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Multiple Sensors with Single HVAC System Control

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Executive Summary

An innovative sensor feedback structure for multiple sensors with single HVAC system control was developed. The disadvantage of the traditional control method using single sensor which can only measure one of the series rooms controlled by the same actuator as this newly developed method can take advantage of all room temperature information. A modular commercial building model for system analysis was also built for making a huge system element replaceable. The occupancy comfort index was modified using the concept of comfort zone to provide the system a metric of comfort. In order to verify the benefits of the new method, a computer simulation program was developed. One year of real weather data and precise mathematical model with 48 states was created to make steady state simulation. The result shows that by using the new feedback information system, we can make the number of comfort rooms increase, reduce the percentage of occupancy discomfort, and save about 15% of energy at the same time.

Keywords: sensor; HVAC; control system; optimization; multi- channel sensing system;

I. Introduction

In commercial buildings it is common to control multiple spaces or rooms with a single heating, ventilating, and air-conditioning (HVAC) unit and controller. Systems configured this may be most commonly controlled with a single sensor in one of the rooms. The controller gets the temperature reading from one room, and supplies heating or cooling to all other rooms proportionally. This method assumes that all rooms have the same load all the time, and therefore the same temperature throughout. This is often a poor assumption, which leads to discomfort and using more energy consumption than necessary.

The reason for controlling multiple rooms with a single controller and a single sensor is cost. It is expensive to install a separate HVAC unit and controller for each room. And it is also expensive to install sensors in every room to get the temperature information.

New technology, particularly wireless sensor technology, offers the opportunity to significantly reduce the cost of sensors such as those used to control space temperature in commercial buildings. However, actuation system is still expensive.

In this paper, we investigate the potential benefit of replacing a single temperature sensor used to control a set of rooms with a sensor network that provides one sensor per room. However, we do not change the actuation. There is still just one controller and one HVAC unit for the set of rooms. The problem is rarely discussed since most multiple sensor usage focused on fault tolerance[1,2] or multitarget problems[3,4]. However, we are interested in the situation that multitarget can't be all satisfied since we only have one actuator.

The focus of the paper is on how to make use of the additional information available from a network of sensors, and an evaluation of how different methods of using the information affect energy performance and thermal comfort. We investigated simple, ad hoc methods and developed a new method that is based on an optimization procedure. The optimization method is designed to be independent of the HVAC system or any model of the HVAC system so that it is easy to apply to a wide variety of systems. It can be aimed at optimizing comfort, or minimizing energy consumption subject to constraints on comfort.

The next section describes the mathematical model of the building, HVAC system, and controls that formed the basis of our computer simulations. The subsequent section describes the thermal comfort penalty function that we used in our computer simulations. Section 4 describes the different methods that we investigated for using sensor information. Results of the computer simulations are in Section 5.

II. Modeling

To experiment with computer simulations, a mathematical model of the system must be obtained. The building model is kept simple by disregarding potentially complex non-linearities introduced by modeling pressure dynamics of the fans, room and ventilation system. On the other hand, the heat exchange, the wall structure, the furniture, solar radiation, and the internal loads will be considered.

We developed a modular structure of a room in a building so that we can easily replace some elements with another and make the number the room adjustable.
First we try to model a single office room of a commercial building. A cross-sectional view of the room, presenting the net heat transfer modeled is shown in Figure 1.

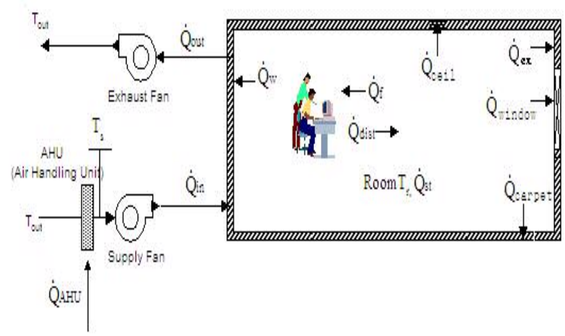

Figure 1. Heat Transfer model of single room

We separate our model into 5 different modules: external wall, insulating window, ceiling, carpet, and the room with internal walls. The values of all parameters used are in the appendix.

We have twelve states for a single room and three disturbance inputs: internal loads, outside temperature, and other space's temperature. The controller input here is assumed to be the energy usage of the system.

The modeling details could be found in appendix.

III. Comfort

To optimize the use of sensor information, we need a comfort metric. This metric will be used as a penalty function. Thermal comfort is affected by a number of variables including temperature, humidity, clothing insulation, air velocity, etc. It is also affected by dynamic behavior such as the temperature changing rate, average temperature change, etc. To simplify this complex function, we adapted the PPD (Predicted Percentage Dissatisfied) function so that all states other than temperature are constant. We make a clothing adjustment based on the season. In order to obtain the PPD as a function of temperature, we also introduced PMV (Predicted Mean Votes) to relate the temperature with the PPD.

The PMV index predicted the mean response of a large group of people according to the ASHRAE thermal sensation scale. These scales are as follows:

+3 hot
+2 warm
+1 slightly warm
0 neutral
-1 slightly cool
-2 cool
-3 cold

Temperature, air velocity, relative humidity, season, human activity, clothing, etc. are the parameters that affects the PMV index. Due to the fact that we focus on the control of HVAC system, we adapted the air temperature and the season as our variable, and keep all other parameter fixed. A thermal comfort program was used to get the relation from temperature and season to PPD as follows:

$$PMV = \left(-8.6479 + 0.2431 * C\right) + \left(0.3442 - 0.0073 * C\right) * T_{air} \qquad (1)$$

where C denotes the cold level and T_{air} denotes air temperature in degree C. Cold level is defined as a monthly based level and set the coldest month to be C=0 while hottest one to be C=11.

PPD stands for the percentage of discomfort people in the environment. Dissatisfied is defined as thermal sensation votes of –3, -2, 2, or 3 on the scale listed above. PPD is related to PMV as follows:

$$PPD = 100 - 95\exp\left[-\left(0.03353 PMV^4 + 0.2179 PMV^2\right)\right] \qquad (2)$$

The ASHRAE comfort zone was defined as the range of conditions that give 10% dissatisfaction. The complaints within this range are more likely a statistical result rather than real thermal comfort level. From control point of view, it makes more sense to control the environment within this range than just a certain value.

Therefore, we set the PPD to be 0 as complaints below 10% and shifted all PPD function 10% lower. And we can have PPD as a function of temperature and the Cold level from Eq. 49 and 50. The integrated function is shown in Figure 9. We will use this function as a benchmark for comfort.

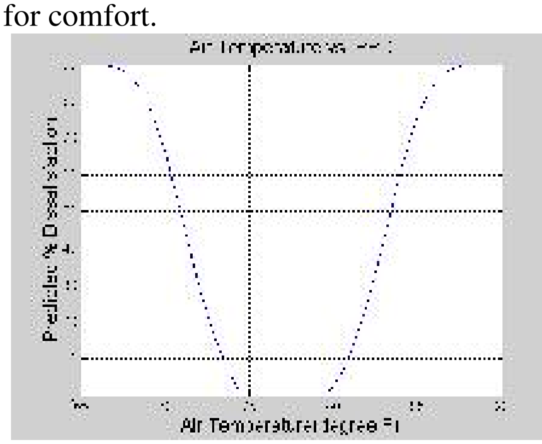

Figure 2. Integrated comfort penalty function

We chose the comfort metric with a comfort zone instead of original PPD function due to the optimization procedure stated in the following chapter.

We want as many as possible people feels comfort in the control strategy and therefore a flat zone is needed in the comfort metric. On the other hand, if we choose original PPD function as our optimization metric, we will have all rooms slightly discomfort as a result.

IV. Multiple Sensor data structure

There are plenty of methods that take more state information and feed into controller. Also there's lots of adaptive way to get exact model parameters by taking more state information. However, we want to develop a model –independent method that can easily applied to any building without knowing it's specific model. The method will be applied in two ways: optimize for comfort and optimize for energy. Apparently optimizing for comfort method will ensure the best comfort according to the comfort benchmark we gave to the control rule. While optimizing for energy method will give a reasonable trade-off to energy usage and keep the comfort level to an acceptable extent.

a) Single Sensor Case

For most building control nowadays, only single sensor is put in one of the multiple rooms controlled by the same HVAC system. This sensor information is taken as the only information for the feedback loop. This method provided a low cost solution of the system, but the comfort will not be guaranteed. The more similar of all room temperatures the more comfort we could gain by using this method. However, even if the building environment are well designed and all rooms are balanced to the space dimensions, there're lots of dynamic behaviors like human activities, different solar radiation angles, outside temperature variance, etc. will make room temperature different one from another.

b) Common Ad Hoc Multiple Sensor Case

There are several simple ways to combine information from a network of sensors. The first method is averaging, which collects all room temperature and take average of them. If discomfort index were a linear function, then this method would provide a least overall complaint result. However discomfort isn't a linear function of temperature, so this method would only provided a quite reasonable method for comfort. From the energy point of view, averaging method doesn't have any energy concern. Though it won't waste any energy in cooling a relative cold room like single sensor case may, it also won't try to save energy when all rooms are within the comfort zone. A variant of the averaging method is to use a weighted average. For example, large rooms could be weighted more than small rooms.

The second ad hoc method is control the worst case room. In other words, this method would use the one control degree of freedom to control the temperature that is farthest from the setpoint, switching rooms when another room becomes hotter or colder than the room being controlled. The purpose of this method is to try to make the room that is most uncomfortable as comfortable as possible. As we could predict, we will always be switching between the coldest room and the hottest room and therefore have some oscillation problem. The room temperature will always be changing as well as the HVAC system.

The third ad hoc method is scheduled switching. It could be arranged timely or randomly. This method provided a statistically average method applied to all room temperature. However, similar to tracking the worst case, this method also has oscillation problem. And it can't guarantee the comfort of any room.

The final method we discuss here is to tracking the difference between the hot complaint temperature, which is the hottest temperature minus reference, and low complaint temperature, which is the reference minus coldest temperature. This method, similar to tracking the worst case, is trying to make discomfort rooms be as comfort as possible. However, this method doesn't have oscillation problem since there're no switching activities.

c) Optimization Method

An optimization method was developed to take consideration of comfort as well as energy. As we could see from above method, none of them take care of the number of comfort rooms. However, as we have only single actuator, we lose controllability for our system at the first place. As a result, we can't control all rooms to the same desired temperature. In other words, we can't make every room feel comfortable as the number of actuator is less than the room number. The idea of the newly developed method is to maximize the number of rooms in the comfort zone, and then either make those rooms outside the comfort zone as comfort as possible or shift the temperature of the rooms in the comfort zone to save energy.

The first step is to shift the maximum number of rooms into the comfort zone. Then at each time all room temperature were acquired, we can calculate the maximum number of comfort rooms at the steady state. Moreover, as we may get more than one set of rooms that has the maximum number of comfort rooms, we will judge which one to be used by the second step.

The second step is to optimize comfort for discomfort rooms. Since the first step only determined the zone instead of a certain value, we still have the flexibilities to optimize the discomfort. If all discomfort rooms are too cold, we simply move the hottest comfort room to the hot comfort limit, and therefore minimize the discomfort of the all rooms. We use a similar approach when all uncomfortable rooms are too hot. And if some rooms are too cold while others are too hot, we need to find an optimal solution to the total comfort. Here we take the modified PPD as our penalty function and do a golden section search that minimizes the total discomfort index based on the maximum comfort room number rule.

If all rooms could be put within the comfort zone, we will apply energy optimization thereafter. When cooling, the set point will be set for the hottest room to the hot comfort limit, while set for the coldest room to the cold comfort limit when heating. The energy can be saved while keeping all rooms in the comfort zone.

We developed an alternative strategy that places more emphasis on energy savings. This method will provide more discomfort than the method above but will use less energy. In other words, the method limits the comfort to an acceptable range and optimizes the energy. First we maximize the number of comfort rooms as the first step above, but then we shifted the extreme temperature room inside the comfort zone to the comfort limit. This method needs an additional check that if the comfort rooms are already within the comfort zone for not wasting energy to move within the comfort zone. Which means that if all the rooms are already in the comfort zone at the initial states, we should not push it to the comfort limit. This method use the additional sensor information to save energy while keeps most people satisfied.

V. Computer simulation

Matlab was used for computer simulation of the comfort and energy consumption. The simulation used the commercial building model as described in section 2, the TMY2 weather data from Sacramento, CA, and different control strategy. We modeled annual energy consumption and average annual discomfort. The program runs one based steady state simulation. As commercial buildings, simulation only runs during the office hours.

The room model included four perimeter rooms with the same external exposure. All rooms have the same width and heights while different in length. The internal loads have pseudo-random behavior that simulated people walking in and walking out of the office.

Then we will balance area loading. Here we assume that the heat transfers between different rooms are negligible, and the HVAC system equipped air duct with diffusers that can be set to justify the thermal input for each room statically. Therefore, we can adjust the flow rate with the diffuser to make all rooms balanced with area loading.

Control strategies applied are single sensor in different rooms, multiple sensor using ad hoc methods, and multiple sensor using optimization methods. We used the PPD without modification to assess comfort. We also used the average number of room in the comfort zone as a comfort metric. Averaged discomfort percentage and the averaged number of comfort rooms will present the discomfort percentage of people and the temperature distribution in the buildings. We computed heating energy and cooling energy separately. The cooling energy is the heat cooling heat transfer rate at the room level. It does not take into account the energy conversion efficiency of a mechanical cooling system.

The result is shown in Table 1. Most of the mult-sensor methods outperform the average single-sensor method on the basis of both energy performance and comfort performance. Moreover, optimization strategy consumes even less energy than single sensor cases, while almost 10% less in discomfort. On the other hand, optimization method with energy concern saves 17.2 % of energy than the average of single sensor cases while the predicted percentage of dissatisfaction drops 5.9% and the averaged number of comfort rooms increases from 1.61 to 2.37. The reason that multiple sensor helps saving energy is because that single sensor method may waste energy in cooling the colder room that has no sensor in it, while the developed structure can always prevent this from happening.

Moreover, we simply compared the averaged method with the single sensor method. The comfort will always be better for averaged method since the PPD function has an exponential growth. However, the energy consumption while has no profit to the comfort of occupancies.

On the other hand, put more sensors in the building may not be the solution to the comfort alone. As we can see from

Table 1 Simulation Result Table

	Cooling Energy (KW)	Heating Energy (KW)	Average Number of Comfort Rooms	Discomfort (PPD)
Single sensor in room 1	14.26	8.61	1.6322	29.3099 %
Single sensor in room 2	14.43	8.21	1.6075	29.9569 %
Single sensor in room 3	13.89	7.80	1.6370	27.7661 %
Single sensor in room 4	15.17	8.07	1.5747	31.2659 %
Average of all single sensor cases	14.44	8.17	1.6129	29.5747%
Multiple sensor optimize for comfort	14.12	7.58	2.3712	20.1074 %
Multiple sensor optimize for energy	13.22	5.50	2.3712	23.9025 %
Multiple sensor average method	13.92	7.07	1.1914	20.5462 %
Multiple sensor Control the worst	20.29	13.3	1.4068	37.0071 %
Multiple sensor Tracking Tmax+Tmin	13.95	7.01	0.9360	23.0541 %

should will always be the same since we compared the averaged of single sensor method with averaged method. However, there're still some cases that the energy consumption is different. When some rooms need cooling while others need heating, averaged method will only do either cooling or heating depends on the averaged temperature of all rooms. But single sensor cases will have some cases cooling and others heating. The energy consumption will therefore be more than averaged method, the multiple sensor control the worst case, it used more energy than the single sensor case but just made discomfort rate higher. To sum up, in order to improve the comfort of the building environment of the multiple room and single actuator structure, multiple sensors and well-designed control strategy are both required.

We also studied how variability of the load affects the energy and comfort performance. The difference of room size and wall mass among all rooms can be eliminated and the effects of the outside temperature could also be decreased to an acceptable level due to the area balancing by the diffuser,. Therefore, internal loads are the main role that caused the temperature difference among rooms.

We ran the same simulation as above for different occupant densities. Since we model occupancy as a random process, we ran the simulation at each occupant density three times and took the average. We compared the results of the optimization methods and the average method to the average of single sensor case and plot the comfort improvement as well as energy saving. Figure 3-5 show the simulation results of our method optimized for comfort.

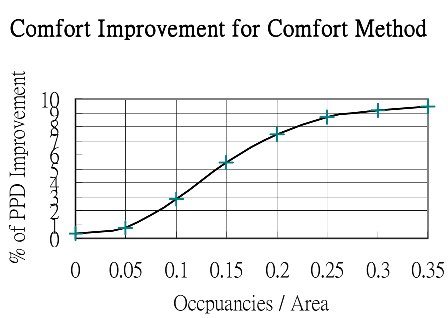

Figure 3. Comfort improvement for comfort method

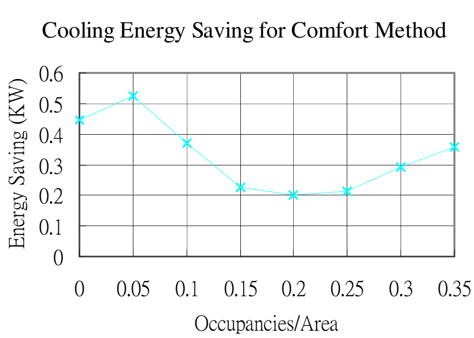

Figure 4. Cooling energy saving for comfort method

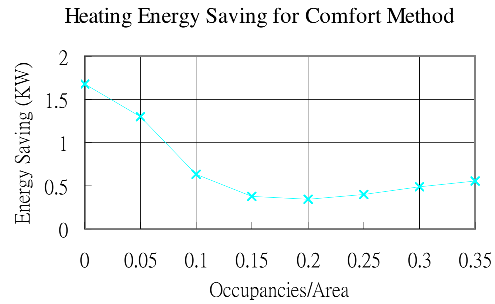

Figure 5. Heating energy saving for comfort method

As we could see from above results, the comfort improvement is increased significantly as occupancies increased for our method optimized for comfort. The energy saving won't increase but we still can always save energy than single sensor methods. Figure 6-8 show the results of energy method.

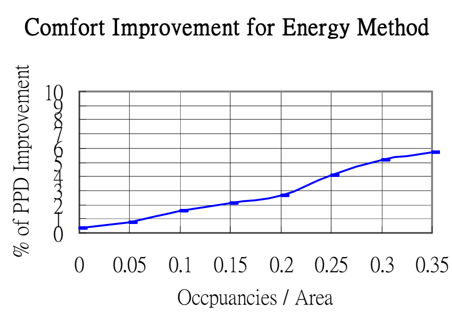

Figure 6. comfort improvement for energy method

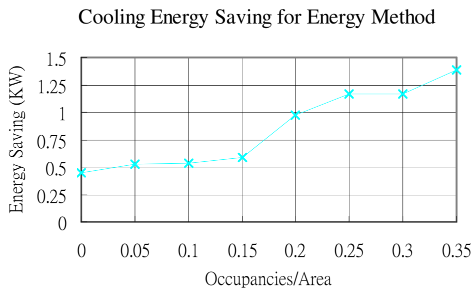

Figure 7. Cooling energy saving for energy method

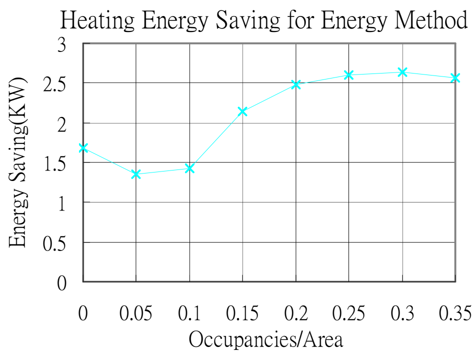

Figure 8. Heating energy saving for energy method

Energy methods provided smaller comfort improvement than comfort method but saved more energy than it. However, compare to the single sensor methods, we always improve comfort and save energy than at the same time.

VI. Conclusion

A method for building HVAC system control of multiple sensor single actuator structure was developed. The method takes advantage of more sensor information and improves the control of building environment. The method is model-independent which makes it practical. Two methods, optimize for comfort and optimize for energy, provided allow for a tradeoff in the balance between comfort and energy. Both methods use less energy and provide more comfort than the single sensor method.

On the other hand, a modular model for the system analysis was also been built to verify the energy and the occupancy comfort. The computer simulation using the model showed that these new methods not only improve the comfort but also saved energy than the widely used single sensor methods. The improvement of comfort was achieved through the systematic usage of additional sensor information. And the energy saving was also achieved by not wasting any energy to overcooling or overheating the room without sensor in it.

A wireless sensor monitoring experiment was also taken place. The results show the capability of wireless sensor application in the real building.

For the future development, the system may try to integrate with the occupancy sensor. Since the occupancy sensor can determine the zone that need or need not to be considered the comfort, it could provide the information to the system and ignore the temperature sensor within the same area. More energy could be saved. On the other hand, as multiple sensor structure was required, it is very important from the system point of view for fault tolerance. More works should be done along these directions.

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