control on a room-by-room basis, we show that it is possible to simultaneously optimize the temperature distribution in a home while reducing the energy consumed by the HVAC system. In our testbed, we estimate that homeowners can reduce their natural gas consumption by 18% while reducing temperature variations in the rooms they use most.

2. UNDERSTANDING EXISTING HEATING AND COOLING SYSTEMS

In this section, we discuss the way existing heating and cooling systems operate in the homes we studied. For this work, we deployed temperature monitoring equipment in each room of three homes, which we call Homes A, B, and C. The homes we studied for this work were all two story single-family houses with single-zone forced air HVAC systems whose owners complained of temperature discrepancies between the first and second floors.

2.1 Shortcomings of Centrally-Controlled Heating And Cooling Systems

Each home we studied exhibited roughly the same types of behavior with respect to its heating and air conditioning system. Each had a 6-10°F temperature difference between the first and second floors during the warmest and coolest months of the year. We found that the airflow from the HVAC system was dramatically different on the first and second floor. Table 1 shows our measurements of airflow coming from the vents on the first and second floors of each home. Each had about a 50% reduction in airflow coming from the vents on the second floor, resulting in a commensurate reduction in conditioned air mass available to heat or cool the rooms. The difference in airflow between the two floors is a plausible explanation for the temperature differences.

Every house we studied had its thermostat in the dining room on the first floor. In two of the three houses, the residents did not even use the dining room on a regular basis, so it made little sense for the HVAC control system to be taking its only temperature measurements in that location. Since the point of measurement was on the first floor close to the central HVAC system, the whole first floor in all three houses roughly followed the schedule that the residents programmed into their thermostat. However, the second floor consistently had 5-10°F temperature variations. In order to keep the second story comfortable, the thermostat would have to be programmed to over-heat or over-cool the first floor. To compensate, the residents generally chose to program the thermostat with some middle ground settings that kept the first floor slightly over-conditioned while the second floor was under conditioned, but liveable. For example,

Home	1st Floor	2nd Floor
A	2.9 m/s	1.4 m/s
B	3.1 m/s	1.6 m/s
C	2.8 m/s	1.4 m/s

Table 1: Airflow measurements taken at each of the three homes in our study. In each building, there was roughly a 50% decrease in conditioned airflow to the second floor.

the programmable thermostat in Home C was set to 68°F during the evening hours while the residents were working in the second story office. The residents reported that they were comfortable between 60-65°F, but they increased the setpoint throughout the home in order to be comfortable on the second floor.

Figure 8 shows temperature measurements taken over the course of an average day in December for Home C. We refer to the difference between the setpoint of the thermostat and the actual temperature in a room as the *temperature error*. On the second floor, the master bedroom is consistently 6-8°F cooler than the dining room on the first floor during the time period shown, making that space uncomfortable for the residents.

Rooms on the first floor can also suffer the effects of unequal airflow. Spaces located near the furnaces tend to receive disproportionately high air flow, resulting in highly variable temperatures. This is because conditioned air from the furnace or air conditioner has to travel through a shorter length of duct which puts less back pressure on the air flowing to these spaces.

Since gas fired furnaces produce conditioned air at temperatures of 130-160°F, rooms close to the furnace can receive high volumes of extremely warm air that has not lost heat while travelling through ducts. The result can be uncomfortably warm and highly variable conditions in these rooms. Figure 2 shows a plot of the air temperature in a room that is close to the furnace and receives a lot of over-conditioned air. The measurements shown in the figure were taken on the opposite side of the room from the HVAC register, so the sensor experiences the same hot and cold fluctuations as the rest of the room.

In this work, we seek to identify the reasons for large temperature errors and to take steps to correct those errors in places where they cause the residents discomfort. More specifically, our goals are to

- Provide additional heating and cooling to rooms with large temperature errors in order to make those spaces more comfortable.
- Allow the user to set different setpoints for different rooms at different times of the day so the living space is conditioned to meet the user's needs.

For example, we found that residents will often heat or cool their entire house so they can be comfortable in just one or two rooms. This represents an enormous waste of energy that can be avoided by ensuring that the actual temperature in a room adheres to the desired setpoint schedule.

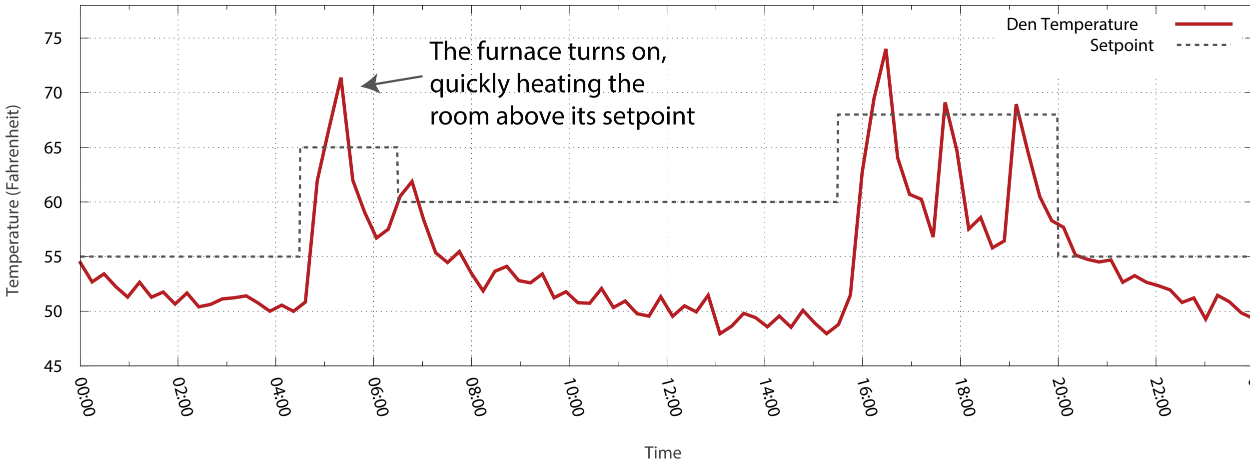

Figure 2: Without correction, even rooms close to the furnace or air conditioner can experience wildly fluctuating temperatures. In the den of Home C, high-temperature air from the furnace quickly heats the room above its setpoint. When the furnace turns off, heat leaks away through the three exterior walls.

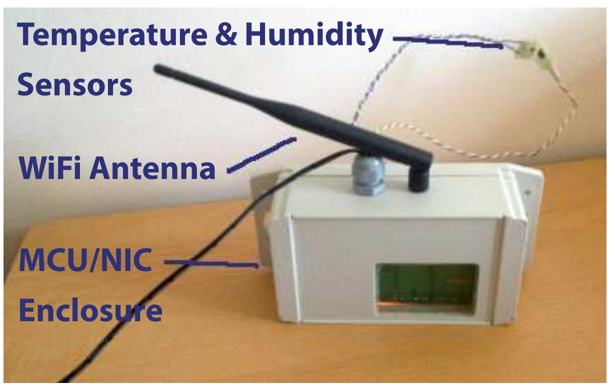

Figure 3: Photograph of temperature sensors used to monitor the environmental conditions in each room.

2.2 A Distributed Environmental Sensing System

In order to understand the temperature discrepancies between rooms' setpoints and their actual temperatures, we developed and deployed embedded temperature and humidity sensors in each room of several single-family houses during the course of a six month period. We chose to develop our own hardware platform because it is cheaper and much more configurable than commercial off the shelf components. Figure 3 shows a photo of the sensors as they were deployed. The hardware and software are variants of the Emonix platform [8], which is a flexible network-connected sensor platform that can be easily reconfigured for various distributed sensing applications.

Each sensor connects to the Internet through the home WiFi network and reports its readings to a central controller at one-minute intervals. We chose to connect our sensors to the Internet using WiFi because it is widely available in residential environments. By contrast, many embedded sensor networks use an intelligent bridge to facilitate communication between a low-end sensor network (eg. Zigbee) and an off-site controller. While this approach can slightly simplify the embedded nodes, it has the disadvantage of increasing the complexity of the overall deployment by adding a new point of failure (the intelligent bridge).

Our nodes collect temperature readings once per minute and transmit them to a centralized off-site controller. The controller logs each temperature reading in a database and returns an application-level acknowledgement to the sensor. Sensor readings are stored locally on the sensor nodes, and messages are retransmitted in case of packet loss.

3. AUGMENTING THE CENTRAL HVAC SYSTEM WITH LOCALIZED CONTROL

In order to reduce temperature error in second-story rooms, we added local temperature controls to a subset of the rooms on the second floor of Home C that were most heavily used by the residents. In addition to setting a global (house-wide) temperature schedule on their programmable thermostat, we were able to provide per-room temperature schedules in these rooms. We assume that occupancy data and analysis techniques are available to evaluate the residents' habits and construct a thermostat schedule that meets their needs. Several existing pieces of work — including commercial products — address this problem [3, 9, 11].

For this work, we allow the thermostat to maintain control over the global temperature settings for the home, and we install additional devices to augment the central HVAC system on a per-room basis. Each room in the home that has localized control installed can have an independent thermostat schedule separate from the main HVAC system's schedule. This requires minimal installation on the part of the homeowner, in keeping with our goal of making it possible for homeowners to do the installation themselves.

We used several techniques to locally adjust the temperatures in each room: register damper control, register booster fans, space heaters, and window air conditioners. Register dampers can be closed to shut off air to areas of the home that are properly conditioned. Likewise, register booster fans can help push air through the ducts into rooms that are not receiving enough air flow to help pull air from the duct system. Space heaters can be used in rooms where the central HVAC system can not sufficiently heat or cool the space, even with the addition of localized register controls.

Except for the register dampers, each of these techniques uses a device that can be controlled by an Emonix smart power strip. The smart power strip has two key components used by our controller. First, the controller can use an internal relay in the smart power strip to actuate the devices that draw power through it. This allows us to easily turn electrical equipment on or off by simply sending a command over the Internet to the power strip. Second, the controller can log the power consumed by the devices connected to the power strip. This allows us to monitor the energy used by our system for the purposes of assessing energy efficiency. Each technique is discussed in detail below.

Control Algorithm

The goal of our control algorithm is to minimize the temperature error in rooms that have local control equipment. Our controller takes as input a temperature schedule for each room in a single family house as well as a set of temperature measurements taken in the room. Two example temperature schedules are shown in Table 2. Based on the room's average temperature measured over the last five minutes, the controller can either turn on or turn off a power strip which controls the registers, space heater, etc. in the room. The controller has 2°C of hysteresis around the setpoint.

If the measured temperature in a room under local control is more than 2°C below its local setpoint[2], the central server turns on a space heater or register booster in that room. If the temperature is more than 2°C above the room's local setpoint, the controller turns off the local control devices. The localized heating in the room will not turn back on until the room stabilizes at 2°C below the setpoint.

The temperature in each room under local control is reevaluated once every minute during the early morning and evening hours. These are the times when the residents in the home are most likely to be using the second story space. During the middle of the day and at night, the local control mechanisms are turned off because the residents are either asleep or away from the house. While the local control mechanisms are turned off, the central furnace system is responsible for maintaining all spaces in the home at a global setpoint. Control actions such as turning space heaters on or off can also be taken once per minute in response to each new temperature reading, but in practice the switching is much less frequent.

```
Data: Temperature Readings
Result: Device state for local heating
foreach room under local control do
    if during household's normal occupancy hours then
        read temperature;
        if temperature below setpoint then
            turn heater on;
        else
            turn heater off;
        end
    else
        relinquish control to thermostat;
    end
end
```

Algorithm 1: Localized temperature control, run once per minute on the controller.

3.1 Register Control

Our first approach to provide localized control for the HVAC system in a home was to selectively close registers that feed parts of the house that are already well-conditioned. A similar approach is commonly used by multi-zone HVAC systems, in which a damper[3] is used to shut off air flow to entire lengths of ductwork that feed sections of the home. In this work, we chose not to use dampers because they are expensive and intrusive to install.

We believed that since all rooms on the first floor of the test houses in our deployment were receiving adequate air supply from the furnace and air conditioner, we could redirect air to the under-served second floor. We tried closing the registers on the first floor manually using the levers on the vents, and in some cases, we used cardboard and duct tape to seal off the duct. Similar techniques have been shown to work in smaller single story homes by other studies [12]. However, this did not have a detectable effect on second story air flow or temperature in any of the three homes we studied. Since our primary goal was to improve airflow and temperature variations in second story living spaces, we could not rely on register control alone.

In some cases, register control was useful to temper the wide variations we observed in first story rooms. As depicted in Figure 2, first-story rooms can often experience dramatic variability in temperature, particularly in rooms located near the furnace. By closing some vents in strategic locations on the first floor, we were able to reduce many of these variations.

We believe that the ducting system in these houses had leaks that allowed air to escape from the system before it reached the second story rooms. The US Department of Energy estimates that between 25-40% of conditioned air in average forced air heating systems escapes through leaks in the ducts [1]. In fact, they estimate that even well-sealed ducts will leak up to 20% of the conditioned air that flows through them. Since the ducts feeding rooms on the second floor are physically longer than those feeding the first floor, there is more opportunity for conditioned air to escape on its way to the register. Furthermore, friction between air and the wall of the pipe causes the air to slow down as it passes through a long pipe.

The perils of closing off the registers that feed large portions of a home are well-known to HVAC contractors and academics alike [13]. Increased back pressure caused by closing off registers can damage some components of the system. The resulting decreased airflow can also reduce the HVAC system's ability to heat or cool the house — decreasing airflow to one portion of the house does not necessarily increase flow to other areas. For this reason, systems that rely exclusively on dampers to direct conditioned air to specific areas in the building may have to allow some air to flow to spaces that do not need it in order to avoid excessive back pressure in the ducts.

Because we were not able to satisfactorily improve temperature discrepancies using register control alone, we tried using other measures.

[2]The local setpoint in a room may be different from the main thermostat's global setpoint.

[3]A damper is a valve that controls airflow through a duct.

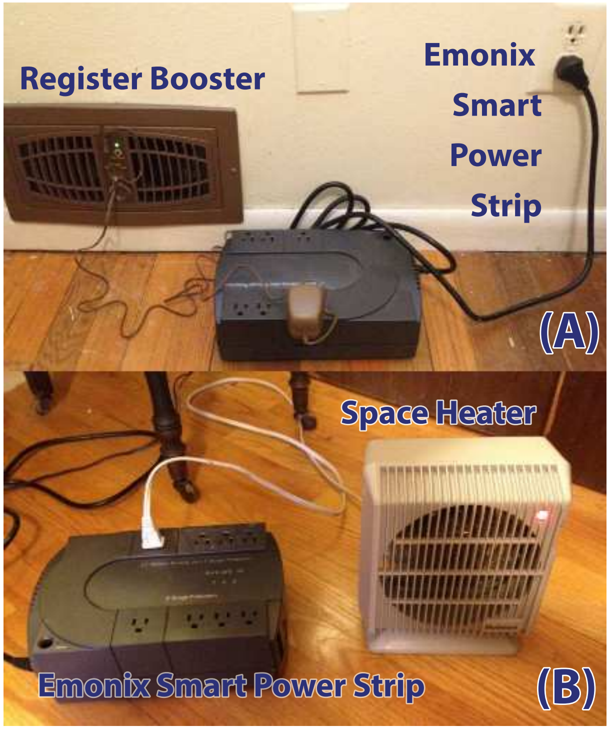

Figure 4: Photographs of our control equipment. (a) A register booster fan is controlled using an Emonix smart power strip by an off-site controller. (b) An Emonix network-connected power strip controls a space heater that provides additional heat in rooms that are too cold during the winter months.

Figure 5: The internals of an Emonix smart power strip include a relay to switch power to the plugs it serves and an analog adapter board to sense the power consumption of the connected appliances. The main CPU sits beneath the analog adapter board along with its WiFi interface that directly connects to the home's network. This allows energy measurements to be relayed to an off-site controller.

3.2 Register Booster Fans

In a second attempt to increase air flow to poorly-conditioned rooms, we installed booster fans in the registers of some rooms. Figure 4 (A) shows a photo of a booster fan installed in Home C. These fans pull air out of the registers, selectively creating lower pressure at the output of the duct system in places where conditioned air was needed. The booster fans we used take only about five minutes to install, and the only tool required to do the job is a screwdriver.

The booster fans we used increased the air flow to second story rooms to roughly 2.5 m/s while drawing only about 5 Watts of electric power. As a result, we observed a corresponding improvement in temperature in rooms that had register boosters.

One drawback of using register booster fans is that they can only work while the central furnace or air conditioner is on. This is also true of damper actuators as employed by multi-zone HVAC systems. Decentralized HVAC control systems that rely only on damper or register controllers would have a difficult time heating or cooling a small portion of a home.

We tested booster fans in two rooms of Home C. The guest bedroom, which has only one small section of exterior wall and its own return, responded well to the boosters. The master bedroom, with three large outside walls and no cold air return, did not benefit from boosters. Figure 6 shows a box plot of the temperatures errors in the guest bedroom during the first half of the month of December, before and after register boosters were installed.

Figure 7 shows a histogram of the temperature error in the guest bedroom before and after booster fans were installed. Before installation of register booster fans on the 8th day of the month, the temperature was on average 2.5°C below the setpoint in the guest bedroom. Ideally, our goal was to increase the temperature in the guest bedroom so the mean deviation from the setpoint is zero. This would mean the histogram in Figure 7 would center around 0. After installation, the average temperature deviation was about 1.1°C below setpoint. This improvement corresponds to about 50% of the achievable goal. Intuitively, an increase of 1.4°C as we saw in the guest bedroom has a noticeable effect on comfort.

The standard deviation of temperature errors also increased after installing register boosters. This is likely because the air coming out of the registers is much warmer than the air in the room. Before installing register boosters, there was less airflow from the vents, and that air was not mixing well with the air in the room because it was moving slowly as it exited the vent. After adding register boosters, the warm air would mix more with the room's air, and the temperature in the room would fluctuate up and down as the furnace cycles on and off through the course of the day.

Unfortunately, register booster fans do not work well for all rooms. If a room is poorly insulated or particularly far away from the furnace or air conditioner, the additional airflow they provide may not be enough to correct temperature disparities. The master bedroom in Home C is one such case. Not only is it poorly insulated and physically far away from the furnace, it also lacks a cold air return. Cold air returns are used to evacuate stale air from the space so that excessive pressure does not build up, allowing air to circulate more freely throughout the house. Thus, the lack of a cold air return can lead to inefficiencies in the HVAC system.

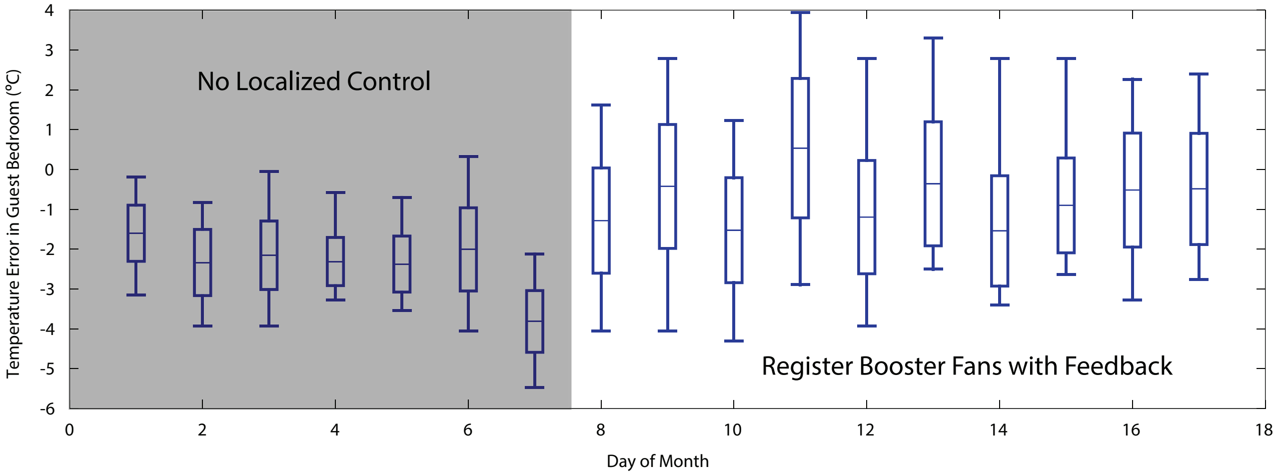

Figure 6: Deviations from the setpoint temperature in the guest bedroom of Home C. Before installing register booster fans, the room was on average 2.5°C below the thermostat's setpoint. Booster fans decreased the average deviation to 1.1°C below setpoint.

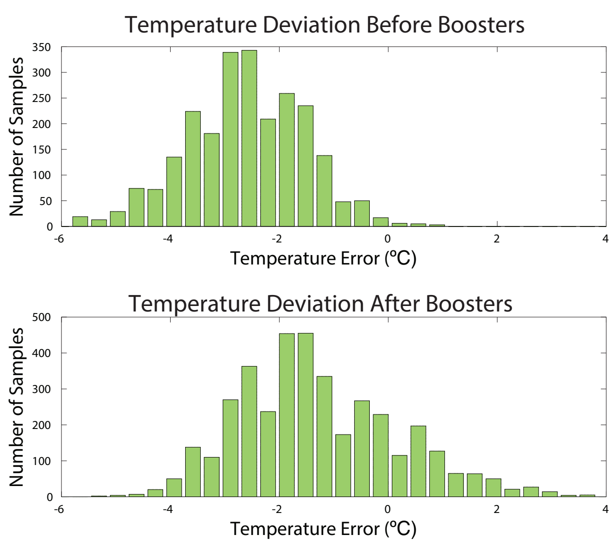

Figure 7: Histogram of temperature deviations from the setpoint in the guest bedroom of Home C before and after the installation of register booster fans. The use of register booster fans decreases the magnitude of the average temperature error by 1.4°C.

3.3 Space Heater

For additional heating capacity in the winter, we added a small space heater in the master bedroom that could be controlled by a smart power strip. If the controller detects that the the temperature in the master bedroom drifts below its setpoint, it can turn the space heater on by sending an asynchronous control message to the power strip. This system could be logically extended to also control actuation of an air conditioning (cooling) unit in the hot summer months.

Figure 4 shows a prototype of this configuration as deployed in Home C. The final system would be more compact, with the control and communication for the space heater embedded in the heater itself. In-wall space heaters could also be used to save space and reduce cord clutter, though this would require more complex installation.

Time Period	Before	After
5:00 AM - 8:00 AM	65 °F	60 °F
8:00 AM - 4:30 PM	60 °F	55 °F
4:30 PM - 10:00 PM	68 °F	60 °F
10:00 PM - 5:00 AM	55 °F	55 °F

Table 2: Set points of the programmable thermostat in Home C before and after adding localized control.

Figures 8 and 9 illustrate the improvements in temperature errors in the master bedroom from using localized control. Figure 8 shows the temperature profile of the master bedroom over the course of a typical day before installing local control in the master bedroom. The temperature in the master bedroom is roughly 5°F below the dining room (where the thermostat is located) and it is 10°F below the setpoint for most of the evening hours. Figure 9 depicts the situation after adding localized control. During two crucial periods — early morning and mid evening — the master bedroom temperature is still slightly below setpoint, but it is actually warmer than the dining room.

4. ANALYSIS

In Home C, we used localized techniques to make the second story rooms more comfortable. We chose Home C as the primary subject for active control, because out of all homes we studied, Home C best exemplified the common problems associated with current HVAC systems. Our main goal was to regulate the temperature in the master bedroom between 60-65°F in the evening while the rest of the house cooled down. This is the room where the occupants spend most of their time in the evening, and it was also the room that had the biggest temperature errors when controlled only by the central heating system. In this work, we assume that a suitable thermostat setpoint schedule can be established either manually or using automated techniques that take account

	Heating °C Days	Natural Gas Usage	Electric Heating
Furnace Only Local Control	804 659	107 Therms 87 Therms	0 kWh 54 kWh
Improvement	18%	20 Therms = 586 kWh (**18.7%**)	(54 kWh)

Table 3: Energy savings that resulted from the use of localized control in Home C.

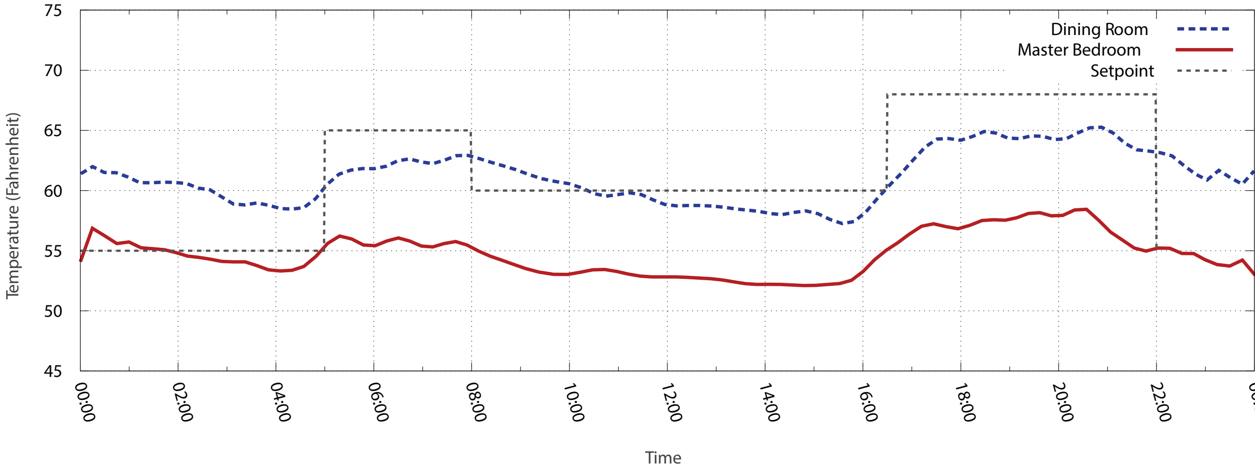

Figure 8: Observed room temperatures for two rooms on an average day in December 2013. The x-axis is the time of day, and the y-axis is the measured temperature. The master bedroom is located on the second floor and receives less air flow from the furnace, resulting in dramatic temperature reductions.

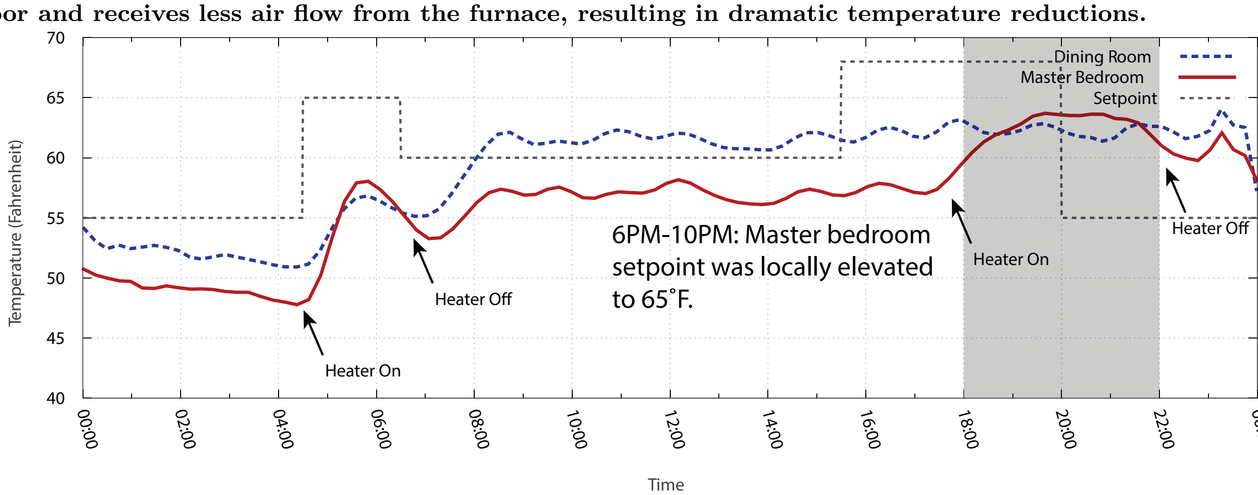

Figure 9: Observed room temperatures for the master bedroom and dining room after adding localized control to master bedroom. The x-axis is the time of day, and the y-axis is the measured temperature. A space heater is used to increase the master bedroom temperature from 6PM-10PM and from 4:30AM-6:30AM. For the rest of the day, the temperature in the master bedroom is allowed to drift away from its setpoint.

of occupancy data as well as user input. Several pieces of work have demonstrated that this is feasible [7, 9, 11].

Prior to adding localized control, the master bedroom had been so cold that the residents only used it for sleeping. This was inconvenient because it also served as an office, so the residents had to move their computers, desk, and files to other areas of the house that were more comfortable.

After adding localized control to target temperature variations on the second floor in Home C, the occupants were able to turn the global thermostat settings down by roughly 10°F during the second half of the month of December. Figure 8 shows the temperature in two rooms as a function of time before adding localized control. Clearly, the temperature in the second-story master bedroom is several degrees below the setpoint of the furnace's thermostat, making that room uncomfortable. Figure 9 shows a plot of the temperatures of the same two rooms as a function of time after adding localized control and setting back the thermostat. In this plot, the temperature in the master bedroom is higher during the hours between 6:00 PM and 10:00 PM. The invariant between Figures 8 and 9 is the temperature setpoint in the master bedroom between 6:00-10:00 PM.

We estimate that Home C used roughly 18% less natural gas after turning the thermostat down. Table 3 shows our estimates of the energy savings in Home C if the setback had been done for the entire month of December. The 20 therm reduction in natural gas consumption during the month of December in Home C is equivalent in terms of energy to 586 kWh of electric power — *more than 10 times the additional energy we expended to locally heat the master bedroom*[4].

To generate the projections shown in Table 3, we used a metric known as *heating degree days* (HDD) to estimate the natural gas used by the furnace. The number of heating degree days for some time interval is the number of degrees the furnace must heat the house above outside temperature multiplied by the length of the time interval in days. A heating degree day over some interval T is defined as

$$HDD = \int_T (T_{room}(t) - T_{ambient}(t))\mathrm{d}t \quad (1)$$

Where $T_{room}(t)$ is the room temperature defined by the thermostat's setpoint, and $T_{ambient}(t)$ is the outside air temperature[5]. For example, if the outside temperature was 20 degrees cooler than the thermostat's setpoint for one day, we would count this as 20 heating degree days.

For each thermostat schedule shown in Table 2, we computed the number of heating degree days for the month of December using the integral in Equation 1. The number of heating degree days is different for the two schedules because the setpoint $T_{room}(t)$ is different, while $T_{ambient}(t)$ was the same for both schedules.

Our local utility (Madison Gas and Electric) models the energy usage of a furnace as a linear function of heating degree days [10]. Under this assumption, the natural gas usage of the furnace should also decrease by 18% because the furnace is the only gas-fired appliance in the house. This model gives a good first-order approximation of the energy usage of a heating or cooling system. By setting the thermostat back in Home C, we were able to achieve an 18% reduction in heating degree days during the month of December while maintaining thermostat schedule in the spaces used most by the residents.

Another important result of this work is that it incentivizes people to use less energy by providing additional benefit: increased comfort. Since the user's point of interaction with the system is the setpoint for the given room, logically users will maximize their comfort by defining a setpoint to suit their needs. Thus, our goal in this work is to optimize the residents' comfort by minimizing the temperature error in targeted areas of the house during time periods when we knew those areas would be occupied. In this way, we improve the efficiency of the HVAC system by conditioning the rooms in accordance with the user's desire, while reducing energy wasted by conditioning rooms that are not in use.

5. RELATED WORK

Network-connected controllers for residential HVAC systems have been introduced in various forms. The Nest thermostat [3] and the Bay Web Thermostat [2] are both commercial examples of so-called "smart thermostats." Both of these devices use a single point of measurement and a single point of control for the HVAC system without providing fine-grained control on a room-by-room basis.

RoomZoner is an academic system that uses distributed sensors to adjust the temperatures of individual rooms in a single-family house [12]. In this work, the authors use damper actuators to selectively cut off airflow to rooms that have reached their desired setpoints. The authors found that dampers worked well for a relatively small single-story house. However, in our experiments we found that this approach did not scale well to larger multi-story buildings.

PreHeat [11] and the Smart Thermostat [9] use occupancy data to establish a thermostat schedule that adapts to building occupants' use of their space. Thermovote [7] uses a crowd-sourcing or participatory sensing approach to establish an optimal temperature setting in an occupied space. In our work, we assume that an optimal thermostat schedule is available, and we focus on finding ways to fit local room temperatures to that schedule.

6. CONCLUSION

In this work we developed new techniques for correcting the shortcomings of single-zone HVAC systems in multi-story homes. We found that single-zone systems do not always serve second-story rooms well primarily because the duct system causes reduced airflow into those spaces. Furthermore, they have no way to identify or correct any temperature disparities resulting from impeded airflow because they lack the sensing and actuation systems required to do so.

In our work, we provide room-by-room sensing and actuation which allows us to maintain tight control over the environmental conditions in each space of the house. We use equipment that can be quickly and easily installed by the average homeowner without using special tools. We have shown that these techniques can both make the living spaces in the home more comfortable and reduce the overall energy consumption of the heating and cooling systems.

Currently, our techniques require the homeowner to program the thermostat and the sensing system with settings that they believe will make the living spaces comfortable most of the time. However, we recognize that these settings may not always be optimal. If the occupants change the way they use the spaces in the home, the settings may need to be adjusted.

For this reason, we believe that our work could benefit greatly from real-time occupancy sensing and prediction techniques. Knowing occupancy information, we may be able to eliminate the need for homeowners to program their thermostats. Such a system would be able to infer reasonable setpoints for the spaces in the home without intervention of the homeowner.

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[4]1 Therm = 100,000 BTU US, and 1 kWh = 3412 Btu, therefore 1 Therm ≈ 29.30 kWh and 20 Therms ≈ 586 kWh [4].

[5]By this definition, it is possible to have a fractional number of HDD because the time interval T could be a fractional number of days.

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