Exploratory Study Towards Streamlining the Identification of Sensor Locations Within a Facility

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ABSTRACT

Significant efforts are being made in the improvement of building automation and control systems in order to optimize the performance of buildings (e.g. reduction of energy consumption). As sensor networks in buildings increase, the complexity of managing them also increases. For instance, the generation and maintenance of meta-data about sensors, such as their location within a building, currently requires significant manual labor. The research described in this paper explores the relationship between different HVAC system sensor measurements and physical characteristics of spaces, and its potential application in streamlining the identification of sensor location within a facility. The energy contained in the conditioned air delivered to each room is presented as a characteristic feature in order to understand the differences between rooms. Being able to understand the relationships between different measurement types and building characteristics is fundamental in achieving an automatic mapping of sensors in buildings, and this paper describes initial observations and results towards this goal.

INTRODUCTION

The increasing availability of sensor data in commercial and residential buildings, and the advances in communications, data analytics, and building automation technologies are proving to be effective and integral components of any modern strategy to reduce energy consumption and increase operating efficiency of buildings. However, these increases in sensing points do not come without new challenges. This study presents the findings of an exploratory study made to support a long-term research project, which addresses the challenge of automatically determining the location of sensors within a building. It explores the possibility of using certain HVAC related sensor data in order to identify the different rooms in a building by combining sensor-driven measurements and construction characteristics.

Considerable efforts have been put into simplifying and automating the identification of energy efficiency improvement opportunities by leveraging deployed sensors. Currently, engineers and facility managers rely on various manual activities in order to obtain information about the configuration, status, and relationships between different building components and systems (e.g., the sensor meta-data).

One type of meta-data that is particularly important is the physical location of sensors within a building. The database systems containing sensor data are typically configured manually (e.g., for each sensor a system administrator specifies the location, name, measurement type, unit of measurement, etc.). However, besides being error-prone, this manual input process needs to be repeated every time the meta-data changes (e.g., reconfiguration of building spaces, sensor replacements, relocations, etc.). This results in inaccurate information about location of sensors within a facility. Without accurate understanding of where the sensors are, it is difficult to effectively interpret the data that the sensors are collecting, and this could lead to misuse of building automation system components.

Previous efforts on creating data-driven sensor location methods have identified ways to cluster the sensors that are located within the same room; however, existing methods do not identify these rooms within the building. It is the objective of this study to introduce a feature, energy content in HVAC delivered air, which can be derived from HVAC system sensors that could lead to identifying the space in which the sensors are located.

We hypothesize that, at least in some cases, it is possible to use the sensor measurements along with some basic knowledge of a building's construction characteristics in order to automatically identify the sensor locations in the building. Determining how to achieve this is a long-term research goal, and the purpose of this paper is to provide preliminary results based on data collected from sensors in an HVAC system for a three-room test bed. We report the challenges identified throughout this study, and offer suggestions for strategies that show promise for solving this problem.

HYPOTHESIS AND THEORETICAL BACKGROUND

HVAC systems design and building energy simulation are based on quantitative estimations of what is the rate at which a building's interior, at a thermal zone level, is loosing or gaining heat. The 2009 ASHRAE Handbook Fundamentals [1] provides an extensive explanation of the assumptions and formulations used to generate heating and cooling load calculations, and the fundamentals of heat flow rates, which represent the basis of our study.

We hypothesize that by comparing the energy content in the air that is being is introduced into a room through the HVAC system (as computed from sensor measurements), and the expected thermal behavior of each room given its construction characteristics and exterior temperature, it is possible to identify to which room the measurements from each sensor correspond.

If a room's set point is maintained constant and the temperature inside the room is consistently kept around the temperature set point, then the HVAC system is successfully compensating for the heat being lost (or gained), which is why we focused on combining the measurements to provide a feature that could be related to the flow of heat from each room, which is the energy contained in the air delivered through the HVAC system.

In this way, sensor measurements are used to estimate the heat gain/loss of each room, and Building Information Models provide building characteristics such as geometric properties, material types, thermal resistance, etc. that can assist in understanding the mapping between the sensors and the expected heat flow rates for each room.

PREVIOUS WORK

Different approaches have been taken to achieve an automatic location of sensors in buildings using signal processing and data analytic methods. For example, Hong et al. (2013) and Fontugne et al. (2012) propose an approach for automated analysis of how different sensors are related through the identification of clusters of sensors that are located within the same room. Calbimonte et al. (2012) worked on using raw data from sensors to infer metadata, such as what type of measurement is being gathered. Although in our study we assume that the type of measurement is known, in a fully automated system the inference of what kind of measurement is being obtained is a fundamental component.

Significant advances, such as the ones achieved by the referenced studies, provide a good framework for an automatic location of sensors. However, they still do not address the identification of which room in the building contains each of the clusters of sensors since the approaches build on the assumption that the exact location of at least one type of sensor is known. Our focus, on the long term, is to find a method that identifies in which specific room within a building a sensor is located. If at least one type of sensor can be reliably traced to their corresponding room, then the other sensors within the rooms could be located using clustering methods, such as the ones proposed in the referenced studies.

Comprehensive methods for estimating heating and cooling loads requirements in a building are defined by ASHRAE Handbook Fundamentals (2009). These methods, combined with Building Information Models (BIM), and increasing availability of data from materials manufacturers enables a better understanding of building thermal performance, not only at a whole building level, but also at thermal zone levels. For this reason, we believe that HVAC systems related sensors is the best starting point to look for a way to achieve an automatic location of sensors within a building.

TEST BED AND DATASET DESCRIPTION

A three-room test bed located in Carnegie Mellon University’s Porter Hall in Pittsburgh, PA was used to make an initial exploratory analysis. Figure 1 shows a layout and 3D model of the space. One of the rooms is a conference room, another a computer lab, and the third one hosts servers and equipment for virtual reality research.

The space has a total area of 1,146 square feet, an envelope consisting of 12” brick walls and interior gypsum wall board lining, and a dedicated variable air volume HVAC system with thermostats in each room. The data is stored using OSIsoft’s PI System (http://www.osisoft.com/), which is specially designed to manage large amounts of time-series data. For each room, 40 different measurement points are recorded, most of them associated with the HVAC system (e.g. room temperature, valve position, damper commands, and set points).

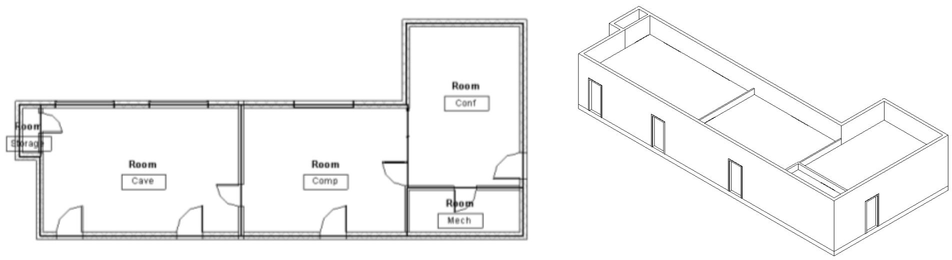


Figure 1. Layout and 3D view of PSII Lab

The data used for this analysis includes the period between April 15, 2012 and August 22, 2013, with evenly spaced time intervals of data collection of one minute. Time series were obtained for each of the different sensors within a room and five of them were selected as relevant measurements for our study: zone temperature, HVAC discharge air temperature, HVAC air volume, set points, and outdoor temperature.

EXPERIMENT DESCRIPTION

The first step was to determine how to use the data collected at the test bed in order to obtain a feature that could help us understand what the heat flow rate in each room could be. An estimate of the energy content in the air introduced through the HVAC system was used for this purpose and is calculated using measurements of air volume and discharge air temperature, using the following expression (1):

$$Q_{HVAC} = V_{HVAC} * T_{HVAC} * \rho * C_P \quad (1)$$

Where, V_{HVAC} is the airflow, T_{HVAC} is the discharge air temperature, **ρ** is the density of air, C_P is the specific heat capacity of air at constant pressure, and Q is the rate of heat transfer (power), which can be considered as a discrete estimate of the energy since measurements were collected every minute. A constant value of **ρ***C_P of 0.018 was assumed.

The logic of this equation is that in order to keep a room at a specified set point, equilibrium shall be maintained between the heat loss (or gain) of the room and the air introduced through the HVAC system. Through the understanding of how much energy is contained in the air that is being delivered by HVAC systems, it is possible to understand what is the heat flow behavior of each room, providing a means of understanding what is the combined effect of construction materials, infiltration rates, occupation, and any other factor that contributes to the loss or gain of heat in a building.

The energy content in the HVAC delivered air combines data generated from two sensors (discharge temperature and air volume), which is why it was important to:

- Understand if there is an apparent relationship between the energy content of the air delivered by the HVAC system and the outside temperature;
- From the two variables used to estimate the energy content in HVAC delivered air, determine if there is one that dominates the relationship between the outside temperature and the energy content.

Upon determination that energy content is closely tied to the outdoor temperature and how the HVAC system adapts to these conditions, a comparison between the energy introduced to each room was made in order to identify trends of energy needs for each room. Absolute and relative amounts of energy were compared, using building characteristics (e.g. floor area, wall area, but most importantly the addition of the area times resistance for all relevant elements for heat loss estimation for each room).

The relative amount is a normalized value of the energy delivered; this normalization is achieved by dividing the absolute energy by construction characteristics from each room (e.g. Surface area, envelope area, window area). For a period of seven days, the set points in the rooms were controlled and set to the same temperature in order to have a period of time without such variation.

RESULTS

Energy estimates. From the estimates provided by Expression (1) it could be seen that different amounts of energy were being introduced into each room through the HVAC system in order to maintain the user required set points, compensating for the net heat losses/gains of each room (See Figure 2).

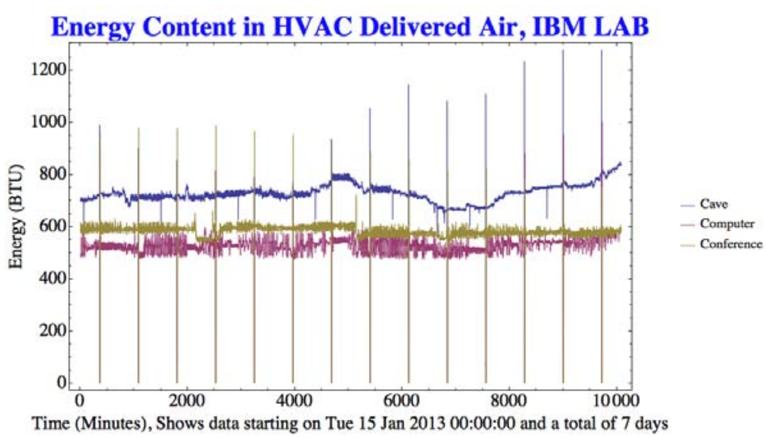
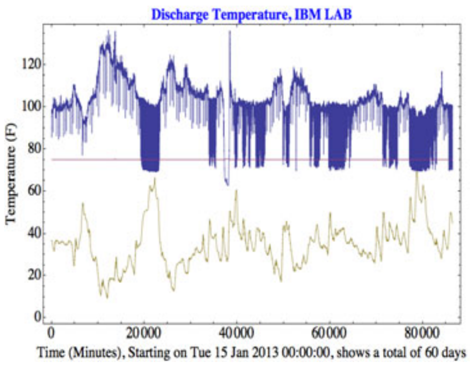
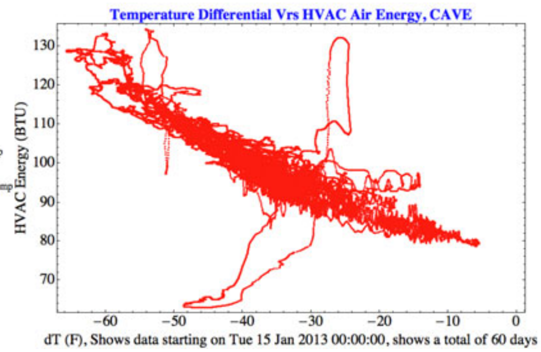


Figure 2. Behavior of energy content in air delivered through HVAC system for the three rooms

Relationship between energy and outside temperature. The initial hypothesis is that there is an apparent relationship between this feature and the outside temperature. By plotting data for the different rooms, and in different periods, it is possible to confirm that there is indeed a linear relationship between these two variables. The most obvious example is shown in Figure 3, where data from the CAVE, the room that hosts servers and equipment for virtual reality research, is plotted in time series form and a scatter plot with the difference in temperature between outside temperature and set-point is plotted on the X-axis and the energy content is represented on the Y-axis. The Pearson's correlation coefficient for the data shown in Figure 1 is -0.82, which could be interpreted as having a very strong relationship between these two variables.





(a) (b)

Figure 3. Time Series and Scatter Plot to show an example of close relationship between exterior temperature and HVAC air energy content

Even though Figure 3 is a good example to show the existence of a linear relationship between the variables, this relationship is not absolute and it varies depending on several factors. For example during this study it was found that changes in set points or differential variations in outside temperature with respect to set points can generate different linear relationships, even for the same room. This can be seen in Figure 4a, where a change in the set point generates two clearly marked linear relationships. For the data plotted in Figure 4b, the resulting Pearson correlation coefficient, -.45, still provides an evidence of a strong relationship between the energy content of HVAC air and the outside temperature.

Figure 5 shows energy content values in absolute and relative, normalized, forms. A clear classification can be observed in both forms; however, normalization allows a more clear differentiation of the rooms throughout time.

Other normalizations were made for this study, including normalization by envelope area, window area, door area, and by adding the product of area and thermal conductivity of the different construction elements of each room. Amongst these, the floor area normalization provides a clear separation when plotted as normalized time series.

Longer periods of time, six months to one-year periods, were plotted and patterns in classifications of rooms were observed when good quality data was available. For instance, it was consistently observed that the relative HVAC energy required by the CAVE versus the computer lab during summers was opposite during winter. Further analysis shall be made in order to understand why this is happening in these rooms.

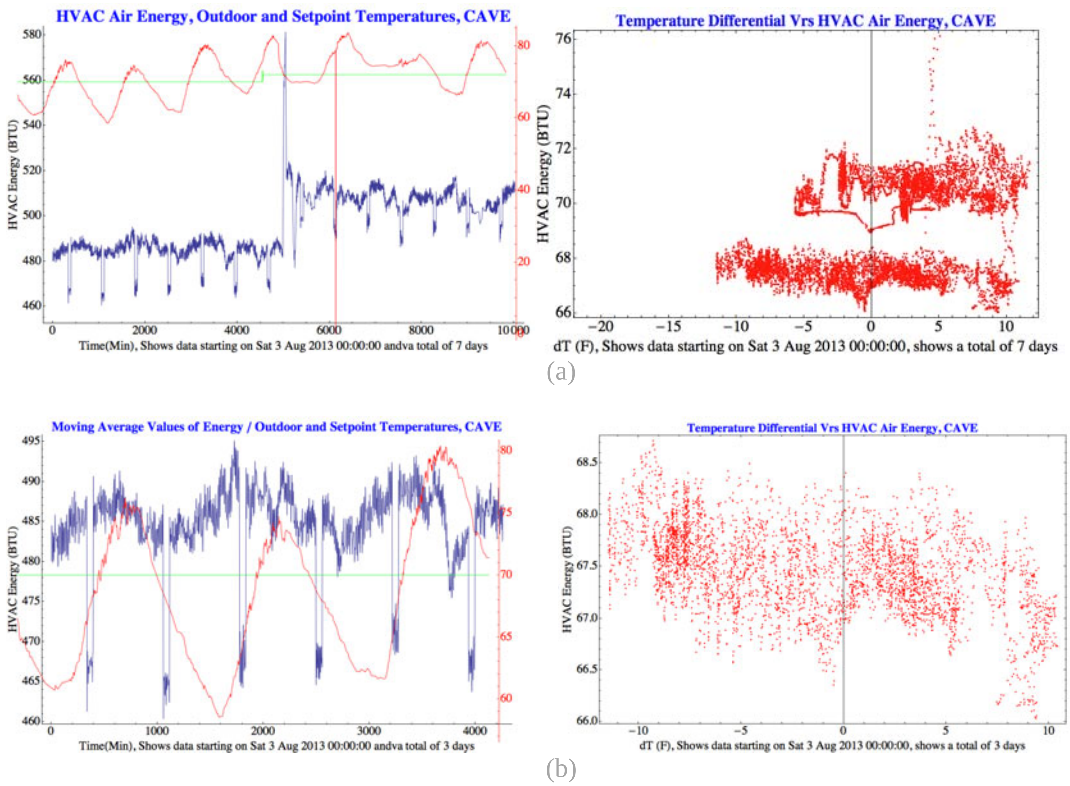


Figure 4. Time Series and Scatter Plot to show an example of clustering due to changes in set point. (a) Shows period of 7 days with change in set point during 4th day; (b) Shows the first three days of period shown in (a)

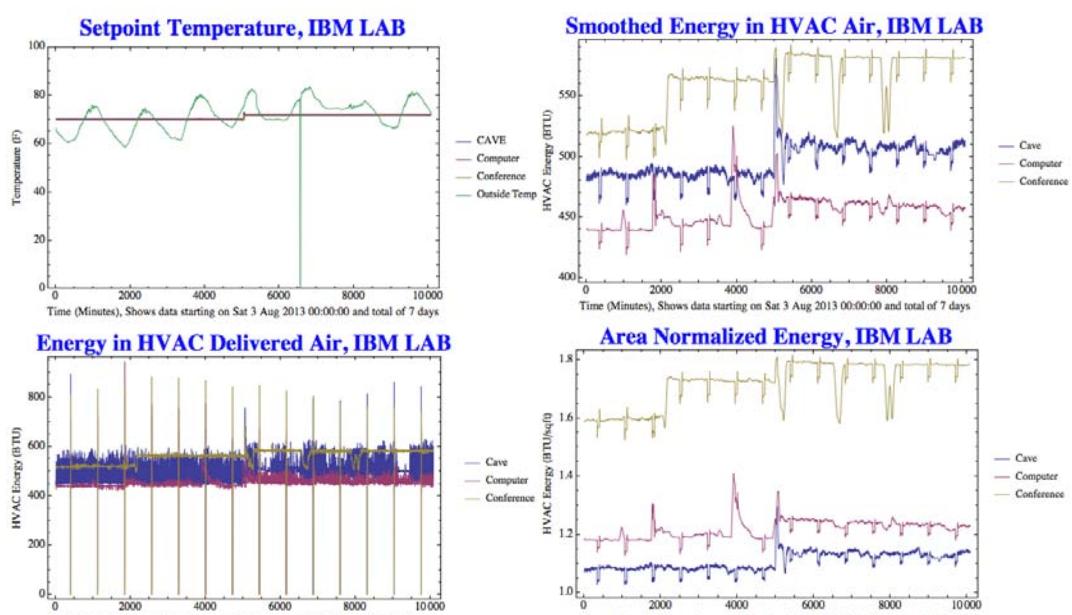


Figure 5. Classification of room characteristics in absolute and relative terms of energy content in HVAC delivered air

CONCLUSIONS AND FUTURE WORK

Achieving an automated approach capable of identifying sensor locations within a facility is a complex problem. This study presents the use of the estimated energy content of the air delivered through the HVAC system, calculated using temperature and air volume measurements. For the test bed used for this study, it is shown that different thermal zones required different amounts of HVAC air energy in order to maintain room temperatures at desired set points, which can be a result of the many different factors that contribute to differences in heat flow rates to and from each room (e.g. construction, set points, occupation, and weather).

Exploration of the data also shows that there is a linear relationship between the energy delivered into a room and the outside temperature; however, the linear relationship between these variables will change depending on variations in set points.

Finally, this study explored the resulting normalization of the HVAC air energy by using the different characteristics of each room. It was found that the floor area of the room was consistently, for this data set and test bed, the normalization element that created a better separation of relative energy values for each of the rooms.

It is clear from this analysis that the data provided by sensors within HVAC systems can be used to understand the thermal performance of different zones within a building. For future work, it is suggested to study in more depth what causes the changes in the linear relationships described in this study, not only between rooms but also for same rooms under different operating and weather conditions. Future work shall also include the understanding of how to link these normalized values with the specific locations. Normalization in this study was made by assigning the data to the rooms based on their real location, but an automated approach needs to recognize which is the right normalization parameter for each data set since the rooms that the data is being collected is going to be unknown.

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