

Sensor-enabled Cubicles for Occupant-centric Capture of Building Performance Data

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ABSTRACT

Building performance discourse has traditionally focused on the evaluation of a specific design. However, to increase the accuracy and ongoing validity of performance analysis, the building science community has come to understand the value of extending the focus beyond design to include the full building life-cycle. In the context of commercial office buildings, building performance analysis has been centered on the heating and air-conditioning system resulting in building instrumentation primarily serving large zones defined at design time. While this coarse level of metering and control may serve the needs of the building, a finer level of detail will be needed to better serve occupants with improved comfort levels. To move toward a more occupant-centric system, the instrumentation of office furniture in the form of sensor-enabled cubicles is proposed. By considering a cubicle to be at the occupant scale, a higher level of data sampling, sufficient to support detailed building performance visualization, is suggested. To this end, an overview of a prototype system that includes data sensing, data storage, and data representation to enhance the state of building performance visualization is presented.

INTRODUCTION

Building performance discussion has traditionally focused on the evaluation of a specific design. However, to increase the accuracy and ongoing validity of performance analysis, the building science community has come to understand the value of extending the focus beyond design to include the full building life-cycle. Continuous measuring of performance-related factors has a long history in the Heating Ventilation and Air Conditioning (HVAC) industry. Building Automation Systems (BAS) are the primary example, where sensors are embedded into HVAC equipment. A BAS collects large amounts of data about the overall performance of a building (global level), but it generally does not address differences at the user level due to its coarse sampling and insufficient coverage of individual occupancy zones (Mo and Mahdavi 2003). As Cole and Brown (2009) have indicated, occupants are generally treated as “passive participants” within an environment controlled through a centralized automation system. Furthermore, the entire interior space is generally treated as a homogenous environment. However, the variability of interior conditions is greater than the exterior environment variation (Addington 2009). When considering building performance, we face a complicated balance between an occupant’s comfort and energy consumption since comfort and energy savings are often inversely related (Yilmaz 2006). Despite many design measures in performance-related factors, to sustain this balance is particularly challenging and complex, which results in compromising comfort in favor of cost saving measures (Robertson 1988). The key challenge in augmenting an occupant-centric approach to understanding building performance is twofold: first, there are no effective means to capture an occupant’s requirements

(data collection). Second, more effective and intelligent means of visualizing the collected data are needed (data representation).

To address this challenge, the office building occupied by the authors is being used as a living laboratory to gain insights on how to better represent building performance based on measured data collected through a sensor network. Buildings consist of many system-based layers of assembly including structure, HVAC, and furniture. In contrast to an HVAC-centric approach, an occupant-centric method, through the addition of a sensor-network embedded in the furniture layer, is described. In a typical office building, the relationship between occupants and their environment is largely negotiated at the furniture scale where each office cubicle defines an occupant's primary boundaries. While considering economies of scale, the availability of information at the cubicle level bears deep potential in how we may conceptualize and evaluate building performance. A working prototype is demonstrated by outlining both hardware and software implementation. First, a hardware implementation is described where each cubicle is turned into a data-sampling cell distributed throughout a typical office floor. Second, novel visualization methods are presented as an integral part of the system by mapping collected data to local features found in a detailed as-built Building Information Model (BIM) (Attar et al. 2010b). Brief demonstration examples of building performance visualization are given, based on the coupling of sensor networks and BIM, while existing shortcomings and key areas of future research are discussed.

OCCUPANT-CENTRIC DATA CAPTURE

Data collection at the cubicle level, to address occupant needs, is not without precedent. Chou et al. (2001) describe a real-time data visualization scheme to create a “personalized and context-aware workplace” within an office space. In this approach, sensors are embedded into an office cubicle as a means to communicate various comfort-related factors to the user in real-time. This work essentially acknowledges the psychological impact of real-time data display as a potent tool for increasing a user's behavioral awareness (Holmes 2007). However, its implementation is limited to one cubicle, and it does not address challenges of representing the collected data in the global context of the building.

Research conducted by the U.S. Department of Energy (DOE) exemplifies the next generation of cubicles also known as an “intelligent workplace” (DOE 1997). This research focuses more on control strategies (user input) than data capture and representation. In the context of architectural practice, Mendler et al. (2006) also provides an example of individually monitored and controlled cubicles based on a Personal Environmental Module (PEM). PEM presents an HVAC-centric approach by requiring major modifications to the ventilation and air supply systems. For instance, a raised-floor system can act as the main plenum to bring air to each PEM for a user-controlled environment. While PEM acknowledges the need for monitoring and controlling of performance related factors at both global and local level, existing buildings often lack the flexibility of a full HVAC and architectural retrofit.

The research project presented here involves an existing office building located in Toronto, Canada. Similar to many commercial office buildings, the office is divided into large open spaces filled with arrays of cubicles to provide semi-private zones for employees. In general, each floor plate is comprised of five HVAC zones monitored by a building operator through a central BAS interface. However, the primary goal of the BAS is system status and equipment monitoring of the general performance of the building. Furthermore, this building has undergone retrofits to meet ongoing business needs without changing the original HVAC design, due to significant cost factors. For instance, some of the large open spaces have been partitioned into smaller zones while the distribution of thermostats and variable air volume air handling units (VAVs) still correspond to the original design assumptions.

Given the ratio of cubicle coverage throughout a typical floor, it is helpful to treat each cubicle as a cell for sampling data within the floor space (see Figure 1). There are multiple advantages to this approach. Each cubicle essentially defines a meaningful local boundary for evaluating comfort and energy usage per occupant. Therefore, as a building layout may undergo many changes, data related to an occupant can still be collected. However, the location of HVAC sensors typically remain unchanged, without major HVAC retrofitting, despite these layout changes. The cumulative effect of data collection at such a high resolution per square foot could itself result in the understanding of new qualities about the larger space.



Figure 1 (Left) Position of thermostats shown as red dots. (Right) Sensor-enabled cubicles shown as green dots.

System Overview

The implemented system can be divided into three layers: data sensing (physical), data acquisition and storage (back-end software), and data visualization (front-end software). The physical layer consists of sensorial end points that measure attributes of the physical environment. The current implementation consists of pre-manufactured, commercially available sensors to collect data related to the various factors of an occupant's thermal comfort, as well as energy usage. These sensors include temperature, humidity, light, motion, CO₂ and an alternating current sensor per outlet. Since there are currently no guidelines on the overall arrangement of sensors, the implemented sensor configuration is a result of informal tests to determine areas of high importance within each cubicle (Figure 2a). Sensor output was measured as (analog) electronic signals. In order to convert the analog sensor outputs into digital signals, all sensors are attached to interface boards (Figure 2b). In turn, one or more interface boards are connected to a Wi-Fi enabled embedded computer using a standard Universal Serial Bus (USB) interface.

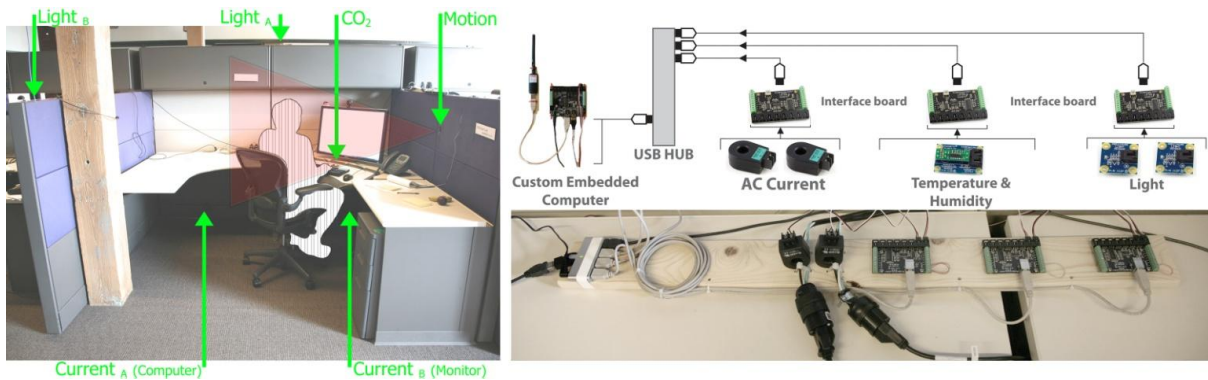


Figure 2 (a) Location of sensors in a typical sensor-enabled cubicle. (b) prototype physical layer.

The back-end software consists of a light-weight client running on an embedded computer. The client reads sensor values for several cubicles over USB, time stamps each sensor value and forwards this data over Wi-Fi to a web accessible Database Management System (DBMS) for posterity. Within the DBMS, the data is stored in a relational format. A separate relation (table) for each type of sensor is used. Additionally, a separate relation maps each sensor's serial number to data

describing the sensor's identity. Storing a sensor's identity data is crucial for correlating the values to local features found in a highly-detailed BIM model of the actual building. The BIM model represents a semantically-rich environment which encapsulates important physical attributes ranging from occupant information to the individual location of each sensor. Building semantics are migrated from BIM to an application framework through the Industry Foundation Class (IFC) file format (Figure 3).

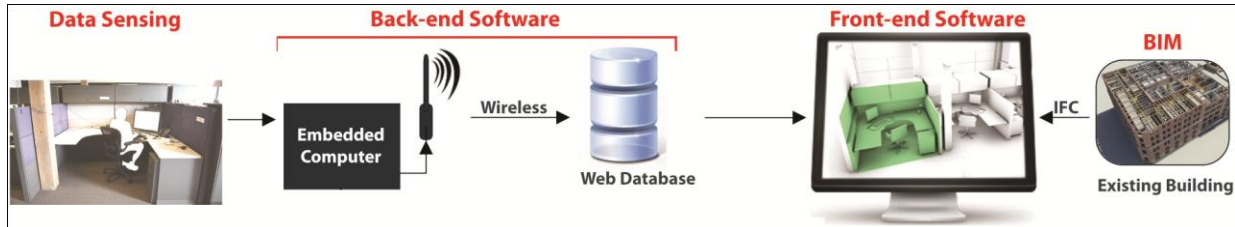


Figure 3 System overview diagram: front-end software correlates stored data with features authored in BIM.

The front-end software utilizes the data stored in the DBMS to facilitate various representation and interaction strategies. Since input can be received from a variety of sensors, a flexible software-architecture is required to accommodate the visualization of arbitrary data. Previous research describes the implementation of such a flexible framework based on an approach of decoupling the input data from visualizations (Hailemariam et al. 2010). In this scheme, a number of well-defined visualization techniques are combined into a unified framework in which the visualizations can be subsequently applied to different input data based on user needs. Building upon this work, examples of visualization techniques related to data such as thermal comfort and power usage are provided.

VISUALIZATION OF PERFORMANCE DATA

The important role of visualization as a method for data interpretation and conceptualization has long been recognized in research literature (Prazeres and Clarke 2005) (Srivastav et al. 2009). In the context of a sensor-embedded environment, a good visualization system can also play an important role in problem-solving and communication (Lee et al. 2008), especially with the increased data resolution coming from sensors incorporated into the office furniture. Today, despite the enormous growth in data capturing mechanisms, existing data-representation strategies are still based on the conventional abstract 2D and numerical data representations found in typical commercial BASs. Figure 4 displays a typical 2D chart representation based on data collected over a 24-hour period from light sensors at a selected cubicle in the office studied.

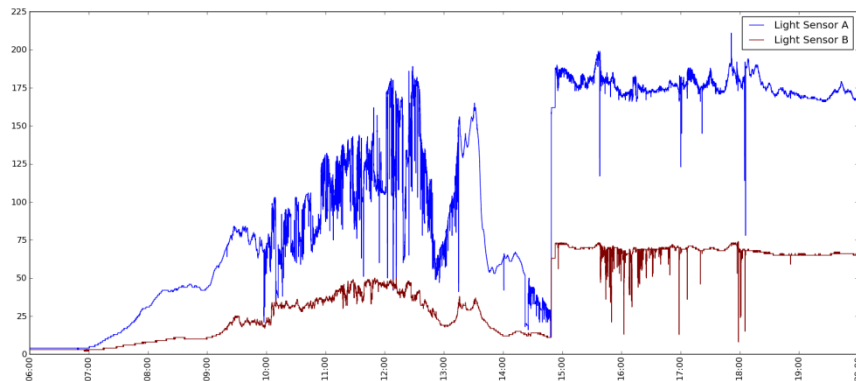


Figure 4 A 24-hour time interval of collected data for light sensors at a selected cubicle.

These graphs facilitate the study of certain trends over time, but do not explain, for example, why the values for Light A and Light B are so different from each other. However, by correlating the values to the features found in a 3D model of the office, it becomes evident that one side of the cubicle (Light B) is more exposed to direct sun light coming from the windows located on the south facing façade. By reducing the gap between the data and the user’s experiential mental model, and by taking advantage of how a user understands the physical world, greater insight into the meaning of the data becomes possible (Attar et al. 2010a) (Hailemariam et al. 2010). To this end, a novel framework is provided for mapping the collected data to local features utilizing semantic-based data pertaining to power outlets, cubicles, zones, floors, etc.

The incorporation of semantic information into the geometric model is integral to the proposed approach for advanced visualization of performance data. The key aspect of the system is to semantically link objects in the real world, such as sensors or cubicles, to objects found in the BIM. This method supports simple location of sensors in a rich 3D model, as well as the aggregation and presentation of the data in novel fashions. In the following section, some important aspects of the real-time data representation methods that were developed are presented.

Hierarchical representation

Similar to many commercial buildings, the office studied consists of multiple tenants, different floors, departments, etc. By coupling BIM with sensor-enabled cubicles, the software prototype supports the breakdown of factors such as power usage into multiple levels of hierarchy according to the context of inquiry. Figure 5 demonstrates a hierarchical view coupled with the 3D scene. This coupling provides a rich representation of selected hierarchies by highlighting the corresponding elements in multiple levels of granularity. Data can be queried ranging from a single outlet, cubicle, or area, to an entire floor by taking advantage of information authored in the BIM. In addition to using BIM to structure data, we also employ BIM to define a bounding box for clipping the 3D scene in order to present the selected hierarchy in a geometrically meaningful way (Figure 5b, c, d).

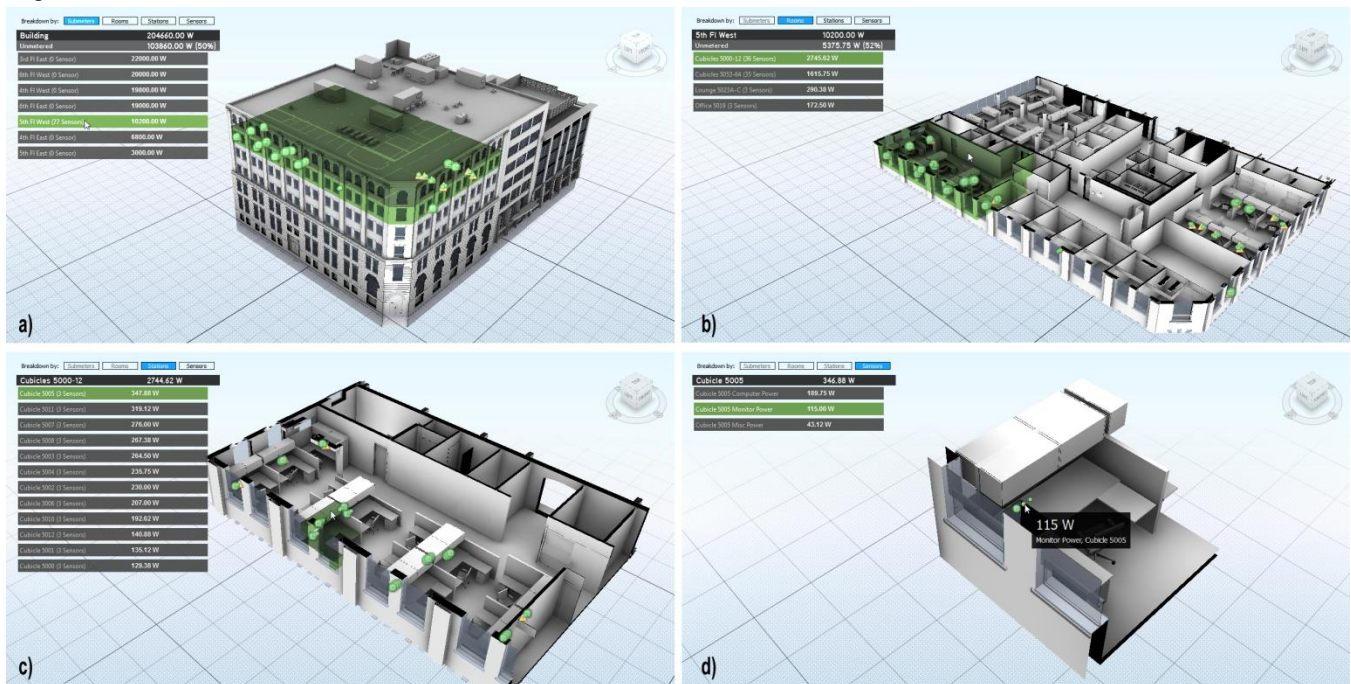


Figure 5 Hierarchical representation of power usage coupled with the 3D scene (a) Floor level (b) Area Level (c) Cubicle (Occupant) level (d) Outlet level (monitor).

Spatiotemporal representation

The spatiotemporal presentation of the data is another important function of the system. Using direct rendering methods, the system can map aggregate values of different time intervals on top of the 3D model for visual analysis (Hailemariam et al. 2010). Gradient shading is applied to surfaces, which attenuate with the distance and the intensity of data points. For instance, temperature sensor values are mapped to color values which are applied to the corresponding point in space (Figure 6). Given the high density of the data collected, this method can be used to approximate the changes across each cubicle threshold.

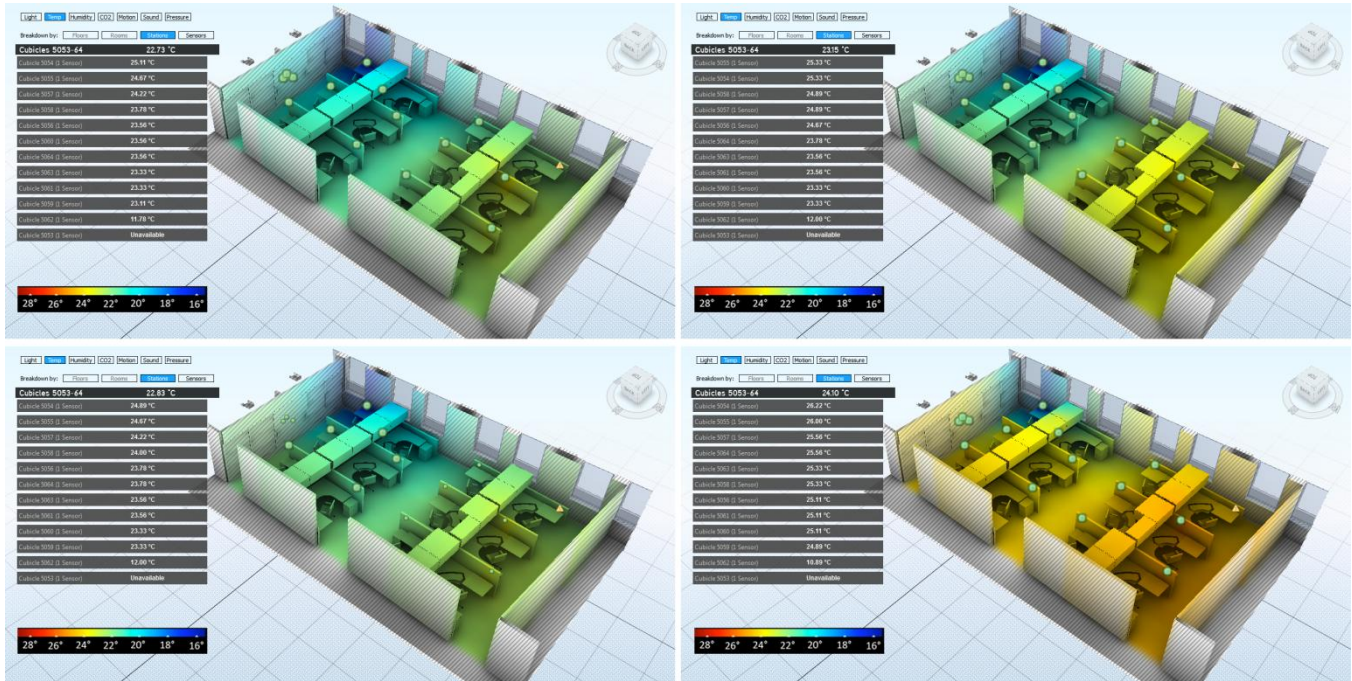


Figure 6 Snapshots of a Time-based visualization of thermal values for a selected zone. Green dots in scene represent sensor locations.

Direct rendering methods such as surface shading are commonly used in simulation packages to gain a deeper spatial understanding about thermal behaviors. This method is also used here to quickly communicate factors such as thermal values throughout the 3D scene. However, unlike a simulation, the system receives sensor data as input. As such, meaningful data is not available at all points in the model. It is therefore crucial to visually differentiate areas that are not yet instrumented, in this case, shown as a hatching pattern (Figure 7a). This is particularly important when considering the building as a whole, providing the user with an overall confidence level in the coverage of the data.

The visualizations are available at various scales, as they are coupled with the hierarchical method described previously, to present a selected factor for a selected hierarchy such as a cubicle, zone or floor. Taking temperature as an example, the user can quickly study thermal variations concerning a selected occupant over time (Figure 7b).

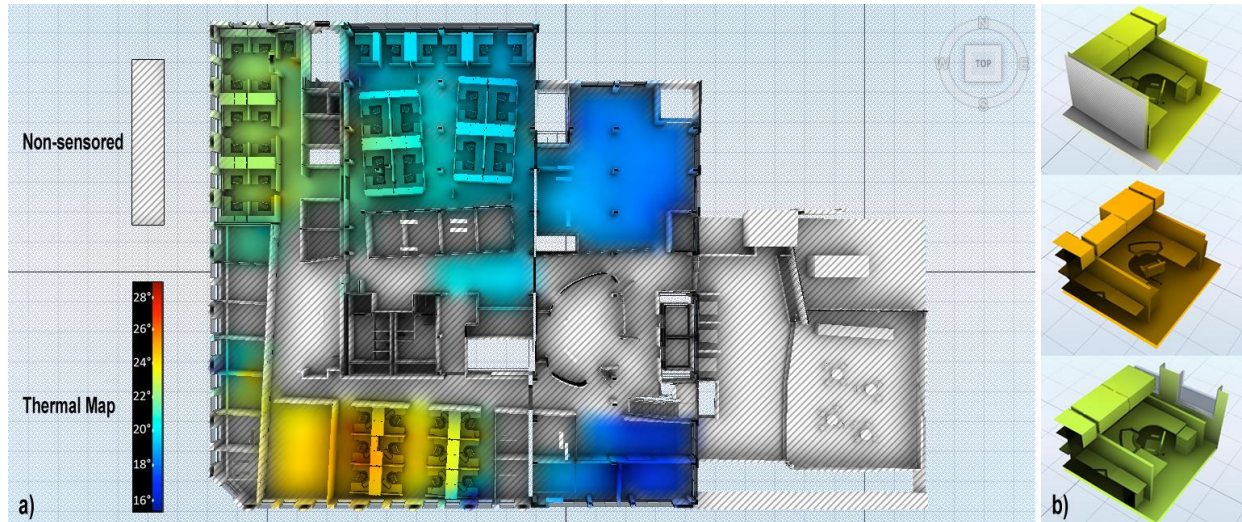


Figure 7 (a) Using a cross hatching to indicate areas without sensors. (b) Comparing subtle thermal changes in neighboring cubicles.

DISCUSSION

The potential to form new understandings about the complex behavioral characteristics of existing buildings holds tremendous potential. The availability and complexity of large-scale data sets will challenge previous assumptions rendering them inadequate to describe complex behavioral characteristics that are inherent in our built environment (Addington 2009). The future challenge is how to provide better tools that will make the best use of the information to gain deeper insights on how a building performs throughout its life-cycle.

While instrumented office furniture would represent an estimated cost premium of approximately 10%, this could result in greater overall savings based on improved understanding of current performance conditions. Also, recent sensor research, including novel power harvesting methods, may significantly reduce this overhead.

The proposed system demonstrates a working example of ongoing research deployed within the office building occupied by the authors. However, a critical aspect of the presentation and visualization of the data, namely a user-centric approach, is still unexplored. Different parties (the owner, occupants, MEP engineers, facility managers) have different perspectives, needs, and specific domain knowledge. For instance, the concept of a building hierarchy has different meanings to architects, engineers, and facility managers. This poses certain usability challenges in how complex building performance data can be aggregated and presented to a specific type of user.

In future work, interaction design will be explored to integrate additional visualization techniques as needed based on user feedback. Research in sensor-enabled environments spans across various disciplines ranging from Media Art and Human Computer Interaction (HCI) to Building Automation Systems (BAS) and Intelligent Environments (IE). This is clearly a multidisciplinary research problem that cannot result in a unilateral answer. A coherent and integrated system will ultimately require a collaborative effort.

CONCLUSION

In this paper, a sample system implementation for data collection using a sensor-network within an existing office setting was presented. While discussing building performance as a balance between energy consumption and comfort, existing approaches to data collection were classified as being HVAC-centric. In contrast, an occupant-centric framework

was presented where each cubicle was treated as a cell for sampling data at a higher-resolution. In this approach, not only could different occupancy needs be addressed, but such a system could also leverage economies of scale for better understanding of buildings at a global and local level. Additionally, a novel approach to real-time visualization of building performance data was contributed. The software application presented is an integral part of a system which addresses several aspects of the complexity inherent in the massive datasets involved in the building lifecycle. Through several examples, the affordances provided by the model for interpreting performance data in 3D space were demonstrated. Taken together, these contributions work toward helping occupants to participate directly and indirectly in greatly improving building efficiency.

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