Towards a Taxonomy of Energy-Efficient Control Techniques

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Abstract. Energy usage in buildings can be reduced by coordinating devices to achieve higher energetic efficiency. Even conceptually simple techniques such as daylighting, occupancy based control or scheduling are known to achieve reductions on energy costs in the order of 20-30%. In fact, multiple techniques have been proposed over the years and, to date, there is no reference text giving them a systematic treatment. In this article we reviewing and categorizing existing techniques applicable the problem of energy-efficient control into an appropriate taxonomy.

1 Introduction

Efficient energy usage in buildings is determined primarily by the building's envelope, by behavioural patterns of occupants and increasingly by the available technology to coordinate devices to reduce energy consumption, while delivering the same level of service.

Building Automation Systems (BAS) increasingly feature digital networks of electronic devices, equipment and appliances that communicate with each other to achieve greater occupant comfort while operating more efficiently. A building controlled by a BAS is commonly referred as a Smart Building (SB). SB are becoming popular and associated with the idea of leveraging the BAS to reduce energy consumption, e.g., by intelligently switching loads based on occupancy information.

Energy usage in buildings can be understood in terms of *energy consumption reduction* and *energy conservation*. The first aspect has to do with a rational use of appliances avoiding turning them on or turning them on partially or even with lower level of service, reducing the quality service. The second aspect refers to the efforts made for reducing energy consumption in buildings and environmental pollution [10]. It can be achieved through efficient energy use (when energy use is decreased while achieving a similar outcome), or by reduced consumption of energy services. Through appropriate control strategies, devices and equipment can be coordinated to help both energy consumption reduction and energy conservation. These are called *energy-efficient control techniques*.

This paper reviews and analyzes the existing energy-efficient control techniques into a taxonomy. This work is of utmost importance to develop models supporting the selection of alternative control techniques automatically. We foresee such models will be required to develop a new breath of tools to assist facility managers in appropriately commissioning their BASs with toward energy-efficient control.

Our text is organized as follows. In the next section the fundamentals concepts of automated control are presented. Then, in sections 3 to 7 we overview the different control techniques, their variants and how they influence energy usage and conservation. Finally, section 8 presents the taxonomy and section 9 concludes.

2 Concepts

A useful abstraction when analysing energy usage is to consider that a facility, a SB for the case, offers services that support activities that take place therein. Illumination, air renovation and temperature can be considered as services. Services are implemented by equipment in given spaces, or parts of the space called zones. Controlling in which part of the space a service is offered is called zoning. Equipments can also operate during designated periods of time to meet a certain level of service. The level of service offered by equipment can be operated among other aspects by varying its output intensity. Greater level of service usually means greater energy consumption. Therefore, it can be said that equipments can be controlled according to the dimensions of *space*, *time* and *intensity*.

Conceptually, the most energy-efficient control system is one that delivers the required level of service for the task in hand in the area (space) where the activity is taking place and for the duration (time) of the activity. In practice, however, and due to limitations of the equipment installation or the built environments, it is only feasible to offer the level of service required for a given activity on a larger zone, for longer period, and at excess level of service, therefore leading to energy waste.

To achieve energy efficiency many techniques or standard behaviours can be applied, those are called energy-efficient control techniques. Combining this techniques, office buildings can achieve huge reductions on energy wastes. Some energy-efficient control techniques offer better gains than others, depending on the buildings location or based on human presence rates inside the building. Some of those techniques will be described further ahead.

Ideally, a very efficient system should have a fine grain of control. The finer the grain of control, the more efficient the system can be. This efficiency is only realized if the system is perfectly adjusted to deliver the required level of service, at the location and for the duration of each activity. Performing these adjustments has a cost which is not negligible. The only way out is for such control to be automated.

Consider a meeting room where a manager stays behind to follow up on a meeting. Let us assume that an energy-efficient task lighting scenario is activated, where only the luminary over the zone of the space where the manager is sitting is at full intensity while the rest are dimmed down. Consider, furthermore, that all luminaries go fully off as soon as the manager leaves This scenario depicts a very adequate control of the illumination service in terms of space, time and output.

3 Individualized control

The finer the grain of the control of the equipment in terms of space, time and output, the more efficient a system can be in delivering the service required by the activities that take place. The fundamental dimensions of equipment control, zoning, flow control and duration have important implications in energy efficiency.

3.1 Zoning

Zoning mainly consists of circumscribing the actuation of equipment or offer services within a space where it is most needed. For example instead of illuminating a whole room to perform a certain a task, which is undertaken in a small area within a room, only the area where the activity is taking place needs to be lit. Surrounding areas could be lit with a lower level of illumination, providing for user comfort still achieving energy consumption.

We distinguish three granularity levels for Zoning which are "All", "Groups" and "Individualized", being the last one where the granularity is finer. On the "All" level one control command applies to all equipments and there are no divisions. For example, consider that light intensity is available but that it applies simultaneously to all units in the space. The energy waste can still be high if, for example, certain zones in the space could be at full off. On the Groups level, devices are grouped into that sets that may accept different commands. For example, they can be switched independently therefore decreasing energy consumption. The Individualised level is where the energy consumption is lower, due to the higher granularity.

3.2 Flow control

Flow control is a control technique that refers to the capability of controlling the amount of output flow on a device. The fundamental principle of flow control is that greater output requires more energy. Therefore, the amount of output should be minimized by adjusting it to the requirements of the tasks being performed in a certain space. For example, different level of service levels can be used in offices and in passageways.

Depending on the type of device, we distinguish three common types of flow control: binary discrete, multilevel discrete and continuous. The simplest type of discrete flow control, is a simple on/off control. This first level only allows two states usually meaning that either the service is being offered at full power or is not being offered at all. This is used for example to turn on/off HVAC systems, luminaries or a group of luminaries. Multilevel allows to choose from a small amount of predefined levels of intensities, for example bi-level discrete flow control, such as off-medium-full strategy which obtains energy savings by interleaving luminaries on and off. Other multilevel discrete controls allow multiple levels of service, common on luminaries and thermostats.

Continuous flow control is capable of delivering a continuous variation of the output of devices. Continuous flow control can be more efficient than discrete flow control. This type of control is achieved through the use of a specific electronic dimming ballast for lighting, variable motor speed drives or even damper valve controls, often applied in HVAC systems. Below, it will be detailed further.

3.3 Duration control

The capability of precisely controlling the time window along which a certain service can be delivered also results in energy savings. Once the activity is over the service can be switched off. Two basic types of limitations exist to implement such precise control. The first one is that the control system does not know when the activities requiring a certain service are taking place and the second one is that control may actually be limited. Certain types of equipment display hysteresis delays, and require a certain safety interval to be observed before being switched back.

4 Activity-based control

Activity based control tries to optimize the control towards the activities that are taking place in the space. Activities are performed for given periods of time, require certain levels of service to be available. Since no system is actually capable of knowing exactly the characteristics of the activity, the control is often based on time and space occupancy prediction.

4.1 Schedule-based control

Scheduling is understood as appointing commands to be executed by devices or group of devices at defined points in time, achieving a certain degree of independent action. Scheduling is frequently to turn on or off lights on determined schedules to meet the requirements of the activities that take place during those same periods of time.

However, scheduling is not limited to commanding devices at certain hours on given dates. Schedules can be also activated or interrupted upon the occurrence of an event or condition. Moreover, a schedule start time can be specified as an offset to the event or condition. For example, consider changing the morning switch-off time scheduling based on the season of the year. Another application would be turning off the lights when people leave rooms. A floating schedule can be used to solve to implement auto power on/off to solve this problem.

4.2 Occupancy-based control

Occupancy control sensors are commonly used in indoor spaces using infra-red or ultrasonic sensors to detect motion. When no motion is detected in a certain space, it is assumed that the space is empty, and thus does not need to be lit. There are two major types of actuation based on occupation detection: movement detection switching and movement detection dimming. In motion detect switching the occupancy sensor switch on/off devices (usually luminaries) according to the motion detected in a room, in motion detect dimming the sensor dims the light to a defined level in the absence of motion. Both types of actuation based on occupancy control to turn on/off or to dim the lights can result in saving substantial amounts of energy [9].

5 Environmental harvesting

Environmental Harvesting aims at taking advantage of external environment conditions to save energy. In literature it is possible to see that there are three major techniques, one applied to lighting systems and two applied to HVAC systems. Daylight harvesting is applied to lighting systems and makes profit of solar light to dim or even to switch off lighting during the day time. Heat gain is applied to HVAC systems and uses solar heat to reduce the use of energy on HVAC systems. Free cooling is used with HVAC systems but in this case it uses the outside cold air to reduce the use of HVAC systems during the night or during the early hours of the morning.

5.1 Daylighting

Daylight is a non-uniform and dynamic form of illumination which, varies in intensity, both spatially and temporally. Therefore, day lighting systems in order to properly work, should be capable of dimming small sectors of interior spaces independently. Using daylighting its possible to reduce in some cases 40% of energy consumption in a commercial building [7]. To achieve daylighting some basic principles have to be fulfilled. Buildings orientation should be such that most of it is within the daylight zone, or even bring the light ballast higher, so it can cover more area. Applying this technique in a proper way gives the occupant the comfort and satisfaction it needs to work, and due to that his work will improve [7].

Using daylight harvesting with the proper orientation and symmetry of a building it is possible to provide over 70% of the required ambient illumination in a building during a year. If an electric lighting control system responds properly to daylight harvesting, the electric consumption will be significantly reduced [11]. The main limitations of daylighting is that photo-sensors are not precise enough—their performance depends mostly on their placement [3].

Another important aspect of daylighting is the interaction with blind controls. Automated blind controls will help control light intensity in the room.

With more natural light the system will turn off or dim the luminaries, causing a reduction of energy consumption. To prevent excessive glare, the system can also automatically close the blinds to avoid glare. An installation of a dimming system with automatic blind control proved to be very efficient, creating a 27% reduction in lighting energy use [4].

5.2 Heat gain

Heat gain is the increase of temperature in a certain space from solar radiation. As the daylighting technique, it also consists of controlling blinds or curtains in order to maximize the environmental temperature in a building, also temperature measurements are needed in order to understand the need of closing or opening the blinds. The amount of heat gain varies depending on the sun strength and the exposure of the window, it also depends on the material of which the building is made of [6]. The position and orientation of a building is crucial to maximize the buildings heat gain. Heat gain technique can also use heat dissipation from other devices, such as from lighting systems to increase the environmental temperature.

5.3 Free cooling

One way to reduce HVAC energy consumption consists of circulating cold fresh air during the night that will cool the building avoiding the need of using HVAC systems during the day. Another advantage if free cooling is that it is done in off-peak hour benefiting from lower electricity tariffs.

6 Intelligent Load Control

Buildings control load and Load management is the process of balancing energy supply and consumption on a network or building by controlling the energetic loads. There are two main ways of doing this, know as Load shedding and Load shifting.

6.1 Load shedding

Load shedding is a deliberate switching off of electrical supply to some parts of an electricity network. So basically, the available electrical power is rationalized, by limiting the energy use or even cutting the energy supply on certain zones. Sometimes there is a need to reduce energy demand very quickly to an acceptable level, if not there might be a risk of turning the entire electricity network unstable or even a completely shut down may occur.

During the hot season, buildings normally have all their HVAC systems working during the day which represents a huge energy consumption that can even exceed, in some cases, the contracted energy power for the building, representing an extra cost. Load Shedding can also be implemented to reduce energy consumption in buildings in different ways. First, building areas may be limited during the peak hours to a certain level of energy consumption which they cannot be exceed even if consumers try to. Load shedding can be implemented by turning off non-critical loads when a facility is being charged to a maximum for power, in order to avoid exceeding the maximum contracted power supply.

Load shedding technique can also be implemented by performing the dimming of lights in the building to reduce the energy consumption avoiding exceeding the contracted energy power.

6.2 Load shifting

Load shifting is a way to manage energy loads, by advancing or delaying consumption into periods of lower energy prices. The limitation is that in some cases the consumer may actually need to perform the task at an appoint time. In this way the consumer still accomplish the task while being at a lower energy price when doing it [5].

7 Occupant buy-in

User buy-in control techniques are techniques that take advantage based on occupant characteristics in order to achieve an energy consumption reduction.

7.1 Adaptive compensation

Adaptive Compensation is a control technique that takes advantage of the human adaptation to the surrounding environment to save energy. For example, to take advantage of the fact that people need and prefer less light at night than they do during the day [2]. Therefore, lighting can be slightly dimmed at night due to the fact that it is dark outside. Similarly in winter when people wear warmer clothing and the air condition is not required to be so hot. It has been found as well that users may tolerate a progressive regression of set points during a period of time, for example the lowering of luminaries intensity to 70% over the course of 20 minutes.

A study performed in an office laboratory where participants had personal dimming control over lighting, and were then exposed to a simulated load shed involving dimming lighting by 2% per minute refers that only 20% of the participants intervened in the lighting control when the luminance level declined 35%, this shows that load shedding might be a valid option for energy costs reduction, since users might tolerate a considerable light dimming [8].

7.2 Set-point relaxation

Set point relaxation is a term that describes the technique of increasing or decreasing a determined set point to save energy. For example if a HVAC system is adjusted to 22 degrees the set point "relaxation" can be between 21 and 23 which varies according to the season, in the winter the set point can be adjusted to 21 degrees and in the summer it can be adjusted to 23. This "relaxation" will be hardly perceivable by the user if done gradually and if the variation between set-points does not exceed more than 2 or 3 degrees. This minor change in the set-point when applied to an entire building can help reducing energy consumption while keeping users comfort [5]. This technique can also be applied to lighting systems: if a user sets the lights intensity level to 80%, the relaxation can be 10% establishing the intensity level at 70% without any noticeable difference.

7.3 Set-point constraining

Maximum level of service set-point constraining basically limits users from setting a level of service above a predefined maximum. Suppose, for example that during the daylight it can pre-defined that no lamp in the corridors can be set to more that 80% and if the user tries to exceed that limit the system will gradually reduces the level of service to the specified level. In some situations, this technique may have a marginal impact in users comfort, which in face of the energy savings obtained can be tolerable.

7.4 Demand Limiting

Demand Limiting consists of reducing power loads during periods where power prices are at a premium cost. Demand limiting is different from load shedding because it reduces the current amount of power versus turning equipment off used on load shedding. For example, demand limiting would be dimming lights for a certain period of time where prices are high or decreasing cooling set points in non-critical areas during peak demand periods. Demand limiting will reduce energy bills as load shedding does but at the same time it will keep consumers comfort level higher [5].

7.5 Ubiquitous control

A more adequate interface allows the occupant to achieve a better control over the surrounding environment. Creating more frequent and more precise adjusted conditions for the task being performed. Consider the case of an occupant that does not leave the seat to turn off a lamp that is no longer needed. Therefore, the ubiquitiousness of control also leads to energy savings.

When energy-efficient control techniques are applied in buildings peoples comfort may be compromised and eventually consumers will stop using energy-efficient control techniques in favour to their personal comfort. Often people use more light intensity than what they actually need. The occupant is less likely to over illuminate if enabled to personalize their own ambiance, selecting their ideal light level for working. It has been demonstrated by a number of studies that personal dimming also results in higher productivity [1].

8 Discussion

A taxonomy of energy-efficient control techniques implemented by SB is presented in Figure 1. The taxonomy is organized into a tree hierarchy. The topmost nodes aggregate energy-efficient techniques based on their main characteristics. Individualized control refers to techniques that are capable of circumscribing control with varying granularity. The Automatic control node has two sub-nodes, the activity based sub-node where energy-efficient control techniques base their actuation on space occupation and Environmental Harvesting that tries to use the environmental condition to achieve energy consumption reductions. Load Control techniques try to manage energy loads in order to achieve energy cost reductions. Finally, User Buy-in gathers techniques that take advantage based on occupant characteristics in order to achieve an energy consumption reduction.

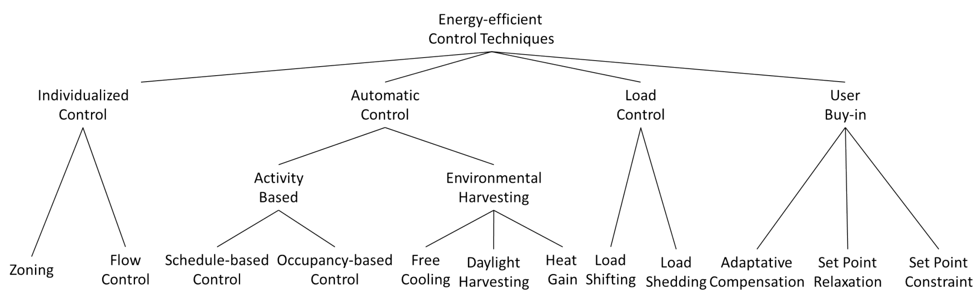

Fig. 1. Taxonomy of energy-efficient control techniques

9 Conclusions and future work

Although a plethora of techniques have been proposed over the years which, if combined, could result in a relevant energy savings, to the best of our knowledge existing systems apply these techniques in isolation. Herein we review and categorize existing control techniques aiming at an abstract model upon which new control can be based.

From literature review we organize the main energy-efficient control techniques into the appropriate taxonomy based on their techniques based on their main characteristics. While doing the literature survey we also identified the expected gains for all the main control techniques.

As future work we intend to model energy-efficient control operations. We believe that such model will be useful as *(i)* an abstraction enabling to separate techniques from specific implementations and *(ii)* understand how to compose the different operations. Another possibility is for different techniques to be modeled according to their energy requirements and the quality of service they deliver. Therefore, the modeling that we envision could also be used to select the most appropriate technique under certain energy constraints. This can be used to implement automated demand-response.

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