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WHAT SHOULD A BUILDING BE CONTROLLED FOR? ASK THE OCCUPANTS!

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Abstract
The energy savings of buildings promised by automatic control systems are often ineffective due to occupants who may not use the features of the system to the full potential at best, or deactivate the system at worst. Therefore, systems that adapt to the occupant over time without compromising his/her comfort are needed. In this paper, we describe such an occupant centred control framework, identify potential research gaps, and demonstrate its effectiveness in a case study.

Keywords:
Building control; energy efficient buildings; smart buildings; user interaction

1 INTRODUCTION

The building sector contributes to 40% of global primary energy consumption, and to 30% of CO_2 emissions [1]. Therefore, buildings offer a large leverage for the mitigation of anthropogenic greenhouse gas (GHG) emissions. Typically, such sustainable approaches are known as low-energy, or (net-)zero- energy paradigms, and are comprised of a combination of sustainable material use, climate- responsive architectural design, on-site renewable energy generation, and advanced control strategies for the operation of building systems (heating, ventilation, air conditioning (HVAC), lighting and shading).

Given the fact that typical building systems have a life span of 20-30 years, the impact of its control system on the energy and emission balance is apparent, and requires to be designed with the goals of energy efficient operation. On the other hand, as humans spend 80-90% of their time indoors, providing a comfortable indoor climate (thermal comfort and indoor air quality) is also a goal of the control system. However, because the preferences of the occupant and the goals of the controller may differ, there is a potential conflict between energy efficient operation on one hand, and comfort on the other. In short, a successful controller must find a good balance between the two.

The goal of this paper is to show that there is a discrepancy between how building systems are operated and how efficiently and comfortably they could be operated if the control would focus on understanding the needs of the occupant, rather than solely focus on technological presumptions. We thus present a new paradigm for the design of building system controls that takes the perspective of the occupant. We argue that occupant centred approaches are the most promising, if not the only approach to achieve both, occupant comfort and energy efficient operation. We demonstrate the effectiveness of the approach using results from our ongoing research.

The paper is organized as follows. The next Section gives a non-exhaustive overview of the state of the art in building control and occupant control research, and highlights the needs for an occupant centric control (OCC) approach. Then, Section 3 discusses the proposed OCC framework. Finally, Section 4 shows results from a case study, and Section 5 concludes the paper.

2 BACKGROUND

2.1 Building Control

Building control and automation considers the control of recurring equipment activities. Typical examples are maintaining the set points for HVAC systems, lighting, appliances, and security

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systems. The objectives of building automation are minimization of energy consumption, improved occupant comfort, and minimization of operational and maintenance costs. The building automation industry is mature with a few key global players (Siemens, Johnson Controls, Honeywell).

In recent years, results from the control and automation and computer science communities have been applied to buildings. It is beyond the scope of this paper to provide a thorough literature review. The interested reader is referred to [2, 3, 4] for comprehensive reviews. A possible classification is provided in [2]. We use a simplified scheme in the following to classify the current trends in three major fields, classical control, modern control and soft control.

Classic control

Classical control is comprised of two-point (or on/off) controllers and the Proportional-Integral-Derivative (PID) controllers. The on/off controllers are provided with a lower and an upper set-point, where the equipment is switched on/off. It is the simplest and most intuitive controller. They are suitable for systems with small inertias, and have conversely difficulties controlling processes with large time lags [5].

The PID controller is the most widely used in industry. It acts by modulating the control signal based on the error between the current process value and its set-point. Despite their wide application, tuning the parameters/gains of the controller has to be done empirically, which may be time consuming, or even impossible [5].

Modern control

Modern control or hard control has been developed in the control systems community as a reaction to the shortcomings of the PID approach. These control approaches are based on rigorous mathematical models, and allow to define, e.g., error bounds on the controller performance (robust control), or minimize a cost function (optimal control). [2]

Amongst these controllers, model predictive control (MPC) combines robust and optimal control [29], and has also been investigated for application in buildings [6]. In the building context, MPC uses both a thermal model of the building and weather forecast to predict the future states of the building over a certain time period, and to generate a control signal for disturbance rejection and constraint handling during this period. It is possible to include occupant models to study their influence on the controller performance [7, 8]. However, the optimal control signal computed by MPC comes at the expense of high computational efforts. Furthermore, the performance of MPC is linked by its nature to the quality of the underlying model. Thus, high initial engineering costs are needed to identify a model structure, its parameters and perform a validation, before the MPC can be applied. While tendencies exist to reduce these efforts [9], MPCs are rarely used in industrial building control applications.

Soft control

Soft control also termed intelligent control uses approaches from the computer science community combining the areas of machine learning, pervasive computing and ambient intelligence [10], initiated by the seminal work of Weiser [11]. Examples include artificial neural networks (ANNs) [12] or fuzzy logic (FL) approaches [4]. ANNs are black-box models trained on a set of available input-output data, from which a non-linear relationship can be determined and then used in control. FL controllers aim to bridge the gap between human language description defined in fuzzy sets for variables, such as temperature (e.g., hot, cold, mild, etc.), and machine instructions with if-then-else logic.

One of the successful examples so far for this approach is Mozer’s ACHE house, which adapts to the preferences of its single inhabitant and reduces energy consumption by means of an ANN and reinforcement learning [13].

2.2 Occupant Behaviour and Comfort

There is a large amount of research studying the conditions in which humans feel comfortable [14].

From adaptive thermal comfort research, it is understood that humans have a large tolerance for comfort, as long as adaptive measures are available [15]. For example, a study based on three databases on occupant satisfaction found that spaces that are air-temperature controlled in a narrow temperature gap (class A) are not more comfortable than those with a larger temperature gap (Class B and C) [16]. The study concludes then that tightly air-controlled buildings are not desirable given their higher energy costs for both design and operation. Rather, the temperature set-points should be based on real-time empirical feedback about their occupant’s requirements. In fact, it is suggested that this occupant feedback capability should be incorporated in normal building control and operation.

A comprehensive review of the scientific literature on occupant behaviour (such as window opening, blind adjustment, thermostat adjustment, and lighting switching) although it may seem stochastic at first, « occupants undertake control actions consciously and consistently » [14].

In conclusion, occupant behaviour and interaction with building systems exhibit patterns, which are characteristic to the user and his comfort situation. Therefore, any building control approach whose goal it is to maintain the comfort of the occupant must include this information in its operational algorithm.

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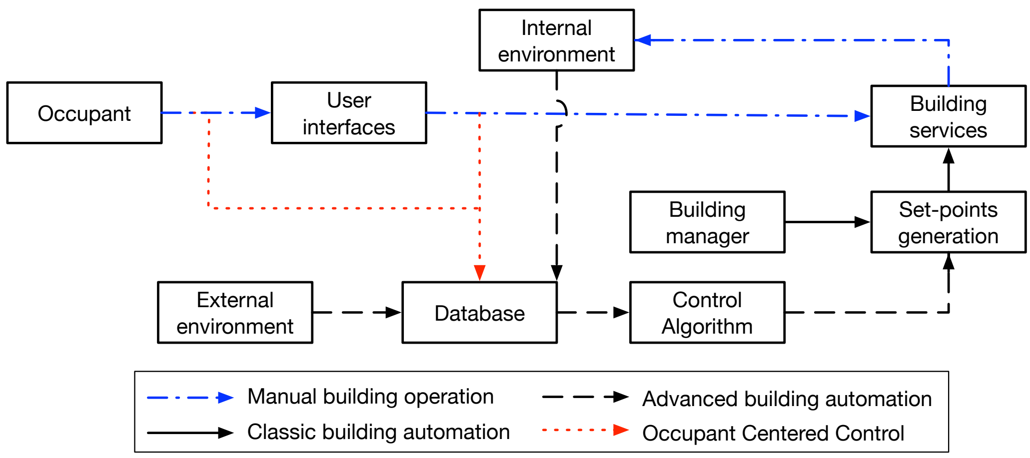

Fig. 1: The Occupant Centered Control framework.

3 OCCUPANT CENTERED CONTROL

In this section, we develop the occupant centred control (OCC) framework. It is illustrated in Figure 1. In a building without any automation, only the manual operation of the building systems exists. The first level of automation is with classic controllers, whereby the set-points for lighting, temperature, etc., are pre-defined by the building manager. This is often done based on experience, without any relation to interior and exterior conditions.

A level higher in complexity are the modern controllers, such as MPC. These use internal, and external environmental conditions additionally, and make a forecast in order to determine the optimal control actions. The set-points are still determined by the building managers.

In the OCC framework, however, it is recognized that the data that can be recorded from either observing the user, or capturing his interactions with the building systems, can be used to infer set-points. This in turn allows to tailor the control actions such that user comfort is truly achieved.

As a consequence, the ability to gather data and determine patterns are key requirements for the success of OCC. Therefore research should focus on (see also [17]):

(i) Scalable, low-cost and low-power hardware for sensing, actuation and communication. This will allow for a dense sensor network to gather data.

(ii) Algorithms for efficient pattern detection and knowledge discovery of both regular user behaviour, but also override actions.

(iii) Methods to derive useful knowledge from these patterns, e.g., set-points, occupancy schedules, etc.

(iv) Holistically integrate these tools into building management system (BMS), such that OCC can be applied to real buildings with little operative overhead.

4 CASE STUDY

Our case study focuses on lighting control in the offices of the author's research group. The details can be found in [18]. In brief, the setup in each of the investigated offices allows us to log

- The illuminance level (minute-by-minute)
- Every trigger of the occupancy sensor (PIR)
- Every action on the manual light switch
- The on/off status of the lights (minute-by-minute)

With this setup, two set-points can be determined. First, the lighting set-point for the switch-on action for the controller is determined by analysing the illuminance levels right before the occupant switch the lights on. Of course, many possibilities exist to derive the set-point. We chose to analyse the data of the past four weeks and use the minimum of the mean and the median value. Second, the time delay (TD) to switch the lights off is calculated by analysing the probability distribution of the motion sensor data, again over the past four weeks. The result is a set of user and time adaptive set-points in each office.

In addition to this automatic set-point derivation, a web interface has been designed in which the user has the ability to both to specify a set-point directly, as well as to operate the lights. This increases the adaptive measures available to the user.

We conducted two experiments. In the first one, we demonstrated the user-adaptive set-points as well as the ability of the system to save energy. For this, the system operated each day randomly in three modes, the manual mode for reference and benchmark, a comfort mode M1, and a savings mode M2. The difference between the last two is that the time delay to switch the lights off is shorter in the savings mode than in the comfort mode. The system operated double-blind, i.e., neither the occupants nor the experimenters were aware of the current mode of

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the system. This was revealed only at the end of the experiment.

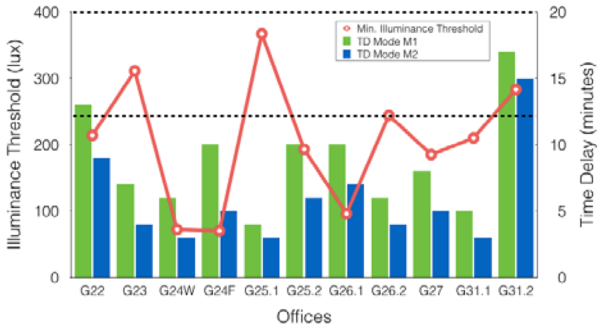

Fig. 2: Results of the first experiment : adaptive set-points.

The results, i.e., the set-points at the end of the experiment are shown in Figure 2. It is clear that each office has converged to individual settings. Furthermore, both the lighting set-point as well as the time delay are well below the generally recommended (and manually set) thresholds. As a result, the OCC method adapted to the occupant, and still reduced the energy consumption. Overall, the savings mode M2 achieved energy savings of 37.9% compared to the manual benchmark, and 73.2% compared to a worst-case scenario (all day lights on). For mode M1, the savings were 23.2%, and 66.8%, respectively.

In the second experiment, the focus was on user satisfaction and acceptance. Therefore, the experiment was conducted in two phases of 6-weeks each in the same mode, first the manual mode, then the comfort mode. Before and after each phase, the occupants were asked to fill out a questionnaire related to general lighting comfort and the satisfaction with the control system. We could conclude that

- comfort of the occupant was not adversely impacted by the OCC method.
- over 85% of the *control-on* actions and 75% of the *control-off* actions of the system were not overridden by the occupants, demonstrating high acceptance of OCC

We then charted the answers related to successful adaptation of the system as well as general satisfaction of the occupant versus the importance of lighting control for the individual occupant. The results are shown in Figure 3. It can be seen that users who were less satisfied, and found that the control system did not adapt to their needs, are the same who deemed automatic control to be of little importance (bottom-left quadrants). Furthermore, a general worst-case scenario, where users deem control highly important yet it fails adapting or leads to dissatisfaction, was avoided since only one person falls into this category.

Overall, in this view, the satisfaction with the control system appears positive. Nonetheless, more appropriate metrics and methods than questionnaires to evaluate control satisfaction are necessary.

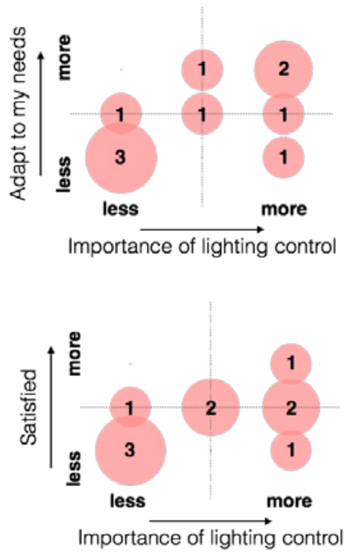

Fig. 3: User answers on adaptation, satisfaction with respect to the importance of lighting control (the numbers indicate the number of respondents).

5 CONCLUSIONS

In this paper we presented the occupant centred control (OCC) framework for the building context. We argued that it is necessarily the only conceivable approach if occupant comfort and satisfaction should be considered as much as possible. We have identified the research gaps for OCC. Finally, we have presented a case study with a first implementation of the OCC framework for lighting control. We have demonstrated adaptive set-points as well as user satisfaction. A potential drawback of the OCC framework is the necessary data management, and related topics such as data security and access. On the other hand, OCC holds the potential to provide individual comfort while reducing the energy consumption of buildings.

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