SMART VIRTUAL BUILDING SYSTEM FOR BUILDING PERFORMANCE VISUALIZATION

Bin Wang, PhD, WangB15@cardiff.ac.uk
Haijiang Li, PhD, LiH@cardiff.ac.uk
Yacine Rezgui, Professor, RezguiY@cardiff.ac.uk
Hoang N. Ong, PhD, ngochoanghcm@gmail.com
Department of Sustainable Engineering, Cardiff University, Wales, UK

ABSTRACT

Over the past few years, BIM (building information modeling) as a revolutionary methodology has not only changed the way of thinking and working in the Architecture, Engineering and Construction (AEC) design area, but also provided an opportunity to extend its functionality to building maintenance areas such as building energy consumption and emergency situation visualization. With the development of science and technology, video cameras and motion sensors become the most common devices to monitor buildings on large scale now. However, video cameras violate privacy when improving security whilst motion sensors cannot provide the same degree of space awareness as video cameras when protecting privacy. Moreover, a huge amount of data generated by instruments in buildings play a pivotal role in getting insight into building energy utilization and emergency detecting. Nevertheless, the visualization to interpret these data is limited to 2D graphs and numerical outputs, which are too abstract to be fully understood by general end-users such as building owners and occupants. This paper proposes a generic smart visual system, supported with several developed ontologies, in which we use BIM as a digital building information provider to work with the state-of-the-art computer game and sensor technologies to build a well-defined interactive BIM-based virtual environment that can keep high degree of space awareness and privacy.

Keywords: BIM – building information modeling, virtual environment, visualization, game engine, sensors

1. INTRODUCTION

Over the past few years, Building Information Modeling (BIM) have been brought into AEC industry and changed many things in terms of design arena over the past few decades. BIM should not be considered as an updated version of Computer Aid Design (CAD), it actually promotes integration and collaboration, which means ideally different stage applications during building life cycle should be effectively "linked" through shared data, information and process (Eastman et al., 2008). Since BIM provides an opportunity to enhance its functionalities, these integration and collaboration could not only go beyond the professional actors to include wider audience, such as end-users, who are lack of professional skills but play a vital role to achieve satisfied building designs, construction and follow on services, but also extend to broader areas such as building performance visualization for building energy consumption and emergency situation monitoring (Eastman et al., 2008).

Current BIM development contributes much to design collaboration and the subsequent economic benefits for design professionals, but very few of them pay attention to building performance visualization for general end-users (RUIZ, 2009). By the term "general end-users" it means the people who will use the building on a practical level such as the building occupants and maintenance personnel. Because they are the genuine users of a building design, it is necessary to pay attention to the energy saving and safety requirements of living and working in the building. Building performance visualization is a rather vague concept: on a macroscopic level, building performance visualization can be seen as a kind of public management means, which protects the fruits of economic development, maintains efficient utilities of building energy , safeguards people's lives and maintains property safety; on a microscopic level, it can be seen as a kind of optimization behavior, which integrates various engineering methods to realize whole building performance's goals. Bearing in mind the current changes in the worldwide climate and security situation, the building performance visualization herein is particularly utilized in addressing energy wasting and fire disasters which are common and directly related to all occupants (Kwan and Lee, 2005, Wong et al., 2011, Yang et al., 2011).

With the development of science and technology, video cameras and motion sensors become the most common devices to visualize and monitor building performance on large scale now (Olsson and Regan, 2001, Dibley et al., 2012b). However, video cameras violate privacy when improving security whilst motion sensors cannot provide the same degree of space awareness as video cameras when protecting privacy. Moreover, a huge amount of data generated by instruments in buildings play a pivotal role in getting insight into building energy utilization and emergency detecting(Yoon et al., 2009, Zeng and Tabirca, 2009). Nevertheless, the visualization to interpret these data is limited to 2D graphs and numerical outputs, which are too abstract to be fully understood by general end-users such as building owners and occupants. Therefore, a reliable and feasible building performance visualization is urgently required to refine building energy and emergency plans; to optimize building energy saving solutions; to trigger a real-time effective fire evacuation guide during the initial stage of a fire disaster for general building end-users

Modern BIM software provides several options to control its output and sound application interface to enable BIM integration with other technologies in different fields for various purposes, which pushes a large amount of feasible extensions to the limits of current BIM development (Conway, 2011, Lertlakkhanakul et al., 2008, Lin et al., 2012).This paper proposes a novel system in which we use BIM as a digital building information provider to work with game and sensor technologies to build a well-defined interactive BIM-based virtual environment that can keep high degree of space awareness and privacy. A number of inputs or output related to building performance can be visualized in real-time on top of informative BIM model in order to present richer context for comprehensive but simple holistic visualization to enhance end-users' understanding. The future aim of such system is to process the data from both sensors and BIM model to suit the task at hand and recognize human activities with maximum privacy in the context of an entire building. For the following content, the related work is first introduced to outline the new generation of building performance visualization based on interdisciplinary science and technology and their merits and demerits to tackle the main problems in practice. The overall system requirement and design is then described to address the needs of BIM-based virtual building systems for a reliable and feasible building performance visualization. The main points and several case studies for such a system implementation are then demonstrated and discussed to better organize the system components to provide an intelligent virtual building system for building performance visualization. Finally, the conclusion and future work is presented at the end.

2. RELATED WORK

Traditionally, building managers employed video cameras and motion sensors to visualize building situations and monitor human behaviors. The good example to illustrate this is the monitoring of high-raised buildings and routine fire drills. After terrorist attack on the World Trade Centre(WTC), the researchers reveal some key factors influencing the success of evacuation in high-rising building and a high-rise evacuation database (HEED) was built by information incorporation from studies of WTC9/11 based on camera and sensor recording in the WTC and several other means such as questionnaires, telephone interviews, and face to face interviews. However, it is time and money consuming, and restricted to specific scenario. To effectively explore building performance in extreme environment, M. Kobes et al. proposed that that the use of serious video game to get a real-time observation of building and human performance might be a promising method for researches in the future as video and sensor recording of real fire evacuations are rare (Kobes et al., 2010). Generally, the approach in emergency experiments or drills is to video the participants (as evacuees) during an experiment or drill, then to ask them to complete a post-evacuation questionnaire to supplement the result of emergency experiments or drills. The reason to employ post-evacuation questionnaire is to investigate non-observable factors such as perception of emergency cues. Recently, X. Cheng et al used this approach to investigate human behaviors in an emergency drill with announced evacuation in a retailed store in China (Xudong et al., 2009). T. J. Shields and K. E. Boyce used the video and questionnaires to survey human behaviors in an emergency drill without announced evacuation in a retailed store in the UK (Shields and Boyce, 2000). Although to video the participants following questionnaires and analysis became the most common method to support the emergency preplanning, it cannot often be conducted, due to the fact that it is simply time and money consuming.

Although video games have been available for almost thirty years, non-professional programmers have only recently been able to modify those games, because the editors used to modify the games (Game Engine) have become sophisticated but conversely simple enough for different end-users (Conway, 2011). W. Yan et al. presents a BIM-Game framework that uses BIM and gaming into architecture visualization to allow end-users to play with their own building designs in a real-time, interactive, and photorealistic virtual environment (Yan et al., 2011). M. Alahmad et al. proposed a real time power monitoring (RTPM) system that integrate end-use detailed energy consumption data with BIM model to create the on-line electronic BIM Model (Alahmad et al., 2010). Ontology, in its simple definition, can be regarded that a computer can understand domain knowledge with rules and goals derived from domain key words and their inter-relationship in that domain knowledge (LI et al., 2011). Dibley et al. introduced a software agent system for building monitors based on ontology to respond to the dynamic and changing building environment (Dibley et al., 2012b). Although this system provides a way to smartly manage the building performance, its graphic interface to demonstrate building monitoring data is still under development for general end-users to understand and control.

3. SYSTEM REQUIREMENT AND DESIGN

3.1 General system requirements

The targeted virtual building system should be able to precisely and reliably visualize and monitor the building energy consumption and emergency situation, and to keep high degree of space awareness and privacy, which can then add “building performance” dimension to building life cycle. It should also be able to provide adaptable energy saving and fire emergency management solutions according to ever-changing building information throughout a building life cycle by intelligently utilizing BIM and game engine on top of ontology. It breaks down building performance visualization solutions into two parts: the solution during the building design, the solution during building usage and maintenance stage. The first solution utilizes virtual environment to accurately visualize the building performance according to digital building information before the real building is on site and then integrates these investigated results into simulation technology to testify and refine the energy and emergency plan of the designed buildings. The solution during building usage and maintenance stage can further employ knowledge engineering (i.e. ontological representation of existing information and semantic building information), sensor technology and algorithms to provide comprehensive real-time energy consumption monitoring and fire evacuation guides on common mobile devices or web browsers for general end-users in the complex building. With augmented visualization technology to mix the virtual and real worlds, end-users can use the proposed virtual building installed in their mobile devices to more effectively find issues of the building energy consumption and get updated evacuation guides during a fire by recognizing symbols existing in both the virtual and real worlds.

3.2 Overall system design

According to the approach of the Triadic Game Design (TGD) proposed by Harteveld (Harteveld, 2011), a virtual environment design is closely related to three interdependent worlds: that are, worlds of reality, meaning, and play. Herein, the world of reality deals with how the virtual environment is connected to the physical world, the world of meaning focuses on the type of value that needs to be achieved, and the world of play resolves the methods used to reach the objectives in a world of meaning. Following the TGD approach to create the proposed smart virtual building system for building performance visualization is expressed in Figure 1, which illustrates what use-cases occur, what actors are involved and how they can be mixed and put together to achieve a balanced virtual system. Our work differs by using a BIM authoring tool (Autodesk Revit) as a building information provider to work with game and sensor technology to build an adaptable, virtual building system on top of ontology with the purpose of refining the energy and emergency plan of the building design during building conceptual design stage and offering real-time building management references related to energy saving and fire evacuation during building usage and maintenance stage. To avoid unidirectional and unsatisfactory data transactions (Shiratuddin, 2011, Conway, 2011, Rüppel and Schatz, 2011, Lin et al., 2012) between BIM ,Game Engine, and sensors, three different methods are proposed (Figure 2): to use a built-in translator, to build a library of BIM standard parts, and to use an application interface (API) connected to a central database (Whyte et al., 2000). Integrated with simulation technology, these building information can illustrate building performance visually, and testify building energy and emergency plans. Then, based on proposed ontology framework, the building information in virtual building system can be mapped with the real building information from various sensors to provide building management references for energy saving and emergency evacuation.

The Unity3D game engine has a built-in translator (Figure 2 (a)) that can directly translate specific 3D building formats such as 3DS, FBX, and DXF supported by Revit into the virtual environment. This way is straightforward enough to be utilized to visualize building designs when the design process is completed and the design is temporarily fixed. However, direct translation of huge BIM models into the virtual environment is time-consuming and the translated information simply contains geometric information rather than semantic information that plays important role in building performance simulation. Normally, this method is utilized to provide the simple geometric framework of a building design. After that, the library approach (Figure 2 (b)) can be employed to selectively combine building information and animation with simulation technology. BIM standard components in the library can be archived for reuse within the virtual environment. This can not only eliminate the time waste of repetitive data translation and optimization of common parts, but also add semantic information and the building behavior animation to the standard components. Thus, The raw geometric information can be rendered in details and dynamic building performance simulations can be added according to digital building information in BIM model. It can initially testify the preliminary design of the building energy consumption and evacuation plan in a proposed virtual building system. If test results are not satisfactory, several iterative steps need to be conducted to refine the building performance design to a satisfactory level by reusing BIM standard components in the library and the building performance simulations. Moreover, the virtual building system can utilize virtual reality devices such as the Kinect motion tracker, activate 3D projector system, and Hand Mounted Display (HMD) in Cardiff Virtual Reality lab to immerse people into virtual building performance simulations to enhance their understanding of building performance during building conceptual design stage.

However, the central BIM model in Revit might be often changed by building designers during building conceptual design stage or by requirements of building reconstruction during building usage and maintenance stage, which can then significantly influence results of building performance visualization. Furthermore, a huge amount of ever-changing building information collected by various sensors should be mapped with building information extracted from Revit in real time within proposed virtual building system. Therefore, the third method of employing C# based APIs connected to a central database has been used to develop a two way information channel between BIM, sensors, and the virtual environment to automate building data transactions among them (Figure 2 (c)). Firstly, it initiates the data transmitting process between BIM models in Revit (as representative software of BIM) and the virtual environment provided by Unity3D Game Engine via the PHP server that holds the MySQL central database. Revit model is separated to FBX model and a semantic information file, and then is sent to PHP server. The server feeds this information to Unity server based on the object IDs of the objects in FBX models and synchronizes Unity server and clients in line with remote procedure calls (RPC). The information transmitting between sensors and virtual environment is similar. The PHP server is the central hub to collect building information in line with the object IDs of the building components, and to transfer required information to the virtual environment in Unity3D. After that, With the help of GPU, and .NET framework, it visualize building performance to monitor building energy consumption and detect emergency situation during building usage and maintenance stage. If the unusual building emergency situation (i.e. fire disaster) is found, this will trigger building evacuation solutions. Specifically, based on optimized A* algorithms, the real-time evacuation path simulation can show different end-users the nearest way or safest way to defined safety points on the mobile devices in real time. With augmented visualization technology, the proposed smart building system installed in common mobile devices such as windows surface pro can integrate the images of real world in the camera with dynamic building information in the central database of PHP server to provide end-users a more visual way to find energy issues and get fire evacuation guides by recognizing natural markers such as exist signs, position marks of extinguishes, and device ID tags.

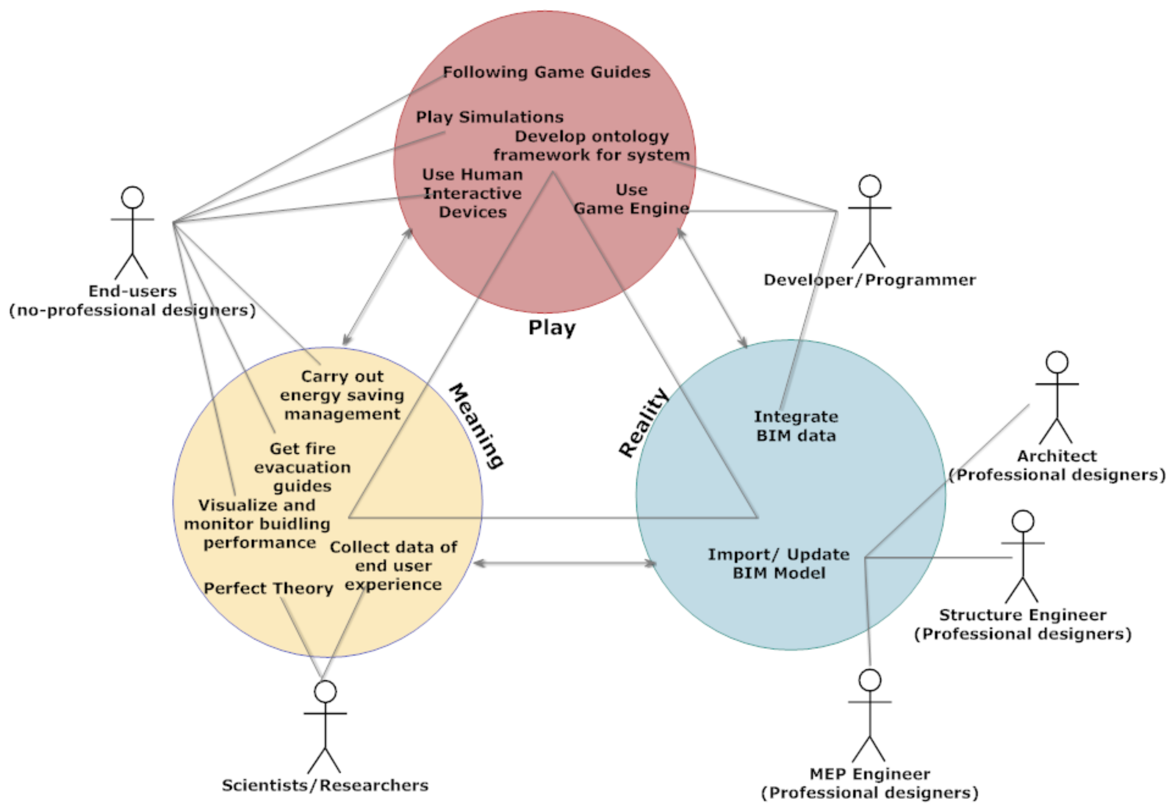

Figure 1: TGD based framework to develop smart virtual building system

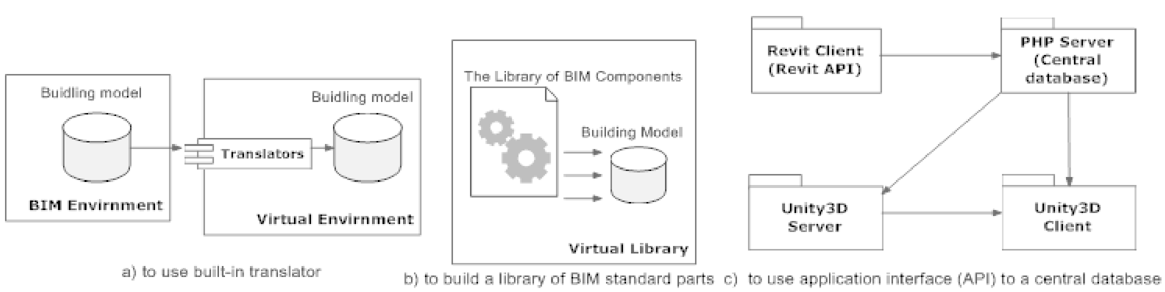

Figure 2: Three proposed method to keep satisfactory data transactions

4. ON-GOING SYSTEM IMPLEMENTATION

4.1 Interface for data transmitting

As stated in section 3, except for to use a built-in translator for data transmitting, the main innovative methods to process BIM and sensor data for building performance visualization in proposed virtual building system are to build a library of BIM standard parts, and to use an application interface (API) connected to a central database. The implementations of both methods are based on the application of database technology. Specifically, categorized BIM components can be collected from open source resources such as bimstore and processed in virtual environment to add necessary animations/physics/script as preferbs. Finally, these classified preferbs can be saved in a MySQL database and loaded in smart building system according to requirements. The reusable BIM component preferbs eliminate the time waste of repetitive data translation and optimization of common parts and add semantic information and the building behavior animation to the standard components. It is convenient to update and load various components from this BIM library through database in real time to support various building performance simulations to refine building energy and emergency plans. To use an application interface (API) connected to a central database for different purposes, the PHP server is a central hub of activities. It receives and filters model information from Revit client and Instrument client, sends the necessary information to Unity client and server, and synchronizes the activities of Unity client and server for different end-users. The referenced sematic information in the PHP server manages the synchronization of geometric and semantic information between Unity client, Unity server, Revit client, and Instrument client (i.e. Sensor client). The package diagram for automatic data transmitting can be demonstrated in Figure 3. For instance, C# based Revit API as Revit client can develop a two way information channel between BIM and the virtual environment. It automatically extracts the geometric and semantic information from the rvt file in Revit and implements it in Unity3D for real-time fire evacuation path simulation via a central MySQL database hold in the PHP server, which is shown in Figure 4. Similarly, Instrument client is under developing on top of ontology.

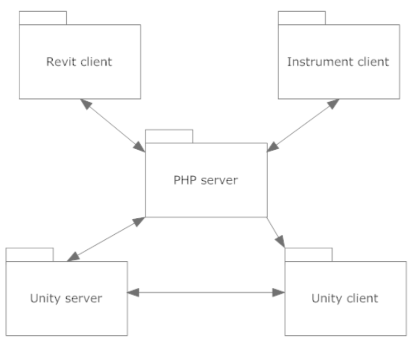

Figure 3: The package diagram for automatic data transmitting

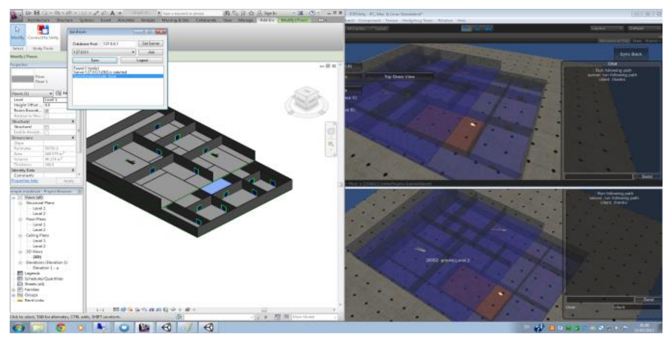

Figure 4: Automatic data transmitting between Revit and Game Engine for real-time fire evacuation path simulation

4.2 Ontology involvement

Although there are several projects working on building ontologies for different purposes (Upadhyay et al., 2009, Mion et al., 2008), the methodology used here would be able to integrate BIM, Game, and instruments to produce a comprehensive ontology covering the whole building life cycle. The five layered framework of virtual building system includes software/hardware infrastructure, functionality infrastructure, agent framework, system ontologies, and applications, which is shown in Figure 5. Various agents can receive relevant input from the ontology service to intelligently control the interaction between BIM, Game Engine, and instrument information to provide various simulations in the functionality infrastructure. The proposed system ontologies and their interrelationships are shown in the system ontologies section of Figure 5. All the ontologies will include relevant domain keywords, the interrelationship between those keywords, and well-defined rules/goals to capture the agents' message content to carry out fire emergency management. Overlapping areas are linking concepts between different ontologies. Specifically, it mainly includes four parts (Dibley et al., 2012a):

Building and human behavior modeling. This begins with a review of the critical factors that influence building and human behaviors. Then, according to these critical factors, the proposed virtual building environment can utilize virtual-reality devices such as the Kinect motion tracker and activate 3D projector system to immerse people into virtual environment to explore and supplement this modeling as well as enhancing their understanding of building performance. Finally, translated ontology from building design manual would be merged into this ontological behavior modeling to accurately simulate building and human behaviors to testify and refine building energy and emergency plans.

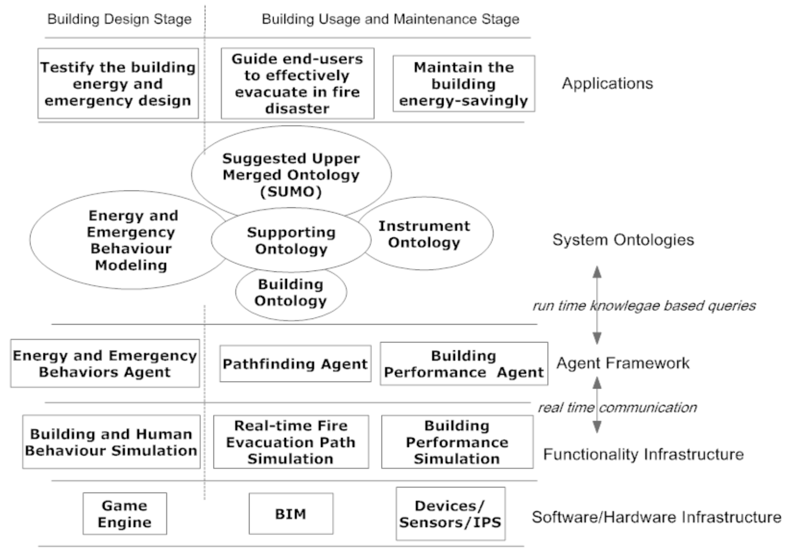

Figure 5: Four layered framework of virtual building system (Dibley et al., 2012a)

Building ontology. This is utilized to capture building geometry and includes the geometric properties of the Revit model as the original taxonomy. The theories of topology and metrology are also employed.

Instrument ontology. Instrument ontology related to key object factors for building performance visualization (Figure 6) demonstrates the sensor instruments, indoor position instruments, door lock devices, and fire alarms, in terms of the information that they capture, their interrelationships, and the associated BIM-based virtual system for information mapping and synchronization.

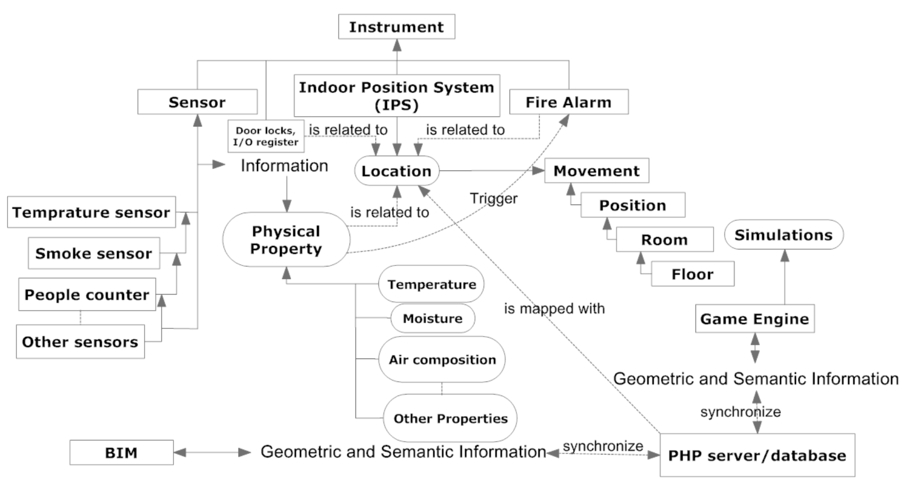

Figure 6: Instrument ontology related to key object factors during a fire evacuation (Mion et al., 2008)

Supporting ontology. This captures domain independent concepts and knowledge based on some key concepts of the Suggested Upper Merged Ontology (SUMO).

4.3 The simulation to visualize building performance

A building management system (BMS) is a computer-based control system installed in instrumented building to utilize a tremendous amount of data to control, monitor, optimize and report the building's mechanical and electrical equipment such as fire systems and security systems for comfort, safety, and efficiency. After refining building energy and emergency plans during building design stage, proposed smart building system combines BMS to visualize building performance for energy saving and emergency detecting in real time . Specifically, the smart building system employs two main areas of knowledge engineering (i.e. ontological representation of existing information and semantic building information), GPU, and .NET framework to visualize building performance. Building ontology, instrument ontology and supporting ontology (proposed in section 4.2) play the key role for agents to understand different data formats, different computer hardware and software systems, different communication middleware etc. in BMS. According to real-time ontology enquiries, the agent can understand the building situation and invoke the appropriate executions to transfer the real-time building performance information to specific data format such as txt. According to Gershon and Eick, it is easy for observer to understand the building situation if the related building information is represented in the context of familiar physical space because perceptual capability of human being are tuned to the physical world (Gershon and Eick, 1995). With the API connected to a central database, both geometric and semantic information in BIM model will be automatically transferred to the smart building system. Then, it visualize various kinds of building performance data stored in txt file on top of 3D BIM model by .Net framework (Figure 7). There are three methods to visualize the captured data: the surface shading, the geometry shape, and interactive graphic user interface (GUI). In terms of the surface shading, the temperature of key instruments in the building can be taken from the sensors and mapped to provide approximate visualization of temperature changes across the space. Whether the key instruments works can be determined by whether the instruments are highlighted in context of the BIM model. With these two kinds of surface shading, not only the real-time distribution of energy consumption can be illustrated, but also the potential risks that may cause emergency situation can be detected. As for the geometric shape, the arrow shapes can demonstrate air-flow in the space (Figure 8), which can then be referenced to judge the direction fire spread with the help of temperature change of the space. Peg shapes visualize occupants' positions in the building to help direct the occupants to evacuate via communication system in the smart building system. Well-defined interactive GUIs allow the end users to get complex and semantic derived data that cannot be depicted meaningfully within the 3D model. For example, if end users select the power outlet, the power usage of outlets can be displayed by Arabic numerals with watt unit. Furthermore, how many percentages of power this outlet is using compared to all other outlets within the space can be demonstrated by the horizontal scroll bar (Figure 8). Similarly, if the end users select the pipe hidden in the walls or celling, the flow speed, the flow direction, and the pressure can be shown in details within the interactive GUIs. Finally, the interactive GUIs in smart building system can visually illustrate the building performance related to building energy and emergency situation. And this visualization, in turn, can assist the fire fighters to distribute firefighting supplies and make corresponding firefighting strategies during a fire.

Figure 7: The simulation to visualize building performance in 2D and 3D

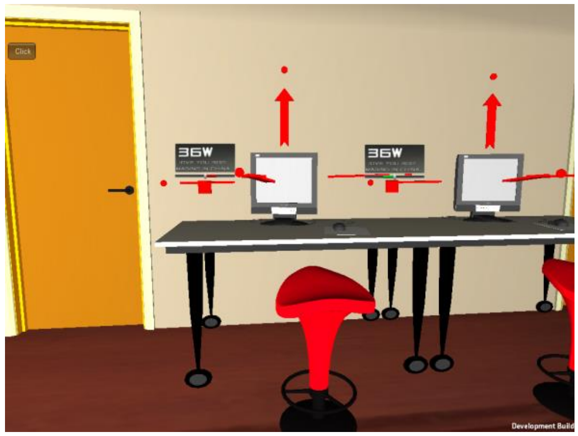

Figure 8: Monitoring air flows using arrow graph and power consuming with bar graph in 3D

5. CONCLUSION AND FUTURE WORK

The smart virtual building system to visualize building performance has been formed and continuously developed to work with relevant simulations to provide building energy saving and emergency solutions throughout the building life cycle. Although similar system have been investigated before (Lin et al., 2012, Ren et al., 2008, Rüppel and Schatz, 2011, Hailemariam et al., 2010, Pauwels et al., 2011, LI et al., 2011), they are not intelligent and accurate enough to use ever-changing building information to intuitively illustrate end-users building performance and normally occur only over one stage of the building life cycle. The proposed virtual building utilizes semantic building information and an ontological representation of existing information to automate building information transmitting between different operation systems, to carry out more accurate simulations according to the ever-changing building information for different purposes and to intelligently integrate relevant simulations as a whole to enhance building performance visualization across the building life cycle. However, the ontologies to support the smart virtual building system are still under development, and the evaluations of the overall system implementation and a full scale case study throughout the building life cycle are needed. The robust network for data transmitting during emergency situation and security issues need to be investigated as well in the future.

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