SMART SPACE WITH A BUILT-IN UBIQUITOUS SENSOR NETWORK (USN)-BASED ONLINE MONITORING SYSTEM AT SUNGKYUNKWAN UNIVERSITY IN KOREA

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ABSTRACT

Recently, advances in smart sensors and information technology have made building structures more intelligent. In particular, the ubiquitous sensor network (USN) system, which consists of a range of smart sensors and a wireless communication network, is being employed widely as an essential tool to provide a safe and clean environment with a range of applications including automation, fire prevention and security. This paper presents, a smart space test-bed with a built-in USN-based online monitoring system established at Sungkyunkwan University in Korea for both functions of structural health monitoring and environmental monitoring. For the structural health monitoring function, accelerometers, strain gauges, tilt-meters were installed at the host structure and the vibration mode shape, deflection and displacement of a specific member of the host structure were monitored in real-time. Temperature sensors, humidity sensors, CO_2 (Carbon dioxide) sensors, windy direction/speed sensors, CCTVs (Closed-Circuit Television) and motion sensors were installed at the appropriate locations for environmental monitoring inside and/or outside the host structure. In addition, all the information obtained from the deployed sensors was collected as a database and an integrated web server which can be connected very easily through the mobile apparatus of the various platforms such as a tablet PC (Personal Computer), a smart phone, MID (Mobile Internet Device), and etc. was constructed. Finally, the built in USN-based online monitoring was integrated with BIM (Building Information Modeling) maintenance for future guidance in ubiquitous environments.

Keywords: Smart Space, Ubiquitous Sensor Network, Structural Health Monitoring, Environmental Monitoring, Building Information Modeling.

1. INTRODUCTION

In recent years, the general construction process including planning, designing, construction and maintenance is being merged with a range of emerging information technologies. In particular, a great deal of research and development (R&D) are being conducted for diverse requirements of both new hardware platforms and software algorithms. Owing to this trend, smart buildings and facilities are being developed rapidly and smart spaces are also being created. A smart space can be defined as an actively changing digital environment combining physical space and ubiquitous computing technology (Cho et al. 2006). It consists of a sensor detecting the spatial information, a broadband network and an integrated program to promote the user's convenience. Over the last decade, there have been many case studies aimed at developing smart spaces. The Adaptive House (Mozer 2005) of University of Colorado is a study of a residence using temperature sensors and light sensors to research the behavior patterns and environmental changes. The Smart-home (Duke University 2011) of Duke University is a study that has been certified the LEED (Leadership in Energy and Environmental Design) Platinum by adopting a range of energy-saving technologies in the dormitory, and The Aware Home (Kidd et al. 1999) of the Georgia Institute of Technology is a study that examined the education, health care, entertainment, and various parts by providing an environment similar to a home. In addition, the Gator Tech Smart House (Helal et al. 2005) of the University of Florida, is a study of environmental monitoring and energy efficiency monitoring, and a study of human activities, such as movement, falls accidents and reminders. Most of these studies provide variable services based on monitored and measured data using sensors to promote the user's convenience.

This paper presents a smart space test-bed established at Sungkyunkwan University's overpass area to implement both functions of structural health monitoring and environmental monitoring with built-in ubiquitous sensor networks (USNs) that consist of variable sensors. Furthermore, an integrated web server was constructed by linking with the building information modeling (BIM) tool. For structural health monitoring, accelerometers, strain gauges and tilt-meters were installed at the test-bed and the vibration mode shape, deflection and displacement of the specific member of the host structure were examined in real-time. For environmental monitoring, temperature sensors, humidity sensors, CO_2 (Carbon dioxide) sensors, wind sensors, CCTVs (Closed-circuit televisions) and motion sensors were installed at the appropriate locations. The test-bed server periodically acquires the data from the USN and stores it at the database server.

The data for both environmental and structural health monitoring were stored and processed through the web server that anyone can access. The data were interlocked with BIM tool to make building management and maintenance more efficient.

This paper is organized as follows: Chapter 2 describes the on-line monitoring system for structural health and environmental monitoring. Chapter 3 introduces the possibility of integrating a BIM system and the data of structural health and environmental monitoring for efficient building management and maintenance. Chapter 4 describes the present condition of the test-bed, and chapter 5 presents the result of test-bed operation and future challenges.

2. BUILT-IN ONLINE MONITORING SYSTEM

The development of multifunctional low-cost smart sensors and low-power wireless communications technology has lead to the realization of a USN, which can sense the condition of structures remotely. USN is a technology integrating the environmental data sensed by widely installed wired/wireless network infrastructure with various sensing devices, and an application service server. The USN is being actively studied and applied in a range of fields for a variety of purposes including military use, structural health monitoring, intelligent logistics management, mobile healthcare, real-time security, environmental monitoring, etc. (Estrin et al. 2001).

In this study, a smart real-time monitoring system was built in a structure for structural health monitoring and environmental monitoring based on a USN (ubiquitous sensor network) technique.

2.1 Structural health monitoring techniques

Real-time structural health monitoring is different from non-destructive testing and is an evolving concept. Smart sensors are attached to structures to monitor the structural health in real-time using this technique. This reduces the labour and repair time and improves the quality, safety and reliability of the structure by analyzing the monitored information.

Structural health monitoring has been studied to enhance both the safety and reliability of structures, from bridges and building structures to aircraft and spacecraft (Rytter et al. 1993).

This technique is divided into a global monitoring technique and local monitoring technique depending on the monitoring area size. The global monitoring technique is so-called vibration-based structural health monitoring that is based on the concept of identifying the structural changes by detecting changes in vibration characteristics in the low-frequency band. This monitoring technique can detect structural damages based on major changes in the vibration characteristics, such as natural frequencies and mode shapes (Kim et al. 2003).

On the other hand, it is not useful for detecting structural damage where the change in modal property sensitivity is small or damage that causes small changes in the modal property sensitivity like the initial crack. Therefore, a local monitoring technique based on the vibration characteristics in the high-frequency band to detect local damage is being actively studied. This monitoring technique can identify damage in a specific part because it detects changes in the adjacent part of the attached sensors, but it has the limitation of a narrow monitoring area (Bhalla and Kiong Soh 2003). These monitoring techniques have been applied successfully to a range of structures including bridges,

buildings, antique structures and mechanical structures (Magalhães et al. 2009; Michel et al. 2008; Júlio et al. 2008; Pierro et al. 2008).
In this study, global health information were sensed with vibration-based structural health monitoring technique using accelerometers, and the structural safety was improved by securing the accuracy of the local health monitoring technique with installed strain gauges and tilt meters on important members.

2.2 Environmental Monitoring

Comfortable indoor environment to improve work efficiency and maintain good health has become an important issue for modern people who mostly live indoors. The quality of indoor air is linked to range of building-related illnesses including SHS (Sick House Syndrome), SBS (Sick Building Syndrome) and MCS (Multiple Chemical Sensitivity) and the proper temperature and humidity have a direct impact on the productivity and comfort of people indoors. In addition, the high humidity of a room increases the microbial activity, such as mould and bacteria, which emit organic compounds and odour and diseases, such as asthma.
Especially, According to the EPA (Environmental Protection Agency) report for exposure the contaminants in the air, the levels of indoor air pollutants may be two to five times higher -and occasionally more than 100 times higher - than the outdoor levels, and levels of indoor air pollutants is very important to people because they spend more than 90% of their life indoors (EPA 1999, 2000; Mølhave and Krzyzanowski 2003; Shah and Singh 1988; Woods 1991).
Therefore, more comfortable, valuable, environmentally-friendly and energy-efficient HVAC (Heating, Ventilating, and Air Conditioning) control systems will be an essential element for future living environments and a HVAC system should be operated automatically and efficiently to successfully accomplish this system.
As a result of continuous research, there are a range of indoor environment standards for thermal and air quality: ASHRAE (American Society of Heating, Refrigerating and Air-Conditioning Engineers) for USA and ISO 7730 for Europe, as listed in Table 1.

Table 1: Thermal Comfort Standards

Evaluation Criteria		**USA (ASHRAE 2003, 2004)**	**Europe (ISO7730, 2005)**
Operative temperature [℃]	Summer Cooling	23.0~26.0	23.0~26.0
	Winter Heating	20.0~23.5	20.0~24.0
Max. mean air velocity [m/s]	Summer Cooling	under 0.23	0.19
	Winter Heating	under 0.17	0.16
PMV (Predicted Mean Vote index)		-0.5 ~ +0.5 (Predicted Percentage of Dissatisfied (PPD) is under 10%)	

Many case studies have been performed to improve the energy efficiency, thermal comfort and air quality. These studies included a study of the design of buildings and the environmental control systems (de Rear and Brager 2002), a study of optimized air diffusion of air-conditioners for optimal comfort and fine energy utilization efficiency (Liu et al 2008) and a study of the development of private air-conditioning systems for energy saving (Pan et al 2005). In addition, systematic studies on the resident's exposure to formaldehyde, volatile organic compounds and health effects are ongoing (Wolkoff et al 1991, Brinke et al 1998, Rehwagen et al. 2003, Wolkoff 2003, Park and Ikeda 2006).
In this study, air-quality and thermal-comfort systems were developed to evaluate a comfortable indoor environment by installing temperature sensors, humidity sensors, CO_2 sensors and wind sensors. In addition, data on the users' behaviour was collected using motion sensors and CCTVs.

3. BIM-BASED SMART SPACE'S MAINTENANCE

Recently, as the construction projects are becoming larger and more complex, the needs of cooperation for each process task are increasing and the demands for improvements in construction productivity are increasing. As an alternative, BIM that contains information on the entire building is presented. Currently, the administration of advanced country and project participants employ BIM to improve the cooperation of efficiency and productivity in various areas. In this study, the data measured from sensors and the results of structure health and environmental monitoring based on the measured data were analyzed by BIM.

3.1 BIM (Building Information Modeling)

BIM is not a simple 3D (Three-Dimensional) model, but it is an architecture design management program to automatically generate a range of information, –information on the quantity, cost, schedule, materials, etc. – and analysis data of a structure, environment, etc.by applying this program, the building operators make a decision accurately and quickly. The management system though BIM shares information on the building`s life cycle effectively, and manages information to prevent problems with data loss, data redundancy and duplication (Bazjanac et al. 2004). 3D CAD (Computer-Aided Design) applications that can design BIM can build a database on the information of each object and can model this information. The types of applications include ArchiCAD, Revit, Micro station, and Digital Project (Eastman et al. 2008).

Industry Foundation Classes (IFC) developed by building SMART is an effective means of information exchanges and standards of BIM in the USA and Europe. The IFC standard was developed to provide information on a building`s life cycle (Nawari and Sgambelluri. 2010).

3.2 Applying BIM for maintenance

When BIM is established on the building, it will include structural information, the graphics of all systems applied to a building and the related specification information of these buildings. In addition, this system contains analysis data performed to determine previous mechanical equipment, control system and other purchases. Based on this data, the owner's decisions on building management are reviewed. After the buildings are complete, BIM is used to confirm that all systems function properly. BIM reflecting modified changes in the construction phase provides accurate information on all systems and space in the completed state, and it is used as a tool for building maintenance. In addition, BIM provides a platform for the user's interface for monitoring a real-time control system and remote facility management. The mergence function applying the features is still in the developmental stages (Eastman et al. 2008).

4. TEST-BED CONSTRUCTION AND OPERATION

4.1 Overview of Test-bed

In this study, a test-bed was constructed for a monitoring system on an overpass area built to connect the 3rd floor of the 1st engineering building with the 2nd floor of the 2nd engineering building in Sungkyunkwan University (37 ° 17'40 .13 "N, 126 ° 58'37 .81" E) as shown in figure 1. The test-bed is a cylindrical steel structure. The ceiling and the wall was composed of stainless steel-frames and 6mm tempered glass, and the floor was paved with concrete on a steel-frame. The test-bed is supported by an H-beam type substructure at 28m away from the 2nd engineering building, as shown in figure 2.

Figure 1: Appearance of the test-bed - Overpass Area in Sungkyunkwan University.

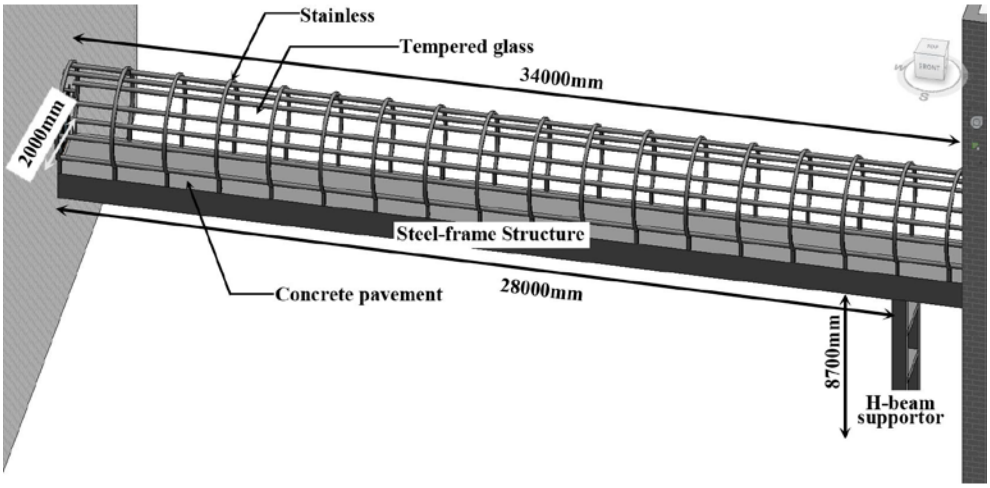

Figure 2: Detailed model of the test-bed.

4.2 Sensors installation for structural health monitoring and environmental monitoring

For structural health and environmental monitoring on the test-bed simultaneously, a total of 8 different 18 sensors were installed indoors and outdoors as shown in figure 3. Table 2 lists the type, location and quantity of the installed sensors. First, three types of sensors were installed including accelerometers, strain-gauges and tilt-meters for structural health monitoring on the test-bed. Three accelerometers were installed along the west side of the bridge from the 1st engineering building to the supports, and another accelerometer was installed on the middle of the opposite side (east side). The natural frequency and mode shapes were determined using the ambient vibration data from these four accelerometers. Two strain gauges were installed to measure the stress where the largest transformation was estimated to occur and the structural health was evaluated by comparing the stress with the allowable design stress. In addition, tilt meters were installed near the 1st engineering building to monitor the changes in the angle that occur naturally or artificially by differential settlement in the test-bed. Thermo-hygrometers and CO_2 sensors were installed to compare the thermal comfort and air indoor quality with the outdoor environments. In addition the wind sensors were installed on the bottom of the test-bed and roof of the 1st engineering building to compare the air-flows in both locations. As the observation of human behavior is important, CCTVs and motion sensors were installed at both entrances to the inside direction.

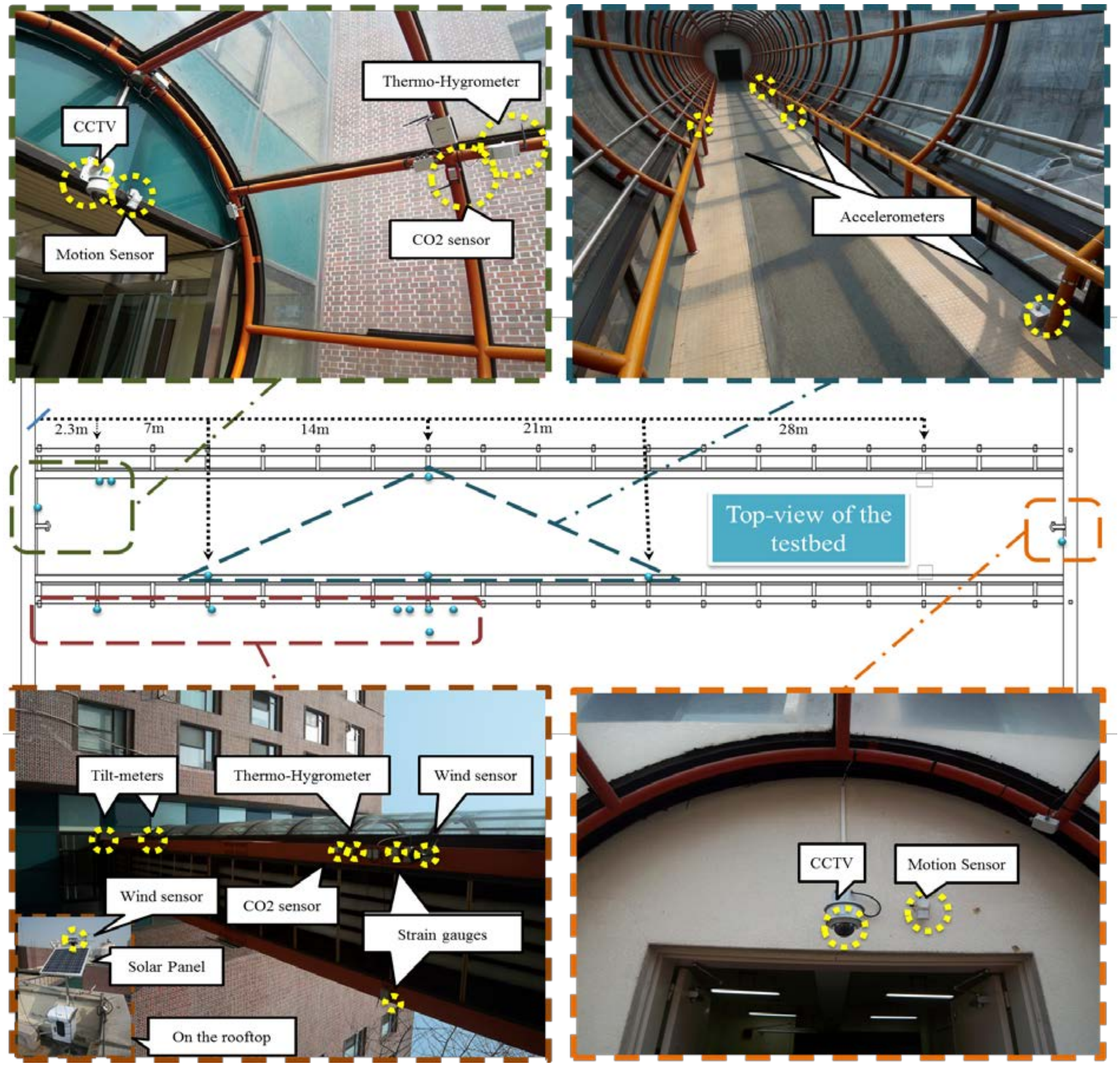

Figure 3: The Layout of the Installed Sensors.

Table 2: Type, Location and Quantity of the Installed Sensors

Sensor Type	Purpose	Measurement Target	Installed Position	Quantity
Accelerometers	Structural Health Monitoring	Ambient Vibration	Indoor	4
Strain gauges	Structural Health Monitoring	Maximum Bending	Outdoor	2
Tilt-meters	Structural Health Monitoring	The Angle of Inclination	Outdoor	2
Thermo-Hygrometers	Environmental Monitoring	Temperature and Humidity	Indoor Outdoor	1 1
CO_2 sensors	Environmental Monitoring	Concentration of CO_2	Indoor Outdoor	1 1
Wind sensors	Environmental Monitoring	Wind Speed and Direction	Outdoor	2
Motion sensors	Environmental Monitoring	Moving Objects	Indoor	2
CCTVs	Environmental	Visual Observation	Indoor	2

The internal states of the test-bed – the movement of people or objects, situations, etc. – were observed in real-time with CCTVs and the floating population were measured from motion sensors. A solar panel was installed on the roof to supply power to some of the sensors to reduce energy consumption.

4.3 Configuration of the ubiquitous sensor network and the integrated server

A ubiquitous sensor network is composed of sensors installed on the test-bed to minimize noise that occurs between the sensors and measuring devices. At the same time, the sensors are interlocked with a distant server. The server, ubiquitous sensor network gateways and IP (Internet Protocol) cameras were installed, as shown in Figure 4, and the IP addresses were assigned based on the internal LAN (Local Area Network) of the campus.

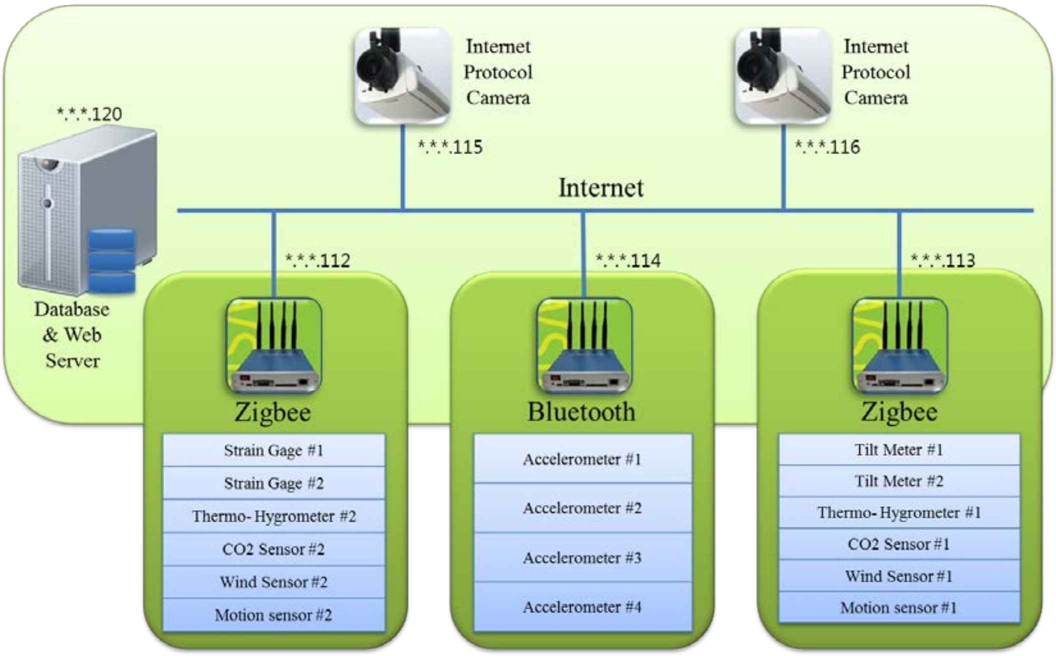

Figure 4: Network configuration for the test-bed.

The Zigbee (a Low-power short range wireless communication technique) based gateways were employed in the USNs because most sensors in the test-bed have small number of communications and a small amount of communication data. On the other hand, the acceleration data has the largest size and requires other functions, Therefore, the Bluetooth (High-speed short-range wireless communication technique) based gateway was used for the acceleration data .

Each sensor has different sizes and measurement periods, so the server creates the databases according to the schedules periodically via the USN. A range of signal processing techniques or statistical techniques were used and the processed data was serviced through a web server. Webpage and a mobile-optimized webpage for portable devices such as smart phones and tablets were configured.

4.4 Integration of online monitoring system with BIM

The information on Smart Space provided through the above process is enormous. Therefore, a tool for effective information delivery is needed. For this purpose, a method interlocking the monitoring information with BIM containing information on the location and properties is presented.

The produced plug-in program was installed to add functions to the information that BIM system already has,. The sensors were inserted in measured locations, the measured database was linked at each inserted sensor object.

From this data, the operator of the maintenance system can contact and check the measured data intuitively. As BIM contains a range of information of the building and analysis data of the structure

and environment, just interlocking the monitoring information with database offers efficient maintenance.
In this study, by being interlocked with BIM systems, the accessibility of smart space information and management convenience are improved. Figure 5 shows the monitoring data interlocked with a BIM system.

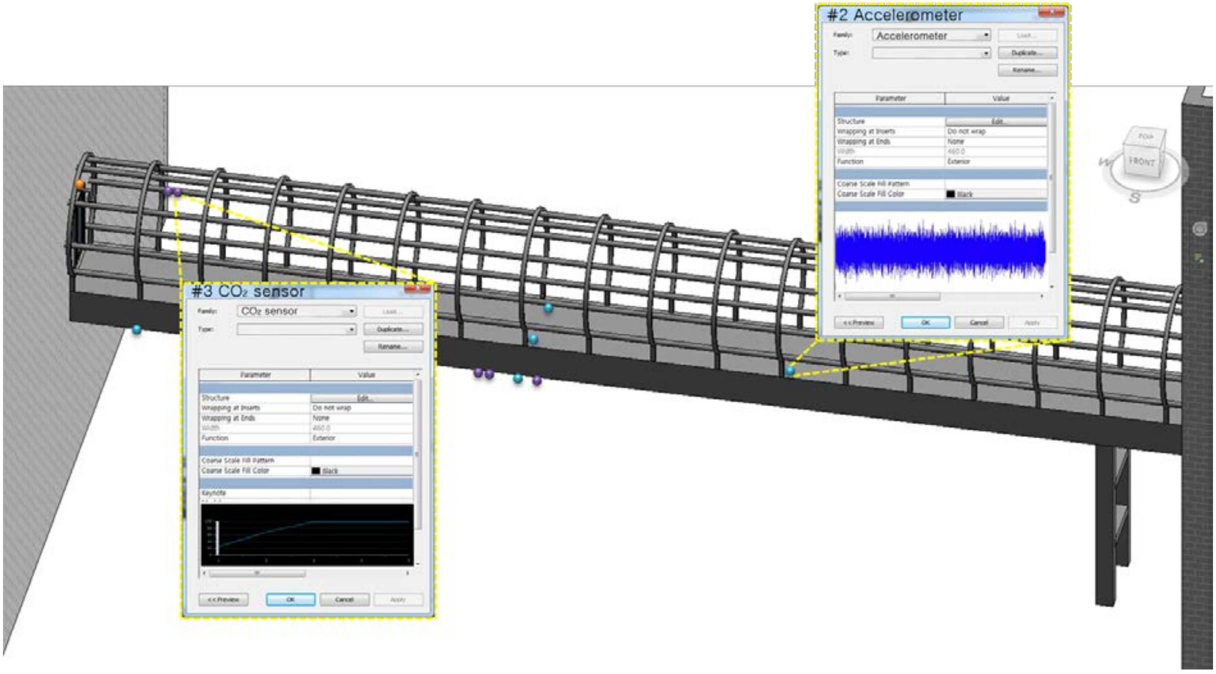

Figure 5: The Plug-in Program for BIM Software.

5. CONCLUSION

This paper introduced a smart space test-bed with a built in online monitoring system established at SKKU in Korea. To ensure structural safety, accelerometer, strain gauge, tilt meters were installed to monitor the vibration mode shapes, and bending displacement. In addition, for environmental monitoring of the structure, temperature sensors, CO_2 sensors wind sensors, CCTV and motion sensors were installed. The data obtained from the sensors was processed through signal processing and statistical techniques, and stored as a database to operate and maintain the structure efficiently. The accumulated data of the structure was interlocked with BIM and is expressed intuitively, which enhances the manager's data accessibility and management convenience.
Finally, by setting up an integrated web server, the database can be connected easily anytime and anywhere through mobile devices, such as PC, smart phones. As the result, the reliability of the structures can be improved.
Currently, several issues including energy-saving and management system are discussed for future guidance eligible to ubiquitous environments. To increase the efficiency of data access, two-dimensional bar code (ex. Quick Response Code) for easy access to the data and a display device (ex. Kiosk, DID (Digital Information Display)) which can show the status of various sensors installed on a test-bed, were considered to be installed. An automatic air conditioning system that can manage the air and air quality effectively without manipulation will be examined in future studies.

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