BIM-BASED LIVE SENSOR DATA VISUALIZATION USING VIRTUAL REALITY FOR MONITORING INDOOR CONDITIONS

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Abstract. This paper proposes a method for an automated live sensor data visualization of building indoor environment conditions using a VR system. The proposed method is based on the integration of environmental sensors, BIM, and VR technology. Such integration provides an opportunity to utilize an immersive and live sensing technology for improving data visualization. In our case study, the environmental data, such as indoor air temperature, humidity, and light level are captured by sensors connected to Arduino microcontrollers. The data output of sensors obtained from Arduino units are stored onto the BIM model and transferred to the developed VR system. The developed system simultaneously visualizes numerical values of sensors' reading together with the virtual model of the building in a VR headset. The result of the case study showed that the developed system is capable of visualizing various indoor environmental information of the building with the VR technology. It can provide users with useful information to help monitoring indoor thermal comfort conditions of the building in real-time, while performing the walkthrough in the virtual environment.

Keywords. Building Information Modeling (BIM); environmental sensor; thermal comfort; Virtual Reality (VR); Arduino; IoT.

1. Introduction

Environmental sensors have been widely used to monitor indoor comfort parameters, such as air temperature, humidity, and light level. They are used for the purpose of providing real-time feedback for occupants regarding their current comfort-related parameters. Using an efficient data visualization method for sensor data is important as it helps users understand and work with the data faster and easier (Richter, 2009). Traditionally, 2D data visualization techniques (e.g., charts, graphs, bar graphs, scatter plots, and maps) are utilized to help understanding and interpreting the meaning of the captured data. Although such

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static visualizations provide users with tools to extract meanings from data more effectively, they have significant limitations. For example, such visualizations can only present certain data types and they are inefficient in presenting the real-time sensor data, such as air temperature, indoor air quality, and wind velocity that is needed for making quick decisions and actions to solve problems. With the growing size of datasets and the complexity of existing data, static information visualization methods become less helpful and such method needs to be improved (Kim et al., 2017; Olshannikova et al., 2015). In addition, interactive tasks cannot be done using static visualizations (Kim et al., 2017).

Recently, various new visualization methods have been developed to enable faster representation of data and to provide interaction. For example, Sicat et al. (2018) developed DXR, a toolkit for building immersive data visualizations. Pre-defined visualizations, such as scatter plots, bar charts, and flow visualizations were connected through filtering and linking. This system enabled users to make their data engaging and insightful in immersive environments. Kim et al. (2017) proposed VisAR system that integrated interactivity to static data visualization using Augmented Reality (AR). Hosokawa et al. (2016) developed a system for visualizing air flow rate of air-conditioner using virtual reality (VR). In addition, efforts to develop methods to improve data visualization have been proposed to support decisions throughout the building life cycle. For example, Natephra et al. (2017) developed a method to integrate Building Information Modeling (BIM), thermal images, and environment sensors to visualize thermal information of building surfaces and support indoor thermal comfort assessment. Motamedi et al. (2014) investigated a knowledge-assisted BIM-based visual analytics approach for failure root-cause detection in facilities management (FM). This study proposed a method to integrate BIM visualization capabilities and sensors to support FM technicians with visualizations that allow them to utilize their cognitive and perceptual reasoning for problem-solving. Based on the previous studies, data preparation stage is required before incorporating with virtual environment. They also lack a capability to integrate real-time data with immersive environments.

On the other hand, real-time sensor readings and enhance data analysis are being increasingly used. Similarly, the Internet of Things (IoT) has been applied in various platforms to enhance the quality of life (Chang et al., 2018), such as air quality, living comfort, work productivity, and traffic control. Vaccari (2015) stated that IoT enables data from network-connected devices to be delivered and transformed into other types of information to be included in virtual simulation.

A large amount of effort has been proposed methods for integrating IoT and BIM to facilitate in various processes in architecture, engineering, and construction and facilities management (AEC/FM) industry. However, previous research on the integration of BIM and IoT is limited and it is mainly focused on the automation of the transfer of sensor information to BIM models (Chang et al., 2018). BIM refers to a digital transformation of information throughout the building lifecycle (Eastman et al., 2008). The integration of BIM and real-time sensor readings, such as environmental condition of workers, can be considered as state of art that can provide further benefits to the operation management (Teizer et al., 2017). Although the integration of BIM and sensor data has the potential for assessing indoor thermal condition, the lack of real-time connections between live sensor information, BIM, and other building-related information sources prevents such assessment. This also prevents effectively analyzing indoor conditions, due to the difficulty in comprehending the correlation between time and changes of indoor condition.

The above-mentioned research gaps encourage investigating a BIM-based live sensor data visualization method that utilizes a non-static visualization technology such as VR for indoor comfort condition monitoring. The immersive experience offered by VR can be used for monitoring and visualizing real-time data of IoT sensors (Eastman et al., 2008). However, there is no research to date that investigates the integration of IoT, BIM and VR visualization for monitoring indoor environment.

This paper presents a framework for integrating BIM geometry information and environmental sensor data to create a live sensor data visualization in a serious game environment. The proposed method defines a system which uses an immersive and interactive VR environment for visualizing indoor comfort parameters. Arduino environmental sensors (e.g., temperature, humidity, light sensors) are used to capture real-time values for related comfort parameters. The sensor data obtained from Arduino units are stored in the BIM file using visual programming environment provided by the authoring software. The data is simultaneously transferred to the virtual environment using the Application Programming Interface (API) of the game engine. The developed dashboard is a tool to provide user with a real-time display of the sensors' readings in the VR environment as the user navigate in the BIM environment. Tools such as Autodesk Revit, Unreal Engine, and its scripting environment were used in our proposed system. The applicability of the proposed method is verified in a real-world case study.

2. Proposed methodology

The BIM-based live sensor data visualization is an integrated framework, which uses a BIM model, sensor data, and VR environment for monitoring indoor conditions. The proposed system helps identifying issues and examine different variables that influence indoor comfort for occupants. The proposed system visualizes the measured values of environmental conditions to provide an initial assessment of parameters related to comfort. It creates a user experience of being in an immersive computer-generated environment that is fed by real-time sensing data gathered through a seamless connection between the systems and the sensors. The proposed methodology comprises three main steps (as shown in Figure 1). The first step is to capture different environmental variables that influence on indoor comfort (e.g., air temperature, humidity level, and light intensity level) utilizing IoT sensors connected to a controller. Sensor readings are then transmitted by the controller to the BIM server and are stored in the model. In this step, BIM model is enriched by live environment data. Geometry information together with sensor data are transferred to the serious game environment (e.g., a game engine) using its Application Programming Interface (API). The visualization of the geometry and sensor data then be performed through VR headsets.

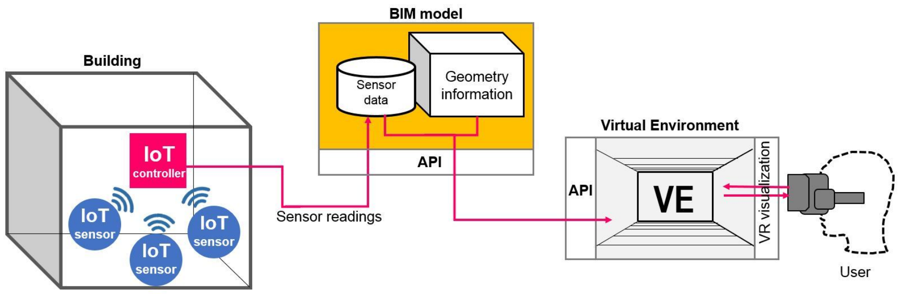


Figure 1. Overview of the proposed framework.

3. Prototype system

The developed prototype system follows the process flowchart shown in Figure 2. The process consists of five main steps. The first step is to create the BIM model and to collect environmental data. In this step, a BIM model of an existing building, which includes geometry information (e.g., walls, ceiling, floors, boundaries of rooms) is created using a BIM authoring software. Autodesk Revit (Version 2017) has been used in our prototype implementation. Environmental data (e.g., indoor air temperature, relative humidity, and light intensity level) is also captured using environmental sensors compatible with Arduino microcontrollers (Figure 2a). The sensors readings are linked to BIM objects and are stored in the BIM model using software tools developed by visual programming (e.g., Dynamo). Consequently, the BIM model is enriched by the environment data (Figure 2b). The third step is to transfer BIM data (e.g., geometry information and sensor data) to the game engine (Figure 2c). For transferring the geometry, a static mesh is generated after transferring FBX files from Revit to Autodesk 3ds Max. Unreal Engine is used as the game authoring environment in our prototype implementation.

In this step, sensor data is also linked to the game environment using visual scripting feature of Unreal Engine. The sensors data is constantly updated using the developed tool to maintain the live stream of data. In the fourth step, the sensor data and the geometry are visualized in the VR environment. For that, a user interface is developed to simultaneously display sensor data and to support interactions with users (Figure 2d). The BIM model with its geometry and information together with real-time numerical values of sensor data are displayed in VR environment. The created virtual environment allows users to perform walkthrough in a building. The user utilizes the immersive visualization provided in the fourth step to monitor the condition in real-time and to identify the indoor comfort level (Figure 2e). The user can also quantitatively analyze the environmental condition by viewing the sensor readings and calculated parameters in the virtual environment.

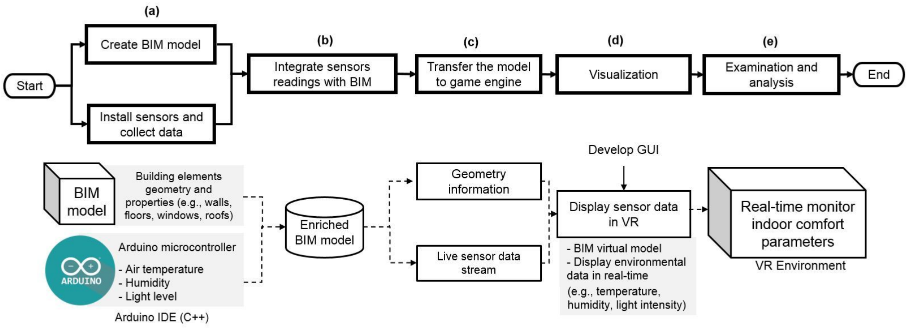


Figure 2. Process flow for integrating IoT sensors and BIM with VR.

The user interface is consisted of three main components that are available on the display screen: (a) First-person player view to give users a first-person perspective when they are moving in the virtual space; (b) Sensor data dashboard to show numerical values of air temperature, relative humidity level, and light level; (c) Minimap to aid users orienting themselves within the virtual model. Figure 3 shows the GUI interface of our developed system.

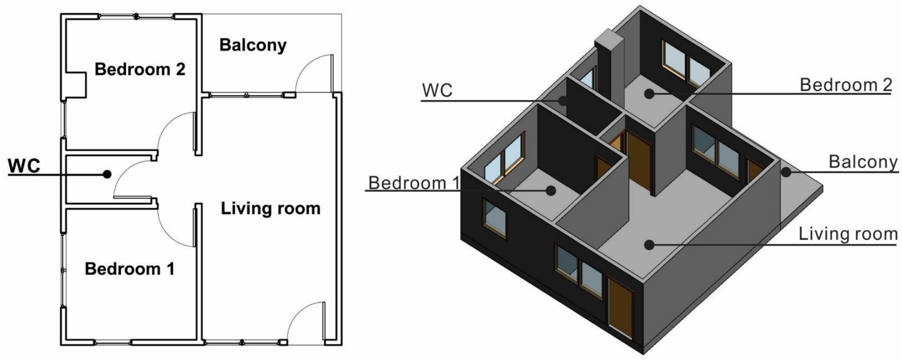
Figure 3. Screenshot of the main interface of the prototype system.

4. Case study

An apartment on the 7th floor of an existing residential building at Mahasarakham University, Thailand was chosen as an experimentation area. The apartment has two bedrooms with shared living and kitchen area, as shown in Figure 4. The environmental data was captured in the winter (November) from 9 a.m. to 6 p.m.

4.1. BIM MODELING AND INSTALLATION OF ENVIRONMENTAL SENSORS

The BIM model of the case study was created using Autodesk Revit Architecture 2017 (Figures 4a and 4b). The placement of environmental sensors is shown in Figure 4b. The placement height of sensors was 1.20m from the floor. Indoor air temperature and the percentage of relative humidity were captured using Arduino compatible sensors (i.e., DHT 11). Temperature range of sensor is from 0 to 50 °C, with ±2°C accuracy. Humidity range of the sensor is 20-90% RH, with ±5% RH accuracy. Photoresistor sensors are used to measure light level in the room. Sensors were set to collect data with time intervals of 1 second.

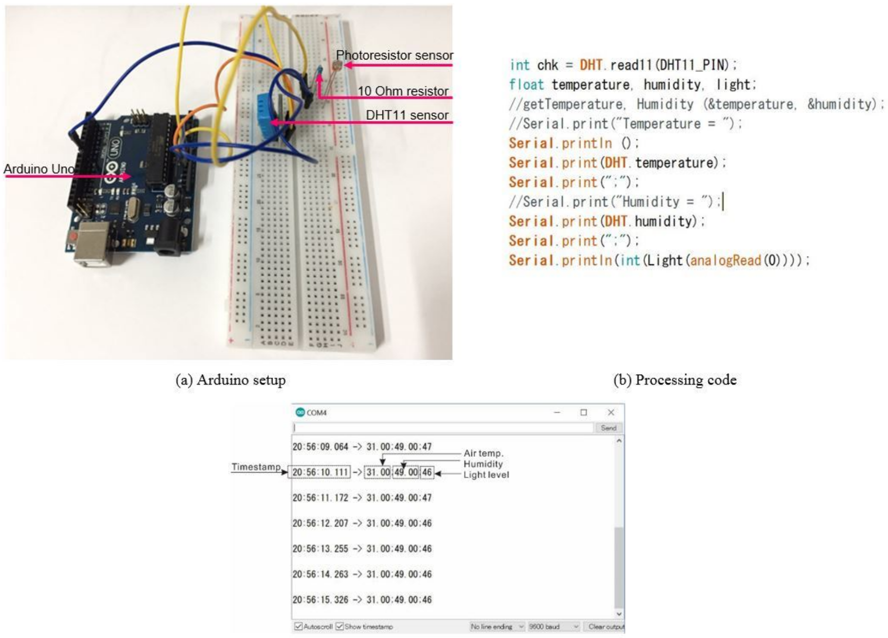


(a) Floor plan (b) 3D BIM model and sensor placements

Figure 4. Experimentation room.

Environmental-sensors are DHT11 sensor modules, which were connected to Arduino Uno microprocessors (Figure 5a). Arduino Integrated Development Environment (IDE) was used for programming the physical board. DHTLib library was installed to measure humidity and temperature readings. In this experiment, pin signal of the sensor was connected to a digital port of the Arduino board to read data output from the sensor. To measure ambient light, photoresistor sensor modules are installed on Arduino boards. Analog pin A0 was used to read value of lighting level.

Once the developed code is uploaded to Arduino boards, sensors start to capture readings. The setup code to run sensors and measure the specified comfort parameters is showed in Figure 5b. The outputs of temperature, humidity, and light intensity level readings were in Celsius (C), percentage (%) and Lux (lx), respectively. Figure 5c shows serial monitor reading of sensors.



(a) Arduino setup (b) Processing code

(c) Screenshot of serial monitor readings

Figure 5. Circuit board setup, processing code, and sensor reading outputs.

4.2. SENSOR READING, BIM, AND GAME ENGINE INTEGRATION

The workflow of transferring sensor reading to BIM is shown in Figure 6. First, DHT11 and photoresistor sensors were installed on Arduino board (Figure 6a). After uploading the developed coded to the board, air temperature, humidity, and light intensity level were captured and the outputs of sensor data were displayed on serial monitor console (Figure 6b). In order to store sensor readings from Arduino Uno to BIM, Firefly plugin provided in Dynamo (a BIM visual programming) was used (Figures 6c and 6d). To link Arduino sensor outputs with Unreal Engine, UE4Duino2 was used (Figure 6e). This plugin helps Unreal Engine to directly retrieve data from Arduino. Consequently, live data visualization using VR in Unreal Engine can be performed (Figure 6f). Figure 7 shows the visual scripting that enable Unreal Engine to receive sensor readings from Arduino.

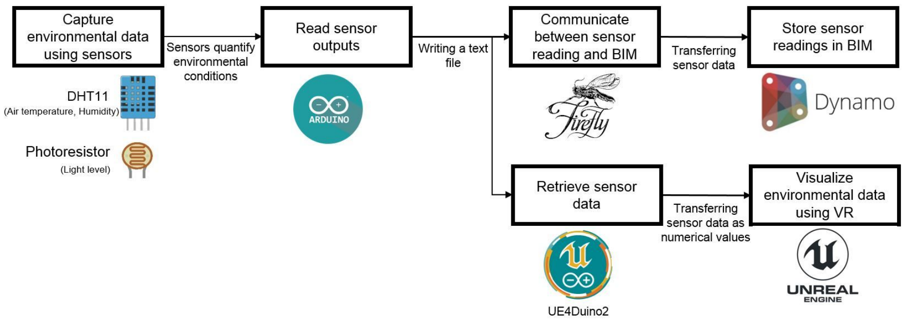


Figure 6. Sensor readings transfer to BIM.

Figure 7. An example of visual scripting to communicate with Arduino (Blueprint).

4.3. STORING DATA IN BIM AND DATA VISUALIZATION IN VR

To store sensor data in BIM, readings were retrieved using Firefly visual programming. Figure 8 shows sensor readings in Dynamo. Sensor readings along with their timestamp were saved as text file (Figure 9a), which can be used for tracking operation history for further indoor condition analytics. Figure 9b shows an example of the environmental data output visualization using the developed system. Numerical values obtained from sensors are displayed on the scene. A user can visually monitor the value of comfort parameters in real-time while navigating the VR environment. Monitoring the comfort parameters in real-time provides users with indoor conditions while having an immerse virtual experience of navigating in the building.

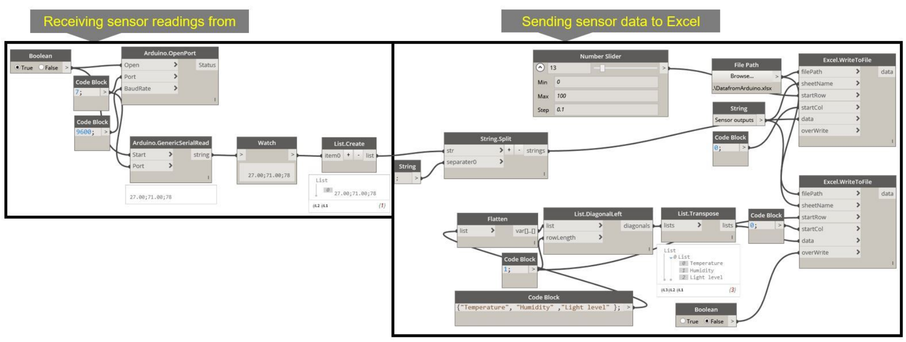
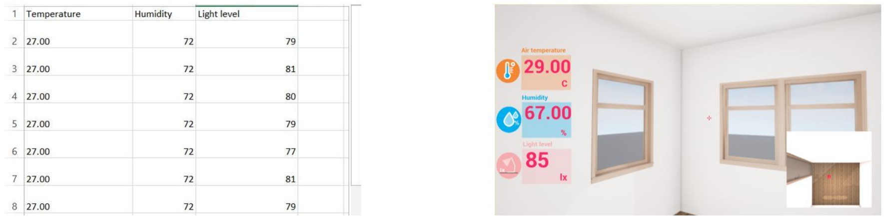


Figure 8. Screenshot of visual script for connecting sensor reading to BIM.



Temperature	Humidity	Light level
27.00	72	79
27.00	72	81
27.00	72	80
27.00	72	79
27.00	72	77
27.00	72	81
27.00	72	79

(a) Transferring sensor data from BIM to store in Excel (b) Data visualization in VR

Figure 9. Example of sensor outputs.

5. Results and discussion

There are limitations and challenges in using BIM-based live sensor data visualization using VR for monitoring indoor comfort parameters.

- Although the developed system provides an ability to connect sensor with BIM and VR, and enables the user to examine air temperature, humidity, and light level through an HMD, only digital numerical values can be visualized. In order to help users easily understand comfort conditions, presenting sensor readings in virtual charts and graphs in VR should be developed.
- In our case study, although visual programming tool of a BIM authoring software (i.e., Dynamo) and its plug in (i.e., Firefly) were successfully used to retrieve sensor readings from Arduino, a full integration of sensor data and BIM to directly store sensor data in BIM should be developed.
- The proposed system enables storing comfort parameters in .xlsx file. However, storing such data using IFC resources to support BIM data exchange is desirable.
- The analysis of the thermal comfort condition of the building is limited only temperature and humidity through digital values retrieve from the sensors. Air-flow rate and mean radiant temperature can also be integrated with our developed system.

6. Conclusions and future works

This paper presented a method for creating a BIM-based live sensor data visualization using VR for real-time monitoring of indoor comfort of an existing building. The advantages of integrating BIM, sensor data, and VR for operation and maintenance included providing the opportunity to support and track indoor conditions in real-time, proactive management of indoor environment, better monitoring and storing of sensing data, and identifying the measured parameters that could affect indoor comfort conditions. By utilizing VR, users were enabled to visualize and monitor the current condition of the room and detect possible issues in real-time. The VR headset is used in this study for maximum immersion, however, the developed application supports non-immersive VR visualizations, such as on a computer screen.The proposed method has been verified in an apartment building in a campus. Air temperature and humidity were captured by DTH11 sensor and a photoresistor sensor was used to measure light intensity level.

Arduino Uno was used to read sensor outputs. In order to transfer sensor readings to BIM and a game engine, tools such as Firefly for Dynamo and UEDuino2 for Unreal Engine were used. Our initial results revealed that the sensor data from Arduino can be successfully transferred to BIM and sensor readings were also successfully integrated with the VR environment. In order to better understand the actual characteristics of the space, which influences the indoor condition, integrating an interactive sensor data visualization with Augmented Reality (AR) can be also explored. Some challenges must be addressed in our future works, such as developing a method to store environmental sensor reading to IFC file, and developing a direct integration between sensor reading and BIM for assessing thermal comfort based on ASHRAE standard. We also intend to investigate a method to integrate other sensors, such as infrared sensors, air flow sensors, and air quality sensors with our system to support an automatic assessment of indoor thermal comfort. Integrating noise sensors in our system can facilitate the assessment of acoustic comfort by visualizing noise level data.

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