# BubbleSense:Wireless Sensor Network Based Intelligent Building Monitoring


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## ABSTRACT

Buildings consume a great amount of energy. The sustainability requirement asks for more efficient energy usage. The first step towards energy efficiency is to understand in detail how, when, and where energy is consumed in buildings. Advances in Information and Communication Technologies (ICT), especially the embedded sensing and wireless communication techniques, enable an intelligent building monitoring for such an understanding. In this paper, we design and deploy a wireless sensor network based monitoring system in a building test-bed, composed of two containers (named BubbleZERO). We deploy a variety of sensors, including temperature, humidity, flow-rate, and $CO_2$ concentration sensors, to monitor our new energy efficient Heating Ventilation and Cooling (HVAC) system. We develop a data management system to manage and distribute the harvested data to all subscribed users. The system has an user-friendly web based interface. Users can access, retrieve, download and visualize the data from their internet browsers.



## Keywords

Building Sense System, Sustainability, Data Management


## 1. INTRODUCTION

Towards green and sustainable living environments, the energy issue has drawn people's great attention in the past decades. As a major resource consumer, buildings consume a large portion of energy. According to [15], 41% of the energy has been consumed to power different types of facilities in buildings in U.S. and the percentage is predicted to increase to 45% until 2035. Although a large volume of energy is used for buildings, a survey from U.S. Energy Information Administration [16] reports that at least 30% of the building energy usage is wasted. Research studies in [9] suggest that the wasted energy could be even more.

In this study, we aim at understanding the limitations of existing energy control systems and further develop a more efficient and sustainable one for the future buildings. According to [15], almost half (47%) of the building energy is consumed for the space temperature control. Therefore, as a pioneer work, we narrow down the energy efficiency design for the space cooling system in this paper, while the design principle can be easily extended for other components of the building.

To approach an energy efficient design, we rely on fine-grained sensory data harvested from the target space. However, sharing a large amount of data, especially in a real-time manner, can be very difficult. Copying data around is surely neither convenient nor efficient. Uploading data to a public server might be a better solution, yet it enforces users to retrieve the interested data from a big dataset. A more intelligent control system needs to organize, store, retrieve, distribute, and visualize data efficiently and automatically. In this study, we deal with the above issue from following two aspects: the *tightly integrated wireless sensing* and *intelligent data management and presenting.* More precisely, we build a Wireless Sensor Network (WSN) that is tightly integrated with various energy consuming devices and deploy the WSN in a fully configurable test-bed, called BubbleZERO, composed of two standard containers. BubbleZERO is completely configurable and contains a lot of new energy efficient facilities inside. To share sensory data to various subscribed groups, we design a data management framework to achieve instant data distribution. We push the harvested data to a data management server and store them in a well designed database system. We develop an user-friendly web page based interface to visualize the data. The framework of our system is shown in Figure 1.


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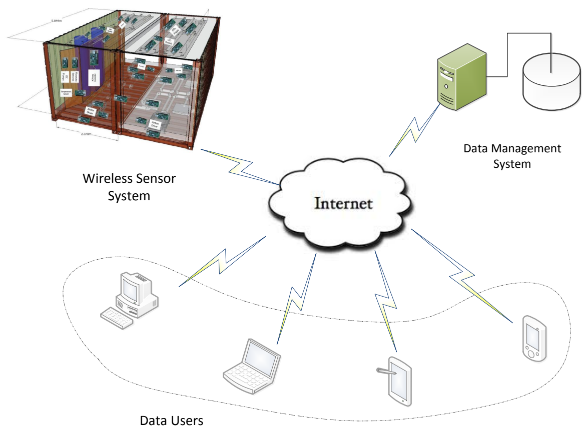



**Figure 1: System architecture**

Translating our design principle to a practical system, however, entails a variety of challenges. First, measuring different types of devices requires integrating many different kinds of sensors. For instance, the hydraulic system needs very accurate measurements of temperature and flow-rate at different places, while environment monitoring needs to measure humidity and $CO_2$ concentration. Fusing different kinds of sensors to the wireless node (mote) requires customized hardware. Second, the communication efficiency of sensor nodes needs to be guaranteed as well. Since sensor nodes might be densely deployed in the room. In addition, other electronic facilities, e.g., Wi-Fi devices, microwave stoves, etc., can interfere with the communication of sensor nodes, the system needs to ensure an efficient and reliable information delivery with minimal communications. Third, uploading data remotely to a data management system is also non-trivial. The program needs to deal with various situations to mitigate the disruptions of the internet connection.

There have been initial attempts made to the smart buildings in previous studies. However, they mainly focus on evaluating or improving the performance of existing systems, and there still exists a rich space to further save the energy in buildings. For example, Jiakang et. al. and Varick et. al. try to cut down the energy consumption of HVAC system from 28% to 20% using occupancy sensors [8, 2]. Jiang et. al. design and deploy an energy audit wireless sensor network in an active laboratory building in University of California, Berkeley [5, 6]. They provide detailed energy consumption map of existing electrical devices in buildings. Dawei et. al. develop a green room management system based wireless sensor network[10]. They focus on saving energy using thermal inertia effect and wireless sensor network. Most of these system are based in existing building, and the flexibility is limited. Our work is different from previous works. By taking advantage of the fully configurable test bed and the low energy equipments, the wireless sensor system proposed in this paper is more tightly integrated with the building and can provide more detailed energy consumption audit and efficiency information of the building system. The introduced data management module could benefit more and make full use of existing sensing resources.

The contributions of this paper can be summarized as follows.

- We design a wireless sensor network integrated with a fully configurable building system test bed. The system is specifically designed to monitor and evaluate the building system and is capable of providing detailed energy information.
- We develop a data sharing framework. The framework can efficiently organize and store sensory data. Data can be easily distributed to subscribed users, helping users to retrieve, download, visualize and analyze data.
- We have experimented with a prototype system, called BubbleZERO, within our designed modules and hardware in two containers of volume around $80m^3$. The experimental results show that BubbleZERO is capable of capturing the energy consumption of devices accurately.

The rest of the paper is organized as follows: In Section 2, we introduce some background about our test bed. The architecture and design details are given in Section 3. In Section 4, we present some of our initial measurement results. We conclude this work in Section 5.

## 2. PROJECT BACKGROUND

Space heating and cooling account for 47% of energy total consumption in buildings [15]. Our first task in this project is to design and test a new HVAC system that uses much less energy. The control and operation of heating and cooling systems in buildings have been developed from very simple origins. If buildings were too cold, heat was added, and if they were too hot, heat was removed. Today these simple techniques to make buildings comfortable are also one of the culprits that makes buildings such large energy consumers. As new technologies are developed to increase the efficiency of buildings, the intelligence of how these systems are installed and controlled must also be increased.

We are working in collaboration with a team of building systems researchers to evaluate the potential of low exergy building systems in the tropical climate. The increase in intelligence of the system is required to evaluate and determine how best to implement the systems. In terms of the system concept, low exergy means that the designs consider the flows of heat in the building along with the temperature of those flows. The amount of heat flowing is one measure of performance of the system, but the temperatures of those flows independently affect the efficiency of the system due to the 2nd law of Thermodynamics. Therefore, while evaluating the prototype systems in the tropics, the measurements of temperatures take on an added importance because we want to optimize not just the adequate heat removal, but also the temperatures we use to remove the heat.

The heat is removed from buildings using a refrigeration cycle. A chiller runs a compressor that cycles refrigerant from a low pressure side where heat can be absorbed from a lower temperature (inside the building) to a higher pressure side where that heat can then be rejected (outside the building). In a typical system design, the chiller components would be sized to move the correct amount of heat out of the building to make it cool without much consideration for the operating temperatures. This is because in the tropics most cooling is done with air. To use air as a cooling medium, it has to be dehumidified first. The dehumidification process requires the air to be subcooled to a point where an adequate amount of water will condensate out of the air, so that when it heats up inside the building a comfortable relative humidity from roughly 40-60% is reached. The subcooling process requires the chiller to generate cooling below 10 $^\circ C$, and this low temperature reduces the system performance.

In our low exergy system design we are trying to find ways to provide cooling at higher temperatures, which will minimize the electricity required to supply the cooling. We achieve this by decoupling the cooling process from the air systems and the required dehumidification. The cooling load is met by a chilled water circuit that provides cooling at 18 $^\circ C$ through a cooling panel with a large surface area. It is still necessary to supply fresh air to the building users, and this air must still be dehumidified at a lower temperature, but the amount of air is independent of the cooling demand and can be optimized. But in order to optimize the system operation for the tropics we need to measure the performance characteristics.

In order to evaluate the operation of the fresh air delivery and the independent cooling panel, there are many variables that must be measured. The goal is to supply the right amount of fresh air for the users, so we must know how many users there are. We must also make sure the air supplied is properly dehumidified so that any risk of humid air infiltration is mitigated. This is a significant risk because with no dehumidification, the cooling panel at 18 $^\circ C$ is still below the dew point of typical air in the tropics of around 25 $^\circ C$, which means that there will be condensation on the panel and water could fall from the surfaces on the ceiling. Therefore we need accurate measurements of the air temperature and humidity as well as methods to consider the potential of infiltration in the system.

We have constructed an experimental building and laboratory, BubbleZERO, where we are testing the prototype low exergy technologies in Singapore. To operate and evaluate the systems we have designed an intelligent wireless sensor network. This network will be used extensively to measure the performance of the prototype systems in the laboratory, but as a fully modular wireless network, it can be easily scaled back for demonstration in the first pilot projects. The BubbleZERO cooling system is made up of a chiller with two water storage tanks, two sets of radiant cooling panels and four decentralized air supply units. There are also a variety of other new systems being tested including $CO_2$ steered exhaust vents, integrated LED lighting, and special LowE coated glazing. The performance of all these integrated systems can be steered and measured with wireless sensor technology. We present in this paper a novel implementation of such a sensor network along with data collection and management system for our low exergy high performance building system.

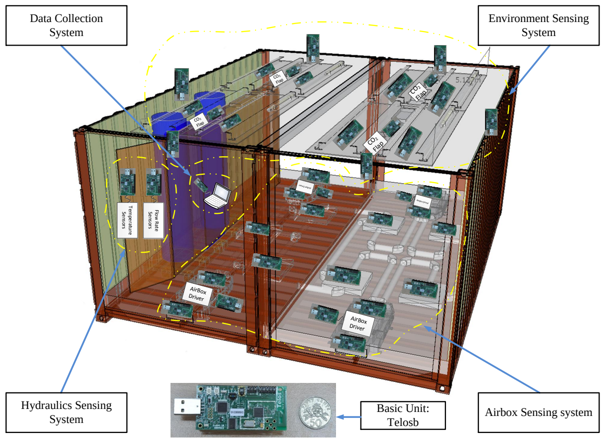



**Figure 2: Sensor deployment**

## 3. SYSTEM DESIGN AND IMPLEMENTATION

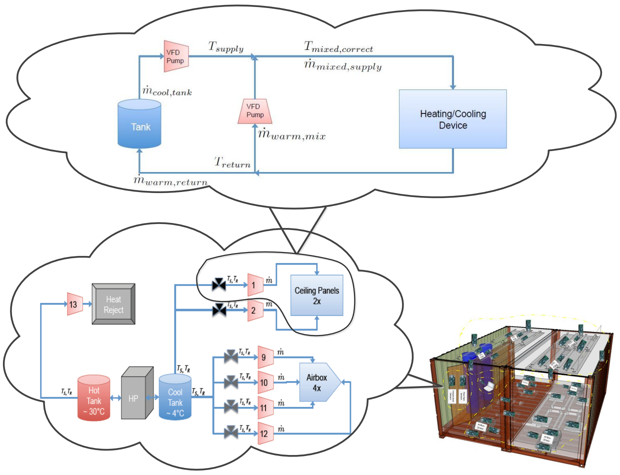
In this section, we begin with an overview of the system. Then we provide an description of design and implementation of the wireless sensor network system. Finally, we introduce the design and implementation of the data management system.

### 3.1 System Overview

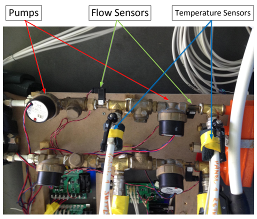
To enable good energy evaluations and energy-efficient building system designs, we design a building monitoring system composed of two parts: Wireless Sensor Network System and Data Management System. Wireless sensor network system includes various sensors and a base-station. Wirless sensors are deployed at different places to collect data periodically. Base-station is used to connect the wireless sensor network with the data management system. It collects sensor data and transmits to remote data management system. Data management system stores the received data in a properly defined data base. It runs at a remote server in the IntelliSys Laboratory in NTU. It also provides a web based interface for end users to retrieve, visualize and even analysis the data. Users can get the desired information from the web browser. The whole system archtecture is shown in Figure 1.

### 3.2 Wireless Sensor Network System

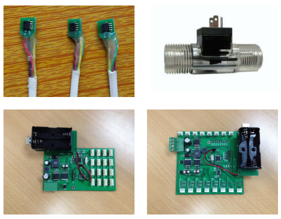
As discussed earlier in Section 2, our low-exergy based cooling system uses water instead of air as the main cooling medium. The dehumidification process is separated from cooling process by using some specially designed air handling unit-Airbox. Complex hydraulic system is deployed in our BubbleZERO to enable proper function of those new devices. To run those systems properly and to evaluate their performances, specially designed sensing system is needed. The key challenge here is to design a highly accurate, low cost yet very flexible sensor system. The sensor system needs to be tightly integrated with various devices and building operating systems in the test bed. To address these problems, we design a wireless sensor network system. The basic unit




(a) System architecture




(b) Real system layout



(c) Sensors and interface boards

**Figure 3: Hydraulics measurement system**

we use to build the system is the open source wireless sensor platform Telosb [11]. Thanks to the miniature property, we can easily integrate these Telosb motes with various kinds of devices. The event driven open source sensor operating system TinyOS running on Telosb ensures the energy efficiency and network flexibility. The low power property enables our sensor motes to operate continuously for several months without changing batteries. The IEEE 802.15.4 standard based wireless communication module on the motes enables a wireless intercommunication, which greatly cuts down the deployment cost and enables a good scalability. Our wireless sensor network system is composed of several sub-sensing systems. Hydraulics sensing system measures the temperatures and flow rates of the water in different pipes, as well as enables the evaluation of the power efficiencies of the ceiling panel cooling system and Airbox air handling system. Airbox sensing system measures the temperatures and humidities of the input and output air, the fan speeds and the power consumptions of the Airboxes. Environment sensing system measures indoor and outdoor ambient parameters which include temperatures, humidities, $CO_2$ concentrations at different locations. The data collection system collects and stores the data from different sensing spots. Figure 2 shows our detailed sensor deployment. Each sensor is represented with a Telosb mote in the figure.

### *3.2.1 Hydraulics sensing system*

Hydraulics sensing system measures temperatures and flow-rates of the water circulating in the hydraulics system at different spots. The Low-exergy based cooling suggests saving energy by providing cooling power at much higher temperature. The implementation of such a system is heavily based on our hydraulics system, which supplies water to the main cooling devices (the ceiling panels) and the dehumidifying device (the Airboxes). Running and efficiency evaluating of those devices require an accurate measurement of the cooling medium circulating in the hydraulics system. According to thermal theories, the power supplied to a devices can be derived from:

$$P = \frac{dm}{dt} \cdot \Delta T \cdot C_p \quad (1)$$

Where $\frac{dm}{dt}$ is the flow rate, $\Delta T$ is the temperature difference between the supplied and returned water, and $C_p$ is a specific constant of the specific cooling medium (water in our situation). Thus the challenge here is to accurately measure the flow-rates and temperatures of the water flow through pipes. Figure 3(a) illustrates the design of our hydraulic based cooling system. Cold water is pumped out from the clod tank, mixed with the water returned from the device, then supplied to the cooling device. The cooling devices are ceiling panels and Airboxes. Such a design enables a fully control of both temperature and flow-rate of water supplied to the cooling devices, thus enables the proposed low-exergy cooling. Figure 3(b) shows the real system deployed in BubbleZERO.

As we can see from equation (1), the temperature measurement is very important in the system evaluation. Practical experience suggests that $\Delta T$ can be quite small when the system is running. As a result, the accuracy and consistence of temperature measurement matter a lot. On the other hand, sensors need to be cheap for a scale deployment as well. As the on-board sensor on Telosb is neither accurate nor cheap, we should find some new sensors suitable for our usage. Finally we utilize the ADT7410 temperature sensors (up-left of Figure 3(c)). It is an off-the-shelf cheap digital temperature sensor produced by Analog Devices. It has a good accuracy and is factory calibrated to be $0.5°C$ accurate[1]. More importantly, the accuracy could be further improved by a manual calibration in practice. However, integrating this sensor to the Telosb mote is not trivial since it uses $I^2C$ interface to communicate. We paid a lot of efforts to design and develop a customized interface board (down-left of Figure 3(c)). The board is capable to interface up to 16 ADT7410 temperature sensors that makes the large scale temperature sensor deployment capable, easy and cheap. An Arm cortex M0 micro-controller is used to interface the temperature sensors through $I^2C$ serial communication. It initializes the sensors, reads the temperatures and then sends data to Telosb mote through UART port. The Telosb mote then forwards the data to the base station through its wireless module.

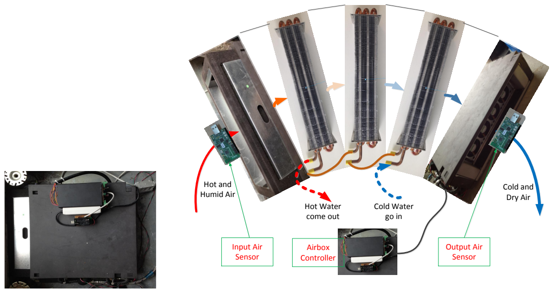
Flow-rate is another key parameter in the power evaluation. We choose the Vision 2000 flow sensor (up-right of Figure 3(c)) from Remag to measure the flow-rates. The sensor suits our usage with good accuracy of ±3% and it's highly repeatable (repeatability better than 0.5%)[12]. The sensor has an easy-to-use digital interface. It outputs pulses with a frequency proportional to the flow-rate. To accommodate the large number of flow sensors in the system and to interface these sensors to the wireless sensor network, we design and build some specialized interface boards(down-right of Figure 3(c)). Each of those boards could interface up to 8 flow sensors. Counting the pulse and then calculating the pulse frequency are performed by a ARM Cortex M3 microcontroller on each board. One Telosb mote is connected to each interface board. Flow-rate data is sent to Telosb mote through UART serial communication. Data is later transmitted to base station wirelessly by Telosb motes. By so doing, we can connect our flow-rate sensors to the wireless sensing network.

### 3.2.2 *Airbox sensing system*

Airbox sensing system measures the running parameters of our air handling units-Airboxes. Space conditioning in tropical climates can't be finished without dehumidification. It is because outside air is usually too humid that cooling it down directly to the desired temperature will cause condensation. For our case, condensation will appear on the ceiling panel and occupants will be unhappy to find their room make rain. Airbox is a novel device we use for dehumidification in our BubbleZERO. Figure 4(a) shows the structure of the Airbox and how it work. The basic principle we do dehumidification remains the same with traditional air conditioning systems. That is cooling the air down to sufficient cold temperature to condensate out the water and get dry air. However, different from the traditional way, we use water as the cooling medium to dehumidify the air. Cold and dry air is supplied to the room through the outlets of the Airboxes. To run, control and evaluate these Airboxes, sensing at the right spots is need. Input and output air parameters including temperature and humidity should be monitored. The speed of air flow through the Airbox and the power consumption of the Airbox itself are some other important parameters. Other important parameters such as the temperature and flow-rate of the water flow through the Airbox are measured through the hydraulic sensing system. We choose Sesirion Sht75 sensor to monitor input and output air of Airbox. This sensor integrates both temperature and humidity sensor on a single small package. Its high accuracy makes it suitable for our usage. It has high accuracy of $0.3°C$ for temperature and $\pm1.8\%$ for humidity at room temperature[14]. We connect the sensor into the wireless sensor network also through Telosb motes. Each Telosb mote connects to a pair of sht75 sensors which measures both the input and output air. The fan speed and power consumption parameters are collected through RS232 interface of the Airbox controller. Some RS232 level conversion boards are developed to interface the Telosb to the Airbox controller. Figure 4(b) shows the sensor deployment of the Airbox measurement system.

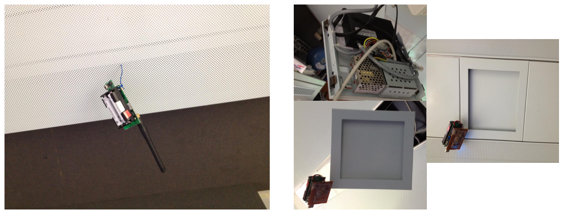
### 3.2.3 *Environment sensing system*

The environment sensing system monitors the ambient parameters. The most sensitive indoor parameters for human beings are temperature and humidity. Another important indoor parameter is $CO_2$ concentration. We use the Sht11 sensor onboard Telosb to measure temperature and humidity parameters. By deploying Telosb motes at different spots in the test-bed, we provide fine grained temperature and humidity distribution information. The sensor accuracy is $0.4°C$ for temperature and $\pm1.8\%$ for humidity at $25°C$[13]. Firgure 5(a) shows the indoor sensor deployment. Batteries are used to power these Telosb nodes to give the flexibility of mobility. It means the sensors can be move to others

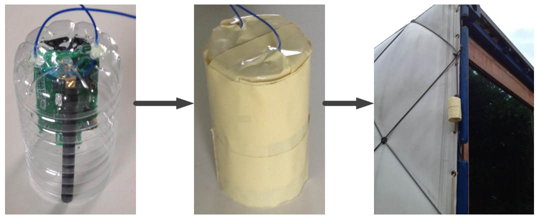



(a) Airbox (b) Airbox work flow and sensors

**Figure 4: Airbox measurement System**



(a) Indoor sensor deployment (b) $CO_2$ flap



(c) Outdoor sensor deployment

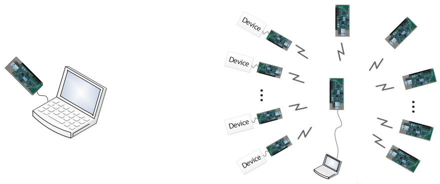
**Figure 5: Environment measurement system**

spots if needed. The $CO_2$ concentration measurement is more difficult. We use a device called CO2 flap to perform the measurement. The $CO_2$ flap is connected to the Telosb node through a RS232 communication port. Telosb reads the temperate and $CO_2$ information and sends it back to the base station. The posssible usage of $CO_2$ can be on-demand ventilation control. Firgure 5(b) shows the connection of the $CO_2$ flap and the Telosb node.

For the outdoor environment monitoring, we measure the temperature and humidity merely. We hang some Telosb nodes outside the test bed. A special consideration here is to protect the sensor from the sun and rain, since the sun can heat the sensor up, thus leading to the sensing error, while the rain can damage the humidity sensor. Firgure 5(c) shows our sensor protection solution. We firstly put sensors in an half cut plastic bottle to protect the sensor from the rain. Then we cover the bottle with reflective white paper to shade the sensor from the sun. The deployment is just to hang these sensors around our test-bed.

### 3.2.4 *Data collection system*

The data collection system is composed of a Telosb node and a laptop (Figure 6(a)). The Telosb node acts as the base-station for the sensor network. It receives all the sen-



(a) Airbox (b) Sensor deployment for Airbox

**Figure 6: Airbox measurement System**

sor data from other nodes and forwards it to the computer through a USB connection. Since the test-bed is small, a simple star-topology can be used to organize the sensor network (Figure 6(b)). The computer runs a data collection program to communicate with the Telosb node to collect the data. The program is developed with the $C\#$ programming language. It has a GUI interface to display the data in real time. At the same time, it also stores the data in files and uploads data to remote data management system (descried in Section 3.3) through internet.

## 3.3 Data Management System

Our key idea of building the data management system is to make the precious research data to be published to the community. Furthermore, we also want to help users to retrieve and visualize the data such that they could gain some direct ideas from the graphs. Building such a system, however is not easy. Challenges are how to design data transfer protocol to ensure reliability, how to organize and store the data properly to support scalability and how to develop the user interface to enrich user experiences. We present our design in the following subsections.

### *3.3.1 Data upload to server*

Data is recorded as log files in the data collection system. Since the data rate is relatively quite slow in our system, setting up a permanent connection to transmit data to the server in a real time manner is not efficient. We improve the efficiency by buffering and sending data batches to server periodically. Thus our problem here is to design a system to support reliable batch-files transmission. There are at least two basic methods to upload file to a remote server: (a) using the file transfer service provided by the remote server, and (b) directly manipulating the remote server if remote access is enabled[4]. In our study, the former approach is adopted. In particular, we developed and deployed a PHP based file transfer service at the server. Our client data collection program uploads data by invoking the PHP script. This solution provides great scalability since the server could support a lot of data sources and provides data storage supports for multiple projects. The advantage of using PHP based data upload is that data can be instantly processed after been uploaded by some other PHP scripts deployed at the server. To ensure the data upload reliability, checksum is used to check correctness and retransmission is made if fail happens.

### *3.3.2 Data storage at server*

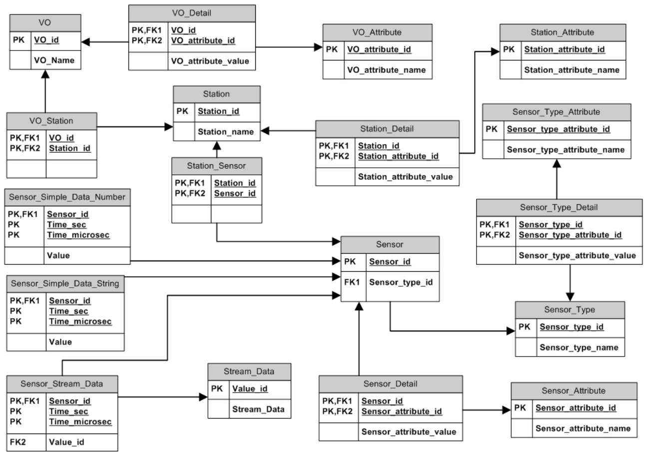



**Figure 7: Database Schema**

After data is received, the server needs to store the data in a fine manner. Storing data as files is surely not a choice since it can be extremely slow to retrieve data from files. A database system is a better option since it's designed for data storing, managing and retrieving. Basically data are stored in tables in the database system, therefore, a simple solution is to store each sensor's data as one table. However it is not robust enough because the data management system needs to remember which table is corresponding to which sensor. Once the data management program collapsed for certain reasons, the system may lose such data relationship information and becomes impossible to record new data to original tables. As a result, the challenge is to design a robust and scalable data storage architecture for the scalability purpose.

To handle various sensor types and support extensibility to new types, the data storage design is not tied to any particular sensor type. It is a generic design of the sensor database whose sensors may change over time. Sensor types are represented as relations while sensor data are represented as time series [7]. Each individual sensor has a unique ID, which simplifies the sensor data access queries. The data are extracted in a unified and predefined way. Figure 7 shows a high level database schema. It records not only the sensor data, but also the sensor information. Thus, adding a new sensor simply means adding one row in serval tables. Sensor data always go to one main table for recording data of all sensors. The corresponding relationship is preserved in the relationship of tables. It also makes the data sharing much easier. Retrieving data means a SQL request to the Database system. As the SQL request can be easily integrated to web pages, we could provide easy to use interface to users.

### *3.3.3 Data Sharing and visualization*

The overall goal of our data management system is to share the data. To this end, we develope a web based application to help users retrieve and visualize the interested data. Users can access data just with an internet browser. From the web interface, user can specify which sensor's data, what type of data, what interval of data they want. Our web application takes these inputs and use Structured Query Lan-

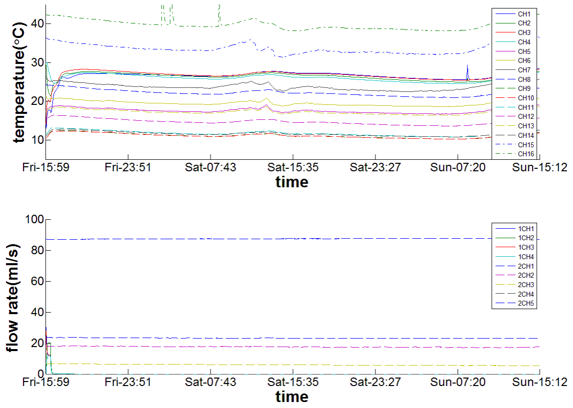



**Figure 8: Hydraulics system measurement result**

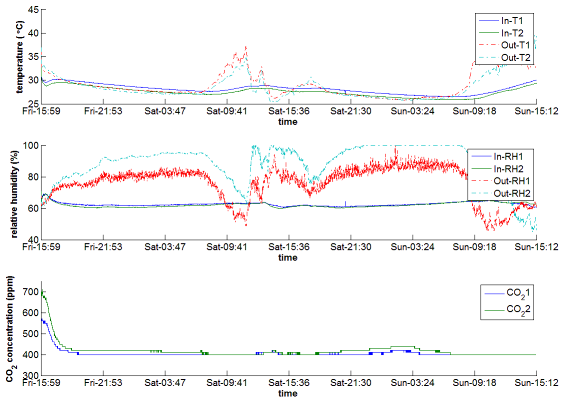



**Figure 9: Environment system measurement result**

guage (SQL) to request the data from our database. The returned data is transformed to graphical pictures by using the Google visualization tool[3]. Users can also download data for a further analysis.

## 4. RESULT PRESENTATION

In this section, we present some of our initial measurement results. Our results for the hydraulics and environment sensing system are from data collected from a two day experiment. In the experiment, we intend to test the performance the Airboxes. three Airboxes run at their full speeds during the test period. The data for the Airboxes measurement system is from one of our 40 minutes experiments with one Airbox. In the experiment, we want to find out the relationship between the Airbox fan speed and the output air temperature.

Figure 8 shows the measurement result of our hydraulics system. Temperatures for 16 sensors and flow-rates for 9 flow sensors are shown in the figure. At the start of the experiment, temperatures and flow-rates change quickly. After some time, they reach stable states and change slowly along the time. The temperatures change along time as the cooling

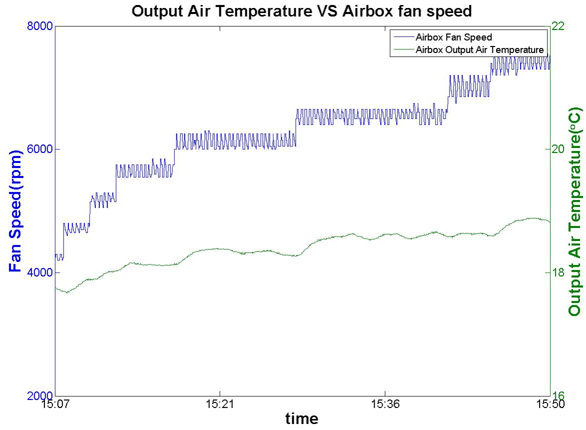



**Figure 10: Airbox system measurement result**

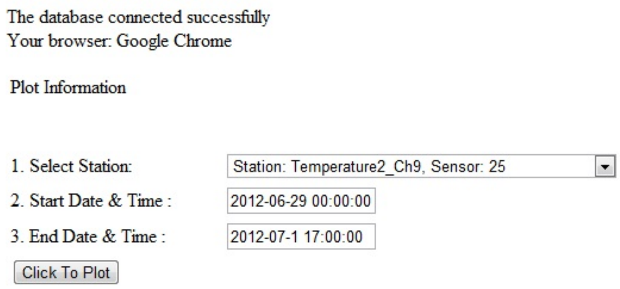
load changes, while the flow-rates remain almost constant. Figure 9 shows the ambient environment changes within the two day. We plot both inside and outside temperatures and humidities of different spots. We can see that the outdoor environment changes a lot during a day. While our indoor environment remains somehow constant due to the conditioning of Airboxes. On the other hand, we also find that Airboxes alone cannot provide enough cooling capacity during the day. The average indoor temperature rises during daytime and drops at night. We also measure the $CO_2$ concentration. The $CO_2$ concentration is high at the beginning of the experiment because researchers stayed in the test-bed at that time. After their departure, the value falls to a low and constant value.

Figure 10 depicts the test result of Airbox. In this test, we intended to figure out the relationship between the fan speed and the output air temperature of the Airbox. We keep the water supply constant and change the speed of the fan of the Airbox. We collect data from the Airbox measurement system. The result shows that the output air temperature will increase as the fan speed increases. They follow a linear relationship. The data can also help us evaluate the energy efficiency of the Airbox.

Figure 11 is the screen snapshot of our data management system. Figure 11(a) shows the web-based user interface with which people can specify the interested data by specifying type, date, etc. The visualization result is shown in Figure 11(b). The visualized result can help researchers get some rough ideas and quickly evaluate the systems. They can further be download from the data set for further analysis.

## 5. CONCLUSION

Sensing is essential for understanding existing building systems, testing new building systems and designing sustainable buildings for the future. In this paper, we design a wireless sensor network that is tightly integrated with various energy consuming devices in our test-bed. The system offers fine grained information for researchers to evaluate the system performance. We also built a data management framework to publish our data to all interested users. It has




(a) User interface


(b) Visualized data

**Figure 11: Screen Shots of data management system user interface**

an easy to use web based interface to help users retrieve and visualization data. In the future, we plan to install more kinds of sensors in the test-bed to provide more aspects of information. On the other hand, we will find the minimum necessary amount of sensors that enable us to run the system at the desired performance.

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