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ADVANCED CONTROL OF INDOOR THERMAL ENVIRONMENTS USING FAN COIL UNITS

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ABSTRACT

The work described in this paper relates to advanced control systems, specifically designed for heating, ventilation and air conditioning in office buildings. This work specifically focuses on the use of state of the art fan coil units with advanced instrumentation and control. The premise of the work is that control systems can be significantly enhanced by using real-time data from a distributed sensor network deployed in the building. Specifically, the performance of control systems can be improved by augmenting predictive (feed-forward) control operations with techniques to improve the accuracy of models. A control algorithm for heating, ventilating and air-conditioning systems is described in this paper that integrates an advanced feedforward control algorithm with conventional feedback control.

This paper further contains a description of a functional prototype used to demonstrate the proposed control algorithm for indoor thermal environmental control. The test-bed used in this work – the Robert L Preger Intelligent Workplace (IW), at Carnegie Mellon University, involves a large number of variables and hence a complex control task, i.e., the test bed contains multiple sources of thermal energy, and multiple constraints and disturbances – both measurable and immeasurable. The algorithms demonstrated in this test-bed are expected to perform satisfactorily on other environments with smaller number of variables.

This paper contains a description of experiments that were performed to validate the comfort and energy benefits of increased sensing using fan coil units that are in installed in two spaces in the IW.

INTRODUCTION

A driver in the development of building control systems is the possibility of facilitating increased occupant comfort while adhering to constraints for performance and energy usage. This work is a novel sensor-based model reference control scheme to achieve improved thermal performance and energy effectiveness with an emphasis on the predictability of the indoor thermal environment. Thermal performance is addressed as system response time and the ability to track a setpoint, factors that are assumed to affect occupant comfort and productivity.

A typical control strategy for HVAC system is based on one element – the comparison of measured space air temperature with the air temperature setpoint from the occupant. In this work, a method to compute "Comfort Temperature" is developed that is used to calculate the setpoint temperature required using a model of the occupant.

Goals of this work include the demonstration of the comfort and energy benefits of increased sensing, an increased maintenance of comfort conditions, and a reduced cost of operation through the use of advanced control algorithms. This work included the selection, installation, commissioning and testing of advanced fan coil units along with the necessary sensing and actuation instrumentation and hardware. These were installed in two open plan offices in the Robert L Preger Intelligent Workplace (IW), at Carnegie Mellon University.

The control strategy developed in this work improves on existing strategies by using integrated feedforward and feedback loops that effectively use data from a large number of sensors measuring various quantities (air temperature, surface temperature, relative humidity, supply and return water temperatures and flow rates, electric power consumption etc.). Models are used in the control strategies that represent the building as well as the HVAC equipment to take into account multiple measured and unmeasured variables that affect conditions in buildings. The models include objective functions to improve the control of indoor thermal conditions in buildings while considering occupant comfort, rapid system response, lower installed cost and reduced cost of operation as described in this paper.

A brief description of related work is described in the next section followed by a description of the research objectives. A description of the test-bed and hardware used is provided along with descriptions of the control algorithms. A brief description of the experimental results is provided. The authors intend this paper to provide an overview of this work with detailed documentation to be presented in a thesis report by the authors.

BACKGROUND

In this section, a summary of the current state of the art with respect to calculation of thermal comfort for HVAC control, fan coil units and HVAC control in buildings is presented.

Thermal Comfort

Thermal comfort has been shown [1,2,3] to depend on air temperature, as well as on humidity, air flow, and radiant temperature and on the individual person (psychological factors). Established research has related measured sensor data (indoor air temperature, humidity, occupant's clo value, etc.) to physiological variables to predict the occupant's thermal satisfaction (the PMV-PPD method). In its current form, the weights for each variable contributing to thermal comfort are fixed, however research has been conducted to introduce a coefficient – a non-dimensional human coefficient that takes into account the variation in individual responses to the thermal environment.

Current HVAC control is typically reactive to air temperature, i.e. the building operator sets a required air temperature and the control algorithm operates to meet that temperature. Therefore, in contrast to the factors described above, thermal comfort is determined only on the basis of air temperature in a space that normally contains more than one individual. In addition, studies [4] have found that provision of personalized control over the thermal environment is key in increasing occupant satisfaction. Fan coil units described in the next section allow such personalized control.

Fan Coil Units (FCU)

A FCU is a zonal hydronic in-room terminal unit containing a fan, heated water coil, chilled water coil and outside air mixer. Outside air is typically provided by a central system ducted to the terminal unit. A thermostat in the space is typically used to control the operation of the FCU [5].

A typical heating, ventilation and air-conditioning system (HVAC) consists of fans, ductwork and terminal units. The air is cooled and heated centrally and distributed to the spaces. The low specific heat of air (1.012 joules / gram C) requires large volumes of air to be delivered to the space to meet heating and cooling requirements. Correspondingly, the size and volume of ducts required is large.

In comparison, the method of thermal conditioning using individual fan coil units requires 1/40 the volume to transport water (specific heat: 4.186 joules / gram C) to the fan coil units. Therefore, an advantage of fan-coil unit systems is that the delivery system (water piping versus air duct systems) requires less building space [a smaller central fan (or none) and little duct space]. Furthermore, for existing building retrofit, it is often easier to install piping and wiring for a fan-coil unit system than the large ductwork required for an all-air system.

In FCUs, thermal energy is transferred from the water to the air at the space being conditioned resulting in lower energy usage. Furthermore, balancing, operation and maintenance requirements are lower for a water based system. The system has the benefits of a central water chilling and heating plant, while allowing local terminals to be controlled individually. Traditionally, FCUs are controlled using feedback algorithms as described in the next section.

Feedback Control

In HVAC, a feedback controller uses the error between the space air temperature setpoint and the measured air temperature in the space. The most common approach of employing feedback is the Proportional- Integral- Derivative (PID) algorithm. Typically, the PID tuning parameters are derived for a specific operating range. Feedback control is simple to implement and performs well as long as the operating range and the setpoints do not vary significantly.

Feedback control, by its nature, is incapable of correcting a deviation in the controlled variable at the time of detection as it initiates corrective action only after the error has occurred [6]. This is a secondary problem to overcome with common feedback control (such as a thermostatic control) – the process delay time [7] – the delay between the application of a control effort (the actuation of a cooling device) and its effect on the controlled variable (air temperature in a space). During that interval, the controlled variable may not respond sufficiently to the controller's activity leading to overcompensation, oscillatory behavior and high energy use and low comfort conditions. Therefore, perfect control is not even theoretically attainable because a deviation in the controlled variable must appear before any corrective action can begin. In addition, the value of the manipulated variable needed to balance the disturbance is sought by trial and error, with the feedback controller observing the effect of its output on the controlled variable, e.g. PID control. Feedforward control, described in the next section, provides a more direct solution by using a model to calculate the value of the manipulated variable.

Feedforward control

Feedforward control is able to reduce system response time and reduce peak energy demand by compensating for uncontrolled but measurable disturbances affecting the controlled process [8,9]. Immediate action can be taken to counteract a change in disturbance conditions. Such systems are typically applied to processes that are sensitive to disturbances and are slow to respond making them suitable for HVAC control. For example, thermally activated building systems and radiant systems using a low water supply temperature (of 25 – 40°C) in heating conditions and high water temperature (16 – 20°C) in cooling, allow the use of renewable energy sources. However, this application requires a feedforward component because of the large thermal inertia of the system

Ideally, the feedforward correction would be so effective that a disturbance will have no measurable effect on the controlled variable. However, in practice, all disturbances cannot be accurately measured and exact compensation is not possible, therefore the main limitation of feedforward is due to the inability to prepare perfect process models or to make accurate measurements. Therefore, pure feedforward control is not used and instead it is combined with a feed back loop [6]. It has been found that combining feedback and feedforward is desirable in that the imperfect feedforward model corrects for about 90% of the upset as it occurs, while feedback corrects for the remaining 10%. With this approach, the feedforward component is not operated beyond its abilities, while the load on the feedback loop is reduced, allowing for improved controller performance.

Integrated system control

Current control practices typically separate global sub system control from local sub system [10]. This is commonly seen in situations where the control algorithms for supply systems in buildings are operated independently from those of terminal units that deliver energy to the space. Individual sub systems are further treated independent of each other, as is often seen when control algorithms for different systems attempt to condition a space without communication with each other. This often leads to conflictary control decisions resulting in poor controllability and low energy effectiveness. The result is poor controllability, energy waste, and costly maintenance.

This achievement of non-interacting control, or decoupling is traditionally one of the goals of multivariable control to simplify the control strategies. Here, a set-point change applied to one controlled variable will have no effect on the other controlled variable. However, interaction between control loops can be exploited to achieve improved overall control thus forming a basis for this work as described in the next section.

DESCRIPTION OF RESEARCH OBJECTIVES

Based on the background presented in the previous section, it was hypothesized that the operation of HVAC control systems can be improved by using real time data from a sensor network deployed throughout the building, by integrating feed-forward with feedback control, and by designing a control scheme that effectively uses higher spatial resolutions of zonal temperature, humidity and air quality.

The objective of this work is to demonstrate the comfort and energy benefits of increased sensing, an increased maintenance of comfort conditions, and a reduced cost of operation through the use of optimized control algorithms. These may be summarized as: (1) to develop methods for combining feedback control and feedforward control using models; (2) to integrate a model of the occupant to represent comfort criteria; (3) to examine the use of models in improving control strategies; (4) to assess sensor network densities for thermal performance; (5) to assess control strategies for operation of LTG fan coils in the Intelligent Workplace.

Specifically, in this work we analyze the possibilities of control of thermal sources for individual spaces based on a fan coil unit (FCU) and give answers to the following questions: (1) how do the fan coils have to be operated to satisfy constraints of thermal performance and energy use? (2) What algorithms are required to combine feed-back and feed-forward control strategies? (3) What is the value of using models to improving control strategies? (4) What is the value of updating the models based on actual performance data? (5) What characteristics are required of the sensor network for such an application?

This work focused on providing an overall view of how the fan coil installation in the IW will work and provide knowledge to create effective operation and control algorithms. Specifically, experiments were conducted to: (1) commission the fan coil units and study their operational characteristics; (2) study the performance of the fan coil units in changing the thermal conditions in the space (air temperature, relative humidity, radiant surface temperature and air flow patterns); (3) study the affect of enclosing the space; (4) study the performance of the control algorithms, i.e. examine stability both monotonic (failure of the controller to respond to a disturbance) and oscillatory, examine performance of the feedforward loop in estimating thermal energy required based on measurements of disturbances, study of the integrated operation of the feedforward and feed back loops and study of the ability of the control algorithm at maintaining a specified setpoint

Results expected from this study include the demonstration of the comfort and energy benefits of increased sensing – maintenance of comfort conditions and reduced cost (chilled / heated water, electricity) of operation by using advanced feedforward and feedback control with algorithms to determine setback temperatures. Reduced need for occupant interaction with the temperature control interface is expected by using the calculation of comfort temperature. This work is to deliver optimized control algorithms for the fan coil installation in the test-bed that can also be applied to other buildings.

THE TEST BED - THE ROBERT L. PREGER INTELLIGENT WORKPLACE

The Center for Building Performance and Diagnostics (CBPD) at Carnegie Mellon University (CMU) in Pittsburgh with the support of the Advanced Building Systems Integration Consortium (ABSIC) has realized the Robert L. Preger Intelligent Workplace (IW) in 1997, a living (always adapted) and lived-in laboratory occupied by faculty, staff and students. The IW represents major breakthroughs realizing advanced requirements for occupant's comfort and productivity, organizational flexibility and effectiveness, technological adaptability, and energy and environmental effectiveness, throughout the lifecycles of all materials, components and systems.

The IW is a living laboratory to enable the interchangeability and comparative assessments of innovations in HVAC, enclosure, lighting, control components and assemblies. The IW is a national testbed for advanced building efficiency with new systems including solar thermal system, absorption chiller, bio-diesel engine generator, desiccant ventilation, and fan coil units. The IW presents complexities of controlling open and closed office spaces with fluctuating occupancy, flexible space allocations and multiple cooling / heating (radiant façade, radiant ceilings, fan coils) and ventilation (windows, fan coils) approaches.

Characteristics of the Building Space

The building space is subject to uncontrolled sources of thermal energy – disturbances that may be measured with the use of sensors, as well as those that are not possible to be measured. These variables represent operating conditions during the normal operation of the building.

Thermal conditions in a space are affected by different controllable thermal sources (e.g. fan coil units), and uncontrolled but measurable thermal sources such as conditions at the physical boundaries (e.g. outdoor weather, solar radiation, presence or absence of an occupant, air temperature in the adjacent space). Typically, un-measurable sources that affect the thermal state in the space include factors such as the number of occupants present in the space, heat generated by office equipment and artificial lighting in the space.

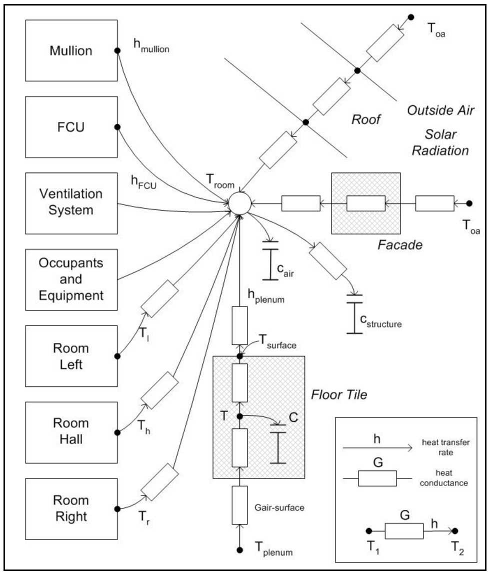

Figure 1: Schematic diagram of variables affecting air temperature in a space

FAN COIL UNIT HARDWARE

This work included the design, procurement, commissioning, testing and integration of advanced under floor fan coil units and instrumentation. Two distinct types fan coil, VKB (East Space) and VKD[1] (West Space) (figure 2) were installed in two offices in IW southern zone. Mounted below the floor level, these units meet the space cooling and heating loads of the space by circulating space air through heat exchangers supplied with chilled or heated water from the central system – the test-bed is situated in a campus environment with a campus grid supplying heated and chilled water to multiple buildings. They also distribute conditioned fresh air from the ventilation unit to the space. Sensors to measure thermal performance, together with control hardware and software are installed for performance evaluation and control experiments.

Three VKB units are installed along the façade in the East space. One VKD unit connected with three floor level diffusers (LDU) is installed in the West space. Return air for the VKD unit is through a chimney (an indoor feature unique to the test-bed, to supply return air to a duct in the under-floor plenum) located in the space (close to the hallway), while the VKB units take return air at the unit itself through the same floor level diffuser.

Two control handles exist for each fan coil – the valve (modulating 0 to 100%) and fan speed (5 speeds). In this work, the 3 VKB units in the East space are controlled together by the same actuation commands.

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[1] VKB and VKD fan coils are made by LTG Aktiengesellschaft in Stuttgart/Germany

The VKB and VKD units are designed as 4-pipe system. However, due to limitations they are installed in the IW as a 2-pipe system. The heated and chilled water to the units is tapped of the supply to the existing radiant heating / cooling system in the IW. As a result, the temperature of the water supplied to the fan coils is the same as that to the radiant system requiring the chilled water supply temperature to be controlled above space dew point. The temperature of the supply water is controlled by the existing controller in the IW.

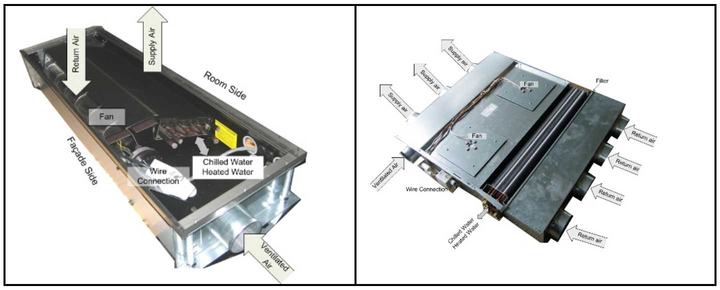


Figure 2: LTG Fan Coil Type VKB (left) LTG Fan Coil Type VKD (right)

SENSOR INSTALLATION

Each space is equipped with sensors to measure the thermal environment including temperature sensors, humidity sensor (also outdoor temperature and humidity), occupancy sensor, radiant temperature sensor, lighting sensors etc. Supply and return water temperature and water flow are also monitored for each space individually. The test spaces are in open plan office; therefore, in addition to installing sensors in test spaces (the target control zones), sensors are installed at the boundary of test spaces and in the adjacent spaces.

In figure 3, a schematic floor plan of the test-bed is presented. A description of the sensors at each locate is: *Location A (Test space):* setpoint air temperature, air temperature (0.6m, 1.1m, 2m), relative humidity (1.1m), occupancy, carbon dioxide. *Location B (Façade):* Surface temperature of the window glass, radiant temperature (of the entire façade in the space), solar radiation (measured by a light sensor facing outward). *Location C (Outdoor):* Outdoor air temperature and humidity. *Location D (Boundary of the test space):* Air temperature (2m). *Location E (Adjacent space):* Air Temperature (2m, at the center of the space). *At the Fan Coil Unit:* Fan speed (0/1/2/3/4/5), supply water valve, discharge air temperature, and return water temperature. A data acquisition board with 32 analog inputs, 2 analog outputs and 8 digital inputs and outputs is used in each space. Control and data acquisition functions are programmed using software running on a desktop computer.

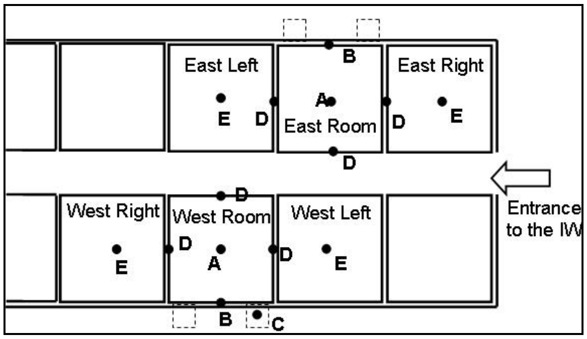


Figure 3: Schematic floor plan of the South zone showing the location of the sensors.

THE CONTROL ALGORITHM

In this work, the controller is comprised of two integrated components (Figure 4): (1) a model based feedforward algorithm that generates a control signal based on measurements of disturbances that affect the thermal state of the space; (2) a conventional feedback algorithm that generates a control signal based on measured system variables (e.g. space air temperature).

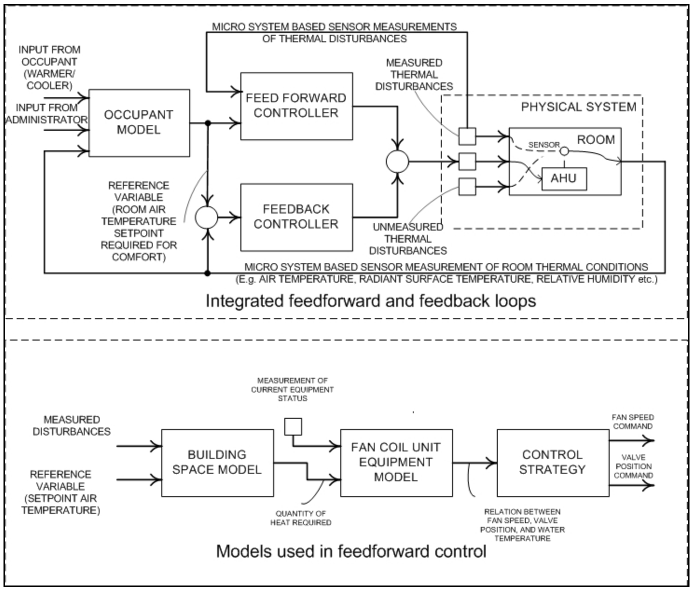


Figure 4: Schematic description of integrated feedforward and feedback loops

The feedforward [11,12] control loop addresses disturbances that are measured and whose affect on the thermal state of the space is known, e.g. solar radiation. The feedback control loop operates on the difference of the expected output from the feedforward loop and the actual measured output from the building space. Therefore, this loop addresses disturbances whose affect on the thermal state of the space is not known or are not measured.

THE FEEDFORWARD COMPONENT

In this feedforward component, beyond measurements that are typically used in HVAC control, additional sensor inputs (e.g. solar radiation, carbon dioxide) are incorporated. These provide information on the building space operating parameters. The feedforward component receives as inputs the values of the measured disturbances as well as the air temperature setpoint. The setpoint is generated by the component described in Section "Calculation of Setpoint Temperature". The feedforward component further comprises of two sub components that contain a steady state mathematical model of the process – Building Space Model and a Equipment Model. These models are mathematical equations that characterize the building space and the equipment. These are described below:

Building Space Model

The first step in the feedforward component is to determine the space load – the amount of energy that must be added or extracted from the space to maintain the setpoint air temperature [13]. A model of the physical characteristics of the space is inverted, exercising this inverted model of the space and using as inputs the reference variable (the setpoint) and the measured values of the disturbances that affect the thermal state in the space, delivers the amount of thermal energy required in the space to counter those disturbances.

The building space model contains descriptions of space geometry, fenestrations details, and material properties of the space being controlled. A lumped component model is used to simplify the behavior of the spatially distributed systems.

Equipment Model

The second step translates the space load to a load on secondary equipment [13]. Fan coil units supply air and thermal energy to the building space that affects temperatures and humidity. Fan coil unit models are created based on performance data from manufacturers, engineering fundamentals, and lookup tables. When exercised in the forward direction this model of the fan coil unit provides a calculated value of the thermal energy delivered by the fan coil unit to the space under specific conditions.

In this control algorithm the inverted form of the model of the fan coil units is exercised. Using as inputs the quantity of thermal energy required and the current operating state of the equipment it is possible to obtain an estimation of the actuation for the fan and the valve required.

The third step [13] in this component is to calculate the fuel and energy required by the primary equipment to meet these loads and the peak demand on the utility system. However, as the test-bed is in a campus setting where chilled and heated water are supplied by a central plant serving multiple buildings, control of primary equipment although considered was beyond the scope of this work.

THE FEEDBACK COMPONENT

The feedback loop takes into account disturbances that cannot be measured although they do affect the space, e.g. door aperture in a closed office. The feedback component incorporates a PID [14] controller that operates on the difference of the reference variable and the actual measured output from the building space. Such an implementation allows the feedback loop to compensate for inaccuracies in the models, unmeasured disturbances and for errors in measurements. The feedforward loop operates with rapid short term actions, leaving the longer term effects to be dealt with by the feedback loop.

THE FCU CONTROL MODULE

There are 3 handles to change air temperature in a space – fan speed (to control discharge air volume) and valve position (to control water flow rate in the fan coil thereby affecting discharge air temperature) in the fan coil unit, and the supply water temperature to the fan coils. The output from the feedback and feedforward components described previously is required to be translated to control these 3 handles. The actuation signals from the feedforward component and the feedback component are averaged and sent to HVAC equipment serving the building space. Presented below are strategies to actuate these handles:

Fan Coil Unit Fan and Valve Control

In the cooling season, an increase in the temperature drop in chilled water across the chiller decreases the chiller operating costs while also decreasing pumping costs – the higher the temperature drop, the less water needs to be pumped with the assumption that the space thermal load is satisfied. Therefore, an objective is to maximize the temperature drop.

Control Strategy 1: the fan and valve in the fan coil units are controlled together using the same control loop output – simplifying the control algorithm.
Control Strategy 2: the principle of a thermostatic valve is used with the objective of ensuring a constant return water temperature that minimizes water flow and chiller power.
Control Strategy 3: the valve and fan are controlled in sequence. The valve is actuated first while the fan speed is kept at a minimum. If comfort conditions are not met after a specified time, then the fan speed is increased. This strategy provides acoustic advantages by minimizing fan speed.

Supply Water Control

The fan coil units are supplied with heated and chilled water from a central system that supplies multiple such sets of fan coil units. Two handles exist to control this central system – the temperature and the pressure of the water supplied. Presented below are strategies to control these handles, although they are not implemented in the experiments performed in this work.

Supply Water Pressure Control –

Control Strategy 1: The differential water pressure is determined based on the fan coil unit specifications.
Control Strategy 2: In this strategy the differential water pressure is set to maintaining the average position of all the valves in the space at 50% thus providing the greatest adjustability of temperature at individual spaces. Possible limitations exist for this strategy includes non-linear operation and hysteresis of the valve.
Control Strategy 3: A third strategy for a given water temperature set point is to set the differential pressure set point to maintain all discharge air temperatures (to satisfy the load) with at least one control valve in a saturated (fully open) condition.

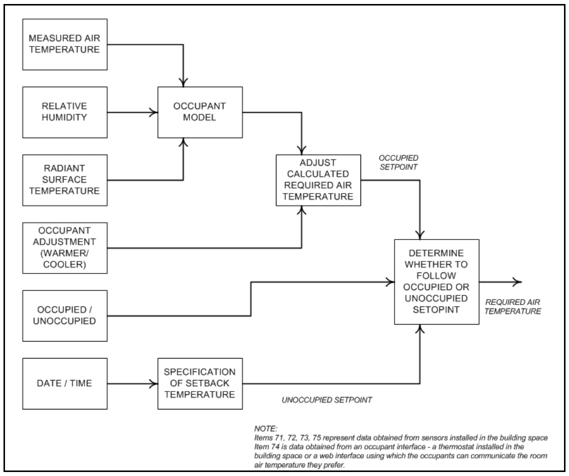
Supply Water Temperature Control –
The optimal water supply temperature at a given load results from a tradeoff between chiller / boiler power and pumping power. In order to minimize power consumption at the chiller plant, supply water temperature should be maximum in the cooling season and minimum in the heating season while satisfying the space thermal load [15]. The control strategy should guarantee that all fan coils will always be satisfied.

Control Strategy 1: In this strategy the supply water temperature is determined as a function of measured outdoor air temperature providing a level of feedforward control.
Control Strategy 2: In this strategy the water temperature is set based on keeping fan speeds of all FCUs in the space at minimum providing an acoustic advantage.

Traditionally, if even the most open fan coil valve is less than 90% open, the set point for supply water is increased (in the case of chilled water); if the valve opening exceeds 90%, the setpoint is decreased. A valve could be stuck, therefore FCU discharge air temperature is also monitored. In the absence of a fault, if one of the valves is consistently 100% open, this could indicate a design fault.

Ventilation Air Damper Control
The control of this damper is based on real time measurements of carbon dioxide, volatile compounds and carbon monoxide compared to established standards for these parameters as wells as the presence or absence of an occupant.

CALCULATION OF THE SETPOINT TEMPERATURE
This section describes the component for determining the setpoint temperature (the reference variable) as shown in figure 5.



NOTE:
Items 71, 72, 73, 75 represent data obtained from sensors installed in the building space
Item 74 is data obtained from an occupant interface - a thermostat installed in the building space or a web interface using which the occupants can communicate the room air temperature they prefer.

Figure 5: A block diagram of a process to determine air setpoint temperature using an Occupant Model

Calculation of Comfort Temperature
Traditional HVAC control systems determine the required air temperature based on a preset value (e.g. set by the building manager) or by a set point specified by the occupant (e.g. occupants sets the temperature on a thermostat to 72F). In this work, instead of only air temperature, a process is used that better represents if a person is comfortable to determine required air temperature. Given a measurement of the current air temperature in the space, relative humidity and radiant surface temperature, it is possible to calculate the air temperature required based on established standards (i.e. a model of the occupant). A seasonal component is also included in the calculation.

The occupant's input of warmer or cooler (using a physical knob or a software interface) is used to modify the calculated required air temperature.

Calculation of Setback Temperature
Control of individual fan coil units is further determined by the presence or absence of an occupant and time of day (within work hours / outside work hours). E.g. if the space is unoccupied during work hours, the required air temperature will be setback to ensure fastest response time, whereas outside work hours the required air temperature will be setback further to minimize energy usage. In this situation preference is given to the setpoint set by central controller.

For reduction in energy usage it is desirable that the band for setback temperatures is as wide as possible, and comfort conditions are met as soon as possible, while observing constraints for discharge air temperature and equipment capabilities.

Administrator Inputs
Administrator inputs include those from a building manager as well as those from a control process operating at a higher level.

These inputs may specify thresholds and constraints for performance, peak demand limiting and energy effectiveness while considering the overall system. This may be included in the process to determine the setpoint by setting upper and lower limits on the setpoint.

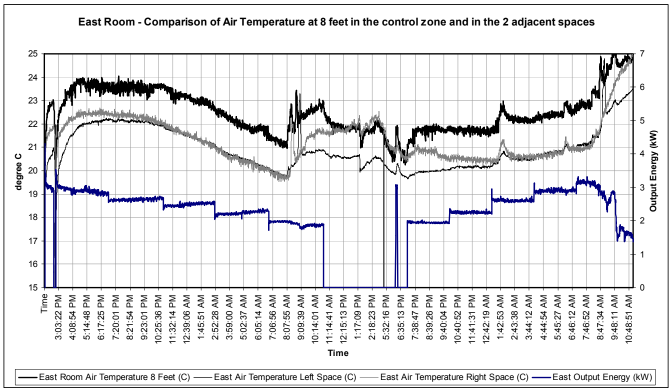


Figure 6: Comparison of air temperature at 8 feet in the control space and adjacent spaces with variation in fan speed.

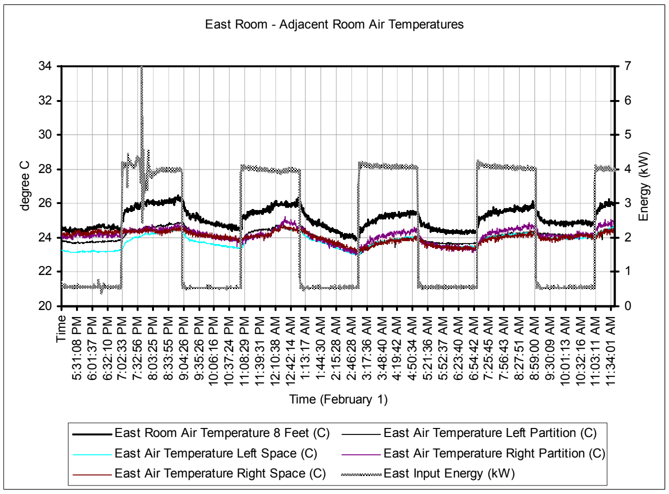


Figure 7: The impact on space air temperature in the control zone as well as in the adjacent spaces is apparent as they follow the square wave of input energy very closely.

RESULTS AND CONCLUSIONS

In this section, a brief overview of the results is described. The data collected (figures 6 and 7) from the experiments was used to determine improvements of this advanced control over traditional methods. The data was also used to determine the sensitivity to sensor location and accuracy.

The test-bed has low thermal mass and large glass area. It was found that measurement of solar radiation is critical. Based on the thermal response time of the space determined under various conditions, the feedforward strategy revealed the necessity in the test-bed to overcool the space in the summer in the morning, before the occupant arrived to account for thermal gain during the day. Night time cooling was activated when outdoor conditions were appropriate.

With integrated feedforward component, the feedback control only changed its output by an amount equal to what the feedforward component fails to correct. The high thermal inertia (because of the open plan office condition) further demonstrated the value of the feedforward component.

MERITS OF THIS WORK

The overall merit of this work is in its ability to demonstrate a system that increases comfort by giving occupants control over the thermal environment in their workspace while maximizing energy effectiveness. Specifically, in this work we develop and demonstrate a control algorithm to provide for individual control over the thermal environment in open plan office spaces. This is more complex than traditional HVAC applications as control algorithms are required to satisfy multiple and often contradictory constraints. The dynamic thermal interaction in open plan spaces is complex and critical for achieving comfort conditions. These are multiple control zones with high degree of interaction between them. Therefore there are a greater number of variables and unknowns. Furthermore, the response characteristics of the building thermal environment vary for different conditions caused by uncontrolled thermal sources affecting the space. This challenge is further amplified by the fact that the problem of controlling the indoor thermal environment is not just a problem of going from one steady state to the next but is dynamic for regulation in a particular steady state.

The use of “Comfort Temperature” increases comfort by using occupant input to modify the required air temperature that is calculated based on established research in thermal comfort. Furthermore, this reduces energy usage, e.g. – using higher air temperature and lower humidity during cooling season. Set-back temperatures further reduce energy use during unoccupied periods while minimizing response time when an occupant enters. The integration of air quality sensing provides increased levels of air quality through active sensing and ventilation control while minimizing energy use.

Integration of feedforward and feedback control loops provides improved building operation. The major contribution of this method of model based control is the reduction in peak demand brought by the ability to predict loads and disturbances and to take immediate action to counteract these. Common control strategies are designed to only arrive at and maintain a set point, whereas the strategies developed in this work add features of satisfying multiple criteria of occupant comfort and energy usage. This reduction in energy usage is made possible by the ability of the control algorithm to use large quantities of data from sensor networks, distributed in space (inside and outside a building) and measuring various quantities (temperature, humidity, flow, illumination etc.), to effectively be used to obtain detailed knowledge about the operational characteristics of the building systems thus enhancing overall building operation.

FUTURE WORK

Open issues at this stage of the work include a detailed examination of the models used in the feedforward component to determine the benefits of updating the model in real time based on system performance. In the future, predictions from a weather information service will be included.

The work described in this paper is a part of a larger research objective to study advanced control systems for office buildings for heating, cooling, and ventilation and lighting functions with an emphasis on maximizing the use of natural and sustainable methods. This work is to serve as a stepping stone towards the control of fan coils in multiple offices integrated with the control of the ventilation system, radiant heating water mullions, electrically operable windows and light re-direction blinds and louvers. Furthermore, it is proposed to integrate IP phones to function as occupant interfaces for communication among occupants and administrators, for effective office environment operation. Using the phone interface the occupants will have the ability to specify temperature setpoints and control the lighting levels in their workspace as well as give feedback to the administrator on whether they are comfortable.

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