Smart IoT desk for personalizing indoor environmental conditions

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ABSTRACT

Occupant satisfaction with indoor environmental conditions remains low in buildings that provide little to no control over the environment. Poor environmental conditions lead to lower productivity and can have negative impacts on health and wellbeing. Personalizing the environment based on user preferences could not only improve health and well-being but also the user satisfaction and productivity. Furthermore, office workers spend most of their working hours in sedentary activities. The use of sit-stand desks has been linked to the reduction of prolonged sitting time resulting in health benefits. By leveraging recent advances in IoT, we monitor the environment around the occupant and utilize different machine learning algorithms to learn their indoor environment related preferences. In this paper, we describe our vision and ongoing work of creating a smart IoT desk that can personalize the environment around the occupant and can act as a support system to drive their behavior towards better environmental settings and improve posture and ergonomics.

Author Keywords

Internet of things (IoT), smart furniture, human preferences, adaptive environments, user interface

ACM Classification Keywords

H.5.m. Information interfaces and presentation (e.g., HCI): Miscellaneous;

INTRODUCTION

People spend about 90% of their time indoors [24]. Indoor environmental quality (IEQ) parameters, such as air quality, ventilation, thermal conditions, lighting, and acoustics are associated with comfort, productivity, physiological and psychological health and well-being of building occupants [2, 10]. In addition, there is a large energy cost associated with maintaining comfortable indoor environments. Buildings consume about 40% of all energy consumed in the U.S., where more than half of this amount is used to maintain adequate thermal and lighting conditions [32].

Despite the large energy spent on controlling indoor environments, occupant satisfaction remains low. Current Heating, Ventilation and Air Conditioning (HVAC) and lighting systems are mostly controlled based on *"one size fits all"* policies. Due to the variations in occupant preferences, centralized HVAC systems are unable to satisfy most of the occupants' thermal comfort requirements [3] while exposing occupants to uniform indoor temperatures. However, long term exposure to uniform thermal environments has been linked to adverse effects on metabolic health and increased risk of cardiovascular diseases [26]. Furthermore, studies show that lighting demands vary based on mood, activities and preferences [12]. Exposure to blue light during the evening or lack of bright white light during the day can also disrupt the circadian rhythm and have a negative impact on human health [29]. Current Building Automation Systems (BAS) and Building Management Systems (BMS) monitor the environment at the zone level, which makes it difficult to control the conditions based on the individual's preferences. In order to improve the overall occupant satisfaction with the indoor environment, it is important to learn user's preferences and control the environment based on those preferences. Additionally, office workers spend around 80% of their working time in sedentary activities [28], which can adversely impact their metabolic health and increase the risk of having cardiovascular diseases [9]. Recent studies show that the use of sit-stand desks can reduce overall sedentary time and have positive impacts on occupant's health and productivity [8].

With recent advances in Internet of Things (IoT), it is possible to monitor the occupant's surrounding environment (microclimate) and their behavior at a much granular level, which reflects their individual preferences. In this paper, we describe an ongoing effort on creating a smart IoT desk which can improve the occupant's satisfaction with the environment, and their health and productivity by personalizing the environment based on their preferences. The goal of the smart IoT desk is to learn individual's preferences and control the environment around the user based on their preferences. Furthermore, the desk can also act as an intelligent support system by cuing the user to reduce their sedentary time and to change their indoor environment to improve their satisfaction and productivity.

In this paper, we focus on three different aspects of the office environment that influences occupant satisfaction, health and

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productivity, namely: thermal comfort, visual comfort and reduction of prolonged sitting. We describe how IoT technologies enable the monitoring of occupant behavior and environmental parameters and how the monitored data can be used to control the environment through solutions that keep humans in the loop. We first discuss some of the related work in these three fields, and then describe different versions of the desk, how it has evolved to its current state. We conclude the paper with future directions towards our vision for smart IoT workstations.

RELATED WORK

Thermal Comfort

The field of thermal comfort in indoor environments was pioneered by P.O. Fanger [15] who conducted large-scale laboratory experiments to understand the environmental parameters that influence thermal comfort of occupants. His work in the 1960s led to the development of the Predicted Mean Vote/Predicted Percentage Dissatisfied (PMV/PPD) models, which are currently adopted by standards, such as the ASHRAE 55 to describe how the indoor thermal environment should be controlled. Later work by de Dear and Brager [11] led to the adaptive model of thermal comfort, which highlighted the importance of contextual factors and past thermal history in determining thermal expectations and preferences of occupants. This model was adopted into the ASHRAE 55 standard to describe how the indoor thermal environment can be controlled in naturally ventilated buildings. Yet, both the PMV/PPD and adaptive models rely on averaged responses from a large group of people and fail to account for individual preferences of occupants.

There has been a recent push towards developing new modelling approaches to learn individual comfort preferences. These approaches typically consist of different sensors to monitor indoor temperature and humidity and an interface to gather thermal sensation feedback from occupants. The models typically try to map the sensor data to the comfort sensation to create individual comfort profiles. Several such systems have been developed in recent years utilizing different modeling approaches, such as fuzzy logic, neural networks, Bayesian networks, logistic regression, linear discriminant analysis etc. [23]. Recent studies have also investigated the monitoring of physiological changes in skin temperature using wearable devices or thermal imaging for developing individualized thermal comfort models [6].

Several studies have also developed approaches to control HVAC systems based on occupant preferences. Such studies show improvements in occupant satisfaction and reduction in energy consumption [14, 18]. However, a recent study showed that centralized HVAC systems are unable to satisfy the majority of occupants in a building because the systems are controlled at a zone level where multiple occupants in the same zone may have different preferences [3]. A potential solution to meet individual requirements could be to implement Personalized Comfort Systems (PCS), which can create a microclimate around the occupant based on their preferences. Several such systems have been developed, such as heating/cooling chair, heating/cooling wrist pads, heating shoe insoles, cooling desk fan [25] and so on. Such systems have the ability to improve occupant comfort and lower the overall energy consumption.

Visual Comfort

Current lighting standards, such as the ANSI/IES RP-1-12, provide recommendations for designers such as minimum lighting levels under different scenarios. However, the existing lighting systems do not account for individual preferences. Inadequate lighting can cause problems with visual acuity and distraction from the task, lower productivity, and lead to eyestrain [5]. Too much or too little light and contrast between task and background surfaces etc. can cause glare and visual discomfort that leads to eye strain and fatigue [5]. When compared to homogeneous overhead lighting, use of task lighting that is directed toward the work surface can improve comfort and satisfaction [19].

Several studies highlight the benefits of using task lighting at work. For instance, providing individually controlled task lighting where users select their own illuminance levels led to the productivity increase of 4.5% in a factory [20]. Furthermore, giving users control over their visual environment also leads to improved mood and satisfaction [20]. Several systems that monitor occupant’s presence and control the lighting system based on occupancy have been developed in order to reduce the overall energy consumption when the spaces are not occupied. However, such systems, which can be found in newer buildings, do not take individual requirements into account. Recent studies have developed methods to learn occupant’s lighting preferences and automatically control the lighting levels based on their preferences [12, 31]. One such method, utilizes sensors to monitor illuminance levels, shading position, and electrical light dimming level, combined with occupant feedback to learn their personal lighting preferences [31].

Although task lighting can improve productivity and occupant satisfaction, such systems typically only consider illuminance levels. The emitted spectrum of light and the associated color rendering quality is another important parameter that impacts the overall health and wellbeing, and artificial light should be designed to stimulate the circadian rhythm [30]. Light rich in short wavelength components (blue) has an alerting effect and light rich in high wavelengths components has a relaxing effect on humans [4]. The duration of exposure to short wavelength light is also an important factor in stimulating the circadian rhythm [27]. Studies have linked exposure to light with strong short wavelength components during night to disruption in the circadian rhythm and increased risk of breast and colorectal cancer [17]. Exposure to bright light during the day and light composed of higher wavelength components at night can help reduce negative impacts on the natural circadian rhythm [29]. Therefore, both the color and illuminance levels of light needs to be controlled to promote occupant productivity and reduce negative health impacts.

Sit-Stand Regimen

Seated work for long periods of time has been associated with discomfort and health risks, such as adverse metabolic health, musculoskeletal disorders and increased risk of colorectal cancer [9]. Reducing prolonged sedentary time with adequate breaks from sitting is associated with improved metabolic health. Even minimal activities, such as standing, rather than sitting, can result in increased daily energy expenditure and can provide resistance to fat gain if adequately distributed throughout the day [16].

Sit-stand desks have recently gained popularity in the workplace as they can provide breaks from prolonged sitting while enabling office workers to perform their duties with a potential to improve productivity. Availability of sit-stand desks and other workstations that promote physical activity and change in positions have been shown to promote increased standing during the day and they are associated with improved worker satisfaction compared to the use of static workstations [8]. In general, the implementation of sit-stand paradigms have been shown to have a positive impact on worker comfort and improvement in worker productivity [22], with emerging evidence on improvement in worker posture [21] and relief of musculoskeletal symptoms [13].

However, prolonged standing also has negative health outcomes, such as lower back and leg pain, fatigue, and discomfort [33]. Previous studies suggest that frequent rotations between sitting and standing, with a ratio between 1:3 and 3:1 sitting to standing time seems to provide health benefits without causing discomfort [7]. Furthermore, since individuals have different preferences and work patterns, the duration and frequency of switching between sitting and standing configurations needs to be tailored to the individual. A common problem in the use of sit-stand desks is the decline in user interest after an initial period. Strategies such as proper instructions for using the desk, motivational information regarding health benefits of sit-stand routine, prompts to change posture, and goal setting have been shown to increase the benefits of sit-stand desks [9].

THE SMART IOT DESK AND ITS EVOLUTION

While there are many recent efforts towards achieving a better office work environment, the main difference between our effort and other desks (e.g., autonomous.ai, cemtrex, etc.) is the utilization of IoT devices to personalize different aspects of the indoor environment based on a human-in-the-loop approach, as opposed to focusing on just reducing prolonged sitting. To achieve this goal, we have continued to add new sensors, features and learning capabilities to the desk. In this section, we describe the evolution of the desk, i.e., the sensors and other features in each version and how they relate to personalizing the environment around the user, utilizing a human-in-the-loop approach.

Version 1

The original version of the desk was created at Arup, London. The desk is an effort to create a more productive and healthier workspace by leveraging recent developments in the field of IoT. Fundamental to the smart IoT desk is the use of digital manufacturing and open source tools and platforms where possible to make new developments open source available to enable anyone to build their own desk. The desk's design is available on GitHub (github.com/arupiot/arup_iot_desk) and can be locally manufactured using Computer Numerical Control (CNC) machine. The desk's tabletop is designed to incorporate the sensors in a seamless way using built in grooves to conceal the electronic components, provide cable management and reduce inconvenience to the user. The desk also incorporates a service zone to provide access to all the cables and allows users to install many types of sensors and gadgets as well as computers, phones, chargers etc. as shown in Figure 2. Figure 2 shows the schematic design and actual implementation of version 1 of the desk.

The first version of the desk utilized Power over Ethernet (PoE) to supply Extra Low Voltage (ELV) DC to power devices such as laptops, smartphones, monitors, sensors, etc. on the desk. The PoE technology provides power and data with a single cable, meaning that each device can have an IP address and can be connected to the internet, creating a truly IoT desk. The ELV DC supply provides a high level of safety, flexibility for reconfiguration, lower cost per point of combined electrical and power connection, fewer compliance tests requirements and increased control compared to AC supply. However, the downside of this approach is the increased amount of cables, as each high power device (monitor and laptop for instance) requires its own dedicated Ethernet cable.

The desk is equipped with sensors, such as temperature and humidity to monitor thermal comfort conditions; illuminance (lux), and correlated color temperature (CCT) sensors to monitor lighting conditions; carbon dioxide (CO_2), volatile organic compounds (VOC) and particulate matter (PM) sensors to monitor air quality. Furthermore, the desk is equipped with a motion sensor to infer occupancy state, and energy meters at PoE injector level to monitor power consumption of each occupant. The desk also has a centrally controlled uplight and a local task light which can be controlled by each individual user. The central lighting changes spectral composition of the light based on the daylight cycle. The task lighting allows the users to adapt the light to their needs, for instance, staying alert and increase visual acuity when there is a need to be more focused on certain tasks. The desk reduces energy consumption by automatically turning off monitors and lighting if no motion is detected for a certain period of time at the desk level.

Using existing open source tools in the market, the backbone for the desk is created for monitoring sensor data around the

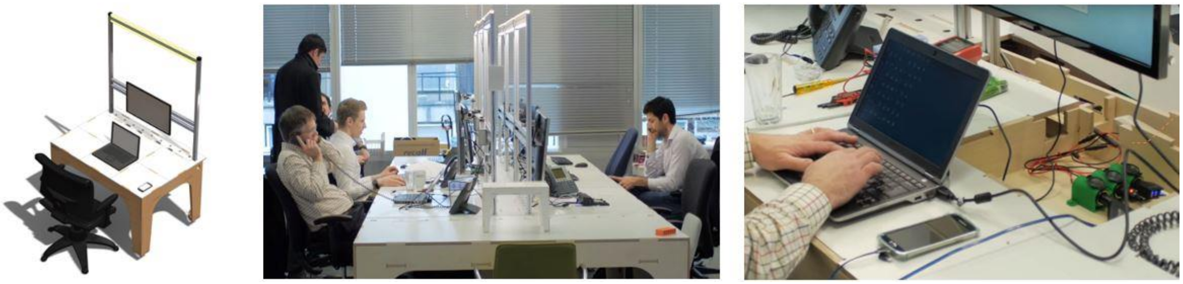

Figure 1: Schematic design of version 1 (left), desks in Arup London office (center), and service zone (right)

user. The desk utilizes influxDB (www.influxdata.com), an open source time series database to store collected sensor data. It also utilizes Grafana (https://grafana.com/), an open source data analysis and visualization platform to create a dashboard to visualize the collected sensor data. In addition to sensor readings, the dashboard also includes calculation of PMV/PPD metrics to evaluate thermal comfort conditions as shown in Figure 1. The sensors and data hubs are manufactured by Tinkerforge (www.tinkerforge.com), which enables plug and play functioning of different sensors, and makes their designs and codes open source. The code for monitoring data from sensors is available on GitHub (github.com/arupiot/deskcontrol). The sensors are connected to a Raspberry Pi 3, which periodically collects and sends data to a cloud instance of influxDB for time series storage.

Metric	Current
Standard Effective Temperature (°C)	4.18
Predicted Mean Vote	-9.98
Percent Predicted Dissatisfied	100.00
ASHRAE 55 Upper Boundary (°C)	22.26
ASHRAE 55 Lower Boundary (°C)	17.26

Figure 2: Monitoring dashboard in Grafana

Version 2

In addition to the components in Version 1, a Radio Frequency IDentification (RFID) sensor shown in Figure 3 was added to the smart IoT desk to identify the user with an RFID tag in order to enable personalized services. The desk could be used by more than one occupant (e.g., hotdesking); the RFID tag enables user profiles to be pulled from the cloud and be used for personalization of the environment. The new version also included addition of USB power sockets and wireless phone charging on the desk surface to reduce clutter from different cables on the desk surface. Due to less widespread device support of PoE, PoE was abandoned from the version 2 desk in favor of a 12V ELV power distribution. Version 2 also included a small screen where the user can view current sensor readings using a joystick mounted under the desk to scroll over different sensor values, control the local lighting and visualize configuration information such as networking status. The goal was to create awareness about indoor environmental conditions and provide a user interface to lighting. The new version was also redesigned to introduce manual sit-stand feature and improve the look of the desk and the placement of the sensors. Figure 3 shows the version 2 of the smart IoT desk and new components added to the desk. This version also included the addition of sound level sensors to monitor the acoustic environment around the user.

Figure 3: Version 2 of the desk (left). Wireless charging (top-right), and RFID sensor (bottom-right)

Version 3

Version 3 includes the addition of motorized sit-stand feature, as well as small adjustments to the sensor placements by adding modular frames as shown in Figure 4. It also includes the addition of a distance sensors to monitor desk height, and how far the user is from the desk. Furthermore, this version also includes the addition of a desk fan and a heater that can be used to adjust thermal conditions, creating a local microclimate, providing the opportunity to relax the requirements on centralized HVAC systems. The current version of the desk enables the user to control their thermal and lighting conditions, and desk height based on their preferences. We have also developed and incorporated algorithms to identify occupancy states from motion sensor data and a framework for activity recognition from power consumption of appliances [1] in order to enable context-aware control of the environment. Figure 4 shows some of the sensors and the Raspberry pi system fitted onto a frame that blends with the desk tabletop. Figure 5 shows the overall view of the current desk.

FUTURE VISION

So far, much of the improvements have been on the hardware

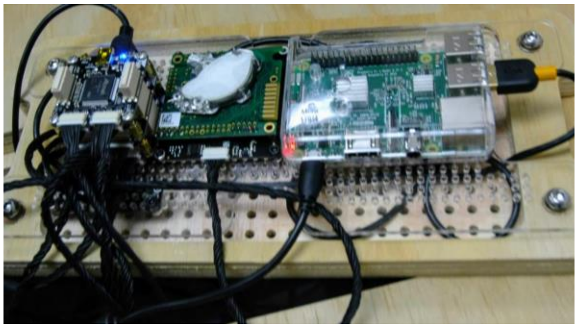

Figure 4: Sensors and Raspberry Pi on the desk

side. The current focus is on adding *'intelligence'* to the desk by developing and implementing algorithms to learn individual user preferences. For example, we are currently in the process of implementing algorithms to learn user preferences for thermal and lighting conditions such as the ones described in [23, 31], as well as profiling their sit-stand preferences. Future improvements will include the implementation of control schemes that can automatically adjust the local environment around the user. We are also working on adding sensors to the desk to measure the vertical and horizontal illuminance, work plane daylight illuminance and solar radiation. After implementing the appropriate algorithms, the next step will be conducting studies in actual office environments to gather user feedback and evaluate the effectiveness of the desk in achieving our goals.

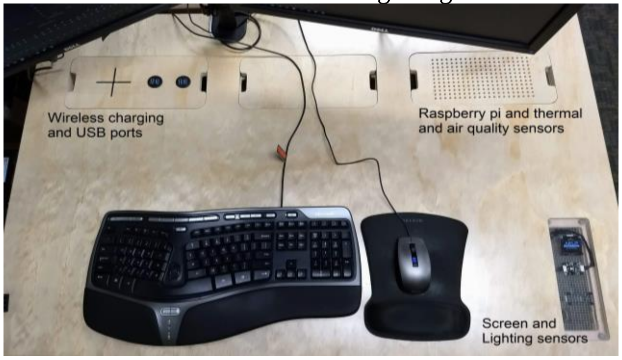

Figure 5: Overall view of Version 3 of the desk

Overall, we envision the desk to adapt to the changing requirements of its user, and improve the overall satisfaction, health and productivity. Although our current focus is limited to thermal comfort, lighting comfort and sit-stand behavior, there are other avenues which can be explored in the future to improve the user's wellbeing. For example, air quality monitoring systems could be integrated to enhance the indoor air quality. Posture detection systems could be added to investigate and improve the ergonomics of the user. As our ability to learn human preferences improves, the workstations in the future could provide truly personalized experiences to enhance their overall wellbeing.

CONCLUSION

In this paper, we described our efforts and vision to move beyond "one size fits all" control of the indoor environments by leveraging the recent developments in IoT to monitor the local environment around each occupant, and using different machine learning techniques to gather an insight on individual preferences of occupants using a human-in-the-loop approach. As a work in progress, we described the systems we use to monitor the environment, and the improvements in the desk design over time. Future work will focus on developing and implementing algorithms to learn user preferences and control the environment based on their preferences. After implementing the algorithms, we plan to evaluate the improvements in occupant satisfaction, productivity and wellbeing by conducting longitudinal and large-scale user studies.

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