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Experimental evaluation of the performance of chair sensors in an office space for occupancy detection and occupancy-driven control

Timilehin Labeodan [a,*], Kennedy Aduda [a], Wim Zeiler [a], Frank Hoving [b]

[a] Building Services Group, Department of the Built, Technical University Eindhoven, Rondom 70, 5612 AP Eindhoven, The Netherlands
[b] Salland Electronics, Katwolderweg 15, 8041 AC Zwolle, The Netherlands

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ABSTRACT

The use of accurate and fine-grained occupancy information in building operation can, in addition to providing visualization of space use, provide worthwhile energy savings when the operation of lighting, heating, ventilation and air-conditioning systems are tailored to actual building occupancy information. Although there are ample off-the-shelf heterogeneous occupancy sensors available for use in practice, the information provided is often coarse-grained and inaccurate. As a result, multiple sensors, which cost more to install and maintain are often used in building operation for occupancy driven control of lighting, heating, ventilation and air-conditioning systems (L-HVAC). This article presents results from the experimental evaluation of chair sensors using sensing techniques based on strain, vibration and a mechanical-switch for occupancy detection in an office space. In addition, results from the application of one of the chair sensors in an open-plan office space as a heterogeneous occupancy detection system for occupancy-driven control of the lighting system in the space is as well provided.

1. Introduction

1.1. Importance of building occupancy information

The development and implementation of strategies that improve the energy performance of buildings has been the focus of a large amount of studies in the last decade mainly due to the impact of building energy use on final energy. The built environment is estimated to be the highest end use energy sector [1,2] and the resulting carbon footprint significantly exceeds that of all transportation combined [3]. Energy figures from the United States Green Building Council (USGBC) [4] suggests that 41% of primary energy is consumed by buildings, which are as well responsible for about 38% of CO_2 emissions. Projections by the U.S. Energy Information Administration (EIA) [5] suggests that with increasing population and economic growth in both developing and developed countries respectively, energy consumption in the built environment is bound to increase in the near future. To enhance sustainability of energy supply and preservation of the environment, there is therefore the need for the development and implementation of measures that improve the energy performance of buildings.

The commercial building sector contributes the largest in terms of floor-space and energy use in most developed countries [6,7]. In the US, commercial office buildings make up the largest within the commercial sector, comprising about 17% of all commercial buildings as well as being responsible for about 17% of energy use [5]. Lighting, heating, ventilation and air-conditioning(L-HVAC) systems are the major energy consuming systems in a typical commercial office building, accounting for well over 70% of the total energy use [8,9]. As office buildings are more often better equipped with sophisticated building automation, control and management systems [10], the availability and utilization of fine-grained occupancy information by the building management system can contribute towards worthwhile reduction in the energy use of buildings [11,12]. Moreover, in addition to energy savings due to energy sustainability and environmental concerns, the use of fine-grained occupancy information can contribute towards worthwhile reduction in the operating cost of buildings.

In practice, there are quite a number of low-cost, off-the-shelf heterogeneous occupancy sensors [13,14] with the ability to provide occupancy information for control of L-HVAC systems (Table 1). Widespread application of these heterogeneous systems is however limited due to a number of drawbacks [15–17]. Passive infrared (PIR) sensors for instance, are low-cost detection systems commonly used in buildings for the control of lighting systems [17], but they are rarely used in demand controlled ventilation applications due to their binary output [15]. On the other hand, carbon

* Corresponding author. Tel.: +31 402473411.
E-mail address: t.labeodan@tue.nl (T. Labeodan).

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dioxide sensors are often used in demand controlled ventilation applications in buildings [18,19], but are also rarely used for the control of lighting systems due to their slow response and sensitivity to environmental conditions [20,21].

To compensate for the drawbacks of individual heterogeneous detection systems so as to obtain more accurate and reliable fine-grained occupancy information, a combination of multiple detection systems is often employed in building operation [15,22,23]. Although these systems offer improved performance and provide more reliable occupancy information, the cost of deployment and management of additional sensing infrastructure remain significant [8]. Recent advancements in sensing technologies, embedded systems, wireless communication technologies, nano technologies, and miniaturization has however made it easier and cost-effective to deploy smarter systems with the potential to provide more accurate fine-grained occupancy information as heterogeneous and explicit occupancy detection systems, which can be used for the control of both lighting and HVAC systems.

1.2. Contribution of this paper

Improving the energy efficiency of key energy consuming building systems through occupancy-driven control [16] is clearly a viable and cost effective means to conserve energy and save cost. As a large number of commercial office buildings still operate using fixed occupancy schedules that consist typically of between 6 and 8 h of 100% occupancy [9,24], the availability of low-cost occupancy detection tools with the ability to provide accurate occupancy information can facilitate and enhance their application and use in building operation.

Sensors embedded in chairs [25,26] are commonly used in the automobile industry and these sensors have the potential to provide more accurate occupancy information that can be used in occupancy-driven control applications in buildings [16]. This paper provides results from the experimental evaluation of chair sensors using sensing technologies based on strain, vibration and a mechanical-switch in an office building. In addition, results from its deployment in an office set-up for occupancy-driven control of the lighting system are as well presented. The subsequent sections of this paper are laid out as follows; Section 2 provides a background on related research on the use of low-cost heterogeneous tools with ability to provide fine-grained information that can be utilized in office buildings for occupancy-driven control applications. Section 3 provides details of the experimental set-up as well as details of the sensors used in the study. A discussion of the sensors performance and application in the test-bed office building is presented in Section 4 while Section 5 provides the conclusion deduced from the study as well as further work.

2. Related studies

Building occupants exhibit varying occupancy patterns, which deviates sharply from the assumed fixed occupancy schedules commonly used in the operation of building systems [11,27]. As worthwhile energy savings can be obtained in buildings when the operation of building systems such as L-HVAC are tailored to actual building occupancy, there has been a lot of emphasis of recent on the need for the development and deployment of tools that can provide more accurate occupancy information for use in building operation [16,21,28].

Amongst the vast numbers of low-cost, off-the–shelf, commercially available heterogeneous occupancy detection systems, passive infrared sensors (PIR) are one of the most commonly used [29]. The sensors detect the presence of humans by measuring changes in emitted radiation [30]. The sensors are low power consuming, which is another key advantage [31]. In building operation, PIR sensors as standalone sensors are often used for control of lighting systems [17]. Their application as demonstrated by various authors [17,29] can yield as high as 70% reduction in lighting energy use depending on the configuration. As stated in [32], a retrofit of an office building with PIR sensors yielded up to 40% reduction in lighting energy use with a payback of 2 years in the form of reduction in lighting energy use.

The application of PIR sensors in building operation, particularly in commercial buildings, is however often limited to the control of lighting systems due to the coarse-grained nature of the information provided by the sensors. The output from the sensors is binary, it is affected by line of sight and the sensor is gives false-negative information when occupants are still [22]. Results from a quantitative evaluation of PIR sensors by the authors in [30] in an office building also suggested that the sensors are prone to false-positives when they are deployed close to HVAC systems or fans. To compensate for false-negative effect, time delays dependent on location of use are often programmed into the sensors' management system [17]. A number of studies have also investigated the possibility of obtaining additional information such as movement [31,33] and count [34] from PIR sensors.

Ultrasonic sensors are another low-cost, readily available occupancy detection system that are commonly used for control of lighting systems in buildings [35]. Unlike PIR sensors, they do not require direct line of sight for presence detection and are more sensitive and less prone to false-negatives. Ultrasonic sensors are however more susceptible to false-positives [36]. Carbon dioxide (CO_2) sensors are another heterogeneous explicit detection tool commonly used in buildings for occupancy detection [18,19]. CO_2 sensors in general provide an indication of the concentration of CO_2 gas in a space. As building users produce CO_2 gas at varying quantities in a space, the amount present in a space at a particular time can provide an indication of occupancy as well as an estimate of the number of people in a space [37,38]. Using CO_2 sensors, the authors in [39] demonstrated that the CO_2 concentration level highly correlated to the number of occupants in the test-space. Unlike PIR and ultrasonic sensors, CO_2 sensors are more often used for demand controlled ventilation applications in buildings [18,40]. CO_2 sensors are however influenced by physical environmental conditions such as wind speed and have a slower response when compared with PIR and ultrasonic sensors [11,16].

More advanced systems utilizing digital cameras [15,21] and different wireless radio frequency based techniques [11,30,41] have as well been demonstrated to have the potential to provide more accurate fine-grained occupancy information as heterogeneous systems for use in the control of both lighting and HVAC systems. These systems are however still in their infancy and as such they are expensive to install and maintain [8]. In addition, privacy concerns and the terminal based [42] nature of some of these devices are also hindrances to their wide application in buildings for control of building systems [16,42,43]. WI-FI signals for instance, though widely available in commercial buildings can penetrate through walls and occupants with multiple devices can be connected to a single access point, thus making it prone to false-positives [43]. In addition, overlap of access points coverage, and inconsistent Wi-Fi connectivity of mobile devices are also drawbacks that limit its use in building operations for occupancy driven control [44].

To compensate for the drawbacks of individual heterogeneous occupancy detection tools, multiple sensors are often combined together to provide more accurate and reliable fine-grained occupancy information [22,28]. The authors in [26] demonstrated the performance advantages of using a combination of sensors for occupancy detection in an office building using a combination of PIR, microphone and a pressure sensor embedded in a chair. The authors demonstrated the ability of the system to provide more reliable