A SURVEY OF CONTROL TECHNOLOGIES IN THE BUILDING AUTOMATION INDUSTRY

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Abstract: Advances in technology infrastructure such as communications, processing power, and data storage over the past several years have created new opportunities for the application of control and automation to many types of systems including those in buildings. This paper describes the state of the art for control in the building automation industry, and reviews new and emerging technologies. Issues specific to the building industry that impact the adoption of new control technology are also discussed.

Keywords: building automation, survey paper, control technologies.

1. INTRODUCTION

In the United States and other developed countries, about one third of all energy use can be attributed to buildings (EIA, 2004). The trend is also for energy use to increase because of the greater use of energy consuming devices inside buildings. A building automation system (BAS) usually refers to a network of control devices that govern the operation of diverse types of electrical and mechanical systems ranging from heating and cooling to access and surveillance. Because the BAS strongly influences energy utilization in buildings, its performance can significantly impact national environments and economies (Kohl, 2001). Demands on the performance of building automation systems are also increasing due to new environmental legislation, rising energy prices, and other changes in cost structures (Meckler, 1994).

Recent improvements in infrastructure technology are helping to meet some of the increasing demands being placed on building automaton systems. In particular, communications and networking technology has evolved considerably in terms of bandwidth and reliability while costs have decreased. These cost decreases have made it economically viable for building automation systems to have a digital communication network between most control devices. The industry is also moving toward standardization of communication protocols, which is making it easier to connect different types of controllers (e.g., ASHRAE, 2001). The ability to share information among controllers has created new opportunities for supervisory control and optimization that are only beginning to be exploited.

Relative costs of processing and storage capability have also dropped significantly over recent years. Control devices in buildings now have the ability to execute substantially more complex control algorithms than in the past. Improved storage capabilities also make it possible to perform functions geared more toward analysis in addition to control. For example diagnostics and performance analysis is a rapidly growing area that is utilizing the advances in processing and storage.

Another change that has been triggered by advances in infrastructure technology is for more controllable elements in a building to be incorporated in the building automation system. Beyond heating, ventilating, and air-conditioning (HVAC), building automation systems are now used to control diverse types of equipment including lighting systems, access and security, fire systems, etc. Also, the number of controllable elements within each category is increasing with such advances as automatic shading devices, fuel cells, solar collectors, and others.

One factor that is continually driving the evolution of building automation systems is cost. Compared with other large-scale applications such as chemical processing and power generation, buildings are low criticality applications where the scale is tipped more toward reducing costs than guaranteeing high levels of control performance. In the past, the capital cost of the BAS was the main consideration, but this is now balanced against lifecycle operating costs. Rises in energy prices and increases in service costs have affected the balance. The use of off-the-shelf technologies is helping to reduce capital costs while improvements in control algorithms are helping drive down operational costs. Legislation related to energy-efficiency and health and safety is also acting as a stimulus for change in building automation systems.

This focus of this paper is on control algorithms that are making use of the advances in the infrastructure technology in the building automation industry. Over the past couple of decades, building automation systems have evolved from being mostly scheduling devices with some analog-based feedback loops to fully networked digital control systems. The paper presents a sample of new and emerging control algorithms and technologies in building automation systems and also identifies some trends and issues that are affecting future development.

2. OVERVIEW OF BUILDING SYSTEMS

The term *building systems* is used here to refer to the electrical and mechanical devices that are controlled by building automation systems. According to traditional controls terminology, building systems thus represent the *plant*. Modern building automation systems integrate the control of a broad range of systems including HVAC, access, transportation (elevators/escalators), security, fire, utility services, etc. There is also a general trend toward the convergence of networking technology used for building automation and that used for other communication services in buildings. In the future, it is possible that building automation may become a general term that refers to any automatic process that is deployed across a single unified building communication network. However, the main function of today's building automation systems remains the control of the HVAC systems. These systems are used to maintain a comfortable indoor environment and good air quality for occupants under all anticipated conditions.

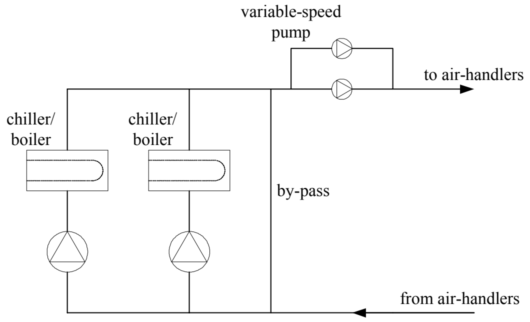

Fig. 1: Central plant example

In large buildings, the HVAC system can be broken down into three main groups of subsystems. The first group is often known as central plant and consists of large items such as boilers, chillers, cooling towers, etc, that are used to create heating and cooling capacity. Heat is transferred between the central plant and the second group of subsystems often known as air-handling units (AHU). Fig. 1 shows a schematic diagram of an example central plant that includes chillers/boilers, pumps and piping for fluid distribution. Examples of controllable devices in central plant include valves, pumps, variable speed drives, burners in boilers.

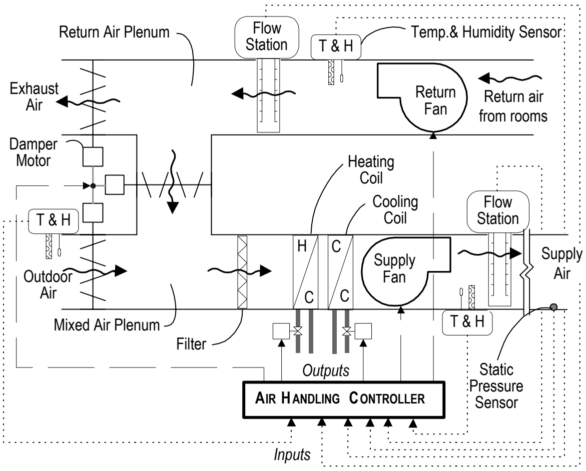

Fig. 2: Example variable-air-volume air-handling unit

The second group of subsystems is air-handling units, which provide air distribution in buildings and comprise systems such as fans, dampers, and heat exchangers, filters, humidifiers. There are two basic types of air-handling unit: constant-air-volume (CAV) and variable-air-volume (VAV). CAV units deliver air at a constant rate to the building spaces where VAV units vary the airflow depending on load conditions. Fig. 2 shows an example air-handling unit. The example unit includes heat exchangers that would receive hot or cold fluid (often water or steam) from the central plant. The supply fan moves air through the heat exchangers and also through filters.

The third group of subsystems comprises terminal units that are located in each treated space within a building. Terminal units are mostly associated with VAV systems and are used to adjust the temperature and flow rate of the air supplied from the AHU in order to meet load requirements. An example VAV terminal unit is shown in Fig. 3.

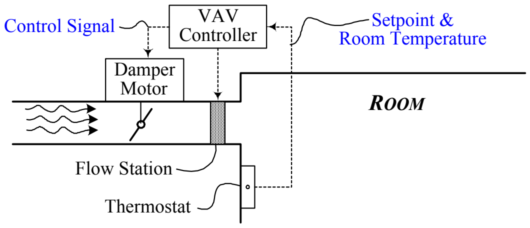

Fig. 3: VAV box and controller

The control of indoor environmental conditions in buildings is similar in many respects to other types of process control in that the objective is to control variables in dynamic systems via interfaces to the physical world in the form of sensors and actuators. However, there are certain features of building systems that will affect the design of control strategies and that may not be encountered in other applications. These features are listed below:

- Dynamic and static non-linearity, time variance, and frequent changes in operating point
- Information-poor data due to few and low accuracy sensors
- Poor resolution from A/D and D/A converters
- Poor sampling rates for trending and data analysis
- Lack of standard control logic, particularly at the supervisor level
- Interacting control loops

Despite the highly non-linear and time-variant nature of most HVAC system, PID control logic is used almost ubiquitously on all modulated devices causing control performance to be highly variable. Certain more critical loops, such as hospital operating rooms, might be retuned periodically, but often the effect of poor control performance is not apparent to occupants because of long time constants associated with the occupied spaces. For example, a cycling loop in an air-handling unit might lead to only very small fluctuations in the conditions of an occupied space.

The low-cost nature of the building industry also means that the number of sensors is kept to the minimum required for control. There is therefore very little redundancy in HVAC system sensor information, which can make it difficult to perform advanced features such as fault diagnosis. Cost constraints also mean that resolution can be coarse in D/A and A/D converters, which can lead to limit cycling in some cases. Most modern controllers allow data to be trended for later analysis, but a problem is often that data cannot be sampled fast enough to capture the dynamics of the faster responding systems. A typical sample period for trend data is one minute, which is too slow for the faster loops many of which can have time constants less than two minutes.

Another problem in building automation is the lack of standardization for control logic, particularly for supervisory functions. Control has evolved to be non-standard because building systems are heterogeneous in nature and every building might have different requirements. The fragmented nature of the building business whereby several contractors might be hired with overlapping functions has also contributed to this lack of standardization. A consequence is that control logic may contain unwanted interactions and conflicting functionality. However, the problem is being remedied slowly by the use of standard tools and design philosophies and improved coordination between contractors made possible by easier information exchange.

Outside of HVAC control, the other functions of modern building automation systems are mostly related to scheduling and event-based actions. For example, lighting control involves switching lights on and off based on occupancy sensors and timers. Fire abatement systems such as sprinklers also get triggered on events as does access control, which involves locking and unlocking entry points. Although control strategies for non-HVAC systems are generally primitive at the current time, these strategies are beginning to evolve allowing realization of untapped potentials for energy savings and improved coordination between systems (Shavit and Wruck, 1993).

3. LOCAL-LOOP CONTROL

Local loop control refers to maintaining a single variable to a setpoint by manipulating a single device, i.e., a SISO (single-input-single-output) loop. There are numerous examples of local-loop applications in building automation systems such as temperature, humidity, pressure, flow, etc. A specific example would be the regulation of a room air temperature to a setpoint by modulating an air-damper that affects the flow of conditioned air into the room. The device (or ‘plant’) in local loop strategies can be separated into two categories: modulating or switched. Modulating devices have an input with a continuous range (constrained between saturation limits) such as the position of a valve. In contrast, a switched device has a finite number of states such as on and off. In large buildings, the split is about one third switched systems and two thirds modulated.

3.1 Modulated Systems

The most prevalent feedback control law used for modulated devices in the building automation industry is PID (Geng and Geary, 1993). The derivative action is most often disabled and proportional-only control is used sometimes on loops where offsets can be tolerated. A problem with using PID control in buildings is that most systems are time-variant and are inherently non-linear. Control performance then varies as conditions change and loops may become sluggish or oscillatory at certain times. Gain scheduling is sometimes used to overcome non-linearity, but this is rare because of the time required to determine an appropriate schedule.

One way to address the local-loop control problem in building systems is to retune the controller when performance becomes unacceptable. A problem with this approach though is that it can be difficult to detect a badly performing loop. This is because only a few variables in a building will be monitored and the effect of one bad loop may be masked from these variables by other loops that will compensate. A manual analysis of variables in every control loop in a building is not feasible and many loop problems thus go undetected. Nevertheless, if poor performance *is* detected in a loop, the traditional approach is to retune it manually. Manual re-tuning is obviously time consuming and there has been an interest for some time now in automating the process. The research community has proposed several auto-tuning techniques e.g., relay-auto-tuning (Åstöm *et al.*, 1992), open-loop step tests (Bi *et al.*, 2000), or a combination of these (Wang *et al.*, 2001) and a number of building automation companies now offer products based on these ideas. In addition to the problem of detecting when retuning is necessary, auto-tuning typically disturbs normal operation of the systems, which may be unacceptable or undesirable.

The research community has also been active in proposing replacements for PID in buildings. New controllers have been proposed based on fuzzy logic (Tan and Dexter, 2000; Wu and Cai, 2000), neural networks (Ahmed *et al.*, 1996), and plant models (Virk and Loveday, 1994). Industry has been slow to adopt replacements for PID for a number of reasons. Firstly, robustness can be difficult to guarantee, especially for the non-linear methods, when subjected to the kind of anomalous phenomena that can occur in building systems (Dexter *et al.*, 1990). Also, any increases in set-up time due to the methods requiring specification of additional parameters will normally make them impractical. Furthermore, some methods turn out to be too computationally demanding for the type of low-cost hardware used in buildings. Lastly, the building industry is generally reluctant to adopt something that may have to be treated like a black box after only recently developing an understanding of PID control.

One approach that has been adopted to address the problem of acceptance is to retain the PID element and create a hybrid solution (e.g., Hepworth and Dexter, 1996; Rahmati *et al.*, 2003; Zaheer-Uddin and Tudoroiu, 2004; Salsbury, 1998). One adaptive controller that falls into this hybrid category that has been adopted widely in the building automation industry is based on pattern recognition (Seem, 1997). The pattern recognition adaptive controller (PRAC) has been received well by practitioners because it is an add-on element to a conventional PID controller. The PID loop is retained and PRAC makes adjustments to the controller parameters to maintain consistent control performance. The method is based on detecting load and setpoint changes and acquiring features that characterize the response. The approach has been accepted well because it is viewed more as an incremental change to existing PID technology rather than a complete redesign. Fig. 4 shows an example PRAC being used on a temperature control loop in a large sports facility.

Another type of adaptive controller that has been used extensively in the building automation industry is designed specifically for use on flow loops that have constant speed actuators (Federspiel, 1997). In these loops, the plant contains an integrator and the static gain can vary considerably during normal operation. In addition, the variance of the noise can change causing changing levels of actuator wear when conventional feedback is used. The adaptive controller continually estimates the maximum static gain and noise variance in order to determine appropriate stroke times for the actuator. The control scheme has been shown to provide more consistent control performance than conventional solutions under various conditions including load and setpoint changes.

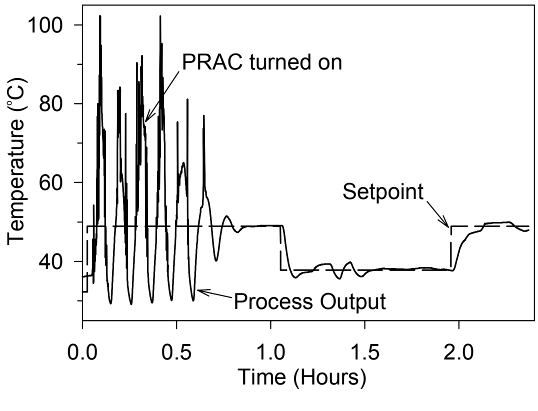

Fig. 4: Data from a control loop in a sports stadium

3.2 Discrete-State Systems

There are many types of discrete-state systems in buildings such as direct expansion cooling systems with on/off compressors, electric heating, chiller and boiler systems, etc. A traditional control strategy for two-position systems is to define a deadband around setpoint and instigate a change in state when the controlled variable drifts outside the deadband. Hysteresis is often used to reduce the number of switches at transition points. A problem with this type of control is that delays and higher-order dynamics in the plant may cause the controlled variable to drift quite far outside the specified deadband in each direction. An alternative solution to the switched system problem is to use a switching algorithm such as pulse-width-modulation (PWM) to generate a pulse train. The advantage of using a switching algorithm is that a conventional feedback loop, e.g., based on PID, can be used to control the switched system. This strategy can then be utilized for split-range control in order to sequence between multiple stages (Salsbury and Chen, 2002).

PWM is a popular switching algorithm in the building automation industry, but it has practical drawbacks, such as: (1) the user needs to set a cycle frequency, the implications of which are not easy to understand; and (2) the oscillation amplitude of the controllable variable will vary with load. Salsbury (2002) suggested an alternative algorithm that addresses these problems. The algorithm implements both pulse width and pulse frequency modulation (PWPFM) and has an an adaptive loop that makes adjustments to the pulse train in order to maintain a consistent amplitude in the oscillating controlled variable. In terms of setup, the algorithm is analogous to the deadband approach in that the user specifies performance in terms of control band around setpoint. This type of setup is more intuitive for practitioners than having to specify a cycle frequency. Fig. 5 shows how PMAC would be incorporated in single path feedback loop, where $D(t)$ is a user-specified control band and $p(t)$ is a pulse signal.

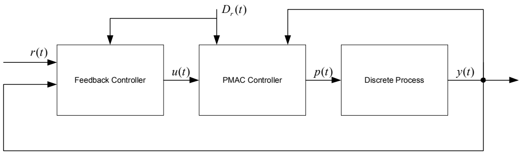

Fig. 5: Implementation of PMAC in a feedback control scheme

3.3 *Cascaded Loops*

Cascaded control loops can be found in several types of applications in building automation systems. One example is the control of variable-air-volume (VAV) boxes that are usually sited in the ceiling void of a building and regulate the supply of conditioned air to occupied spaces. These boxes receive air from a centrally located air-handling unit and they vary the volume of air supplied to the rooms by modulating the position of dampers. In some units, cascaded control is implemented by using airflow in the inner loop and temperature in the outer loop. There are many other variants of cascade control and they are often called reset strategies. In reset strategies, the outer loop may not use a PID controller, but instead just switch between two values when a variable crosses thresholds. Manipulation of setpoints in local loop controllers has been an active area of research and the problem is often formulated in terms of optimization. Optimization strategies are discussed in Section 5.

4. SUPERVISORY CONTROL

This section begins by describing a new approach for conceptualizing, designing, and implementing supervisory logic that is starting to become popular in certain parts of the building automation industry. Section 4.2 then presents a sample of supervisory control strategies that are used to optimize the operation of building systems.

4.1 *Conceptual Framework*

Supervisory control operates at a higher level than local loop in the conceptual hierarchy of a control strategy. This type of control typically impacts the operation of local loops via setpoint and mode changes. When supervisory logic is coupled to a local loop and is discrete in nature, the overall strategy is referred to as hybrid control. In the past, supervisory control logic would be implemented in the form of IF-THEN statements in the proprietary language of the control device. Control logic would become very complicated, non-standard, and difficult to troubleshoot.

Recently, the conceptual framework of state machines has been adopted in certain parts of the building automation industry. State machines are implementations of state-based logic, which is a standard way of describing event-driven decisions used in control. The growth of tools for designing and testing state machines has helped fuel the adoption of the concept. State diagrams also provide a clearer form of abstraction for control functionality that simplifies design and makes troubleshooting easier.

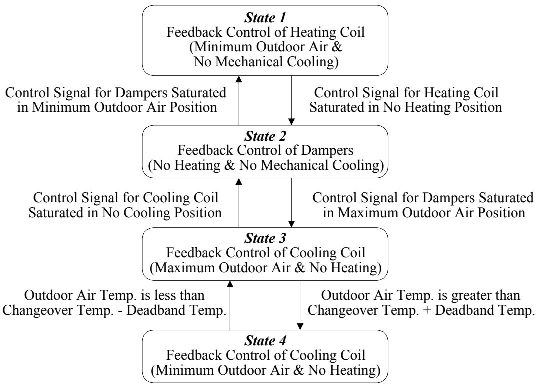

Fig. 6: State diagram for AHU Sequencing

An example of where a state-based control strategy would be used in building automation is to provide sequencing between different subsystems in an air-handling unit (Seem *et al.*, 1999). Air-handling units are air delivery systems comprising fans, heat exchangers, dampers, etc, that regulate the delivery of conditioned air to occupied spaces in buildings. Sequencing control logic is needed to move active control from one subsystem to another as conditions change, such as when moving between heating, cooling, and ventilation modes. An example of a state machine that handles different states in the temperature loop of an air-handling unit is shown in Fig. 6.

The control strategy presented in Fig. 6 is used to control the supply air temperature using three separate feedback controllers, with one controller dedicated to controlling the heating coil, one to the cooling coil, and one to the dampers. By using separate controllers for each process, the controller gains for each controller can be tuned to match the dynamic characteristics of the process it is controlling without regard for the other processes. At any given time, the logic only allows one controller to be operating.

Timers are used to delay switching between modes and this has been found to be more robust than using dead zones in the control signal range. Adoption of the state machine concept is reducing product development time and making testing and validation of control strategies much easier.

4.2 Supervisory Control Strategies

A general goal of modern building automation systems is to satisfy comfort requirements with minimal energy use (Mathews *et al.*, 2001). Traditional approaches that are adopted to achieve this goal are operation scheduling and setpoint manipulation. Scheduling involves determining optimal times to turn on and off systems each day. An optimal solution to the scheduling problem requires a predictive capability that takes into account building dynamics and also both deterministic and stochastic disturbances such as weather and load changes. The industry has adopted some of the simpler approaches to optimal scheduling (Jobe and Krarti, 1997), but the more complex approaches, such as those based on neural networks, remain at the research stage because of difficulties in guaranteeing convergence and robustness.

In many buildings it is advantageous from an energy point of view to operate systems continuously and alter setpoints rather than switch the systems on and off. One such control strategy is known as night-setback and this involves lowering heating setpoints and raising cooling setpoints during unoccupied periods. The main idea is to balance the addition or removal of heat with the energy storage capability of the building structure. Bloomfield and Fisk (1997) showed that night-setback strategies could save on the order of 12-34% in energy depending on the building type. A night-setback strategy can be optimized in two respects: through intelligent selection of setpoints, and by predicting the times for setpoint change. The latter problem is similar to that of optimum start and examples of prediction-based algorithms adopted by the industry are given by Seem (1989).

As more building elements are linked to the automation system, the opportunities for applying optimization have increased. One example is lighting systems, which use a lot of energy in buildings and also generate internal loads that affect the heating and cooling systems. Energy use can be reduced through better coordination of the lighting and HVAC systems (Shavit and Wruck, 1993). Optimization strategies have also been proposed for certain types of building systems that facilitate energy storage, e.g., thermal (ice) storage systems (Henze *et al.*, 1997). Energy storage systems are able to reduce energy costs by making sure that energy is drawn from the power grid at times when costs are lower. The appearance of real-time pricing for energy in certain parts of the world is also creating a demand for more intelligent control strategies (Daryanian and Norford, 1994). Peak load management is a related strategy that seeks to shed loads in order to avoid large spikes in demand, which can incur significant cost penalties. Seem (1995) proposed an adaptive load-shedding control strategy and demonstrated significant energy savings for large buildings.

In many climatic regions, outside air can be used to cool a building at certain times in the year. The control strategy that is used to determine when to use outside air and when to use air that is brought back from the conditioned spaces is known as an economizer. The optimal switchover point is related to the sensible and latent loads on the heat exchangers. The typical solutions adopted by the industry are to use either temperature or enthalpy measurements of the two air streams to determine when to switchover (Spitler *et al.*, 1987). However, a potential exists for developing an improved strategy that takes into account the characteristics of the heat exchangers that are affected. An improved strategy might also incorporate a method for determining whether mixing the two air streams would be advantageous for certain conditions.

The heterogeneous nature of building systems and the complexity of interactions make most optimization problems highly non-linear and difficult to solve. Furthermore, a centralized approach to optimization is not always feasible because limitations in network bandwidth can make the problem ill-conditioned due to insufficient information. A distributed approach to optimization may be one way to address some of these problems and research has already begun on applying these ideas to building systems (van Breemen and de Vries, 2001).

5. COMMISSIONING AND DIAGNOSTICS

Diagnostics encompasses fault detection, isolation, and evaluation/estimation. Commissioning is broader in scope and may include setting up, configuring, tuning, and validation as well as diagnostics. During a commissioning exercise, it is normally possible to disturb the operation of the systems in order to evaluate performance. This is in contrast to performing diagnostics during normal operation and allows two categories of diagnostic methods to be defined: (1) those that use test signals and are mostly for commissioning and or troubleshooting; and (2) those that analyze data from systems under normal operation. Although diagnostics has been a growing area of research for some time now (e.g., Hyvarinen and Karki, 1996), the building automation industry has only recently begun to adopt the ideas. Reasons for delays in adoption are concern over reliability and false alarms and the cost of setting up the diagnostic system.

The non-diagnostics part of commissioning is also an active area of research with the main motivation being to reduce installation costs through shorter set-up times. Some technologies that have evolved in other industries and are beginning to impact building automation are plug-and-play, and interoperability. There has also been a growth in the number of tools available to assist in set-up with the aim being to automate some of the more routine tasks and use expert knowledge to guide users more efficiently through the process (Clapp and Blackmun, 1992). Traditionally, the term commissioning would be used to describe activities performed when new systems are installed, but it is now also used in reference to existing systems. Re-commissioning, retro-commissioning, and continuous-commissioning are terms that have been used to describe application to existing installations (IEA Annex 40).

The demand for commissioning and diagnostics is being fueled by more stringent legislation on aspects such as air quality, energy use, etc. In some buildings, commissioning costs can be comparable to the cost of the building automation system itself (Wilkinson, 2000). Also, several research studies have demonstrated that commissioning and diagnostics have the potential to save on the order of 20% in energy costs in commercial buildings (Wei *et al.*, 2001). The reason why potential energy savings are so large is that most building systems are not operating properly and some studies have indicated that up to 50% of buildings have problems (Piette, 1996).

Easier access to control point data has made the operation of building automation systems more transparent. Modern systems usually allow any combination of variables that are accessible on the control network to be trended for analysis and software that can produce graphs and perform analysis is now widely available. Increased transparency means that problems that might have gone unnoticed in the past are now more visible. Access to data from the control system and the availability of simulation tools also makes the cost of identified problems easier to ascertain. These changes have made operators (and customers) more aware that systems are not operating optimally and that improvements are possible. New businesses based on offering diagnostic services are now growing to meet the increasing demand from customers that these advancements are creating. The following section describes some of the newer analysis methods that are beginning to emerge in the industry.

5.1 Analysis Methods

A popular approach suggested for diagnostics in buildings is based on the use of mathematical models. Model-based diagnostics is a well-established area of research and has been applied to building applications for some time now (Haves *et al.*, 1996). In general, model-based methods do not work very well in practice due to the difficulty in properly characterizing the non-linear behavior of building systems in mathematical terms. Inevitable model inaccuracy causes false alarms, which prevents the approaches from gaining acceptance. Methods based on pure black-box models are probably the least practical because of the costs associated with obtaining the prerequisite training data. Black-box models also tend to be poor at extrapolating and because of this they become unreliable when conditions change. Models that are formulated from physical laws, such as those in thermodynamics, can reduce the need for training data and improve extrapolation ability, but accuracy is still very difficult to characterize. Also, physics-based models require parameters to be specified that may be difficult or costly to obtain.

Although model-based methods can be demonstrated to produce favorable results when the model is accurate, the methods are not normally viable for building applications due to the reliability problems and costs associated with setting up the models. Another approach that is probably better suited to building systems is to adopt a statistics-based analysis. Statistics is a broad field, but the general idea is to formalize the handling of uncertainty. This approach is needed in building systems because of the complexity of the systems themselves, unknown interactions, stochastic disturbances, etc.

As in most control systems, the primary function of a building automation system is to maintain designated variables at their setpoints. A logical focus for diagnostics technology is therefore on the control loops. Modern large buildings can have hundreds or thousands of control loops and a manual analysis of each loop's performance is not feasible. In the past, only a few of the more critical loops would be targeted for monitoring and many problems would therefore go undetected. In other industries, automated loop performance assessment has already reached a certain level of maturity with several companies offering commercial products. However, the techniques developed for other industries such as the minimum variance approach (Harris, 1989) are not always applicable to building systems for the following reasons:

- Comparison to 'ideal' control performance frequently yields bad performance indices in building systems even when the loops are tuned as well as they can be. This is due to the fact that most loops in buildings use PI control, which is poorly matched to the highly non-linear and time-variant nature of the plant.
- Trend data can be of poor quality. Sampling rates can be too slow making it impossible to evaluate dynamic performance of some faster loops. Also, data may be badly quantized due to coarse resolution.
- Mode changes and discrete elements in the systems can lead to anomalous behavior that can interfere with performance assessment by making signals non-stationary.

Faced with the above limitations, one approach to control performance assessment that has yielded good results is peer-to-peer comparisons. This approach is possible because most large buildings contain several groups of loops that are of similar type. An obvious example would be terminal units or VAV boxes where a large building may have hundreds of these. Seem *et al.* (1999) suggested several measures of performance for control loops in buildings including variants of setpoint error signal, control signal variability, and control signal value. Seem proposed calculating exponentially weighted averages (EWMAs) of these quantities where the forgetting rate is set according to the dynamics of the loop type. An example of EWMA performance indices calculated for a group of VAV boxes in a building is shown in Fig. 7. The figure shows that two of the boxes are substantially different from the rest and would warrant further investigation.

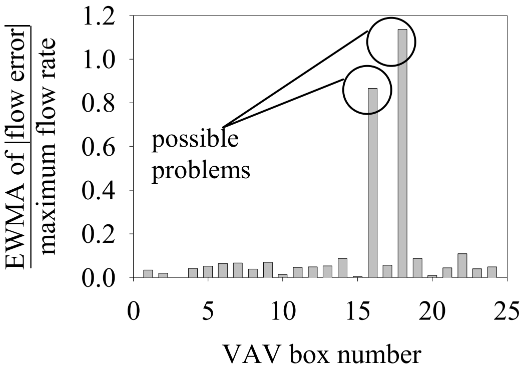

Fig. 7: Example setpoint error peer comparison of 25 VAV boxes

Standard statistical tests can be used to determine which EWMA values are significantly different from the rest. The approach can also be improved by determining thresholds from historical data rather than from a current sample of values. An advantage of the EWMA approach is that it can be used to detect failure-type faults even when sampling rates and signal resolution are poor. Because of cost constraints, building automation system networks tend to have little bandwidth available beyond that associated with the basic control functions. A hierarchical approach to diagnostics is therefore favorable whereby EWMA-type indices are first used to rank loops according to performance. The N worst loops could then by targeted for a more rigorous assessment by increasing the sample rates and by using more sophisticated analysis methods.

Improved diagnostics can be obtained when systems are able to be disturbed outside the bounds of normal operation. Although this approach is more expensive and disruptive than just observing normal operation it does have some important advantages. In particular, issuing test signals allows performance to be interrogated faster and in a more repeatable way (Haves *et al.*, 1996). The approach is therefore useful at commissioning time when buildings are not occupied and artificial disturbances can be tolerated. The approach can also be used to troubleshoot problems that have been detected during normal operation. In building automation systems, typical types of test signals are step changes applied to either open- or closed-loop systems. Tools that analyze responses to step changes are available and these are used for both tuning loops and diagnostics.

Another technique being used in the building automation industry for diagnostics is to make use of mode changes and certain other events triggered by the supervisory logic in order to gather data at strategic operating points. This approach melds well with the state-based control paradigm as changes between states are clearly identified. An example of how this can be used for diagnostics is to consider the switchover point between heating and cooling. At this point, the inlet and outlet temperatures across the heat exchangers should be approximately equal at steady state. Significant differences between these temperatures can indicate a fault condition such as leaking valves, sensor error, stuck valve, etc (Glass *et al.*, 1994).

Another important class of analysis methods used for diagnostics in the building automation industry is based on rules that are derived from expert knowledge. A number of companies offer services based on this kind of analysis and results can be favorable if the rules have been properly defined for the considered systems. The profitability of the approach is dependent on the balance between the amount of time required to set-up the rules and define thresholds and the size of the considered class of systems. The approach is therefore particularly profitable for packaged systems that are manufactured to a given specification in large quantities. Examples of these systems in buildings are VAV boxes, rooftop air-conditioning units, chillers and boilers. The cost structure changes when dealing with more expensive pieces of equipment such as chillers, and more sophisticated analysis methods such as vibration analysis can then be cost effective.

6. DEVELOPMENT TOOLS

Another technology that is transforming certain parts of the building automation industry is that of computer-based design and development. Recent years have witnessed a large increase in the number of computer-based tools available across all professions within the building industry. However, the generally fragmented nature of the building industry has meant that tools have evolved somewhat independently causing them to be incompatible with each other. This situation is changing now though and efforts are underway to develop generic data models so that tools from different disciplines can share information (Hitchcock, 2003). An example of this is when a geometric design of a building is imported into an energy simulation program and combined with descriptions of the energy systems.

In the building automation industry, simulation has come to play a major part in the development, testing, and validation of control strategies. A typical development cycle now includes simulation and emulation testing of control strategies. Emulation refers to hardware-in-the-loop simulation and is used to verify the implementation of a strategy on a target platform. In addition, plant models that were originally developed for energy simulation are now finding uses in control strategy testing and validation (Haves *et al.*, 1998). Rapid prototyping, automatic code generation, and easier-to-use control logic design tools are also all diffusing through the building automation industry and improving productivity.

Research has also focused on ways to improve the integration and sharing of information throughout a building lifecycle (Yu *et al.*, 1998; Karola *et al.*, 2002). This philosophy is finding application in the building automation industry where an example would be the use of plant models developed during the design process for both control and diagnostics during the operations phase (e.g., Salsbury 1998; Salsbury and Diamond, 2000). Data can also be gathered from the control system during normal operation to refine and calibrate simulation models that were developed at the design phase for the purpose of performance tracking and continuous commissioning (Liu *et al.*, 2003).

7. CONCLUSIONS

The paper has provided an overview of developments in the building automation industry over recent years. A sample of new control technologies was presented and some of the practical issues associated with building systems were described. Compared with other applications of control technology, building automation is generally a highly cost-oriented business. In most buildings, the goal is to provide acceptable comfort conditions at the lowest possible cost. Recent years have seen a change in the balance of the cost structure with operational costs rising in importance relative to capital costs. This trend is also likely to continue due to increasing energy and maintenance costs. The future is therefore likely to see a rise in demand for technologies that could offset these changes such as optimization, diagnostics, and commissioning.

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