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Fault-detection through integrating real-time sensor data into BIM

Detección de fallas en tiempo real por medio de la integración de sensores de información en BIM

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ABSTRACT

Real-time sensor data in a building information model (BIM) can help facilities managers with daily monitoring and fault detection. A prototype BIM-based visualization tool Adafruit IO Reader (AIOR) was developed to interface real-time, inexpensive Internet of Things (IoT) sensor data feeds in Autodesk Revit. Data feeds were retrieved from the Adafruit IO server, saved as text files, and displayed both in tables and line graphs. Users are visually navigated to corresponding sensors in Revit. A fault detection algorithm based on comfort levels set by ASHRAE 55-2017 locates sensors with abnormal values and highlights them with alerting colors in 3d views. The key contributions with this prototype tool is that sensor data could be displayed in a BIM-based software program; data were compared against ASHRAE 55 comfort standards; and alerts were shown in Revit when they were missing or out-of-range.

Keywords: Building Information Modeling; BIM; IoT Sensors; Fault detection; Facilities management and operation; Revit API.

RESUMEN

Una herramienta prototipo-de-visualización-BIM Adafruit-IO-Reader-(AIOR), fue desarrollada para intervenir al instante, transfiriendo información crítica al programa de Revit diseñado por Autodesk. Una vez transferida la información es retribuida por medio de la computadora de Adafruit-IO y traducida como base de datos o gráficas lineales. AIOR es de bajo costo y pertenece a los sensores de datos del Internet of Things-(IoT). Los usuarios son guiados visualmente a los sensores correspondientes en Revit. El algoritmo de detección de fallas se basa en los niveles de comodidad establecidos por el ASHRAE-55-2017. El algoritmo localiza los sensores con valores anormales y los marca con diferentes colores en imágenes tridimensionales. El contribuidor clave para es el sensor de datos es visible dentro de un programa de BIM. La información puede ser comparada con los datos establecidos por el ASHRAE-55 y el sistema de alerta es visualizado en Revit cuando estos valores están fuera de los estándares establecidos.

Palabras clave: Modelos de Edificios e Información Virtual; BIM; Sensores IoT; Detección de Fallas; Manejo de Sistemas Operativos de Edificios; Gerentes de Instalaciones; Revit API.

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1. INTRODUCTION

A building information model (BIM) can be used as a platform to track sensor data. One method is to use the Revit API (application programming interface) to integrate BIM and sensor data for facilities management (FM).

1.1. Leveraging BIM for FM

BIM is “a digital representation of physical and functional characteristics of a facility” (1). This digital representation (3d model) is rich in data and information which can be shared for multiple purposes, such as energy simulation, clash detection, cost evaluation, and facility operations and management. There are intrinsic synergies between BIM and FM (2). One of the biggest potential contributions of BIM for FM, however, lies in its long-term competence of providing FM services in the operation and maintenance (O&M) phase. The duration of O&M phase spans 30 years or even more, and the cost of building O&M makes up 75%-85% of the total cost, which imposes considerable influence on and offering possibilities of huge cost saving to the industry (3).

1.2. Integration of BIM and sensor data

One of the main purposes of sensor analytics is to find trends and patterns. By studying these, researchers can not only figure out what happened and is happening, but also predict the change of data in the future. Another purpose is to discover anomalies. By examining deviations from a pre-established setpoint, people have a better understanding of what is not in good condition or out of control. This is significant for proactively preventing equipment failure, warning information can be generated for troubleshooting and maintenance when a part of heating, ventilation and air conditioning (HVAC) system does not function properly (4).

With the advent of “smart building” technology, more buildings have been equipped with intelligent building automation systems (BAS). In a BAS system, several types of sensors are needed to continuously acquire a large amount of data (5). Real-time sensor data helps with evaluating building performance and data-driven decisions related to facility operation and management (6). The employment of BIM-and-sensor-data integration is not confined to buildings. It also applies to other structures that require daily monitoring and management, such as bridges and dams.

One of the strategies to integrate BIM and sensor data is to attach the real-time data to geometric and spatial information extracted from the model (6). Such a “dynamic” BIM goes beyond a static source of information that comprises only limited design and construction data. Through this dynamic BIM, facility managers are able to visualize and monitor the status of sensors and facilities (7). Problems can also be detected and located immediately. Dynamic models have the potential to minimize the cost on facility operation and lowering the possibility of abnormal conditions that jeopardize the comfort and safety of building occupants.

1.3. BIM + sensor data + fault detection

The purpose of sensor fault detection is to identify faults and pinpoint the location and type of them. The definition of “faulty” can be described as the deviation from normal sensor measurements, which indicates an abnormal working status of sensors due to hardware malfunction or failure. However, there is another interpretation of “faulty” based on the concept of thermal comfort. In the context of indoor thermal comfort, “faults” are detected on the basis of temperature and humidity, standards that are set by the ASHRAE and ISO. For example, RH data from a data feed is examined with the comfort RH range (20%-80%) defined by ASHRAE 55-2017. Any RH values lower than 20% or higher than 80% will be defined as “faulty” and not desired for good thermal comfort. Types of “faults,” when defined with a comfort zone in a psychrometric chart, are linked with how people feel about the thermal condition in the space where they are. In this context, there can be up to eight types of faults as combinations of temperature and humidity: “hot,” “dry,” “cold,” humid,” “hot and dry,” “hot and humid,” “cold and humid,” and “cold and dry.”

Building information model can be used is to visually track sensor data and provide fault detection for comfort ranges (temperature and humidity). “Values out of ranges” indicates the existence of anomalous sensor data values. The definition of “ranges” is based on ASHRAE 55-2017 comfort zone, in which temperature ranges from 68°F to 78°F, and RH ranges from 20% to 80%. ISO 7730 can also be used for defining ranges.

2. BACKGROUND RESEARCH

There have been several previous research projects and case studies of the application of BIM for FM including those for BAS (or BMS) and the integration of its real-time data into BIM models.

2.1. Understanding the framework of BIM for FM

The value of BIM application in FM lies in that BIM improves the current manual process of information handover and contributes to more accurate and accessible FM data for more efficient work order execution. However, BIM for FM faces challenges ranging from methodologies, shortage of knowledge about implementation requirements, and BIM expertise in FM industry (8). Three different universities showed how BIM could be used to simplify FM workflow (9), integrate an integrated multi-view visualizer for interfacing HVAC information to support troubleshooting (9), and use a third party software EcoDomus as the center of the BIM-FM framework, integrating information from BIM and other systems (10).

2.2. Integration of sensor data into BIM

Analyzing sensor data alone does not contribute much to understanding facility condition, since data makes far more sense when they are analyzed in a “context” (5). This context can be provided by spatial information from building information models, which enables a visualized and integrated way of data analysis. For instance, by integrating data into BIM from temperature sensors installed in HVAC systems, FM managers can look for discrepancies between temperatures in adjacent rooms to detect system faults (11).

Attempts of integration BIM with various sensing technologies and devices are made in past research projects regarding multiple areas in building automation (12). For example, temperature, humidity, and energy consumption sensors were used to implement post occupancy evaluation and real-time energy performance in a residential building (13). Data retrieved from fire sensors were utilized for establishing a fire alarm management system to determine the authenticity of fire alarms and to prevent disturbance because of false alarms (14).

The integration of sensor data with BIM is not confined to indoor environments shown by the application of RFID and GPS sensors for creating a model that estimates locations of tools, equipment, and materials in construction projects (15) or load sensors in a crane navigation system where the position of lifted objects is displayed with video cameras in the context of a building and surroundings (16).

The structure of sensor readings can vary, but key attributes such as sensor ID, reading ID, data value, and time stamps are always required. Sensor metadata can be considered as descriptions of data, or "data about data" (17). They provide necessary information for sensor discovery and data processing (5). One major purpose of the sensor metadata is to easily keep track of anomalies. For example, when faulty values are detected in data analysis, researchers want to find out which specific sensor is responsible for the abnormal data values. To locate the correct sensor, a database of sensor metadata including the sensor's serial number and other categories of supporting metadata can be developed (17). Sensor placement is critical; "incorrect sensor [light] placement can compromise system performance, cause discomfort to occupants and diminish savings" (18).

Kazado et al. makes the case that "the BIM model cannot show real-time information related to the performance of the building in the operational stage." (19). Yet, an excellent example of BIM + BAS integration is Dasher 360 developed by Autodesk (20). Dasher 360 collects data from a wide range of sensors including temperature, RH, CO2 concentration, sound level and light intensity sensors. However, the loss of a large amount of data values one month should have been announced by warnings, either somewhere on the main interface or in the sensor list, in order to figure out the cause of this data value loss. Sensors have also been put in social housing and comfort parameter readings taken within the building information model (21), and augmented reality used to visualize sensor readings by programming Dynamo in Revit and using Unreal Engine (22). Another project used light sensors to control shades and louvers in BIM through Dynamo rather than the Revit API (23). BIM + sensor data is an expanding research area; these are just a few examples.

2.3. Fault detection algorithms

Fault detection has been successful in many engineering domains including automotive and industrial manufacturing for decades, but its application in AEC industry is still under development (24). Real-time data collection for detecting abnormalities is important ensure the proper function of facilities and equipment. Fault detection is achieved through algorithms. Some of them are quite simple and straightforward, and many are advanced types such as the statistical generation model (SGM) (25), adaptive-neuro fuzzy inference system (ANFIS) (26), and machine learning algorithms, for example, a "prediction-correction" process (24).

A fault detection algorithm does not have to be complex to be useful. It just has to be accurate within the bounds of its context. For example, a null reading from a temperature sensor in a room is also a fault if a value is expected. Determining the reason for the null reading might be complex, but the algorithm (check for null readings) is not. Another example is checking for a value within a specified range. If the value is not in the range, it is a fault. For example, a temperature set point might be 72 oF (22.2 oC) and the float 3 oF (20.6 oC to 23.9 oC) to achieve comfortable working conditions. A temperature reading of 80 oF (26.7 oC) would be considered a fault in this case, but perhaps not for another set of conditions/ranges.

3. METHDOLOGY – *ADAFRUIT IO READER (AIOR)*

The Revit API allows users to add new features. One of the benefits of using Revit API is that it frees users from repetitive manual operation with automatic batch processing developed for particular functions (27). Adafruit IO is a free cloud-based service that serves primarily to display, store, and retrieve real-time data. It is compatible with both hardware and software such as Arduino and Python with projects connected to the Internet or Internet-enabled devices.

Adafruit IO Reader (*AIOR*) is a new Revit plugin that was writ-ten to integrate IoT sensor data and BIM to visualize sensor data and navigate users to corresponding sensors in Revit. There three phases to the workflow in creating the *AIOR* tool were preparation, tool development, and validation of usability (Figure 1).

3.1. Preparation

The code that supports the *AIOR* was developed in Revit Macro IDE. An application level macro is desirable to ensure that the tool can be opened in more than one Revit session and all necessary references have been loaded automatically when a new macro is created.

3.2. Tool development

Two types of connections can be found in the development process. A unidirectional connection exists between beacon sensors (hardware) and Adafruit IO Server (cloud-based platform). Sensors collect data and upload them to the server. In contrast, the interaction between the cloud-based platform and software is bidirectional. *AIOR* initiates requests for synchronization to retrieve data from the server, and concurrently, the server provides data files by downloading data to a local folder and importing to *AIOR*. Not all data from the server is necessary. For example, these IoT sensors used in the research collect real-time temperature, relative humidity (RH), and voltage data. Only temperature and RH data were used. These values are combined with pre-defined parameters including setpoints and comfort zone ranges (threshold values) to generate alerts when there are sensors that fault. There were nine main features coded, divided into three categories: file and user settings, data display and visualization, and comfort zone (Figure 2).

3.3. Detailed workflow of tool development

The tool development was broken into three sections: data retrieval and pruning, fault definition, and sensor model visualization (Figure 2). Features in *AIOR* were realized either using information from only one section (e.g. feature #1 – #4, #6 – #9), or combining information from multiple sections (e.g. feature #5).

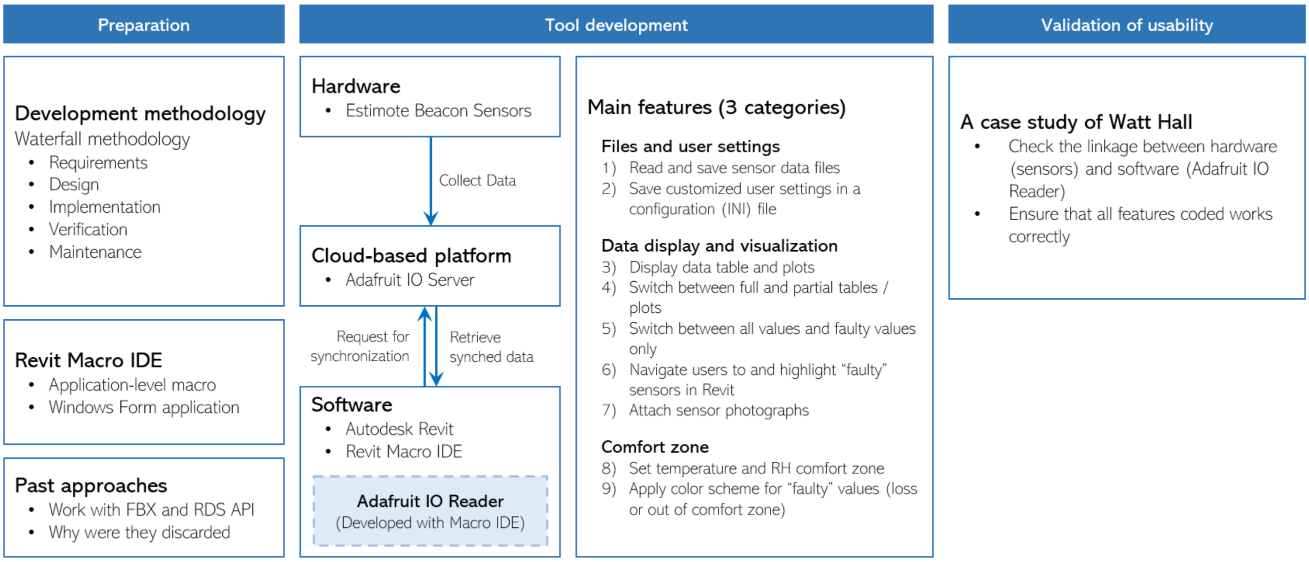

Preparation
Tool development
Validation of usability
Development methodology
Waterfall methodology
Requirements
Design
Implementation
Verification
Maintenance
Revit Macro IDE
Application-level macro
Windows Form application
Past approaches
Work with FBX and RDS API
Why were they discarded
Hardware
Estimote Beacon Sensors
Collect Data
Cloud-based platform
Adafruit IO Server
Request for synchronization
Retrieve synched data
Software
Autodesk Revit
Revit Macro IDE
Adafruit IO Reader
(Developed with Macro IDE)
Main features (3 categories)
Files and user settings
1) Read and save sensor data files
2) Save customized user settings in a configuration (INI) file
Data display and visualization
3) Display data table and plots
4) Switch between full and partial tables / plots
5) Switch between all values and faulty values only
6) Navigate users to and highlight "faulty" sensors in Revit
7) Attach sensor photographs
Comfort zone
8) Set temperature and RH comfort zone
9) Apply color scheme for "faulty" values (loss or out of comfort zone)
A case study of Watt Hall
Check the linkage between hardware (sensors) and software (Adafruit IO Reader)
Ensure that all features coded works correctly

Figure 1: Methodology and design workflow.

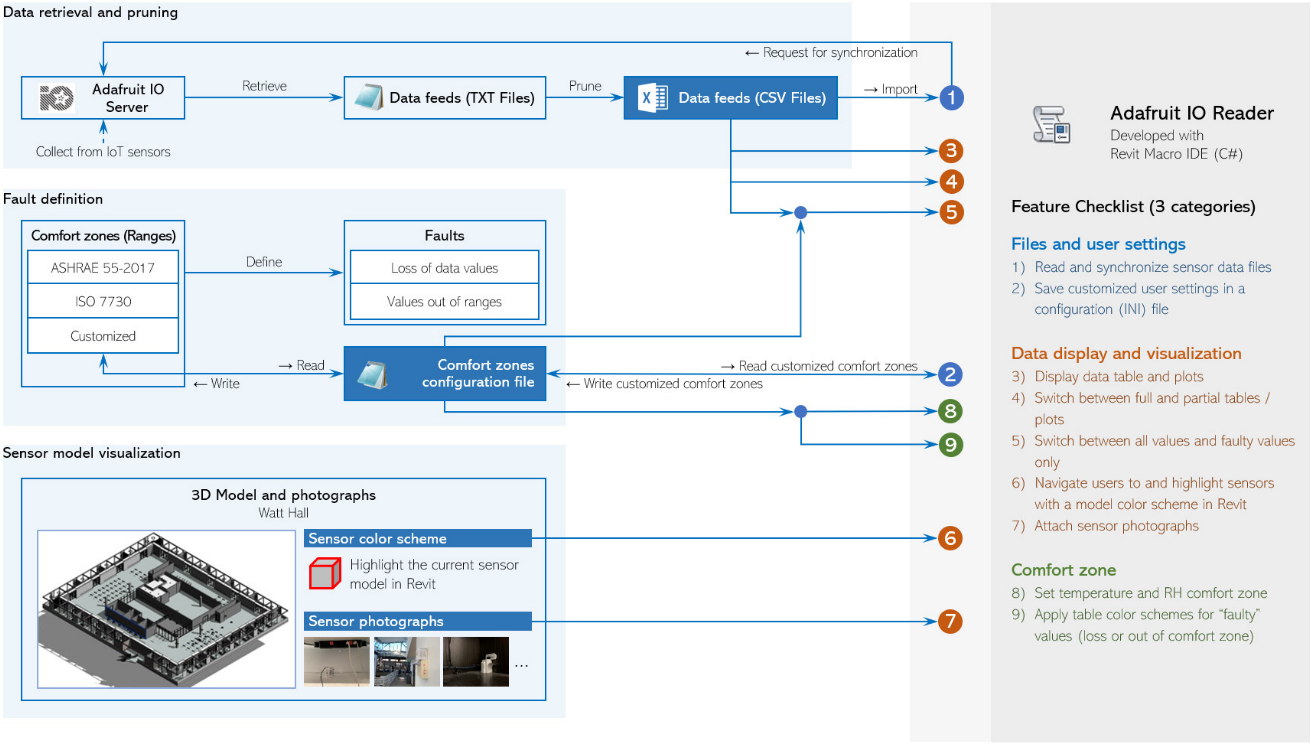

Data retrieval and pruning
← Request for synchronization
Adafruit IO Server
Retrieve
Data feeds (TXT Files)
Prune
Data feeds (CSV Files)
→ Import
Collect from IoT sensors
Fault definition
Comfort zones (Ranges)
ASHRAE 55-2017
ISO 7730
Customized
Define
Faults
Loss of data values
Values out of ranges
→ Read
← Write
Comfort zones configuration file
→ Read customized comfort zones
← Write customized comfort zones
Sensor model visualization
3D Model and photographs
Watt Hall
Sensor color scheme
Highlight the current sensor model in Revit
Sensor photographs
...
1
2
3
4
5
6
7
8
9
Adafruit IO Reader
Developed with Revit Macro IDE (C#)
Feature Checklist (3 categories)
Files and user settings
1) Read and synchronize sensor data files
2) Save customized user settings in a configuration (INI) file
Data display and visualization
3) Display data table and plots
4) Switch between full and partial tables / plots
5) Switch between all values and faulty values only
6) Navigate users to and highlight sensors with a model color scheme in Revit
7) Attach sensor photographs
Comfort zone
8) Set temperature and RH comfort zone
9) Apply table color schemes for "faulty" values (loss or out of comfort zone)

Figure 2: Detailed workflow of tool development with the feature checklist.

3.3.1 Section #1: data retrieval and pruning

The first section concentrates on building the "hardware-platform-software" connection for data retrieval and pruning. IoT sensors update data at a regular interval of 15 minutes. All data are stored on Adafruit IO Server, and users can sign in with a valid username and password on the Adafruit IO homepage to get access to data. With the username and the AIO key, a query that gets all available feeds from the user can be as simple as a URL in the web browser. For example, every feed in Adafruit IO is assigned a unique feed key that can be used to check real-time data in this feed.

After replacing the strings in the braces with a valid username, feed key and AIO key, users are be led to the data feed file. It includes not only data values, but also information about the data ID, feed ID, feed key, created time, created epoch and expiration time. There are also commands that make changes to the feeds, such as inserting, replacing, and deleting, etc., as long as the username, feed key and AIO key are provided. This simplicity of authentication allows more users to get access to and manipulate data without signing up for an Adafruit IO account and improves the efficiency of sharing data within a research group.

The original data files are downloaded from Adafruit IO Server and saved as CSV files. These files are pruned before they are imported into the *AIOR*. The process is divided into three steps: prune (to reduce redundancy), reorganize (to pair the data properly), and translate date and time (for the correct time zone). All the steps above were accomplished by a C# function in *AIOR*. CSV files after pruning are ready to be imported into the tool and displayed in both tables and line plots. In addition, these files will be connected to sensor models in Revit to achieve the goal of visualization through combining real-time sensor data and 3D models.

3.3.2 Section #2: fault detection

Two types of faults are considered: loss of data values and values out of ranges. “Loss of data values” means there is no valid temperature or RH data at a specific point of time. This results in a “nan” in a data table and it is often related to hardware glitches or battery power issues. “Values out of ranges” indicates the existence of abnormal sensor data values. The definition of “ranges” is based on ASHRAE 55-2017 comfort zone, in which temperature ranges from 68ºF to 78ºF, and RH ranges from 20% to 80%. Besides ASHRAE 55-2017, ISO 7730 can also be used for defining ranges. All data values that do not fall in these ranges are treated as “faulty” and result in colored cells (orange – higher than the maximum; light blue – lower than the minimum in data tables on the main interface).

In addition to ASHRAE and ISO comfort zones, users are free to customize these own comfort zones. However, manually set numeric values will be reset to default values after the program is restarted. Therefore, an extra configuration file that stores these values. Customized values are written to this file from comfort zone dialog box in the tool, and they can be read back from the file.

3.3.3 Section #3: sensor model visualization

The third section focuses on various visualization strategies, including 3D models with color schemes and on-site photographs. This visualized information is combined with data files to finally accomplish the main goal to integrate real-time sensor data into BIM.

4. WATT HALL CASE STUDY

4.1. Overview

Watt Hall on the USC campus was selected as the case study building. Five IoT sensors were installed in different locations for data collection. These sensors were originally installed for a project named TrojanSense (28). Temperature and RH data in Watt Hall third floor southeast corner (building science corner), upper Rosendin Gallery (two sensors), Watt 212, and Watt B1 was gathered and at the same time uploaded to Adafruit IO server. The intent was to demonstrate that the data from the five sensors could be retrieved by the *Adafruit IO Reader*, values shown in Revit as both tabular and line plots, and faults detected and highlighted in color with the corresponding sensor and its location.

4.2. Hardware

The hardware used in the case study were developed by the TrojanSense team. They consist of ASAIR AM2302 IoT sensors powered by AA batteries and connected to Arduino ESP32 board with a Wi-Fi and Bluetooth microcontroller. These sensors collect temperature, relative humidity, and voltage data. Sensors were attached to the outside of the 3D-printed shells. Batteries supplied power to ESP32 boards and microcontrollers. These parts were put into the shells and installed under a studio desk, on a fire alerting device in upper Rosendin, on the staircase connecting lower and upper Rosendin, under the desk in Watt Hall 212, and on the wall in Watt Hall B1.

4.3. Software

The Revit model was provided by USC FMS. The opacity of some building elements and the viewing angles are adjusted to ensure that sensor models are visible. The model of IoT sensors were created as a Revit family to be added to the model based on “Sensor Photos” and measurement of sensor dimensions.

To work with *Adafruit IO Reader*, the first step is to get program files and copy them to the specified folder. The program is started with Macro Manager in Revit, in the “Manage” ribbon. First, select “Application” tab control and any macro from A to E. Then, click on “Run” button to run the selected macro. Running the macro brings up the highlighted sensor model in a 3D view and the main interface of *Adafruit IO Reader* with real-time sensor data retrieved from the server.

In the main interface of the *Adafruit IO Reader*, most of the space on the main interface window is used for data table view panels and line plot view panels for visualizing sensor data. The interface is comprised of 12 modules:

1. Menu bar items: Commands related to synchronizing sensor data with Adafruit IO server, clearing data display on the interface, editing thermal comfort zone, and file path for storing sensor data files.
2. Sensor list: Dropdown list containing five IoT sensors installed in Watt Hall. By selecting any sensor from the list, the program automatically loads temperature and RH data files and displays them in view panels. The program also takes users to the selected sensor model and zoom in to the view of that sensor.
3. Revit element ID: Every sensor model in Revit is assigned a six-digit Revit element ID. This is used in source code to create the many-to-one relationship between data feeds and the sensor model.
4. Update data: A shortcut button for synchronizing sensor data with data feed stored on Adafruit IO server.
5. Reset filter: A temporary button for developer’s testing and debugging only.
6. Temperature tab control: Switch between temperature data table and line plot.
7. Temperature view panel: Display temperature data table (by default) and line plot.
8. RH tab control: Switch between RH data table and line plot.
9. RH view panel: Display RH data table (by default) and line plot.
10. Room photo: Display the photo of the room where the sensor is installed.
11. Sensor photo: Display the close-up view of the sensor.
12. Display settings: settings related to manipulating data tables such as filter values according to start and/or date, or the status of values (faulty or normal).

4.3.1 Data retrieval, pruning, and synchronization

Sensor data is not automatically synchronized with the latest version on the server. It must be done manually either from menu bar or the shortcut button on the interface. The average time spent on data syncing in the tool is approximately 8 seconds, so it is not ideal to make tool users wait by synchronizing data every time the program is launched.

4.3.2 Save customized settings

The bidirectional interaction between the configuration file and *Adafruit IO Reader* can be used for customized comfort zones. The program reads the customized setting from the file and displays the setting in the Comfort Zone window, where users are free to adjust the threshold values for new settings.

4.3.3 Data tables and plots

Data tables and line plots take most of the space on the interface, and they serve as the basis of other program features. Data tables in AIOR share the same layout as those CSV files that can be opened with Excel. The most recent 1,000 data values are available in both data tables. This is the amount of data for approximately 15 days. Past values older than 15 days will be erased and replaced by new values to dispose space for storage. Line plots, as a more visualized presentation, are generated based on data values in the second column. Users can switch between tables and graphs with tab controls at the upper left corner of view panels. Both data tables and line plots can be manipulated by different display settings to allow users to focus on a specified portion of data.

4.3.4 Full and partial tables / plots

Manipulation of data tables is completed by "Display Settings" on lower right corner of the main interface. One of the settings is named "Date Filter." Sometimes, there may be a time range of interest where data values need special attention. AIOR provides a date filter that allows users to focus on only an excerpt from the full table. Either start date or end date, or both dates can be used for setting a range. The filter works on not only to data tables, but also line plots. With such a filter, the line plot view looks like "zoomed in," enabling the observation of data fluctuation in a more legible manner with a smaller scale.

4.3.5 All values and faulty values

Another "Display Setting" is named "Faulty Values Only." To enable this, users just need to check the "Faulty Values Only" box in "Display Settings." This feature was designed for users to quickly locate faulty values defined by the current comfort zone at work. All values within the comfort zone are filtered out by this setting. A blank data table indicates that all values recorded are considered normal. When "Faulty Values Only" box is checked, line plots will be temporarily unavailable since the appearance of faulty values is, in most cases, sporadic rather than continuous. Such data values with little or completely no chronological continuity are not sufficient for generating line plots.

4.3.6 Navigation to sensor models

When "Run" button is clicked, Revit will begin to execute codes in the selected macro and switch current view to the sensor model associated with this macro. Meanwhile, the main interface will show up, providing a wide range of information including sensor data value tables, line plots, currently working comfort zone, etc. Users can also take advantage of features introduced in previous sections, such as "Display Settings," to manipulate the display of data.

4.3.7 On-site photographs

For every sensor in the list, "Room Photo" and "Sensor Photo" are displayed next to data tables. These photographs were stored in a separate folder, and they can be updated by replacing files at any time. Photographs are tied up with data tables; every time a sensor is chosen from the combo box and corresponding data tables loaded, these photographs are displayed next to the tables.

4.3.8 Comfort zone presets

The comfort zone options define an acceptable range for data values that can be considered as "normal." Two major standards of thermal comfort zone, ASHRAE 55-2017 and ISO 7730 (including summer and winter), are provided in the tool for needs in different indoor environment. Threshhold values for ASHRAE and ISO comfort zones are read from psychometric charts and saved as presets.

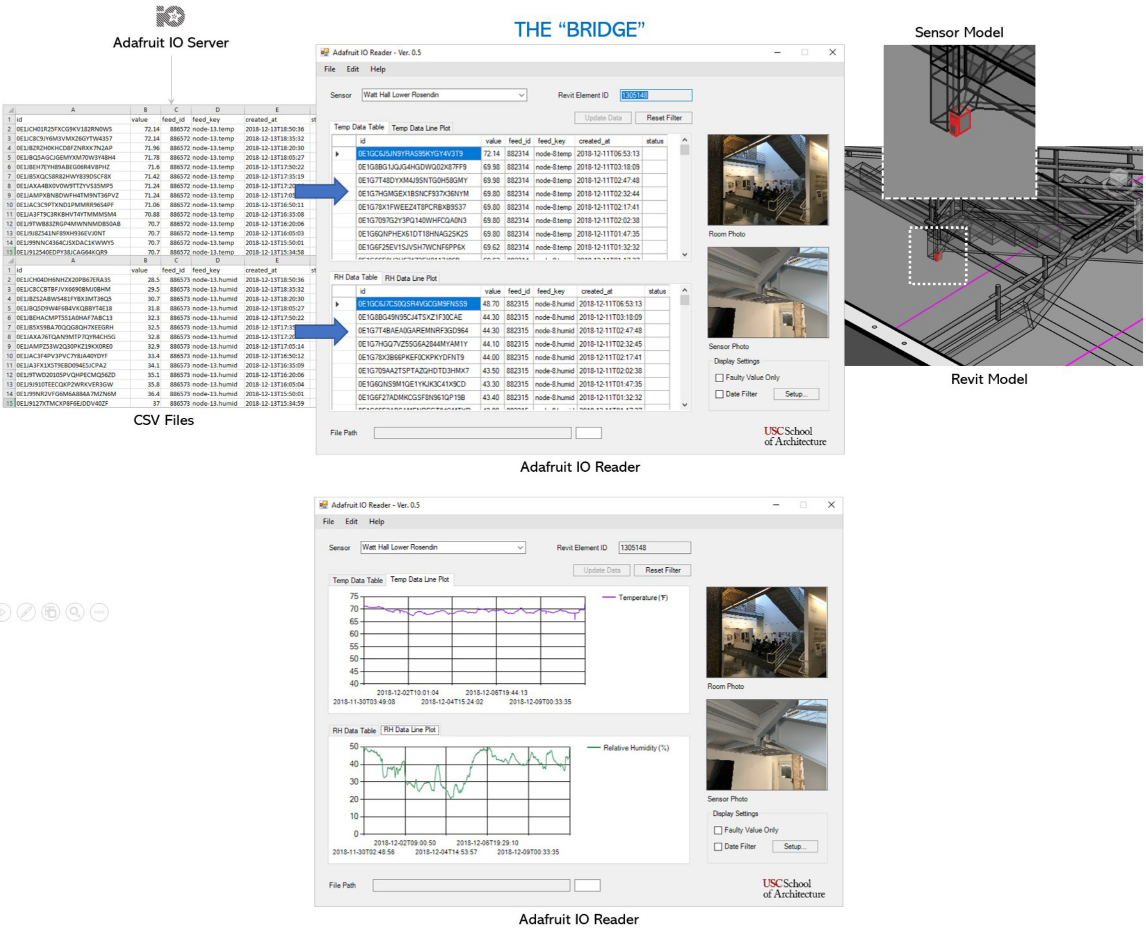
4.3.9 Color schemes

Color schemes are associated with the definition of comfort zones. With a comfort zone set, data values can be categorized as "too high," "normal," or "too low." Values higher than the maximum threshold value are marked with orange; lower than the minimum are colored with light blue. Users can easily distinguish "faulty" values and when these values occurred, which can help with figuring out the reason for faults.

5. DISCUSSION AND FUTURE WORK

Adafruit IO Reader is a new plugin that provides users access to temperature and humidity data and visualization of fault detection in Revit by interfacing with real-time IoT sensor data feeds stored on an Adafruit IO server. By putting together information from different sources, the tool works as a "bridge" between sensors and data feeds on the cloud, navigating users to sensor models in Revit while loading data feeds to the main interface from the server (Figure 3).

AIOR is composed of nine main features separated into three categories as previously mentioned. These features are examined with the case study of Watt Hall, and most of the features performed satisfactorily by always producing desired outputs, except for some minor issues with the navigation to sensor models. Of particular note is the integration of the data within a building information model. FM personnel can use Revit to check the sensor list, discover the location of the sensors in the digital model and by the room photographs linked to each sensor, and show the data as tables or line plots. Settings can be created to define a "fault." In the case study, ASHRAE 55 and ISO 7730 were used to set high and



	A	B	C	D	E
1	id	value	feed_id	feed_key	created_at
2	0E1JCH01R25FXCG9KV182RN0WS	72.14	886572	node-13.temp	2018-12-13T18:50:36
3	0E1JC8C9JY6M3VMXZ6GYTW4357	72.14	886572	node-13.temp	2018-12-13T18:35:32
4	0E1JBZRZH0KHCD8FZNRXK7N2AP	71.96	886572	node-13.temp	2018-12-13T18:20:30
5	0E1JBQ5AGCJGEMYXM70W3Y48H4	71.78	886572	node-13.temp	2018-12-13T18:05:27
6	0E1JBEH7EYH89ABEG06R4V8PHZ	71.6	886572	node-13.temp	2018-12-13T17:50:22
7	0E1JB5XQCS8R82HWY839DSCF8X	71.42	886572	node-13.temp	2018-12-13T17:35:19
8	0E1JAXA4BX0V0W9TTZYVS35MP5	71.24	886572	node-13.temp	2018-12-13T17:20
9	0E1JAMPXBNBDWFH4TM9NT36PVZ	71.24	886572	node-13.temp	2018-12-13T17:05
10	0E1JAC3C9PTXND1PMMRR96S4PF	71.06	886572	node-13.temp	2018-12-13T16:50:11
11	0E1JA3FT9C3RKBHVT4YTMMMSM4	70.88	886572	node-13.temp	2018-12-13T16:35:08
12	0E1J9TWB83ZRGP4MWNNMDBS0AB	70.7	886572	node-13.temp	2018-12-13T16:20:06
13	0E1J9J8Z541NF89XH936EVJ0NT	70.7	886572	node-13.temp	2018-12-13T16:05:03
14	0E1J99NNC4364CJSXDAC1KWWY5	70.7	886572	node-13.temp	2018-12-13T15:50:01
15	0E1J912540EDPY38JCAG64KQR9	70.7	886572	node-13.temp	2018-12-13T15:34:58

	A	B	C	D	E
1	id	value	feed_id	feed_key	created_at
2	0E1JCH04DH6NHZX20PB67ERA3S	28.5	886573	node-13.humid	2018-12-13T18:50:36
3	0E1JC8CCBTBFJVX6690BMJ0BHM	29.5	886573	node-13.humid	2018-12-13T18:35:32
4	0E1JBZS2ABWS481FYBX3MT36Q5	30.7	886573	node-13.humid	2018-12-13T18:20:30
5	0E1JBQ5D9W4F6B4VKQBBYT4E18	31.8	886573	node-13.humid	2018-12-13T18:05:27
6	0E1JBEHACMPT551A0HAF7ABC13	32.3	886573	node-13.humid	2018-12-13T17:50:22
7	0E1JB5XS9BA70QQG8QH7XEEGRH	32.5	886573	node-13.humid	2018-12-13T17:35
8	0E1JAXA76TQAN9MTP7QYR4CH5G	32.8	886573	node-13.humid	2018-12-13T17:20
9	0E1JAMPZ53W2Q30PKZ19KX0RE0	32.9	886573	node-13.humid	2018-12-13T17:05:14
10	0E1JAC3F4PV3PVC7Y8JA40YDYF	33.4	886573	node-13.humid	2018-12-13T16:50:12
11	0E1JA3FX1X5T9EBD094E5JCPA2	34.1	886573	node-13.humid	2018-12-13T16:35:09
12	0E1J9TWD20105PVQHPECMQ56ZD	35.1	886573	node-13.humid	2018-12-13T16:20:06
13	0E1J9J910TEECQKP2WRKVER3GW	35.8	886573	node-13.humid	2018-12-13T16:05:04
14	0E1J99NR2VFG6M6A884A7MZN6M	36.4	886573	node-13.humid	2018-12-13T15:50:01
15	0E1J9127XTMCXP8F6EJDDV40ZF	37	886573	node-13.humid	2018-12-13T15:34:59

Sensor: Watt Hall Lower Rosendin
Revit Element ID: 1305148

id	value	feed_id	feed_key	created_at	status
0E1GC6J5JN9YRAS95KYGY4V3T9	72.14	882314	node-8.temp	2018-12-11T06:53:13	
0E1G8BG1JQJG4HGDWQ02X87FF9	69.98	882314	node-8.temp	2018-12-11T03:18:09	
0E1G7T48DYXM4J9SNTG0H58GMY	69.98	882314	node-8.temp	2018-12-11T02:47:48	
0E1G7HGMGEX1BSNCF937X36NYM	69.80	882314	node-8.temp	2018-12-11T02:32:44	
0E1G78X1FWEEZ4T8PCRBXB9S37	69.80	882314	node-8.temp	2018-12-11T02:17:41	
0E1G7097G2Y3PQ140WHFCQA0N3	69.80	882314	node-8.temp	2018-12-11T02:02:38	
0E1G6QNPHEX61DT18HNAG2SK2S	69.80	882314	node-8.temp	2018-12-11T01:47:35	
0E1G6F25EV1SJVSH7WCNF6PP6X	69.62	882314	node-8.temp	2018-12-11T01:32:32	

id	value	feed_id	feed_key	created_at	status
0E1GC6J7CS0QSR4VGCGM9FNSS9	48.70	882315	node-8.humid	2018-12-11T06:53:13	
0E1G8BG49N95CJ4TSXZ1F30CAE	44.30	882315	node-8.humid	2018-12-11T03:18:09	
0E1G7T4BAEA0GAREMNRF3GD964	44.30	882315	node-8.humid	2018-12-11T02:47:48	
0E1G7HGQ7VZ5SG6A2844MYAM1Y	44.10	882315	node-8.humid	2018-12-11T02:32:45	
0E1G78X3B66PKEF0CKPKYDFNT9	44.00	882315	node-8.humid	2018-12-11T02:17:41	
0E1G709AA2TSPTAZQHDTD3HMX7	43.50	882315	node-8.humid	2018-12-11T02:02:38	
0E1G6QNS9M1QE1YKJK3C41X9CD	43.30	882315	node-8.humid	2018-12-11T01:47:35	
0E1G6F27ADMKCGSF8N961QP19B	43.40	882315	node-8.humid	2018-12-11T01:32:32	

☐ Faulty Value Only
☐ Date Filter

Figure 3: The "bridge" – Adafruit IO Reader put together information from multiple places.

low values for temperature and relative humidity. If the room values were outside of these settings, the sensors would be highlighted allowing facilities managers immediate feedback to uncomfortable conditions. A fault is also detected if there is not a value ("nan") being sent by the sensor.

Future work includes addressing existing limitations and expanding the functionalities of *Adafruit IO Reader*. The main areas of work include improving the speed of the workflow, updating the code, allowing the use of data feeds from other sources, and imbedding the tool in existing facility management platforms.

The combination of visualized sensor data and sensor models were evaluated by a case study of Watt Hall, and the result showed that *Adafruit IO Reader* is able to achieve the integration by navigating users to sensor models, while providing corresponding sensor data information that is open to customized manipulation through various display settings. The findings of the research are of value for FM managers buy providing visualized results for decision-making processes related to HVAC systems and thermal comfort. *Adafruit IO Reader* could be a prototype for developing more sophisticated products that help the data management in FM or be integrated into currently used FM platforms to better streamline workflows with more exhaustive information during regular management work and troubleshooting work. The specific contribution of this research is that the display of sensor data, definition of "fault" (for comfort – defined by ASHRAE 55 and ISO 7730), and links to the sensors' locations occur directly within the BIM software.

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