Development of a Virtual Reality Integrated Community-scale Eco-Feedback System

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ABSTRACT

A growing number of community energy initiatives have enlarged energy-related social networks to the community level. Information provision is deemed as an important role in such programs while energy data disclosure offers a great opportunity to promote energy savings by engaging energy-related actors. However, it is crucial to communicate this data in an effective way. In this research, we develop a Virtual Reality (VR) integrated eco-feedback system that enables both occupants and facility managers to interact with real-time energy consumption data represented in a community scale 3D immersive environment. This paper presents the detailed front-end and back-end design and development of this novel VR-integrated eco-feedback system using Georgia Tech's campus as a test case for implementation. The VR-integrated community scale eco-feedback system is capable of visually characterizing differences in energy consumption across a large number of buildings of different types, and will be tested by users in future research. This research, when deployed broadly in cities, may help promote energy-aware behaviors of occupants and timely intervention strategies to achieve energy savings in urban areas.

INTRODUCTION

Community energy initiatives and programs are surging in response to expanding interest in decentralized energy systems, and a core component to their success is civic participation (Van Der Schoor and Scholtens 2015). With an increasing number of building energy consumption data disclosure ordinances, energy-related actors within the building ecosystem have potential to benefit from increased access to this information. How this data is delivered and presented is extremely important, since effective data communication impacts both the engagement of a community's residents and the decision making ability of facility managers (Kontokosta 2013). Involvement from both of these stakeholders may lead to more sustainable behaviors and, by extension, more energy savings. In this way, it is important to distribute energy information in a more accessible, understandable, and intuitive way. In this paper, we leverage advanced visualization technologies to integrate electricity consumption data into an eco-feedback system and develop a novel form of eco-feedback at the community level. A prototype of the VR-integrated community eco-feedback system is carried out to illustrate the design principles and explain the front-end and back-end development details. In addition, we discuss the potential benefits of this system and limitations to be addressed in future research.

BACKGROUND

In recent years, a growing number of community energy initiatives have taken place around the world, promoting development of energy-related social networks where groups of consumers become "prosumers" and enlarging them from the individual to community scale (Van Der Schoor and Scholtens 2015). Community energy programs and initiatives, whose main goal is to create more sustainable energy systems and well-informed citizens, are regarded as suitable tools for arousing awareness of energy sustainability, engaging participants' behavior changes, increasing public acceptance towards renewable energy, and cutting down carbon emissions (Seyfang, Park, and Smith 2013). Information provision has been regarded as an effective tool to alleviate information asymmetries in an attempt to modify attitudes or behaviors (Owens and Driffill 2008).

Increasing building energy data accessibility has offered an unprecedented opportunity for data provision at the community level. Mandated and voluntary building energy data disclosure ordinances have been implemented across states and cities in the U.S., and have been viewed as promising public policy tools since they can help address information asymmetries between different actors in the building energy ecosystem (Kontokosta and Tull 2016). Through this disclosed information, there is potential for community residents to better understand the spatial patterns of energy performance and engage in energy-related policies in their neighborhood (Kontokosta 2013). Of importance, it is also contended that the energy data should be presented and communicated in an effective way to engage users and improve the usefulness of the data (Kontokosta and Tull 2016).

Additionally, for facility managers, information management is crucial for successful facility management with respect to communication and decision-making (Alexander 2013). Many studies concerning energy data visualization focus on individual buildings with the aim to achieve better energy performance through control optimization and fault detection and diagnosis (Piette, Kinney, and Haves 2001; Gerrish et al. 2017). The benefits of providing energy performance information at the community level for facility personnel have not been well explored. With spatial analysis of building energy performance data, better informed investment decisions can be made and energy-intensive clusters can be identified (Kontokosta 2013). Since facility managers are challenged with handling a huge amount of complex technical data, it is crucial to extract useful information from the data and present it in a simplified and effective way.

Eco-feedback systems provide energy usage information through a graphical user interface, which is a desirable choice for effective information delivery. Eco-feedback systems have been widely implemented to address information asymmetries and promote more sustainable behaviors of end users. By reviewing results from published trials of over 500,000 subjects, the average electricity reduction was quantified to be 7.4% among individuals with feedback information about the environmental impact of their activities (Delmas, Fischlein, and Asensio 2013). While some refute that engagement is often only for the short-term, Burchell et al. (2016) found supporting evidence for long-term engagement with eco-feedback that is put in a community context. This study carried out eco-feedback research in a Smart Communities program and provided feedback within the context of community action. The results provided supportive evidence of long-term engagement and behavior change.

Design of the user interface shows significant impacts on engagement and energy-saving behavior (Jain, Taylor, and Culligan 2013; Jain, Taylor, and Peschiera 2012). Information representation has long been recognized as having an important role in eco-feedback systems. Recently, proliferating technologies in advanced visualization such as virtual reality (VR) present an unexplored possibility in information representation for eco-feedback systems. Virtual reality creates an interactive 3D world with a strong sense of presence through human-computer interfaces (Bryson 1996). Compared with 3D applications on desktop PCs, participants do act and feel differently in immersive virtual environments (Bowman and McMahan 2007). The secret to the success of VR is that it can provide users with a realistic experience. Such technology has been used to monitor and collect data on people's choices and behaviors within the built environment (Heydarian and Becerik-Gerber 2017; Heydarian et al. 2015). VR is also utilized in urban public-participation planning where individuals can interact with virtual environment of the real world which is highly engaging and interactive (Al-kodmany 2002). Immersion has been demonstrated to contribute to a more intuitive understanding of data and better perception of data relationships (Donalek et al. 2014). VR-based information visualization provides an effective means to provide an immersive and interactive environment that reduces information clutter, alleviates cognition load and improves overall understanding of the dataset, especially with spatially diverse and multi-dimensional data (Bowman and McMahan 2007; Park, Kapoor, and Leigh 2000).

VR offers a great opportunity for energy data representation where users can access the information in a more intuitive and interactive way, which may lead to better understanding and more effective interpretation. Implementing eco-feedback at the community level in an immersive environment shows considerable potential for pushing energy-aware behaviors of occupants and timely intervention strategies targeting inefficiencies by facility managers. However, identification and implementation of the most important design factors when developing such a system has not yet been thoroughly explored, and is a critical step to further VR-integrated community scale energy feedback research. To address this gap, this paper describes the design and development of the VR integrated community eco-feedback system in detail.

METHODS

A prototype of the VR-integrated community eco-feedback system was developed. In this paper, we use the term "community" referring to its territorial and geographical notion as suggested by Gusfield (1978). The Georgia Tech campus was used as a test bed community for designing the prototype. Electricity consumption data at the 15-minute interval was provided by Georgia Tech Facility Management and data from 1/1/2013 to 12/31/2016 was chosen to be presented in the virtual reality environment. Front-end and back-end development of the prototype system are explained in the following paragraphs.

Front-End Development. Users can access the interactive VR-integrated eco-feedback system through a Head Mounted Display (HMD) that supports a stereoscopic view of the campus in relation to the user's position and orientation. Users use a pair of hand touch controls to move, explore, and change the virtual environment through sensor-based head, eye, and motion tracking. The VR-integrated system was developed to provide the users with information about building energy performance across the community in an immersive environment, which offers the users the opportunity to interact with the system. Interactivity within eco-feedback systems has been suggested as a key means to motivate users to adopt energy conservation behaviors since it enables the users to understand and get familiar with their energy consumption (Mccalley, Midden, and Haagdorens 1980; Weiss et al. 2012). The VR-integrated system involves interactions like navigation allowing for user scalability and teleportation within the virtual environment and visualization of building energy consumption and corresponding energy performance. Before entering the VR environment, the screen resolution, graphics quality and the monitor can be selected according to the users' needs. A calibration process is followed to register the HMD and hand controls for head position and hand poses tracking. In the VR environment, users can access (15-minute interval) energy consumption data through dragging a timestamp slider that drifts above the user's rendered left hand. The immersive VR environment is synchronized in real time according to the head position and orientation determined by sensor fusion process. Building energy performance at the community level can be examined at a birds-eye view by zooming all the way out, which the user can accomplish by standing on their toes and looking up. Alternatively users can zoom in by looking down and kneeling to check the energy use status of individual buildings at the ground level. Users can navigate laterally through a point-and-click interaction with their rendered right hand. Buildings are presented by colored 3D building models. External environmental scenes are built by using real life aerial images, which provides the users a sense of presence and real experience traveling across the campus. Building energy performance information is displayed via a text tag showing the energy use intensity numerically (EUI, W/m^2) above each virtual 3D building model and its corresponding color, as can be seen in Figure 1 and Figure 2.

Figure 1. Birds-eye view of campus buildings' relative energy performance in the VR-integrated community scale eco-feedback system

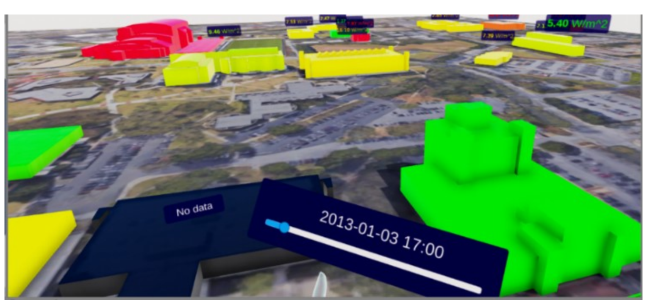

Figure 2. Ground level view of buildings' relative energy performance in the VR-integrated community scale eco-feedback system with timestamp slider visible

Shneiderman (2003) suggested that techniques such as color coding can be utilized to help to address the problem of 3D information visualization. In addition, color-coded eco-feedback has proven to be an effective information representation that is easy to understand and engaging to users (Francisco et al. 2018). Therefore, a color-coding scheme is applied in this system to indicate the energy performance of individual buildings. The color of the 3D building model is determined based on normative comparisons. EUI of each building is first calculated by dividing energy consumption with the building's area (Equation 1). Next, to ensure the energy performance comparison is reasonable across different types of buildings, these values are grouped and ranked by building type at each 15-minute interval. In this prototype system, four building types are identified: office, laboratory, residential and recreation. Buildings with missing data are excluded from the comparison during missing-data time periods and are colored black with a text tag showing 'No Data'. Then the rank number of each building is normalized to a 1-100 range (Equation 2). For example, there are 24 (*max rank*) office buildings in the system. If an office building A at a certain time consumes the least energy (*rank*=1) among all offices, the *normalized ranking* equals 1. The 3D building model is thereafter colored from green to red by linearly interpolating its normalized rank number.

$$EUI = \frac{Electricity\ consumption}{Floor\ Area}\ (W/m^2) \quad (1)$$

$$Normalized\ ranking(type) = a + \frac{b-a}{max\,rank - min\,rank} \times (rank - min\,rank) \quad (2)$$

$$Where\ a = 1; b = 100; \max rank = building\ number\ of\ a\ certain\ type$$

This VR-integrated eco-feedback system not only allows the users to explore the energy performance of a single building but also facilitates users' familiarity with energy consumption across their community. Users can easily conduct energy performance comparisons among buildings within the community. This may elicit a feeling of competition or group identity which has been positivity associated with encouraging sustainable behaviors (Siero et al. 1996). Such experience is likely to increase the users' sense of community, which is suggested to be positively correlated with both behavioral intentions and energy-saving behaviors (Dixon et al. 2015). By monitoring building energy status across the community facility managers can also obtain an easier and more intuitive way to identify sudden changes in building energy consumption and locate those with poor performance in a timely manner. Reactive inspections and maintenance can then be implemented to explore the root causes of such inefficiencies.

Back-End Development. The back-end development of the prototype system was configured in Unity (V2017.1.0f3; 2018 Unity Technology). 3D building models are built based upon the information of each building's footprint from Mapzen ("Mapzen an Open, Sustainable, and Accessible Mapping Platform" n.d.), which are streamed and mapped into the VR-integrated system. Building performance data including building IDs, EUIs, and rankings are stored in a database as a .db file in the data processing module. When the application executes, *DataWizard* queries the EUIs and rankings data from the database according to each building's ID and stores the information in arrays. Next, it reads both the EUI and ranking data at a given timestamp selected by the user or generated by the system. Then it interprets the paint of the 3D building models and projects the EUI data in the text tag. In this case, we define that if the normalized ranking number is between 1 and 50, the color ranges from green to yellow while if the number is between 50 and 100, the color ranges from yellow to red. The timestamp automatically moves forward when users do not interact with the timestamp slider.

The project was compiled and pretested in Unity to internally validate that all design functionalities produced correct outputs before being deployed into the HMD for users to access and interact with the virtual campus and explore the community energy performance.

LIMITATIONS AND FUTURE WORK

The community level VR-integrated eco-feedback system still faces several limitations to be addressed in future research. Due to the accessibility and cost of VR systems at the present, community residents may find it hard to engage in such a system. For the time being, this platform may be more attractive and beneficial to facility managers. Additionally, the presence of missing data and the limited number of buildings of certain types within GT's campus may decrease the reliability of the normative comparison results. Since VR applications outside traditional fields are still limited, it is important for us to first investigate whether the immersive environment provides any unique benefits in facilitating energy-saving awareness and inefficiencies identification. The prototype system will undergo user testing on its usability and iterations of the design and development process before full-scale implementation. Users' behavior and interactions with the system can be monitored to help gather an in-depth understanding of users' perceptions and feedback of the system, and help iterate the design.

CONCLUSIONS

In recent years, a number of community energy programs have emerged aiming to arouse awareness and promote sustainability at the community scale. Building energy disclosure ordinances at the community level offer a great opportunity to improve energy information access for both the residents and the facility managers of a community. However, this data should be provided in such a way that allows for easier access, less cognitive load, and faster comprehension. This paper proposes a VR-integrated community eco-feedback system and discusses the principles guiding the design and development. In addition, it describes its potential for inciting sustainable behaviors and assisting with identifying inefficiencies within a community. In the wake of advanced visualization technology development and data accessibility, it is important to explore the possibilities of promoting energy sustainability by leveraging such resources. This research extends eco-feedback literature by introducing a novel form of eco-feedback. Our system leverages virtual reality technology and is implemented at a community scale, which has the potential to encourage energy-aware behaviors and aid facility management personnel with the detection and localization of building energy inefficiencies across a community of buildings. When employed broadly in cities, this system may engender broader energy savings.

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