

BIT – Building Impulse Toolkit: a novel digital toolkit for productive, healthy and resource efficient buildings

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Abstract. This paper presents the “Building Impulse Toolkit” (BIT), a novel array of digital sensors and methodologies for the transient and holistic tracking of occupant response in the built environment. BIT aims to enable the dynamic monitoring of occupant comfort, productivity and well-being in order to inform responsive and predictive control strategies. Further, to assess user experience in order to facilitate the design and operation of future resource-efficient and occupant-centred buildings. This paper describes the preliminary results and limitations of this novel toolkit and, subsequently, discusses the future research and development required.

Keywords: Occupant response, intelligent buildings, dynamic control, environmental monitoring, Internet-of-things

1. Introduction

The digital sensing and control of building components is in its infancy, but offers exciting opportunities to shape new intelligent buildings that provide safer, healthier and more productive environments whilst using fewer resources [1]. The principal challenge in this field is to understand how the various transient environmental characteristics (e.g. visual, thermal, acoustic, air quality, vibration and interaction) that define an internal environment act simultaneously to affect our overall sense of comfort and satisfaction and how this in turn leads to changes in productivity and wellbeing. Knowledge of these relationships would enable us to construct intelligent buildings and control novel building technologies in a far more effective and user-centric manner. In the absence of this holistic and transient data on occupant comfort and satisfaction, the use of resource-efficient measures and technologies can be (and often are) very disruptive for occupants [2]. This challenge is particularly timely in order for new resource-efficient, healthy and productive buildings to meet the demand of the extra 2.5 billion people that are expected to live in cities by 2050 [3].

Artificial intelligence (AI) can unlock the potential of extensive digital occupant data to unveil the holistic relationships between occupant productivity and well-being, and transient indoor characteristics [4]. However, there are still several obstacles to large-scale deployment of productive and satisfactory AI-enhanced buildings, namely: a lack of methods to capture transient occupants data [5] without being disruptive (but maximising user acceptance); availability of large scale deployable toolkits and digital

platforms to collect environmental data with high spatial granularity [6]; holistic measurements of occupant response and its interrelations [7].

Novel toolkits that include methods from other disciplines, such as behavioural science or Human-Computer interaction, for capturing occupant response are therefore needed in order to effectively inform intelligent buildings. These novel toolkits should be able to address: “When” - collecting transient and dynamic data from occupants and environment [4]; “Where” - gathering data from several locations in the building through ubiquitous devices [5]; “Who” - targeting user acceptance, disruption, and unobtrusiveness when collecting feedback from occupants [6]; “What” - collecting holistic data on occupant response and the environment [7]; “Why” - being a component of a wider intelligent system where sensors and actuators are connected to maximise occupant satisfaction and productivity whilst reducing resource consumption.

This paper presents a multi-domain novel toolkit, called Building Impulse Toolkit (BIT) (Figure 1) for gathering direct and indirect occupant response to the environment and discusses the strengths and limitations of the BIT Station. The novelty of the toolkit lies in the: 1) Development of a new type of electronic device for direct occupant feedback; 2) Use of novel indirect methods simultaneously; 3) Holistic approach 4) Extension of the toolkit to include façade components.

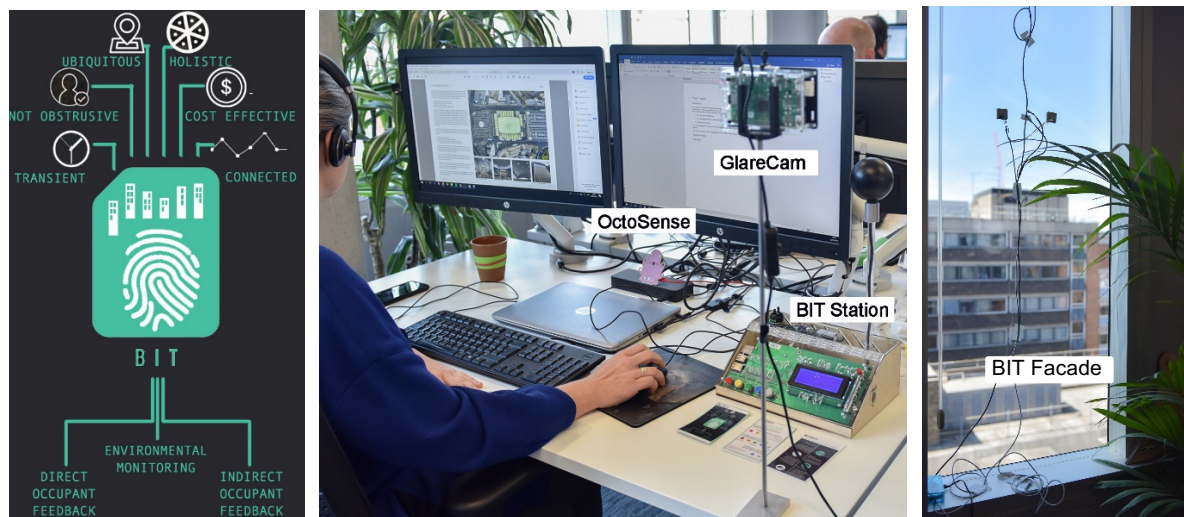


Figure 1: Characteristics of BIT and overall architecture (credit photo:Arup): a. Concept and definition of BIT; b. Toolkit installed in a real office environment; c. BIT Façade installed in a real office environment

2. State of the Art

Direct means of gathering occupant feedback on environmental conditions and its effect on comfort, productivity, well-being have been widely investigated. These are methods used to gather subjective information on environmental conditions. These include quantitative methods, such as paper, mobile-app, web-based or tablet surveys and polling stations, and qualitative techniques such as interview and walkthroughs. Ordinarily these methods are used in post-occupancy evaluations (POE). The most prominent POE surveys are: the Building Use Studies (BUS) [8] and The Centre for Built Environment Building Performance Evaluation (BPE) toolkit [9]. However, these current methods are generally time-consuming, disruptive to occupants, sensitive to bias and only representative of a moment in time, as occupants are usually asked to remember environmental preferences and comfort conditions from weeks in the past.

Whilst direct feedback from occupants is a highly valuable source of information, new methods are required to increase ease-of-use and granularity in time, creating high-frequency and meaningful information about occupant response. High-frequency surveys can even lead to occupant survey fatigue and progressive user withdraw from pilot studies [10]. The use of polling stations as an electronic physical survey could be more time-efficient. Konis [11] used a polling station with electronic survey

questions paired with illuminance operative temperature measurements. A fixed-desktop polling station for real-time building occupant feedback was also developed by Pedersen and Petersen [12], where the station was prompting users to answer 5 minute surveys whilst monitoring the thermal environment. Recently, Berquist et al. (2019) have investigated the use of wall-mounted polling stations to gather occupant feedback on thermal and air quality in sport facilities whilst again monitoring key environmental parameters. However, these electronic devices still require a similar amount of time as the equivalent high-frequency, short, web-based or paper systems and tend to be related to only a few environmental domains instead of being multi-domain. For instance, none of them investigates occupant satisfaction with their personal control of the environment.

Indirect methods for collecting occupant feedback include all methods that do not ask occupants for direct feedback but infer their response and level of satisfaction from indirect measurements. These methods have the potential to be less disruptive to daily occupant activities and time-efficient, allowing building systems to adapt more frequently than would be possible with direct occupant feedback. These methods include facial thermal imaging [13], facial action unit detection [14], micro-expression recognition, brain waves and any wearable technology for reading physiological response. Also, any inference based on occupant interaction with the environment to adapt and customise it. While some of these methods can be really disruptive, such as brain wave monitoring or galvanic skin response, others have the potential to provide a subtle and seamless monitoring of occupant response. However, indirect occupant monitoring requires careful design and development to ensure privacy protection and consent.

Lastly, methods for objective IEQ monitoring have been progressively developed to be less intrusive and complemented by software platforms for users [15] or embedded in ordinary environments such as IoT desks [16] and toolkits. These existing toolkits gather information through wireless sensors and send data to the cloud for post-processing and displaying. However, measurements are often limited to the easiest environmental characteristics to be monitored, while novel AI methods could be applied for capturing the quality of the environments.

3. BIT – a holistic IoT toolkit to monitor occupant response to the environment

3.1. Overall description and methodology applied

BIT was developed at the department of Engineering, in collaboration with the Department of Psychology and the Facade team at Arup. Figure 1 shows an overall view of the toolkit, which includes: 1) a novel electronic device for collection of direct occupant feedback and the environmental monitoring (BIT Station), which is complemented by a web-based application and survey; 2) a novel low-cost camera device for measuring occupant interaction with the façade, luminance levels, Daylight Glare Probability (DGP) and vertical illuminance (GlareCam); 3) “Octosense” [12], a webcam that monitors facial action units (FAU) and can potentially be complemented by a thermal imaging camera to read the skin surface temperature of occupants; 4) a low-cost IoT façade toolkit to monitor the main environmental characteristics of the façade and user interaction; 5) a digital platform for the storing, post-processing and interaction between each single component.

Data is collected in situ and then, since all the devices are connected to the network, remotely stored in a protected database at the University of Cambridge. Real-time monitoring is then available through a dedicated web-interface. All the devices can then communicate with each other through MQTT protocol, in order to pair environmental monitoring with occupant response.

BIT has been developed from the single board processor Raspberry pi [11], which enables a cost-effective and modular method to implement IoT digital toolkits, since many compatible digital sensors are available on the market that require low-cost wired connections. The cases of this toolkit have been manufactured through 3d-printing and laser-cutting. To keep costs low, this toolkit uses the client wireless network connection and open-source software where needed.

All the BIT devices (Table 1) can then be deployed across an indoor space to collect data with a high granularity in space. They also have the potential to be battery powered to ensure higher flexibility.

Table 1 Description of toolkit components and characteristics monitored

BIT component	Function	Characteristics monitored
BIT Station	-Environmental monitoring -Direct occupant feedback	-CO2 levels [ppm] -Solar radiation [W /m ²] -Horizontal Illuminance [lux] -Noise level [dB] -Air temperature [°C] -Relative Humidity [%] -Mean Radiant Temperature [°C] -Presence of Discomfort -Level of satisfaction, productivity, stress and fitness
BIT Glare	-Monitor visual environment for glare assessment -User interaction with the facade	-Vertical Illuminance [lux] -Luminance levels [cd/m ²] -DGP -Blind usage is inferred by HDR images and machine learning algorithms
BIT Facade	-Monitor key environmental parameters related to facades -Track User interaction with facades	-Surface temperature [°C] -Air temperature [°C] -Vertical Solar radiation [W /m ²] -Vertical Illuminance [lux] -Distance of the blind from floor -Tilt angle of the blind

3.2. Direct methods for gathering occupant feedback: concept development and testing

For the development of the first prototype of BIT station several different layouts/designs were considered. These were created through discussions with the Department of Psychology and the User Interface team at Arup. Moving on from this, considering aspects including flexibility (variety of data), cost and user-ability, two final designs (Figure 3) were chosen in the pre-selection phase to be tested for their user-ability. Sixteen participants took part in a test of both prototypes without being given any instructions to assess how quickly they learned what they had to do and how quickly they did it. After this short test they were asked a series of questions to gauge their impression of the two prototypes. These lessons were then taken forward to the next prototype stage. The final polling station works in two different modes: it can either be used to capture the level of occupant satisfaction, or, alternatively, to record occupant discomfort. To gather the level of satisfaction, the occupant is prompted by means of light stimuli, but occupants can volunteer to register environmental discomfort whenever they feel it is necessary. The interface has been tested to assess its potential and identify ways of improving this prototype.

The final station prototype was then given to volunteers to assess it against traditional web-based survey, which were sent during the day through emails and that allow users to record discomfort in any moment. These tests were undertaken during two working days in real office environments. A total number of 103 interactions were recorded using the BIT Station, whereas 69 questions were answered by occupants through surveys. Occupants were then asked to rate the level of intrusiveness and ease of use of both web-based survey against a desk station (Figure 3). Ease of use of the BIT Station was ranked much higher than traditional web-surveys, while level of intrusiveness gave similar results. After interviewing volunteers, it emerged that user perception of the level of intrusiveness is related to personal user preferences between having a physical object on the desk and receiving a large number of survey notifications. However, to record instant perception of discomfort, the station discomfort buttons were proven to be a more effective manner to transiently monitor the presence or absence of discomfort.

The final BIT station prototype was then installed, together with the rest of the BIT toolkit devices, to test its ability to capture time-stamped occupant response during the day and capture transient changes

in the environment (Figure 4). At 9am, 11am, 1pm, 3pm and 4pm occupants would therefore see a light flash on the polling station prompting them to answer questions related to their productivity and comfort. Further throughout the day, the occupant could register their discomfort by simply pressing the discomfort buttons according the type of discomfort they were experiencing. The toolkit is currently being tested in two real office environments and it will collect data throughout a full year of deployment. Further deployments are planned to better inform the development of the prototype polling station.

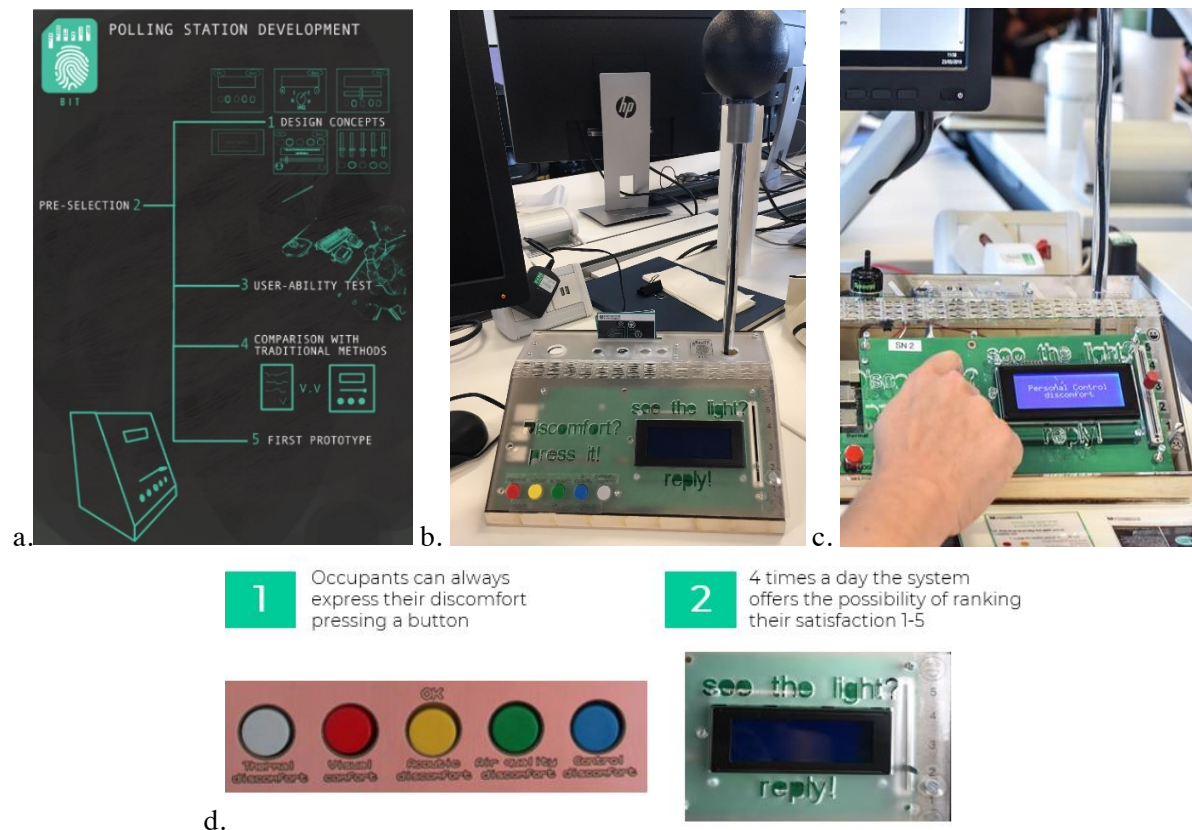


Figure 2 Polling station development and final prototype. a. Design process of the station; b. Final prototype; c. Example of users using the station to express their discomfort; d. description of the two function modalities: 1. Discomfort mode 2. Comfort – Satisfaction mode.

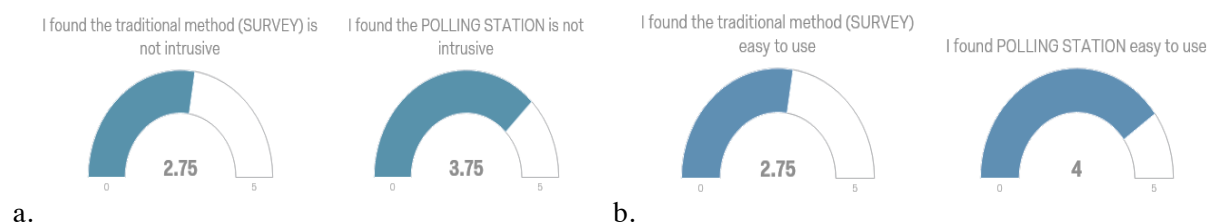


Figure 3 Comparison between web-based survey and electronic devices: user response in terms of (a) intrusiveness of the system and (b) ease of use.

4. Conclusion and future development

The holistic assessment of occupant comfort, productivity and well-being requires a variety of sensing technologies to be integrated seamlessly into the built environment. Novel toolkits and methods tested in BIT offer the potential of gauging occupant response and preferences, unveiling the relationships between the environment and occupant satisfaction, productivity and well-being.

BIT is still at a first prototype stage and further work is needed to validate and optimise its application in real world environments. Physical electronic device stations appear to offer a promising direct means

of capturing data from occupants, but also in collecting the data that is needed to help develop more indirect data capture techniques, such as those using facial expressions. Future work is required to address the following issues: 1) Ethical consequences of collecting occupant response and preferences in the office environment; 2) Development of more devices that can capture indirect occupant response; 3) Increase of user-ability of the BIT polling station and decrease its obtrusiveness, potentially embedding it in ordinary office environments such as mobile phones and desktop with sensing technologies.

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