Supervisory Control for Energy Savings and Thermal Comfort in Commercial Building HVAC Systems

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Abstract

The operation and maintenance of commercial building HVAC (heating, ventilation, and air-conditioning) systems is illustrative of an industry that can benefit from the insightful use of all available information sources. Modern HVAC systems using direct digital control can potentially provide useful performance data. Occupant feedback complaint data and HVAC system trend data are stored within modern maintenance management databases. This paper will address the specific issue of integration and application of these fundamental sources of information, using some modern and novel techniques. Examples are found in, but are not limited to the following areas: discrete-event, continuous, and hybrid control system theory, artificial intelligence, statistics, system identification, databases, etc. Methods specific to these areas can be used to synthesize a supervisory controller. The objective of this controller is to reduce energy costs, improve building occupant comfort, fault detection and diagnostic capability. At the same time, the entire process needs to be stable, and the influence of occupant behavior needs to be taken full advantage of. The controller will achieve these objectives by performing and/or prioritizing the appropriate actions to be taken either automatically or by facility operators. Furthermore, the cost and scalability of the entire effort described can be positively influenced by recent technological advances in computing power, sensors, and databases.

Introduction

Energy savings and thermal comfort are important to both facility managers and building occupants. As a result new innovations in the field are constantly under investigation. Many facility managers are charged with the operation of a hybrid mix of building types and HVAC systems. Additionally, specific nuances such as varied zone heating/cooling requirements and other disturbances need to be handled properly. They may include the geographical climate, weather, seasonal changes, as well as building occupancy trends due to varied shifts and operating schedules. A volatile energy market exists in the U.S. due to the current or incipient deregulation of utilities. Therefore, the cost of energy and pricing rate structures is another variable that all building managers and their technicians must contend with.

There are several business processes and physical operating systems which are often mapped onto management information systems. Hence repositories of information sources are not necessarily linked and used as interdependently as they should. When they are, it is more often on an ad-hoc/heuristic basis. Reduced potential cost savings may result from the sub-optimal use of these information-rich sources. Recent technological advances may also be used to achieve the desired objectives of reduced energy usage and improved building occupant thermal comfort. To address this, the primary goal of this paper is to do the following:

- Illustrate some of the current issues in commercial building HVAC systems.
- Discuss some of the current research efforts which address improvements in the operation of commercial building HVAC systems.
- Investigate how the treatment of existing unresolved problems should evolve, so that the gap between current practice and research efforts can be minimized.

Current Industrial Practice

This section provides an outline of the language used to characterize future developments in energy usage and thermal comfort.

Historical Treatment

Historically, there have been advances made in how to treat the issues of energy, thermal comfort, and commercial building HVAC systems. The concepts and ideas that set a baseline for how the HVAC/facility management industry perceives these issues will be covered in this section.

Energy Commercial building HVAC systems consume large quantities of electricity. Therefore it is paramount for facility managers to take advantage of lower energy rates and more advantageous rate structures. Typically, electricity bills consist of many different components. There is usually a fixed service charge, in addition to a per kW-h (kilowatt-hour) rate charge for the amount of energy consumed. There is also a demand charge based on the peak electricity usage averaged over a short time period per billing period.

With the advent of deregulation, other rate schedules are becoming available, such as the time-of-use rate and real-time pricing. The time-of-use rate varies the demand and rate charge pricing, typically according to season and/or time of day. With real-time pricing, customers may be able to obtain wholesale prices hours in advance of them going into effect. Therefore, higher rates can be anticipated and appropriate actions can be taken to reduce energy costs. However, this will require more sophisticated hardware and software than may currently exist. Computerization of energy usage and price tracking may become necessary to be on par with a real-time pricing schedule.

Although pricing is important, it is one among many factors that influence energy usage. Consideration should be given to the weather, building area changes, operations and schedule changes, and changes in building equipment. They all drive current and traditional methods of energy conservation.

Thermal Comfort Historically, there have been many studies pertaining to thermal comfort of building occupants. However, none have set the baseline for how thermal comfort is measured as much as the largely celebrated work performed in the early 1970's (Fanger 1972). Fanger's PMV-PPD model has been widely accepted for design and field assessment of comfort conditions. It is the industry standard for measurement of thermal comfort, as set forth in ISO Standard 7730 (ISO 1994).

The following are definitions of PMV and PPD:

PMV predicted mean vote, predicts the subjective thermal sensation rating of a large group based on 6 variables (4 environmental, 2 personal) that affect the human heat balance:

1. Activity . . . . Personal
2. Clothing . . . . Personal
3. Air Temperature . . . . Environmental
4. Mean Radiant Temperature . . . . Environmental
5. Relative Air Velocity . . . . Environmental
6. Air Humidity . . . . Environmental

Quantitatively, PMV is measured on the ASHRAE thermal sensation scale (ASHRAE 1997), ranging from {-3 . . . 3} as follows:

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

PPD predicted percent dissatisfied, predicts the expected fraction of a large group that will align with a subjective assessment of hot or cold above an absolute PMV level of 1.5 scale units (between slightly warm and slightly cool). It is basically an expression of 'potential complainers'.

Even though this scale is a nice characterization of thermal comfort, building occupants are different in their tolerance levels and there is naturally a certain variance in the thermal sensations of a group. Fanger's studies revealed that any complaints, however few, are often taken as an indication that the HVAC system is defective, or at least badly operated. As a result, facility operating personnel will often expend man-hours in response to that complaint. The corrective action is often to change the thermostat setting simply because of complaints of *individual* persons in a large group. So therefore these particular persons will perhaps be satisfied, but on the other hand, others may become dissatisfied. As a result even a larger number than before may complain.

A natural question then arises: Should facility operators change the thermostat setting in response to thermal sensation complaints ? We might consider that 'warm and cold' dissatisfied levels are associated with the *average* or *majority* response of a group of people in a zone, rather than with a single individual. Perception of temperature is influenced by uncontrollable and unpredictable changes in metabolism, clothing, posture, attention to the environment, task requirements, etc. We'll discuss specific methods of responding to complaints in more detail based upon modeling these random components later.

Commercial Building HVAC Systems The evolution of design, operation, and maintenance of buildings has changed significantly in the past 20 years since the advancement of controls/AI technology. In a recent paper, (Moult 2000), a review of modern DDC was provided. Before 1980, almost all HVAC controls installed in large commercial buildings in North America were pneumatic. They lacked in functionality due to their inability to directly control the actuator and potential bias introduced by the dynamic physical properties of pneumatic components. The DDC controller replaces the function of pneumatic components; signals are digital rather than pneumatic, and building automation systems control the actuator directly.

The advancement of information technology and databases over the past decade has also seen quite an improvement. This has been very important in the maintenance sector of the commercial building HVAC industry. Often, tracking of corrective and preventative maintenance labor and material costs had been difficult. Costly overruns and lack of real-time and accurate information on system status prevailed due to decoupled information repositories. Newer more robust maintenance management systems take advantage of the power of relational databases. These systems allow for more accurate and reliable information tracking capabilities. Fewer cost overruns, human errors and faults in HVAC systems can be attributed to lack of real-time information and unmanageable information sources.

Hybrid problems

Here we provide a comprehensive list of hybrid problems that result from the intersection of the issues discussed thus far.

- A structured, analytical yet practical approach to finding a balanced, optimized tradeoff between energy savings and thermal comfort costs does not exist.
- High maintenance costs are commonplace due to lack of adequate preventative measures, fault detection and diagnosis capability, and prioritization planning for fixes.
- High maintenance costs also stem from duplicated efforts in responding to complaints whose cause is classified incorrectly, or not at all.
- There exists an inability to develop a structured, theoretically sound yet practical approach to responding to complaints caused by a building operation policy mismatch with occupant thermal comfort.
- The development of on-line tuning rules is necessary to improve response to control performance-related building occupant complaints.
- There exists an inability to manage the task of linking, consolidating and streamlining all available information sources to solve these problems in a practical manner.

Current Research Efforts

Energy

Passive Solutions There are currently many research efforts investigating the use of passive or natural techniques in building design to achieve both thermal comfort and energy objectives. Architectural and structural design are the subject of studies performed (Zmeureanu & Fazio 1989; Andresen & Brandemuehl 1992; Shaw, Treadaway, & Willis 1994; Russell & Surendran 2001) that provide examples of the impact of design on energy consumption and thermal comfort. Other studies (Reddy, Norford, & Kempton 1991; Seem & Braun 1991) present ideas to save energy by using peak-load shaving. These methods appeal to the intelligent use of building thermal mass, involving pre-cooling of the structural thermal capacitance and furnishings.

Active Solutions Active solutions can provide alternative methods where analyses and optimization become useful for the purpose of energy reductions. Optimal control is investigated as a method for achieving reduced energy usage and improved building occupant thermal comfort for thermal energy storage systems (Braun 1990; Price & Smith 1998; Henze, Dodier, & Krarti 1997). Optimal controllers are hailed as the theoretical upper bound (best possible) for achieving their specified objective, minimizing some given cost function by the use of dynamic programming. A typical cost functions is as follows:

$$J = \sum_{k=0}^{L} R_k P_k \tag{1}$$

where k = hour of the day, L = Total number of hours in simulation, R_k = Cost of electricity at hour k, and P_k = Plant's electric power consumption at stage k. In some cases P_k is a function of other variables, such as zone temperature, other uncontrolled variables, or broken down into more tangible elements such as fan, heating, and cooling power. Finally, J = Cost of operating plant for the length of time given by L.

The optimal solution can apply to a specific type of pricing rate structure and HVAC system. It may provide charging and discharging strategies for a generic thermal energy storage system or even zone temperature setpoints for various other types of HVAC systems. There are some obvious limitations in the literature as to the types of systems, operational modes, etc., which these methods have been applied to. A more general framework needs to be developed, including the use of a broader range of information types. The practicality of using of optimal control is currently not warranted because more simple PI controllers can do the job for most buildings with less computational memory and processing requirements. However, perhaps only with more generality and data mining may it be considered as a necessary tool.

Thermal Comfort

General Thermal Comfort Fanger's PMV index has been the hallmark of many research efforts to develop improved methods to provide comfortable environmental conditions for building occupants. Unfortunately, measuring PMV for use in a control system is a difficult task. This has been addressed by the use of many sophisticated techniques (Sherman 1985; Federspiel 1992) including fuzzy logic (Hamdi, Lachiver, & Michaud 1999). However, we may use building occupants as a source of information to qualify and quantify their *own* comfort levels. Thermal sensation complaint data exists within the databases of maintenance management systems and is ubiquitous, 'free' data. It also provides an indication of comfort *directly related* to the human condition. Therefore building occupant feedback, whether solicited or unsolicited can be thought of as information that may suitable for use in a feedback control system. Although it is not directly measurable, or quantifiable with the PMV index, there might exist some unexplored ways to shape and consolidate this data.

Unsolicited Occupant Feedback Recent work (Federspiel 1998) provides a preliminary treatment of the impact, statistical analysis and use of occupant feedback. The study presents a comprehensive examination of thermal sensation complaints taken from a large empirical dataset from operating buildings. This includes measurements of frequencies and statistics of temperatures, response times, and actions taken in association with complaints found in logs. Later, a statistical model based upon level-crossing theory was presented (Federspiel 2000) to develop a way to predict the frequency of hot and cold complaints. The parameters of interest are the frequency (ν_T), mean (μ_T), standard deviation (σ_T), and standard deviation of the rate of change ($\sigma_{\dot{T}}$) of temperatures at which building occupants complain of being too hot or too cold.

Theoretically, we can think of there being 5 processes in this model. The main process is the building temperature, and each hot and cold complaint level has 2 processes associated with it as follows:

Complaint Level or Process A continuous process representing the fictitious statistically-based temperature level, a ‘control alarm’ of sorts, that the majority of building occupants in a zone complain at when too hot or cold.

Complaint Events A discrete random sequence which represents the exact instants in time at which the building occupants complain of being to hot or cold. This process coincides with the building temperature at these particular instants.

Figure 1 is provided to aid in illustrating the concepts stated above.

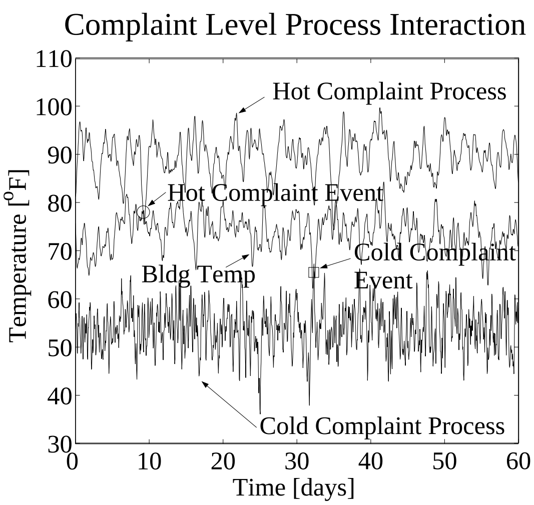

Figure 1: Plot of Complaint Process Interaction with Building Temperature

Essentially, the continuous complaint level statistics are unknown model parameters which cannot be measured and are shown in Table 1 (capital subscripts used for continuous levels).

	Mean of T[a]	**Standard Deviation of T**	**Standard Deviation of $\dot{T}$**
Hot	μ_{HT}	σ_{HT}	$\sigma_{\dot{T}_H}$
Cold	μ_{LT}	σ_{LT}	$\sigma_{\dot{T}_L}$

[a] Refers to an arbitrary complaint temperature level

Table 1: Table of Non-Measurable Complaint Model Parameters

Estimates of the non-measurable model parameters in Table 1 are mathematically based upon the measurable statistics shown in Table 2 (lower case subscripts used for discrete event processes and capital subscripts used for continuous levels).

Formulas relating the model parameters in Table 1 to the measurements in Table 2 can easily be derived. The usefulness of this model is that the performance of the temperature control system can be characterized by the measured building temperature statistics, and the mathematical model

	Frequency	**Mean of T**	**Standard Deviation of T**	**Standard Deviation of $\dot{T}$**
Hot	ν_h	μ_{hT}	σ_{hT}	
Cold	ν_l	μ_{lT}	σ_{lT}	
Bldg		μ_{BT}	σ_{BT}	$\sigma_{\dot{T}_B}$

Table 2: Table of Measurable Statistics

relates them to complaint levels. Therefore, this work provides a very useful benchmark for future work in developing new algorithms and policies for the purposes of achieving the main objectives.

An example of this is presented (Martin, Federspiel, & Auslander 2002; Martin 2000), where computer simulation methods were used to compare two different strategies for responding to unsolicited thermal sensation complaints in buildings. The model described was used to simulate complaint behavior, and significant modeling detail of a single-zone space was simulated as well. The key objectives in this simulation study were to show that an alternative ‘new’ strategy performed better under normal operating conditions than policies that are typically used today in industry.

The scope of this study provides an example of operational innovation and use of building occupant feedback via complaint data. Unfortunately, the techniques involved off-line as opposed to on-line optimization, and the results are limited to the specific modeling parameters, operating conditions and objectives. However, it does provide an original method demonstrating how complaint information can be used in an operational setting.

Commercial Building HVAC Systems

There is certainly room for innovative ideas and theories to be developed in order to improve overall HVAC system advancement and utilization. Recently published literature (Moult 2000; Seem, House, & Monroe 1999) addresses new technology and the potential for the use of available information sources using fundamental ideas. A new ‘control performance monitor’ implementing a basic averaging algorithm to compress and integrate large amounts of data was presented. Condensing data will allow building operators to identify HVAC equipment that is wearing prematurely due to excessive movement. Other indicators include control system temperature error and airflow damper position (also called variable air volume or VAV box) error, whose out-of-limit values might indicate either unstable or poorly tuned PI controllers. Basic indicators such as these may also help to aid facility operators to prioritize maintenance for HVAC system components. These performance indices may also be useful in a real-time fault detection system, aided by comparison of stored data in an expert system database. This idea is an excellent way of consolidating information, and practical implementation is not a roadblock since the algorithm requires so little memory. However, the scope of indicators used might be broadened, including metrics addressed in other work, (Martin, Federspiel, & Auslander 2002) and perhaps even other new more insightful ones.

Hybrid Issues

Attempts to link together several common problems with the control of HVAC systems from an enterprise-level standpoint has seen some interesting treatment in research (Shoureshi, Torcellini, & Rahmani 1992; Teeter & Chow 1998; van Breemen & de Vries 2001). The integration of multiple methodologies to achieve our main objectives may involve ANN's (artificial neural networks), fuzzy logic, optimal control, and is implemented hierarchically. Systems can 'learn' the characteristics of the building and determine the best strategies regardless of building type, HVAC system type, disturbances, etc., by using a supervisory controller.

A divide and conquer approach was proposed to develop a system-level solution by *structuring* each of the problems coherently. In doing so, the concept of autonomous agents in the field of AI (artificial intelligence) is employed. Each agent has its own purpose, and combining them together by highlighting all dependencies gives an aggregate approach to solving the problem. Objectives discussed earlier (Shoureshi, Torcellini, & Rahmani 1992; Martin, Federspiel, & Auslander 2002; Seem, House, & Monroe 1999) may be good candidates for this independent agent-supervisory control methodology. Hybrid control theory may be used for stability analysis and supervisory control synthesis. These treatments are very comprehensive and do a good job of generalizing the plant in question. However, the thermal comfort penalty functions are not based upon measured complaint data.

Treatment of Existing Unresolved Problems

Supervisory Control

By definition, a supervisory controller should be much more than an open-loop coordinator of local controllers acting on off-line stored, in-active information, or optimization results. It should have this functionality by default, in addition to providing real-time on-line discrete enabling/disabling and continuous signals to its component controllers. The basic problem of supervisory control (Cassandras 1993) is to impose some closed-loop control on a hybrid system so as to force some desirable behavior of the system as a whole, and all of its constituent parts.

New Opportunities

Occupant Feedback The issue of how occupant feedback can be used as a viable information source to improve thermal comfort and reduce energy usage is still an open research question at this point, and requires further in-depth study. It can potentially be used to complement the standard air temperature measurement to achieve the desired objectives. Measurement and regulation of air temperature is typically implemented according to some time domain performance specifications and tuning of PI gains, using the structure provided by control theory.

In order for the 'measurement' of occupant feedback via database repositories to allow for regulation of thermal comfort and energy usage, a similar structured theory needs to be developed. The question is: what is this structured theory, and how do we use/process the complaint information ? Perhaps a combination of methods among multiple areas, such as from hybrid controls, (van der Schaft, Schumacher, & Schumacher 2000), AI, and statistics needs to be employed. The problem is that we don't really know how to use this information in a theoretically optimal fashion yet, in order to automate or provide facility operators with the best possible actions to achieved the desired goals. Our aim is to make progress towards answering these questions.

Optimization The use of optimal control to achieve the goal of reduced energy and thermal comfort has been proposed in several research studies. Most clearly, we've seen the use of dynamic programming to solve the optimization of the cost function presented in Eqn. 1, posed as either a constrained or unconstrained problem. Both methods are valid candidates for further study. In the unconstrained optimization problem, we can consider the linear combination of penalties on energy and comfort costs. Additionally, we propose that the comfort penalty be based upon the complaint model presented before (Federspiel 2000). Hence the optimization problem can be posed as follows:

$$J = \sum_{k=0}^{L} \gamma_1 R_k P_k \quad \gamma_2 C_k \tag{2}$$

where k, L , R_k, P_k, and J are as in Eqn. 1. C_k = Cost of complaints predicted by complaint model, and γ_1, γ_2 = weighting factors associated with energy and complaint/comfort costs, respectively.

Alternatively, if considering a constrained optimization problem, we may use thermal comfort as the primary constraint, again appealing to the complaint model presented earlier. The resulting optimal control law commonly provides a control signal to the plant. Alternatively, a thermostat setting strategy might be proposed to achieve the optimal control objectives. However, there may be other setpoints such as VAV flow controllers, chiller setpoints, etc., for which similar optimal strategies may be derived. It's best to keep the optimization as general as possible so that the methods are applicable across a broad scope of plant types. Hence, we must find a solution to the following:

$$\min_{\mu_{\mathbf{X_L}} + \mathbf{L_L Z} \leq \mathbf{X_r} \leq \mu_{\mathbf{X_H}} - \mathbf{L_H Z}} J \tag{3}$$

where the inequalities shown in the constraint above are element-by-element inequalities, and:

$\boldsymbol{X_r}$ = Vector-valued random variables associated with all 'system alarm' (including complaint) setpoints having vector-valued windows of acceptable values $\boldsymbol{X_L}$ and $\boldsymbol{X_H}$

Z = Vector of n Standard Normally Distributed Independent Random Variables

$\boldsymbol{L_L}$ = Cholesky Decomposition of covariance matrix of system alarm setpoint variances

$\boldsymbol{L_H}$ = Cholesky Decomposition of covariance matrix of system alarm setpoint variances

Note that the choice of the constraints is somewhat artificially based upon the statistics of the complaint or alarm model. More research needs to proceed in this area for full realization of the potential of this alarm level-based constraint.

We also assume that all variables of interest (the system 'alarm' levels) are statistically independent and normally distributed. This assumption is not necessarily valid and provided for convenience of presentation. It will have to be validated or disproved in further work, although normality of complaint 'alarm' levels has been documented (Federspiel 2000). Another important consideration is that setpoint strategies are almost always discontinuous in nature. They occur as discrete events, not in a continuous fashion. Therefore, achieving the solution to the optimization problem may become much more difficult. This may be well served by current research efforts in the realm of hybrid control theory, such as methods described in recent literature (van der Schaft, Schumacher, & Schumacher 2000).

Complaint Modeling For most HVAC systems, the result of optimal control discussed in the previous section may include zone thermostat setting strategies. Therefore it is necessary to obtain the statistics used to generate the constraints of the complaint levels. If updated in a real-time setting, these statistics allow the predicted complaint model to achieve an adaptive on-line functionality. The complaint model becomes dynamic rather than static, and provides a partial solution to structuring and using occupant feedback in a theoretically suitable fashion.

However, complaint rates are often low, and the occupant feedback so sporadic that updating a complaint model adaptively may not have sufficient 'persistence of excitation' required for model validity. In this case, it might be feasible to pursue periodic occupant feedback via solicitation (potentially a questionnaire via a website interface). This would serve to supplement the incoming unsolicited data during 'slow' periods where there is a lack of existing information to update the model.

There are still other collateral ramifications of using occupant feedback. Bulk statistics may not always perfectly characterize the current thermal comfort levels, and building occupants cannot be modeled as perfect sensors. Occupants can learn to adjust their complaint behavior for a variety of psychological and sociological reasons. Hence we can only assume that measured data is based on normal behavior and any pathologies must be interpreted on an individual basis.

Unresolved Issues One of the many unresolved issues that are currently being investigated in the HVAC industry is FDD (fault detection and diagnosis) (Ahn, Mitchell, & McIntosh 2001; Chen & Braun 2001; Dexter & Ngo 2001; House, Vaezi-Nejad, & Whitcomb 2001). Although only briefly alluded to in this paper, it is a topic that appears to be of recent growing interest to facility managers, HVAC vendors, and researchers. In the brief treatment of FDD mentioned prior (Seem, House, & Monroe 1999), a new approach to using compressed volumes of data/information was useful. The addition of occupant feedback can potentially boost the capabilities of FDD, specifically in the area of classification. Expert system knowledge can be probabilistically modeled, if the maintenance management databases are sufficiently populated. Hence information about the existing causal relationships between occupant complaints and their potential reasons can be demonstrated. We recognize that the leading three causes of complaints can be classified as follows:

1. Poor control performance of local controllers.
2. Fault of any kind, ranging from 'soft' faults such as sensor miscalibrations to 'hard' faults such as chiller engine motors seizing.
3. Completely normal operation, where the complaint is due to building occupant disagreement with the standing facility operating policy (especially thermostat settings).

Fuzzy logic may be useful to classify the three categories for causes of complaints, since they are not necessarily mutually exclusive. In fact, there may be a degree of membership of each or any of the listed causes of a building occupant complaint. The 2^{nd} step after classification is to initiate a response of some sort, whether it is a single action, multiple actions with varying degrees of intensity, or a prioritization of potential actions to be taken as a result. All of these methods, including the use of occupant feedback for complaint model updates, adaptive optimization and fuzzy classification techniques will help to develop prioritization and response strategies. We'll need to aggregate the computation and implementation of these strategies through the use of a supervisory controller. From an organizational standpoint, the supervisory controller might relate to the remainder of the system as shown in Fig. 2.

The hierarchical structure of the supervisory controller may be tied together in the agent-controller fashion used in previous research (van Breemen & de Vries 2001), with multiple objectives achieved individually by each agent, and centrally coordinated. The analysis and synthesis of the supervisory controller for system stability and performance may be implemented with hybrid control theory.

Conclusion

- Occupant feedback can be structured and used as a viable source of information to achieve the objectives of improved thermal comfort, reduced energy usage, and greater FDD capability.
- The analysis and synthesis of a supervisory controller may utilize hybrid control theory concepts to achieve overall system stability and desired performance.
- A supervisory controller must also be designed to be applicable to a broad spectrum of disturbance patterns, operating conditions and modes, building and HVAC system types. At the same time it should be structured hierarchically, and use advanced AI agent-controller methodology and task coordination.
- The machinery of the supervisory controller involves the implementation of optimal control-based setpoint poli-

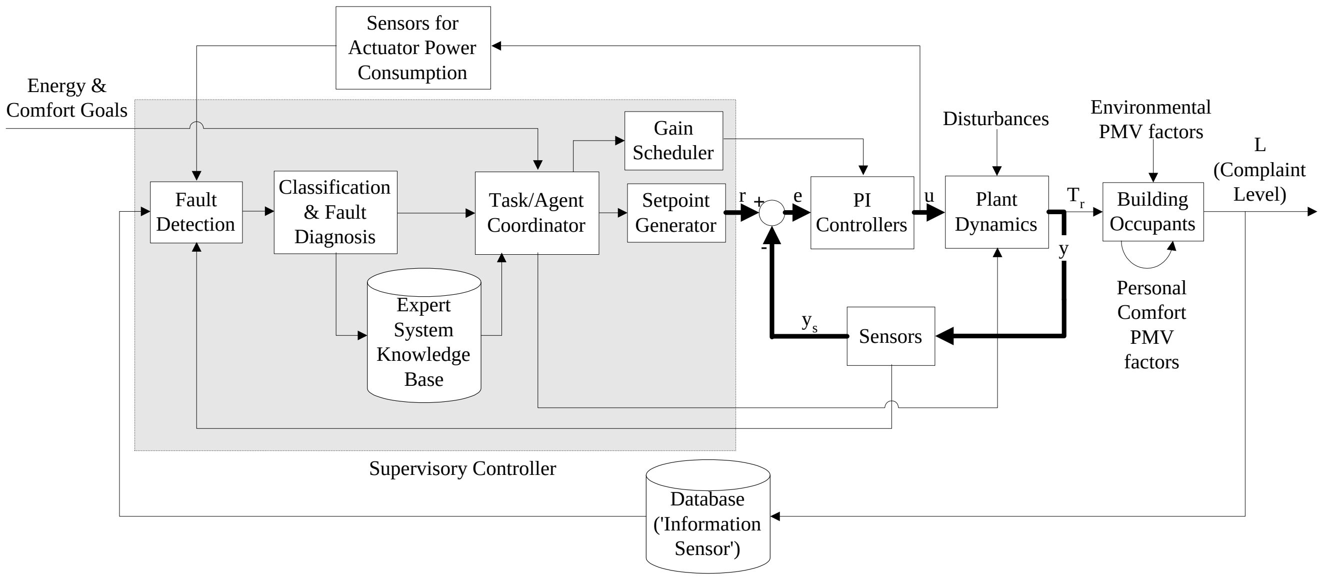

Figure 2: Supervisory Controller Block Diagram

cies, real-time adaptive PI gain scheduling, and complaint model updating.

- With the recent technological advances in computing processing power, sensors, and databases, DDC automation of these algorithms should become practically feasible.

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