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Interactive Visualization of Energy Efficiency Concepts Using Virtual Reality

P. Häfner, J. Seeßle, J. Dücker, M. Zienthek & F. Szeliga

Institute for Information Management in Engineering, Karlsruhe Institute of Technology, Zirkel 2, Karlsruhe, 76131, Germany

Abstract

Virtual reality is an important topic for the engineers of tomorrow. This is especially the case when it comes to modeling, visualization and interaction with complex information structures and concepts. The paper presents the results of a synergy between a practical course in virtual reality and energy efficiency in public buildings research. The practical course focuses on acquiring knowledge of virtual reality hardware, software and applications by simulating an interdisciplinary industrial project. The project consist of two tasks. The first task is to build a system for capturing the users' behaviour and energy use in public buildings and the second task is to create a virtual reality system for interactive visualization of the collected data. With this goal in mind, an office room with sensors, automation devices and energy consumers was created. A virtual reality low cost system was then used to represent the virtual office and to augment it with real-time information.

Categories and Subject Descriptors (according to ACM CCS): I.3.7 [Computer Graphics]: Virtual reality—Applications;

1. Introduction

Energy is what drives everything, yet we can only witness it indirectly. The way we perceive energy – by its effect on our surroundings – is the reason that we use it so carefree. Energy may be consumed where we don't expect it, thus leading to energy waste. Until now the burden of providing us with tools to be more energy efficient was with the industry. New developments in technologies give us new household appliances for our households that are much more energy efficient than before. But this is no longer enough. We need to address the lack of awareness with regard to energy efficiency and energy waste on the consumer side. People are usually not conscious about the amount of energy they consume. Accounting periods of energy suppliers normally include several months, therefore the understanding of individual consumption rates is very difficult. In addition, due to difficult interpretation of traditionally delivered energy data, decisions made are often incorrect or inefficient. It is because of these reasons, that a good energy visualization model is required. An important step towards this goal is to allow the user to perceive his/her use of energy in a more direct way. This means to visualize the impact of his behavior on his energy consumption.

This paper presents the results of a student project on energy efficiency research topics during a virtual reality practical course. On the one hand the theoretical understanding and the practical experience of virtual reality is thought. On the other hand the research project on energy efficiency in public buildings is driven further and the understanding of real world research problems is taken into consideration of the courses curriculum. The students created and use the Energy Experience Lab (EELab) as a validation platform, working in interdisciplinary teams. The EELab gives the ability to explore new ways of real-time visualization of power consumption in public buildings and further such visual investigations in a 3D real scale virtual world can lead to insights into relationships in the complex data. These systems will allow to amplify our knowledge about the dynamic behavior of energy anywhere. This makes it possible to augment the real world with a 4D spatio-temporal visualization capability that supports decision-making relating to energy flows. Potential users of such systems are facility managers, energy consultants or facility owners, which will monitor and control the energy efficiency of the buidlings remotely using their virtual building representation.

In the following chapter a short overview of related work and previous scientific research will be given. Next section

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gives detailed descriptions of the Energy Experience project and its implementation.

2. Related Works

The degree of energy efficiency in the utilization of a building heavily depends on behaviors of its occupants. This can be explained by the fact that a large part of the energy-costs result from the spendings on maintaining the comfort of the building's occupants. Intelligent energy management systems are designed to increase energy efficiency while living up to the comfort standards expected by the occupants. This creates a need for a holistic information model that utilizes not only the data related to the building's structure, building automation systems (heating, air conditioning) and environmental factors (weather, light), but also the behavior of the users, as seen in the European project KhoholEM [ACW*14].

The European project Adapt4EE aims to develop and validate a holistic energy performance evaluation framework that incorporates architectural metadata, critical business processes and consequent occupant behavior patterns, enterprise assets and respective operations as well as overall environmental conditions [EMVAMG14]. For the analyses of occupant behavior a top-down approach is used. The occupant analysis is based on a model of the company's business processes, the power consumption measurements, environmental factors and occupancy sensors (RGB-D, existing environmental, PIR and other low cost occupancy sensors).

The visualization of energy data provides a useful interface between the consumer and the consuming devices. Classical approaches to energy visualization make use of various data representation methods, such as graphs and diagrams. The issue with these visualizations is that they don't relate to the users' 3D environment, their interactions and behaviors within. The same applies for all levels of granularity, from a consumer device up to whole buildings, districts, cities and countries [KBGT12]. In addition to the energy consumption and generation in a 3D space, the time evolution is very important.

In recent years, we observed a wide spread of Augmented Reality (AR) use in building management [Bra10]. "Open Energy" is an open-source energy infrastructure, designed as a platform to explore new systems of energy use visualization and use optimization for both domestic and industrial environments. The system consists of a hardware energy monitoring device and a software real-time data visualization utility based on AR application.

Another project using AR applications to promote energy efficient building solutions is the Lobby Showcase of the Fraunhofer Center for Sustainable Energy Systems (CSE) [NGU13]. With thousands of sensors placed inside and outside of their new headquarters, the 5CC building will be a living laboratory gathering and sharing live data. The goal of the AR project is to create a new interactive tool for Building Technology research.

An important part of understanding energy and being energy efficient is the effective presentation of the data and the reduction of complexity. Here we can greatly benefit from virtual reality using immersive visual data mining. This approach allows the projection of data on higher dimensional spaces, using multiple views, and enables the exploration and interaction with the multi-dimensional data in an intuitive and natural way. Good example is the CAVE-SOM system, which couples the Self-Organizing Map algorithm with the immersive Cave Automated Virtual Environment (CAVE) and has been successfully applied for the analysis of wind-power generation data [WLM11].

About using virtual reality to affect behavioral energy efficiency programs talks the Standford professor Jeremy Bailenson in his keynote speech at the Efficiency Exchange Conference held in Portland, OR in 2013 [Bai13]. Kim et al. reviewed 150 journal articles from 2005 to 2011 about the use of virtual reality for the built environment [KWL*13]. They found that the number of publications in the area of architecture, design, construction are the greatest number of all VR articles and conclude that the use of VR for facilities management and lifecycle integration is in its infancy, but has great potential.

3. Implementation

3.1. The Virtual Reality Practical Course

The virtual reality practical course was conducted according to the methodology proposed by [HHO13]. The participants were university students from the field of mechanical engineering, computer science and engineering management and worked on the project in interdisciplinary groups. The total amount of time and effort was 120 hours during one semester, which corresponds to 4 ECTS points.

3.2. Project Overview

The objective of the Energy Experience Labs is to be able to reproduce a public building environment in real time, thereby automatically and remotely monitoring and controlling its energy efficiency. To achieve this ambitious goal, the project takes into account two essential components, a system for capturing the energy related data installed in a real office room and the virtual reality system representing the virtual building and visualization metaphors. The interfaces between the two systems allows the bidirectional communication. The Energy Experience Lab was created as a testbed for validation of concepts developed during the project. An overview of the implemented system components in displayed in Figure 1. Next section describes them in details.

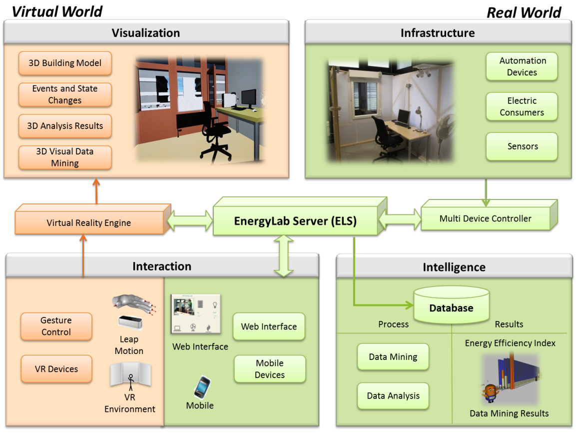

Figure 1: *System Architechture of the Energy Experience Lab*

3.3. Real Office

The hardware devices in the real environment of the Energy Experience Lab can be classified in the following three groups (see Figure 2):

- Sensors: indoor and outdoor temperature, CO2, humidity, light, motion, pressure (used to integrate in a chair) sensors, light barrier for counting the number of occupants in the room
- Automation devices: for windows, blinds, door, wireless socket-outlet for remotely switching on and off the devices and for measuring power consumption
- Energy consumer: lamps, heater, air conditioner, ventilator, computer, monitor

Figure 2: *Hardware of the Real Office*

The Multi Device Controller (MDC) was developed as a middle point between all hardware devices and the Energy Lab Server (ELS)(see Fig 1). The MDC receives infrared, radio and cable signals from a range of supported devices and forwards them to the ELS, and vice versa. For this purpose, the devices' protocols have been reverse-engineered to extract incoming information or build outgoing commands. Furthermore, a new communication protocol has been developed as means of communication between all clients, including the MDC, and the ELS. It is a byte-based protocol, built up of 8 Bytes, making it efficient when it comes to transfer time, yet containing important information such as message type, device ID, current sensor value and a variety of control bits like subscription to updates, request of current value or Received Signal Strength Indicator (RSSI) of wireless devices. Using sockets, clients like the web interface or a VR environment connect to the ELS allowing the ELS to inform the clients immediately after receiving value changes from the sensors.

Directly accessible over a server URL connection, the web interface is a platform used to interact with the EELab. The different values and controls of the sensors and devices can be monitored and accessed. The interaction between real world and virtual reality is a key feature of the EELab, thus the actions done over the web interface are directly transmitted into the virtual reality or other clients.

As the core access point of actors, sensors and all devices and interfaces the database builds the core information piece of the EELab. The mySQL database is continuously filled with information of all sensors and actors in the real world office. Furthermore, the database is accessed by the different online and virtual interfaces, such as the VR environment or the web interface.

3.4. Data Analysis

3.4.1. Data Preprocessing

In order to capture current energy consumption data, continuous SQL database queries are performed allowing the high-end data visualization to be established. During this process the raw data from different sensors and actors is not only visualized, but preprocessed and interpreted. There are three basic steps that need to be carried out during the data analysis.

The first step is the determination and readout of the data. This is done according to the relevance of the data, as well as according to their measure type. Therefore, the transmitted sensor data is prioritized. The more important they are for the visualization of energy efficiency, the more likely they are handled. For example, electricity consumption data are prioritized over humidity data. The data sets are acquired by classes. Thereby it can be guaranteed, that only comparable measured values are visualized simultaneously. Thus, a classification of the sensors and actors of the EELab has been developed.

After a class-wise and prioritized collection of data, steps of preprocessing and interpretation take place. As a part of the preprocessing, the data is cumulated, averaged and its deviation is determined. Absolute values are difficult to interpret by the users. For this reason, easily readable and interpretable comparison values are required. In the course of the project the arithmetic mean and its deviations were chosen. They have the advantage that at any moment, users can accurately detect whether their current behavior or rather the actual composition of active devices is efficient or not. In addition by using the historical average, the approach is kept very generic, which is the reason why it can be transferred to different scenarios. Therefore statements about the relative behavior of many users can be made, even if they work in different buildings or use other consumption devices.

Hence, the preprocessing of data occurs in fixed periods of time, which is why the database is updated only with the new values. Depending on the time of day or rather hours of work, the arithmetic mean has a different level. For this reason, the data analysis takes into account a day and night rhythm. If the current time is not an official working time (e.g. during the night) or if nobody is in the office (e.g. holiday, weekend), the average value is automatically set to zero. Beyond an integrated presence sensor supports this scenario. In a final step, the integration of a calculation methodology, which is intended to illustrate the user behavior concerning the energy efficiency, is carried out.

3.4.2. Energy Efficiency Index

The objective of this project is to increase awareness of energy efficiency at the user level. To achieve this goal the user is to receive direct feedback in response to his current behavior. This feedback is given by the developed Energy Efficiency Index (EEI). This index represents one of the core data analysis in the project. It is developed according energy standards and facilitates the intuitive and interactive visualization.

To facilitate the measurement process, three kinds of energy usage can be differentiated: temperature adjustment, electronic equipment and lighting. The climate depends on the difference of the temperature inside and outside the building, the number of open windows and doors, the state duration, the time one uses the room and temperature of heater or respectively air conditioning. The evaluation of the electronic equipment is approximated with average values of influential factors such as working hours. The electricity used for lighting depends on the difference between the brightness outside and the desired luminance inside, the number of people in the room and the number of light sources. Based on this information and on the DIN standards of the different segments (temperature adjustment: DIN 4701; lighting: DIN 5034-6 and DIN EN 12464-1) an ideal value for the power consumption is calculated in real time by special algorithms. Then the ideal value is compared to the current consumption.

The three sub-areas, lighting, climate and electronic equipment, are weighted according to consumption and thus yield the Energy Efficiency Index. Generally the EEI ranges between $(0,\infty)$. Thereby a value of 1 represents a good use of energy. An index with a value below 1 represents a very efficient use of energy. The user should seek to amend his/her behavior to get this feedback. If EEI much higher than 1, the user should change his/her consumption. Basically, a value of 1.8 can interpret like "the user consumes 80% more power as the ideal value". But you have to be careful with this interpretation, because of the involvement of some qualitative and average values. So, by getting direct feedback to one's behavior, the user is motivated to improve his individual EEI in real-time.

3.5. Real-time Visualization

3.5.1. Visualization Paradigms

Different 3D visualization paradigms have been developed for the purposes of Energy Experience Lab:

- Environmental applications
- Passing events
- Current measured energy data
- The user behavior with respect to energy efficiency

During the project, an integrated solution displaying all four aspects in one immersive model, emerged. The virtual environment, the real-time visualization algorithms as well as the data preprocessing and analysis were implemented using the virtual reality authoring tool PolyVR [Häf14], which allows easy and fast development using python scripts. Other benefit of the virtual reality software used is the deployment and experience of the applications in scalabe VR environments (from desktop to CAVE) and various tracking systems and interaction devices.

A major part of the virtual world is a 3D model of the whole building where the real office room is located. Additional 3D models for the interior especially automation devices and electric consumers were modeled using the free modeling tool Blender in order to correspond to the real world.

Our virtual models are programmed so that they simultaneously reproduce any interaction that happens in the real world. Conversely, any virtual action in the model can be simulated to simultaneously produce a genuine result in the real world. All state changes of consuming device in the EE-Lab can be represented visually. Thus, the radiator appears red when it is switched on, while the light bulb icons shine when the light is turned on. Other animations are for example the computer start-up, a rotating cooling fan as well as the opening and closing of doors and windows.

The energy data model is three dimensional, built up along three different parameters. The x-axis represents periods of time, the y-axis shows the different consumption devices and the z-axis displays the amount of energy consumed (see Figure 3). Over time, the model evolves by having various columns added to it, which represent the energy consumed by the different devices. For each time interval and for each device, a new column is generated. The columns are displayed in groups, which were previously assigned according to the measuring unit. For example: power needed (Watts), temperature (T) or humidity (%).

In order to guarantee a fast and intuitive capture of information, data related to historical consumption values is displayed instead of absolute quantities. This permits the consumer to evaluate whether the current combination of consuming devices is better than the historical average. This check can be performed at any point in time. Therefore, the model simulates the behavior of different consumers or different environmental situations (night, day, winter, summer, etc.), independently of the physical conditions (e.g. building geometry) or energy efficiency of the device. Furthermore, several additional columns exist, such as the individual device average consumption rate and total energy consumption. These appear at the edge of the model. To facilitate easy data analysis, a particular column color coding has been implemented. This means that columns are colored according to different consumption levels as well as by the unit measured. If the current measured value is below historical average, the corresponding part of the column appears blue. If it is higher, the column appears red.

A visual timeline of actions (or events) is integrated into the model and represented by different pictograms (e.g. open door/window, turned on light bulb, etc.), which are attached to the columns for corresponding time intervals (see Figure 3). In addition to the analyses based on columns, current data can be displayed in an information box. The panel is implemented in the virtual world and different measurements can be seen while navigating through the panel.

Additional visualization paradigms are developed during the project, but not implemented due to time restrictions. One of them is a sky element which will illustrate the level of energy consumption. It will show different weather conditions on top of the columns, so that the users are able to detect and control their energy needs. Bad weather (rain, clouds, snow, etc.) means high energy consumption, whereas good weather (sun, blue sky, etc.) indicates lower consumption. As a further extension, a data skyline which represents the cumulated consumption average is intended to be implemented. The skyline is built up in a similar way as the columns and would appear at the end of the model. The higher the skyline rises, the higher the previously measures are. Thus, statements about the energy consumption can be made through the skyline horizon.

3.5.2. User Behavior

Aside from the visualization of current data, it is essential to provide easily understandable feedback of the users' behavior. Therefore, our model includes a visual, user-friendly feedback on various consumption events that can take place. Here the implemented Energy Efficiency Index provides the basis. At the moment, there are three different ways to illustrate user behavior.

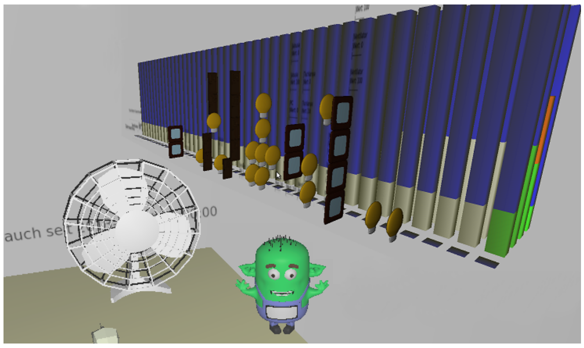

Figure 3: *Implemented visualization paradigms: 3D energy data model x-time series, y-consumption devices, z- energy consumption; events; virtual avatar representing the actual user behaviour (EEI).*

The first one is the virtual world floor color. A red ground surface indicates inefficient consumption behavior in contrast to a green floor which would mean efficient behavior. The second way, expresses the user behavior through the size of the consuming devices. For example, the user can be alerted by a growing radiator to reduce its consumption or by a growing PC monitor to turn off the computer.

The third variant represents a more playful approach where serious games can be introduced. Using the free modeling software Blender, a virtual avatar was created. Based on its color, appearance and facial expressions, as well as with the help of its comments, the avatar expresses the actual user behavior (see Figure 3). A green and happy avatar represents efficient user behavior. A yellow colored, serious avatar shows a critical situation, whereas a red, angry avatar indicates a bad behavior and inefficient energy use. In brief, the avatar changes its mood and color depending on the EEI and therefore gives, in a playful way, valuable advices to the user.

3.6. Interaction

For the virtual reality system low cost hardware devices are used: A passive stereo TV for visual output, Kinect RGBD camera for head tracking and Leap Motion for gesture control.

There are two interaction types between the users and the system (see Fig. 4). The system can be controlled via a web interface, allowing the user to use a tablet or a smartphone. The user can navigate and interact with the virtual world via Leap Motion. Provided with three infrared sensors and two cameras, Leap Motion records data of the exact position in a three dimensional system and other parameters (e.g. speed) more than once per second. Different gestures were implemented into and connected to the virtual world using the communication protocol VRPN, used the exchange with the virtual reality authoring system PolyVR. The key advantage of the input device Leap Motion is that the user doesn't need a control panel. The system can be controlled through gestures only. Therefore, the concept is very intuitive and thus increases the degree of immersion in the virtual world. An inherent disadvantage, however, is that this device is only suitable for desktop VR setups, such as the one used for EE-Lab project.

Figure 4: *The 3D TV (left), implemented gestures (top right) and the web interface (bottom right).*

4. Conclusion and Future Works

In order to be able to discuss the energy issues of today, a large amount of complex information needs to be communicated in a fast and timely fashion. Particularly in the field of facility management an easy and prompt feedback of consumption data is very important. This is largely a concern during the operation phase of buildings. Therefore, new and creative, but also understandable approaches, for monitoring and controlling of energy data are required. With the VR solution and implemented concepts in the scope of Energy Experience Lab, we propose solution fitting these requirements – a collaboration platform for energy monitoring and maintenance with the objective of increasing energy efficiency. In the scope of this project, various paradigms for the real-time visualization of energy consumption data of buildings were developed. This in combination with a gesture-controlled interaction enable a quickly, understandable capture and analysis of energy data.

The next step in the project will be the qualitative and quantitative evaluation of the implementation in order find out which impact the system has on the user behavour and to test its applicability for monitoring and control or energy efficiency. In further stages of the project, additional visualization paradigms for air flow simulations, spatial temperature distributions and consumer behavior patterns will be introduced, allowing us to better understand the occupants' impact. Another task is the development of data mining algorithms, implemented specifically for visualization in immersive environments. Next step is to combine our research in the area of knowledge management and to incorporate semantic technologies for more intelligent virtual worlds. Another idea for the future work is creating a virtual reality serious game about energy awareness based on the created virtual world and the EEI avatar.

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