The 8th International Conference on
Structural Health Monitoring of Intelligent Infrastructure
Brisbane, Australia | 5-8 December 2017

Application and Visualization Techniques for Advanced Sensor Networks

Case Study: Sensor Installation in Skilled Trades and Technology Centre

G. Mustapha[1], R. Hoemsen[2], R. Spewak[3], K. Knight[4]

[1] SMT Research Ltd. – Canada, Email: gamal@smtresearch.ca, [2] Red River College – Canada Email: rhoemsen@rrc.ca, [3] Red River College – Canada Email: rspwak@rrc.ca, [4] Red River College – Canada Email: kdknight@rrc.ca

Abstract

Structural Health Monitoring of bridges and heritage buildings are essential to ensure modern rehabilitation techniques and materials continue to perform as expected. In addition, SHM systems play a key role to ensure new buildings perform as expected with respect to energy efficiency and durability. This paper focuses on the application of advanced sensor networks and data visualization techniques on a building instrumented as a 'living lab' located in Winnipeg, Canada. The Building Envelope and Technology Access Centre (BETAC) and SMT Research have installed a substantial network of sensors embedded throughout the new Skilled Trades and Technology Centre located on the Red River College campus in Winnipeg, Canada. A total of seven different building envelope types have been instrumented throughout the exterior building envelope as well as the roof and green roof assemblies. The sensor set installed throughout the building consists of heat flux sensors embedded inside specific assemblies along side temperature sensors positioned across the insulation material. In-situ effective R-value can be measured from the installed sensors and compared to controlled tests performed on mock-up test walls in the Dual Environment Test Chamber located in the Centre for Applied Research in Sustainable Infrastructure (CARSI). Field analysis will be performed in real-time during normal building occupancy throughout the temperature extremes inherent to Winnipeg. This paper will demonstrate the methodology and sensor set required to obtain the required quantitative data as well as introduce visualization techniques using augmented reality and virtual tour methods. Augmented reality allows a user to view the building through a Smartphone with live data displayed on the screen and virtual tour methods allowing the user to walk through the BIM model and select sensors to graph and compare.

1. Introduction

This paper covers the methodology and sensor sets used to perform real-time performance analysis of buildings. This includes a unique sensor set for energy performance monitoring as well as a novel approach for data collection and data visualization. The results and analysis will be compiled over a one-year period in order for the building to experience all seasons, the results will be presented at SHMII-9 in 2018. Funded by Manitoba Infrastructure, Red River College is constructing a $60 million, 9300m^2 (100,00ft^2) Skilled Trade and Technology Centre (STTC) that will house laboratory and shop space for up to 1,000 students. The building itself will be used as a 'living lab' as the individual instrumented building components can be tested as per the current method for evaluating energy efficiency as outlined in the BC Building Code, 2012. The building components can be tested in a controlled environment using the facilities of CARSI and then validated in the final constructed STTC building.

The thermal characteristics of materials shall be determined by calculation or by testing in accordance with the applicable product standards listed in the BC Building Code. (BC Building Code, 2012). The code stipulates that energy efficiency rating for buildings are calculated or simulated. These calculations require inputs such as the building geometry, size, as well as knowledge of specific building components with known R-values. Calculated R-values do not take into account variations in construction, assemblies consisting of various components such as window frames, studs, fasteners, inconsistent insulation, variable air gaps, thermal bridging and deterioration of assembly components over time (Modera, M. P., Sherman, M. H., and Sonderegger, R. C.,1985). The major contribution of this project is to design a system capable of measuring heat flux over a large surface in order to encompass an assembly consisting of different materials. The heat flux in conjunction with the change in temperature across the assembly will give you the in-situ effective R-Value.
The installed sensor suite provides a complete analysis of the roof systems moisture performance as well as the thermal performance of the green roof area. A second set of sensors are installed in specific building components and throughout the different wall systems that comprise the building envelope in order to monitor the moisture and thermal performance of the building envelope.
The impact of this study is to establish a quantitative metric to benchmark the energy efficiency of pre-existing assemblies and materials. This will allow unique materials, assemblies and construction techniques to produce a quantitative measurement that can be recorded and monitored. Energy savings will be achieved by maintaining optimal thermal efficiency over time as the monitored wall structures will essentially be subject to continuous real-time commissioning.
The presentation of the data and visualization will use technology emerging from the Internet of Things (IoT) space as well as the latest software tools used for Augmented and Virtual Reality. These tools will allow anyone to easily inspect wall structures simply by using a Smartphone camera while in the building or remotely by walking through he building in a virtual environment. Currently, the state of the art for sensor visualization is limited to isolated sensor views and static plots distributed over separate views, which are considered inefficient and difficult to use (Clifton Forlines and Kent Wittenburg. Wakame, 2010).

2. Sensor Installation Plan

Moisture Detection Sensor (MDS) were installed in the roof system as well as the building envelope. Heat flux and temperature sensors were installed in strategic locations to measure effective R-value. During construction, other unique assemblies and methods were identified and instrumented as reviewed in this section. Sensors will be compared to external and internal environmental effects, carbon dioxide (CO_2), and occupancy sensors along with an external weather station that will be used to correlate cause and effect events in relation to fluctuations with internal sensor telemetry.

2.1 Roof Moisture Detection Grid

Moisture Detection Sensors were installed in 6m (20ft) segments over the entire roof to form a 3m x 3m (10ft x 10ft) grid. The green roof had double the density to form a 1.5m x 1.5m (5ft x 5ft) grid (Hermes, Jamieson, 2015). This sensor grid was installed during roofing so the roof was continuously checked for moisture during and after construction. The roof was segmented in various work packages, each color segment as shown in Figure 1 were installed in one day. Tape coordinates were transferred to a Trimble GPS marking unit that allowed the installers to install the tapes exactly as indicated on the drawing.

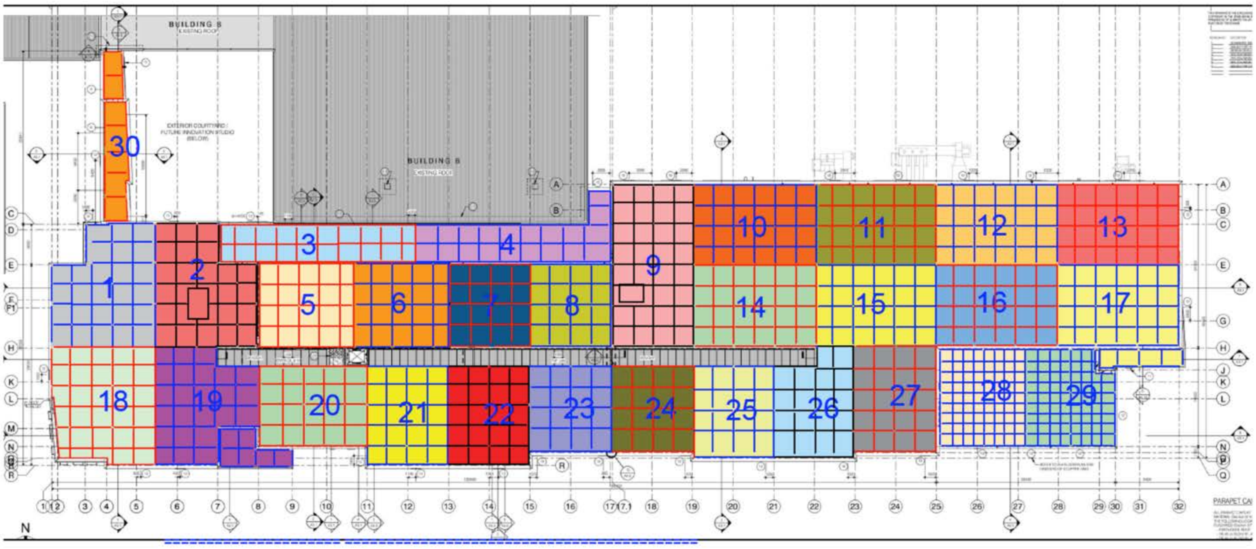


Figure 1. RRC STTC Roof Grid

Figure 2. Sensor Grid Installation

The installation started in the fall of 2016 and continued into the winter. Keeping the roof dry and free of rain and snow were challenging. Figure 2 shows the sensor grid installed with the insulation being installed immediately after.

2.2 Green Roof Performance Monitoring

Moisture Detection Sensors are installed in a grid with double the density as the regular roof. In addition to moisture detection under the membrane the thermal performance of the roof is analyzed using heat flux sensors on the underside of the roof and temperature sensors on the underside and topside of the roof.

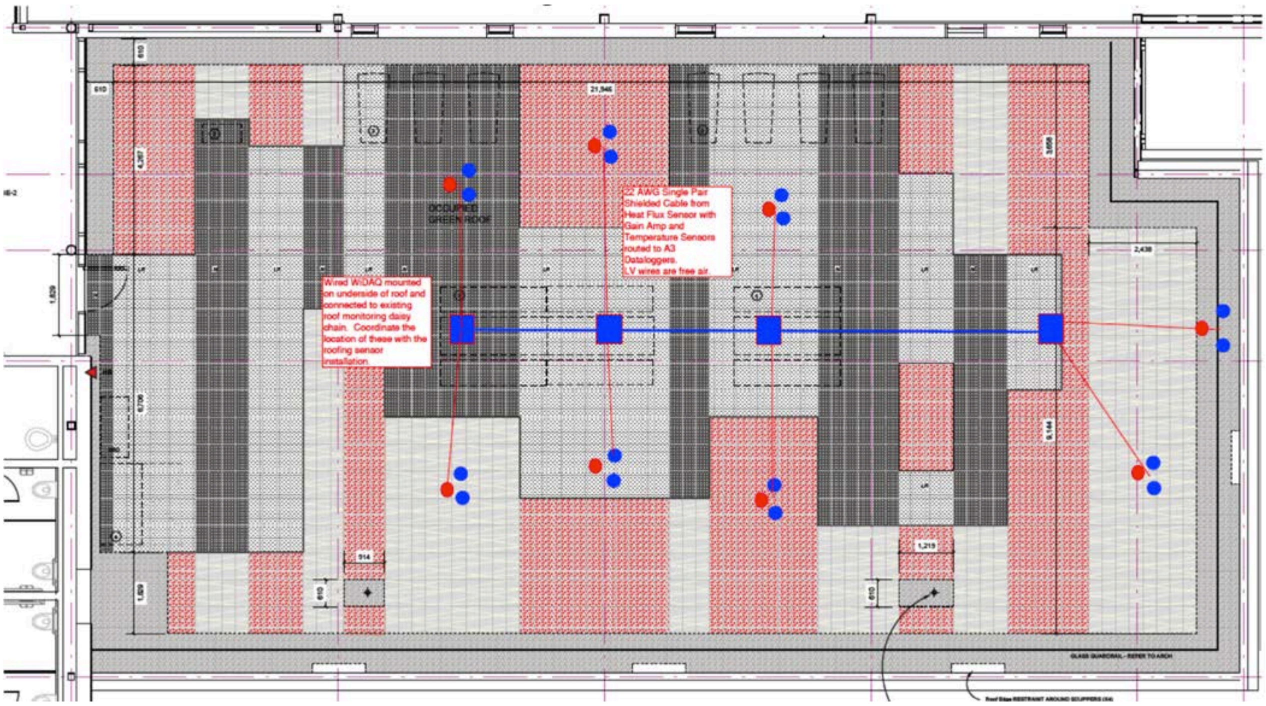


Figure 3. Green Roof Thermal Performance Sensors

The top side of the roof consists of planters in removable trays. Soil moisture in these trays are monitored using wireless data loggers.

2.3 Building Envelope Sensor Installation

The STTC building contains seven different wall types, including variations of masonry, metal siding and curtain walls. The type of sensor and placement is dependent on the wall type and mounting assembly. Moisture Detection Sensor (MDS) tape was placed in areas susceptible to moisture intrusion, Point Moisture Monitoring (PMM) sensors were placed in the plywood mounts for curtain walls and a combination of heat flux and temperature sensors were placed around specific compound assemblies and insulation types to measure thermal efficiency. A typical sensor installation with temperature, heat flux and differential pressure is shown in **Error! Reference source not found.** and Figure 5. Differential pressure sensors were installed to observe the airflow magnitude and direction through the building envelope assemblies.

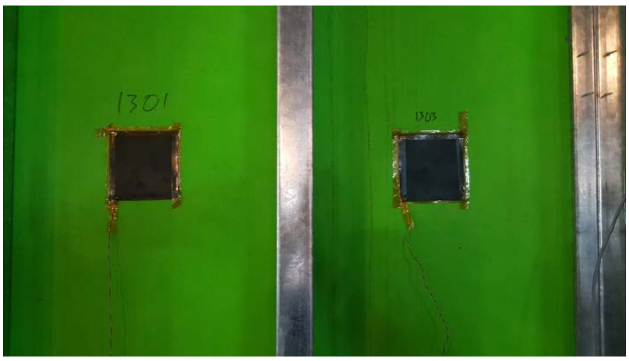


Figure 4. Interior Heat Flux Sensor Installation

Figure 5. External Heat Flux, Temperature and Pressure Installation

In-situ R-value is typically measured using a hot-box apparatus in a controlled lab environment and is performed on a single uniform material (Modera, M. P., Sherman, M. H., and Sonderegger, R. C.,1985). This is mainly due to the fact that heat flux sensors are dimensionally small and are unable to encompass a large assembly. Also, the cost of heat flux sensors with high sensitivity is cost prohibitive and the data acquisition is difficult due to the small signal to noise ratio. R-value measurements require heat flux sensors to be mounted on the surface under test with temperature sensors placed across the assembly. Heat flux is calculated as shown in equation (1) (Modera, M. P., Sherman, M. H., and Sonderegger, R. C.,1985).

$$U = \frac{1}{R} = \frac{Q_A}{\Delta T} \quad (1)$$

where: Q_A = Heat flux in W/m^2
T = Temperature difference across assembly under test
R = R-value
U = U-value

RSI (SI) = R-value (U.S.) × 0.1761101838

The ability to perform a heat flux measurement over a large surface area was addressed by designing a large lower cost heat flux sensor used in conjunction with a high gain instrumentation amplifier. Controlled tests were performed on mock-up test walls in the Dual Environment Test Chamber located in the CARSI facility. Field analysis will be performed in real-time during normal building occupancy of the building throughout the temperature extremes inherent to Winnipeg and compared to the results generated in the lab.

2.4 Solar Tube Instrumentation

Solar tubes were installed to route natural light into the building. Potential issues were identified by the owners and building science experts who advised to monitor the perimeter of the solar tube enclosures for accumulated moisture under the roof membrane while monitoring the interior relative humidity and temperature so that the dew point can be calculated.

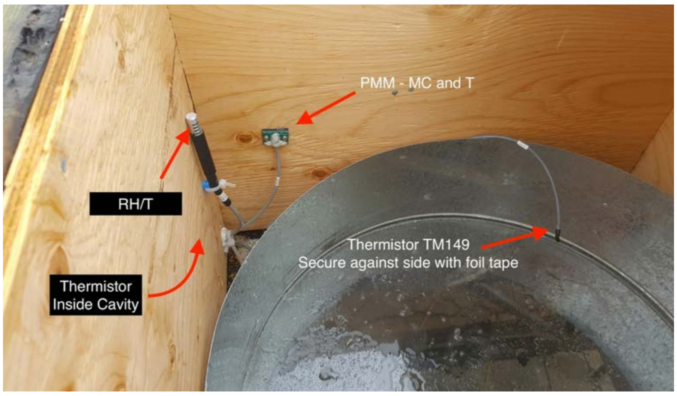


Figure 6. Solar Tube Instrumentation


Figure 7. Trapped Condensation in the Solar Tube

2.5 Parapet Instrumentation

Parapet details are another potential area that owners and building scientists are concerned about. Both curtain wall detail as well as the steel stud detail were recommended for monitoring. Sensors were installed in the curtain wall and steel stud assemblies on all four wall facings in the building. The sensor deployment is shown in Figure 8.

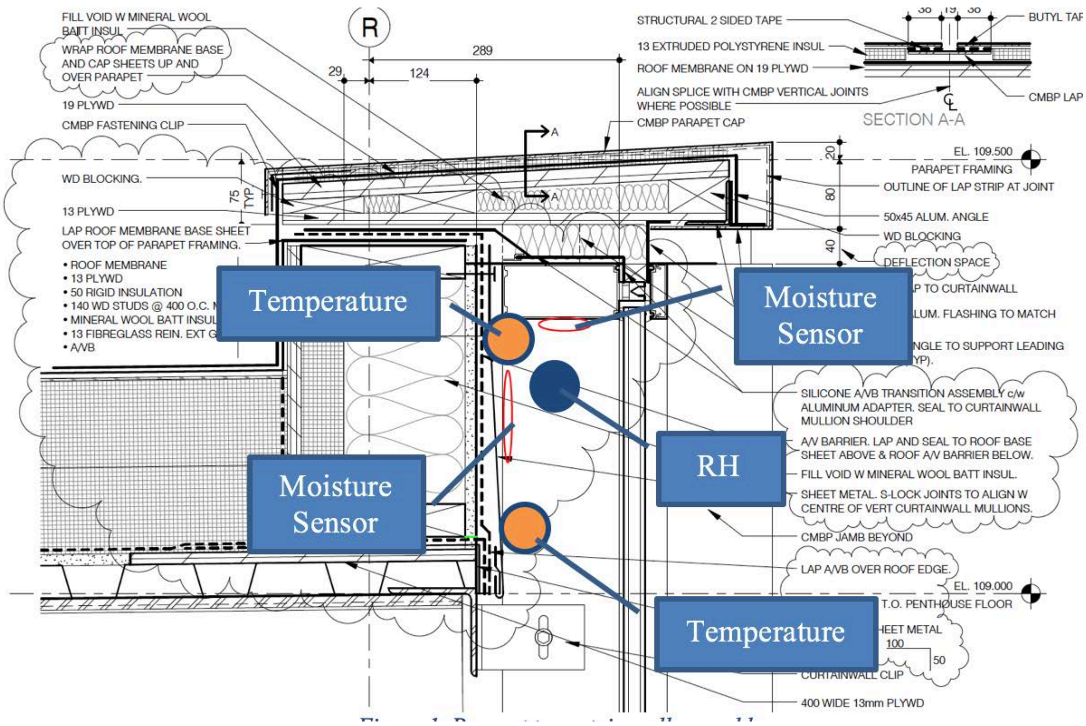
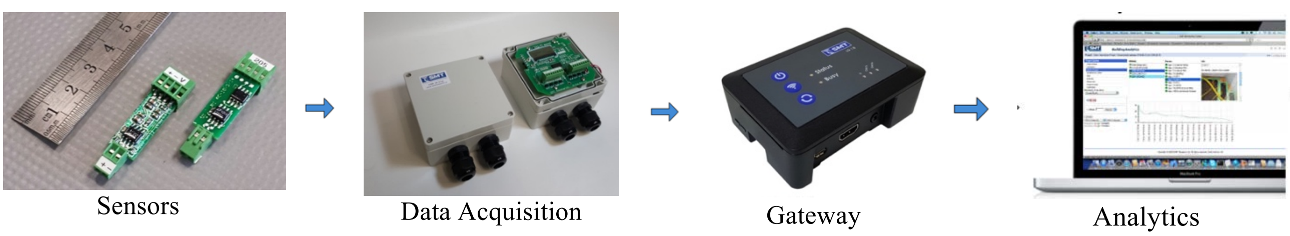


Figure 8. Parapet Sensor Installation

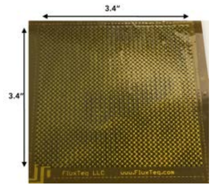
3. Data Acquisition Hardware

The selection of data acquisition hardware and data analysis interfaces are an important aspect of the monitoring system solution. Moisture detection tapes on the roof were routed to 48 channel board multiplexers which were daisy chained to each other using a wired Controller Area Network (CAN) bus (Mustapha, Gamal 2012). Building envelope data acquisition units were connected to the network by joining the daisy chain through 8 channel data acquisition units. The data acquisition units transmit data to a local gateway that synchronizes data with a cloud based server. Sensors in non stationary areas or areas that are difficult to access transmit data wirelessly to a gateway over a unique channel over 802.15.4 in order to not interfere with other internal wireless systems. (Mustapha, Gamal, 2010)



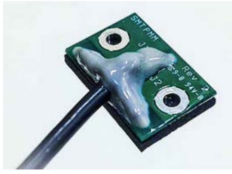
3.1 Sensors

Heat Flux (HF)
A large heat flux array was designed specifically to cover large complex areas so the heat flow of the insulation material and surrounding sensors can be recorded. Heat Flux sensors are connected to instrumentation gain amplifiers prior to being connected to the Data Acquisition unit (Cirenza, Chris, 2017).



Moisture Detection Sensor (MDS)
Moisture Detection Sensor tapes are adhered under windows and areas susceptible to moisture intrusion. These are the same sensors used in a grid formation on the roof. (Mustapha, Gamal, 2007)

Point Moisture Measurement (PMM) Sensors
PMMs are embedded in the wood frames around the curtain wall assemblies and give a percent wood moisture content reading of the wood. (Mustapha, Gamal, 2007)



Relative Humidity (RH)
RH sensors are used within building envelope cavities, areas such as the solar tubes, and in different air spaces to understand the movement and accumulation of humid air throughout the building (Mustapha, Gamal, 2008).

Temperature
Thermistor sensors are used for temperature compensation with Moisture and RH sensors as well as for temperature gradients for heat flux sensors (Mustapha, Gamal, 2008).

Differential Pressure Sensors (DPS)
Differential pressure sensors are used to determine the direction of airflow through the building envelope (Mustapha, Gamal, 2008).

4. Data Visualization Techniques

One of the most important aspects of structural health monitoring is disseminating and understanding the data collected. This involves identification, comparison, and correlation tasks which are performed on vast amounts of spatially embedded sensor data recorded over time (Gennady Andrienko and Natalia Andrienko, 2005). The datasets collected contain challenging features including big data with spatio-temporal attributes. The ability to browse this data using a classical interface is available where sensors can be selected, data can be viewed and sensors can be grouped and graphed together. In addition to this, the ability to overlay sensors on a building drawing allows a user to identify the sensor location and helps in understanding the situational awareness around the sensors.

Two additional data presentation methods will be implemented as part of this project are Augmented Reality and Virtual Reality. These methods will make sensor exploration and analysis more informative and interesting. By creating data analysis tools that are visually accessible and digestible to the bulk of the general population, living labs have become interesting to much more than just building scientists and researchers. Creating interactive tools can spark an interest in education and awareness on sustainable construction and innovative design. These presentation methods also form another branch of research and development for the college to pursue in the future.

4.1 Analytics

Using standard data analysis tools such as sensor overlays and graphing tools, wet areas can be easily identified and data trends pertaining to these areas further analyzed using standard graphing tools. Figure 9 illustrates a typical roof grid sensor overlay, tape segments in red have exceeded a specific threshold. Selecting a sensor graphs the trend as shown in Figure 10.

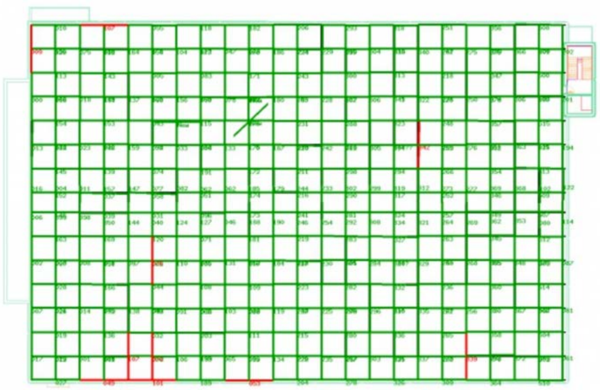


Figure 9. Roof Grid Highlighting Wet Areas

Figure 10. Analysis of Specific Area

4.2 Augmented Reality

Using a custom Smartphone app, data can be extracted from embedded sensors and overlaid over the image in a smartphone display. Once the app recognizes a unique identifier in the camera viewfinder, data pertaining to the sensor location is accessed from the cloud based server and populated on the image, displaying real-time data over the view shown on the camera. The app identified the image as shown in Figure 11 and displayed real time temperature and humidity information from sensors embedded in the wall. This creates a highly interactive environment for educators, students, and visitors of the space. Being able to tangibly associate building assemblies with real-time data with a mobile device also creates an opportunity to very easily investigate the surroundings of the instrumented areas.

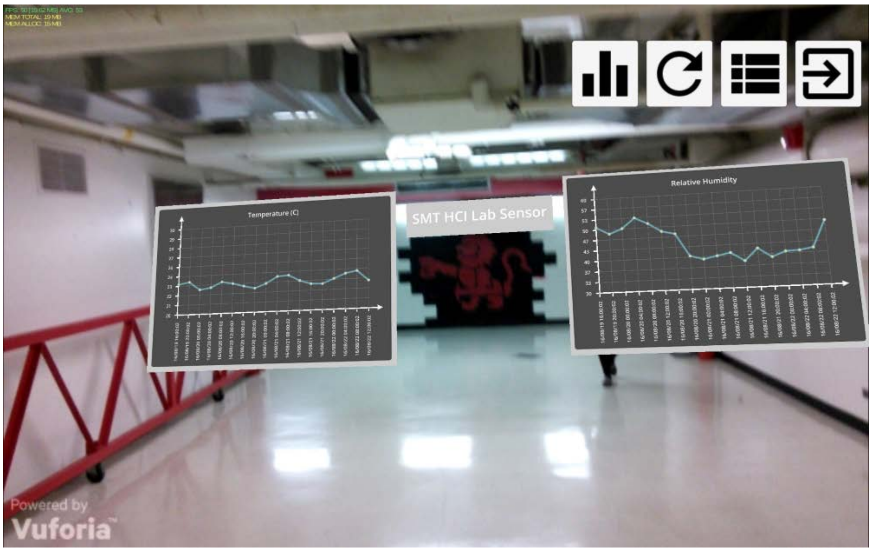


Figure 11. Augmented Reality View

4.3 Virtual Reality

The BIM model for STTC was ported into a gaming software engine, Unity. Sensors were populated throughout the BIM model. Using common gaming controls, users are able to virtually walk through the building and select sensors to view their data. Multiple sensors can be selected, graphed and compared while walking through the building in a virtual environment. Creating a contained environment marrying the real-time sensor data and the BIM model allows for on site and remote exploration of the structure. This allows students and visitors to interact with sensors in restricted and hard to reach areas from a centralized dashboard. For researchers and Building Scientists, this creates an environment to visually investigate both the 3D model, and its corresponding data in a singular analysis ecosystem.


Figure 12. Virtual Reality View of STTC

3. Conclusions

The sensor deployments at the RRC Skilled Trades and Technology Centre proved to be an invaluable tool during construction as it helped quantify the extent of various roof leaks. An understanding of the condensation in the solar tubes during construction has also been an asset as methods to mitigate the stored moisture are being reviewed prior to having the solar tubes freeze during the winter. The data visualization techniques have been tested with building science practitioners. They indicated that the ability to have an overview of the spatio-temporal data will allow for a more in-depth analysis of cause and effect of the building with respect to the data being analyzed. The sensor data will be collected over the period of a year and compared to lab tested assemblies and simulated models to determine if these sensor sets can be used to maintain the status of high performance buildings such as the RRC Skilled Trade and Technology Center. The results will be presented in ISHMII-9 in 2018.

References

BC Building Code, Revision 9. *Housing and Small Buildings* Section 9.36. Energy Efficiency.

Cirenza, Chris, *PHFS-09 Heat Flux Datasheet*, Blacksburg, VA, 2017.

Clifton Forlines and Kent Wittenburg. Wakame: sense making of multi-dimensional spatial-temporal data. In *Proceedings of the International Conference on Advanced Visual Interfaces*, AVI ’10, pages 33–40, 2010.

Gennady Andrienko and Natalia Andrienko. Visual exploration of the spatial distribution of temporal behaviors. In *Information Visualisation, 2005. Proceedings. Ninth International Conference on*, pages 799–806. IEEE, 2005.

Hermes, Jamieson, *Membrane Monitoring Technician Manual*, Vancouver, BC, 2015.

Modera, M. P., Sherman, M. H., and Sonderegger, R. C., *Determining the U-Value of a Wall from Field Measurements and of Heat Flux and Surface Temperatures, Building Applications of Heat Flux Transducers*, ASTM STP 885, E. Bales, M. Bomberg, and G. E. Courville, eds., ASTM, 1985, pp. 203–219.

Mustapha, Gamal, *Point Moisture Measurement Datasheet*, Vancouver, BC, 2007.

Mustapha, Gamal, *Moisture Detection Sensor Datasheet*, Vancouver, BC, 2007.

Mustapha, Gamal, *Relative Humidity Sensor Datasheet*, Vancouver, BC, 2008.

Mustapha, Gamal, *Temperature Sensor Datasheet*, Vancouver, BC, 2008.

Mustapha, Gamal, *Differential Pressure Datasheet,* Vancouver, BC, 2008.

Mustapha, Gamal, Controller Area Network CANKey Datasheet, Vancouver, BC, 2012.

Mustapha, Gamal, *I3 Datasheet*, Vancouver, BC, 2010.