A SYSTEM FOR MONITORING AND MANAGING INDOOR AIR QUALITY AND ENVIRONMENTAL CONDITIONS

by

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ABSTRACT

The quality of indoor air depends on different types of pollutant sources existing in a semi-enclosed environment. The sources can be biological, chemical, or toxic pollutants. These sources can cause health issues and discomfort for occupants. One of the indicators of poor indoor air quality is Carbon Dioxide (CO_2). CO_2 can be used to indicate the indoor air exchange rate. The lack of air exchange means higher levels of CO_2. High levels of indoor particulates can also be an indication of poor air quality. Due to the lack of fresh air, air circulation, and air filtration, the level of contaminants can be higher in some parts of a semi-enclosed space. In pursuit of higher energy efficiency, mechanical ventilation and circulation are necessary to manage the indoor air quality. This thesis describes a system to monitor and manage indoor air quality with the use of ventilation and circulation. The system will introduce fresh air and circulate existing air as needed to keep the indoor air quality within acceptable levels. This keeps the occupants healthy and comfortable. The end result of this research was a sensing system and a control system that communicate wirelessly. The sensing system was able to monitor the environmental changes and the control system was able to show the ability to manage the indoor air quality and the environmental conditions.

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LIST OF ABBREVIATIONS

ADC	Analog to Digital Converters
ASHRAE	American Society for Heating, Refrigerating, and Air-Conditioning Engineers
BSU	Boise State University
CO	Carbon Monoxide
CO_2	Carbon Dioxide
CFM	Cubic Feet per Minute
DMA	Direct Memory Access
EPA	Environmental Protection Agency
FAA	Federal Aviation Administration
GPIO	General Purpose Input/Output
HAL	Hardware Abstraction Layer
HSIL	Hartman Systems Integration Laboratory
HVAC	Heating, Ventilation, and Air Conditioning
I^2C	Inter-Integrated Circuit
IHAQ	In Home Air Quality
LCD	Liquid Crystal Display
LED	Light Emitting Diode
MAC	Media Access Control
NIH	National Institute of Health

NIOSH	National Institutes for Occupational Safety and Health
PM	Particulate matter
RTC	Real-time clock
SD	Secure Digital
SPI	Serial Peripheral Interface
UART	Universal Asynchronous Receiver Transmitter
USB	Universal Serial Bus
VAV	Variable Air Volume

CHAPTER 1: INTRODUCTION

1.1 Heating, Ventilation, and Air Conditioning

In pursuit of energy efficiency, we are building tighter houses that are energy-efficient to save cooling and heating costs. However, one has to wonder about the indoor air quality with lack of circulation and ventilation. Could energy-efficient houses have sick building syndrome? Could reduced circulation and ventilation lead to health issues? One can argue that a leaky house is good for air quality, as fresh air from outside is constantly being exchanged with inside air. However, the downside to this is higher cooling and heating costs.

A Heating, Ventilation, and Air Conditioning (HVAC) system is an automated system used for climate control in semi-enclosed spaces. It provides occupants with a comfortable environment. The most important criteria for an HVAC control system is providing a reasonable and acceptable temperature range by providing heated or cooled air. It has been suggested that people in developing countries have a wider range of thermal comfort level than those in developed countries. The HVAC system deals with the content of air inside a semi-enclosed environment that could affect the health and comfort of occupants. The health aspect is usually secondary, as most HVAC systems lack proper air quality sensors. The lack of air exchange between inside and outside can affect the indoor air quality.

When thinking about energy efficiency, one of the most important decisions to be made regarding a house is the efficiency level of the heating and cooling system to install. The operating efficiency of a system depends as much on proper installation as it does on the performance rating of the equipment. Improper design and installation of the HVAC system has negative impacts on personal comfort and on energy bills. The improper design can also degrade indoor air quality or even threaten the health of the occupants (e.g., improper venting).

The purpose of HVAC control systems is to control air conditioning, heating, and the amount of ventilation required for an enclosed or semi-enclosed environment. This is mostly done through controlling temperature and humidity level. The most popular HVAC systems are designed to deliver and maintain air at a set temperature with low energy usage and infrequent maintenance. The HVAC unit controls the inside temperature by controlling when heating or cooling is turned on. It also controls the air circulation inside an enclosed area, and the amount of fresh air intake (if this feature is installed) from outside using ventilation. Regulating the fresh air intake controls CO_2 levels for better air quality in the occupied space. HVAC manages indoor air quality by controlling the volume of circulated air inside the occupied area and supplying fresh air from outside. Circulation of existing air and introduction of fresh air helps to dilute contaminants in a semi-enclosed space.

1.2 Air Quality Management

Traditionally, a temperature sensor controls the home heating and cooling system. This control has been in used for ages, even when houses were “leaky.” This has worked well. With modern construction practices, houses are built tighter for energy efficiency. Should we rethink how the heating and cooling system is managed? Energy-efficient houses result in reduced heating and cooling. Houses with minimal leaks have less circulation, because less temperature variance results in fewer heating or cooling cycles. With houses being energy-efficient, there is little air exchange with the outside air, compared to leaky houses caused by the low ventilation levels. Should mechanical ventilation be introduced? If so, how much? How should this be controlled? It is a trade-off between indoor air quality and costs of heating and cooling. Energy-efficient homes can be installed with an Energy Recovery Ventilator or Heat Recovery Ventilator to use the outgoing air (used air) to pre-condition the incoming air (new air), to save on cooling or heating costs. This constant introduction of fresh filtered air improves the indoor air quality, e.g. reduce Carbon Dioxide (CO_2) level and other contaminants. This is using the principal of dilution.

The quality of the indoor air depends on the different types of gases present/generated and particulate pollutants in a semi-enclosed environment. Pollutants can be generated from diverse types of sources such as the biological, chemical, toxic, and airborne particulates [1]. All of these pollutant sources can create discomfort, health issues, or even death in some severe situations.

The CO_2 level can be used to indicate air exchange rate. With little to no air exchange, the level of CO_2 will increase from the occupants. A high level of CO_2 can equate to higher level of contaminants due to lack of fresh air and circulation. Mechanical ventilation requires energy, e.g. opening a damper or operating a DC motor or blower to move air. This brings up the issue of control and deciding the quantity of air to bring in when weather is hot or cold. The control decision should be based on various factors, e.g. temperature, humidity, and/or CO_2, in addition to temperature.

This leads to the theme of this thesis: using sensors, ventilators, and dampers to maintain indoor air quality. The goal of this thesis is to showcase a method to control HVAC systems, sensors choice, and ventilation and circulation control to manage indoor air quality and keep it within an acceptable level.

1.3 ASHRAE

ASHRAE stands for the American Society of Heating, Refrigerating, and Air-Conditioning Engineers [2]. ASHRAE develops standards for people concerned with the refrigeration process and the design and maintenance of indoor environments. ASHRAE standards establish consensus for the method of testing and performance criteria to guide the HVAC industry.

Indoor air quality is the most commonly discussed aspect of indoor environments. There are multiple international conferences on indoor air quality. One such international conference is Indoor Air, hosted at various international locations. Indoor air quality has direct effects on the occupants' health as well as the perception of an acceptable indoor environment. In the United States, ASHRAE Standard 62.1 [2] is used to quantify what is an acceptable indoor air quality. To provide adequate ventilation for a satisfactory indoor air quality, ASHRAE Standard 62.1 requires that the outdoor air ventilation rate must be based on the number of occupants in an enclosed place. ASHRAE Standard 62.1 recommends the minimal amount of outdoor air introduced to a semi-enclosed environment to be 20 cubic feet per minute (CFM) for each person.

1.4 Outline

The following chapters discuss the topics of an HVAC control system, management of indoor air quality, and the sensing system unit as they relate to the scope of this thesis. Chapter 2 discusses the work that has been performed prior to the start of this thesis, including a description of the sensing system unit. Chapter 2 also contains a description of existing technology developed by other researchers. Chapter 3 addresses the importance of indoor air quality and why it should be an essential part of the HVAC control system. The types of pollutants, their sources, and air quality management are also covered in Chapter 3. The hardware design for the HVAC control system and sensing system unit can be found in Chapter 4. Chapter 5 discusses the firmware design and development for the sensing system unit and the HVAC control system. The testing and results of the design are detailed in Chapter 6. Finally, Chapter 7 provides conclusions and a discussion of the future work.

CHAPTER 2: EXISTING TECHNOLOGY AND PREVIOUS RESEARCH

2.1 Existing Technology

Air quality management using sensors and HVAC control systems is very important for people's health. The Environmental Protection Agency lists indoor air quality among the top five risks to human health [3]. The reason is that indoor air can contain contaminant levels two to five times greater than outdoor air. Thus, the research and implementation in an HVAC control system is substantial. Several groups have completed work on various systems used for HVAC control. Although the work and research of these groups performed well for their application, the research involving a larger set of sensors is minimal. Since their work relates closely to the goals of this thesis, a comparison of the current research to their research is important.

Delta Controls is a company specializing in control systems [4]. Their HVAC system is targeted towards large buildings. Delta Controls' goal is to decrease the power consumption of the HVAC systems. They contend that half of the energy used in a building is consumed by the HVAC control system. Therefore, the focus of their research is to decrease the amount of power usage from the air conditioner and furnace. They focus on the HVAC controls system, damper, and fans. Their research on the sensing system side is minimal. Delta Controls uses a thermostat as a sensing element. Thus, their HVAC system will respond to temperature changes, but no other sensor data will be taken or used to control the HVAC system. As such, the system does not have the ability to manage indoor air quality.

Nebil Ben-Aissa [5] conducted research for Johnson controls Inc. on HVAC control systems. Their research focus was on a different type of HVAC control. The target of the research was controlling the airflow in and out of a building. This type of HVAC system is referred to as Variable Air Volume (VAV) [5]. Nebil Ben-Aissa analyzed, modeled, and simulated the VAV system for HVAC systems. Figure 1 (following page) shows the idea of the modeled system by Ben-Aissa. Although the system controls the amount of supplied air and the exhaust air, it only uses a temperature sensor to control ventilation and circulation of the air. The system does not have the capability to read CO_2 measurements to get an estimate of contaminants in the enclosed environment. Furthermore, the modeled VAV system simulated by Ben-Aissa is designed for substantial changes in the sensor data. Therefore, the system only responds to large variations in the sensor measurements.

The goal of another research project, by Nabil Nassif and Samir Moujaes from University of Nevada Las Vegas, was to reduce the energy consumption in HVAC control systems [6]. Nassif and Moujaes claim that the focus of the research is preserving air quality for large buildings. The research done by Nassif and Moujaes does not use any type of sensors to monitor environmental changes. Although their system is supposed to have the ability to control the amount of fresh air coming in from outside, it is difficult to do so without the use of any sensors. The system will be running constantly to replace air, which will increase the energy usage for the HVAC control system.

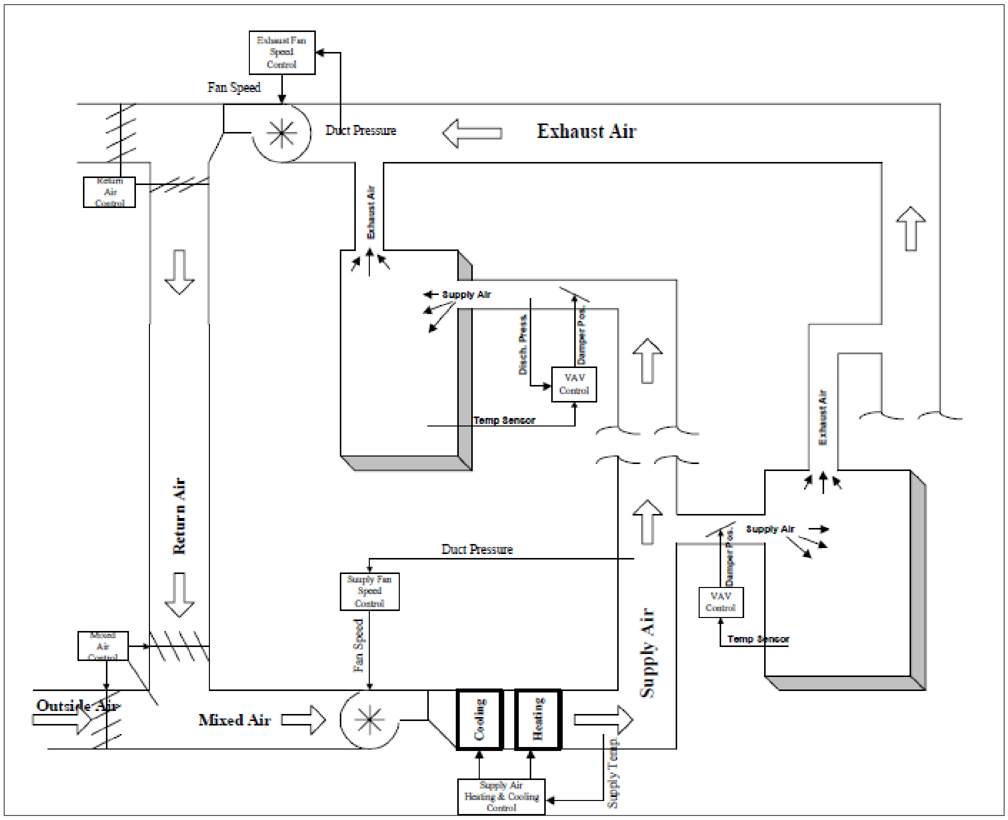

Figure 1: The VAV model by Ben-Aissa

In addition to research groups, many companies developed different types of thermostats used to control HVAC systems. The smart thermostat is the latest development in thermostats and HVAC control systems [7]. Honeywell Lyric, ecobee3, Aprilaire, and Nest are examples of a smart thermostat system [8]. Smart thermostats have various features and access through the Internet. The scheduling feature of a smart thermostat keeps the temperature at specific levels depending on user settings for the time of the day. Smart thermostats have the capability to connect to a Wi-Fi router. As such, it can be controlled using a smartphone or a computer. The user has the ability to remote access the thermostat from anywhere with web access. Although smart thermostats have various features, they only use a temperature and humidity sensor to control the HVAC control system. Smart thermostats don't have the ability to control the indoor air quality.

They are designed to be more user-friendly and keep the temperature and humidity within occupants' comfort levels.

2.2 Previous Research

The existing technology section showed that there is minimal research into using a wide range of sensors in an HVAC control system. Thus, the usage of multiple sensors that can provide data on the current indoor air quality and the environmental conditions of a semi-enclosed area is essential. From previous Federal Aviation Administration (FAA) and National Institute of Health (NIH) funding, Hartman Systems Integration Laboratory has developed an In-Home Air Quality Monitoring (IHAQ) system. IHAQ has been adopted into this research with minor modifications. This system will be used to obtain sensor readings in managing indoor air quality. We are able to use IHAQ because it has been designed to be adapted for other research projects. The flexibility of the sensing system allowed it to be easily integrated into other systems.

The main design aspect for a flexible and generic sensing system is the motherboard. In order to have a wide range of sensors and the ability for adapting to meet the changes needed for a flexible system, a motherboard must be designed in such a way that it can provide broad resources for various sensors. The design must include a way for transmitting the data and storing the measurements on the motherboard. The actual size of the system must be taken into consideration, to allow the usage of a wide variety of sensors. Finally, the power consumption must also be considered to make sure that the power and voltage supplied by the motherboard can accommodate all the sensors.

2.2.1 In Home Air Quality Monitor (IHAQ)

The IHAQ system was designed and implemented by the Hartman Systems Integration Laboratory. The purpose of the research was air quality monitoring inside homes. The target of the design was to create a flexible sensing system that has the capability to operate as a stand-alone unit and as a group (wireless sensor network), with the ability to save these measurements on onboard non-volatile memory and transfer the data to a computer for live analysis. Figure 2 illustrates the full sensing system unit in the enclosure. The figure shows the inlet and outlet for airflow needed to measure the airborne particulate, the Liquid Crystal Display (LCD) screen for the user interface, and the buttons to change the display on the LCD screen.

Figure 2: The IHAQ sensing system in full enclosure

The major electronic components of the sensing system are the microcontroller, the sensors, communication hardware, storage, the user interface, and power management. The architecture of the IHAQ sensing system hardware is shown in Figure 3.

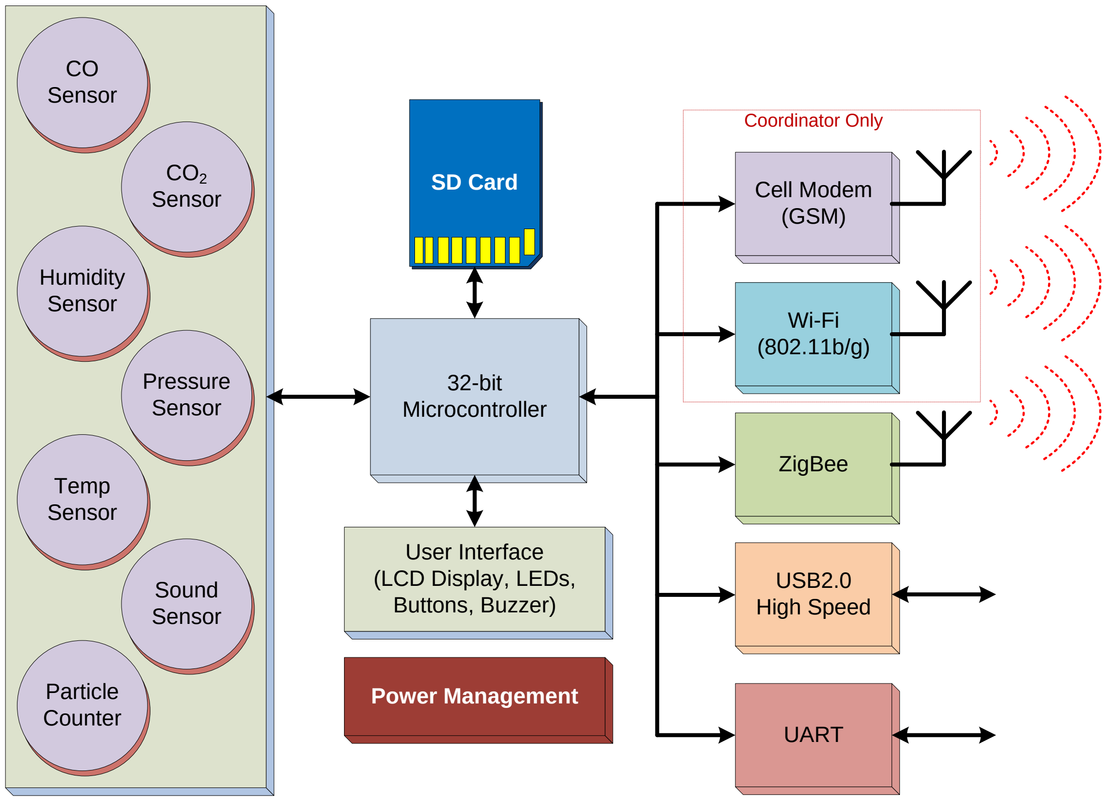

Figure 3: IHAQ Sensing system major hardware components [9]

In order to provide the resources required for different sensor types, a microcontroller had to be selected that could offer a selection of peripheral devices, handle various communication protocols, run at high speeds, and include the large memory needed for a large codebase. In general, any embedded system requires the general peripheral devices and communication protocols. Devices such as Analog to Digital Converters (ADC), General Purpose Input/Output (GPIO) pins, and Direct Memory Access (DMA) are commonly needed peripherals for an embedded system. Some of the useful communication protocols required to communicate with the sensors are the major protocols such as Inter-Integrated Circuit (I^2C), Serial Peripheral Interface

(SPI), Universal Asynchronous Receiver Transmitter (UART), and Universal Serial Bus (USB) interface. Taking all of these factors into consideration, the Atmel's 32-bit ATUC3A3256S microcontroller was chosen to be used on the in-home air quality monitoring system (IHAQ). The performance of the microcontroller and the different types of peripherals and communication protocols are the reason this microcontroller was chosen to be used on the IHAQ project.

Different communication mechanisms are used to acquire sensor measurements and communicating the status of the sensors. I^2C, SPI, UART, or ADC/DAC protocols allow the microcontroller to interact with and obtain the latest data from the various sensors. They are also used to interface to the user interface and to store measurements onto a non-volatile storage device, such as a Secure Digital (SD) card, on the system. The other usage is to transmit the sensor data and/or to connect to a computer to graph the measurements. This allows the user to graph the measurements while the system is running. The sensing system is configured with a UART connection and USB interface. These communication interfaces are used to connect the system to a computer when wireless transmission is not available. UART and USB are serial communication with the computer that gives the ability to read the sensor data using serial protocol software.

Any sensing system requires the guaranteed integrity of sensor data. Sometimes a malfunction in the system can happen. A malfunction will result in lost communication with the outside world (e.g., sensor gateway or computer). The sensing system requires on-board non-volatile data storage to save all the sensor measurements to be used for later processing. The sensing system is equipped with a sizable SD card for data storage. This will allow the sensing system to run for weeks without the need to move the sensor measurements out of the SD card. The data saved on the SD card can be accessed by removing the SD card from the sensing system and plugging it into a computer. The data and measurements can also be accessed by connecting a USB cable between the computer and the sensing system on startup.

The IHAQ sensing system includes a variety of sensors that measure CO_2, CO, temperature, humidity, pressure, and sound level. The reason behind choosing these sensors is because the focus of the IHAQ sensing system is environmental monitoring. These sensors were chosen to measure different conditions that are directly related to people's health and comfort. The sensors were chosen carefully to measure ranges that can be encountered by occupants during normal daily life.

Interfacing with all of these sensors at the same time is complicated and challenging. Some of these sensors can be easily accessed using a standard digital interface or communication protocol by connecting directly to the microcontroller. Other sensors require some type of voltage or current amplification circuit connected to an analog-to-digital converter chip that will use I^2C or SPI to communicate with the microcontroller. The different types of sensors change the hardware being used to communicate with the different sensors. They also change the firmware design since the various sensors require different types of communication code.

One of the essential parts of the sensing system is the airborne particulate matter sensor. The IHAQ sensing system can provide a real-time assessment of the air quality using the airborne particulate counter. The system has an airflow channel with a fan that collects a sample of the air from the surroundings. The hardware for the airborne particulate counter uses a laser that shines into the airflow channel, creating a scatter whenever airborne particulates are in the channel. An analog circuit converts the scattered light from the laser into an analog signal. This analog signal is then converted to a digital signal by the microcontroller's analog-to-digital converter. The microcontroller translates these readings into particle counts in an air volume. These data are presented in two different sizes (large: > 1µm, or small: <1µm) and the respective counts.

2.2.2 Firmware Design

The design of the motherboard, the sensor interfaces, and communication protocols are only half of a flexible sensor system. The other half is the firmware implementation. The firmware is written into multiple layers of code, with each layer having its own set of independent software modules. Each one of these modules has a well-defined task. The different layers of firmware and the independent modules provide better portability and greater flexibility for the system. This allows for easier integration of new sensors or different communication devices, or even moving the full code base into a different microcontroller. Figure 4 gives an idea of how the firmware design is layered into high and low level code. The high level layer includes the general sensor application and modules specific to each sensor. The other major part of the high level code includes the system time and the scheduler required to run the different tasks of the program. It also includes communication code needed to communicate with the various sensors. The low level part of the code deals with the microcontroller level software. In this level, the system deals with the device addresses, system registers, and the low level communication protocols.

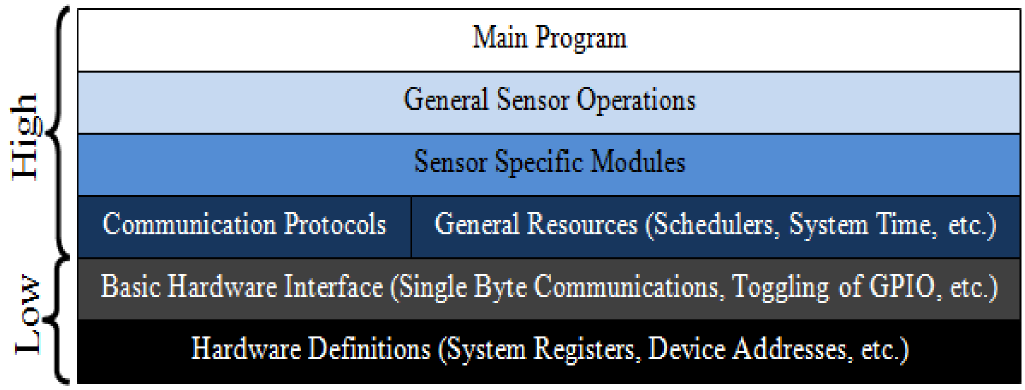

Figure 4: Code Layering Diagram

2.2.3 Application to Current Research

The research for this thesis uses the IHAQ as the sensing system. IHAQ has the various sensors required for this work. Using the IHAQ's sensor data, the control system will have the ability to determine the quality of the indoor air and the management of the environment. The IHAQ sensing system requires minor hardware and firmware modifications for communicating with the HVAC control system. Since the decision has been made for the sensing system and control system to communicate wirelessly, it is necessary to add a wireless transceiver and associated firmware.

CHAPTER 3: MANAGING AIR QUALITY

Air quality refers to the state of the air around us. Good air quality indicates clean and unpolluted air. Pollutants can decrease the air quality and change it from clean to harmful. Poor air quality occurs when pollutant levels reach concentrations that can endanger humans' health. Understanding the exposure and the sources of these pollutants is essential to be able to control indoor air quality. Ultimately, it will be helpful in determining how to manage indoor air quality and keep the air quality at a good and clean level.

3.1 Pollutants Exposure

We face a variety of health risks as we go about our day-to-day lives. Whether we are commuting by car, flying in commercial airlines, or engaging in recreational activities, exposure to environmental pollutants is unavoidable. There are some we choose to accept because to do otherwise would restrict our ability to live. There are some we choose to avoid if we have the information to make informed decisions. Indoor air pollution is one risk that you can do something about.

Controlling air quality refers to all the activities and actions required to establish that the air we breathe is safe. The air quality management process is a system of understanding the sources that contribute to the pollution of the air inside an enclosed environment, the health effects of these pollutants on the occupants, and the steps required to reduce and/or control these sources to reach or maintain cleaner air.

A growing body of scientific evidence suggests that the air within homes and other buildings can be more seriously polluted than the outdoor air in even the largest and most industrialized cities [10]. Other research indicates that people spend approximately 90% of their time indoors [11]. Thus, for many people, the risks to health may be greater due to exposure to air pollution indoors than outdoors. It has also been shown that air circulating through a high-efficiency filter does reduce contaminants [9]. For the filter to be effective, it needs air circulation.

Interestingly, people who may be exposed to indoor air pollutants are often those most susceptible to the effects of indoor air pollution. Such groups include the young, the elderly, and the chronically ill, especially those suffering from respiratory or cardiovascular disease.

3.2 Indoor Pollutant Sources

There are many sources of indoor air pollution in an enclosed environment. Some of these pollutants come from sources such as combustion (airborne particles of different sizes and harmful gases), building materials (airborne particles of different sizes and outgassing), and furnishings (outgassing). Combustion pollutant sources include oil, gas, kerosene, coal, wood, and tobacco products. Building materials and furnishings can be very diverse. For example, asbestos insulation, wet carpet, cabinetry, and furniture made of some pressed woods are different examples of building materials and furnishings that release pollutants [1]. Household cleaning and maintenance chemicals and personal care products can add contaminants to the indoor air. These pollutants decrease indoor air quality and can be a health risk to occupants.

Figure 5 shows the different indoor pollutant sources inside a house [12]. The indoor pollutant sources can be divided into biological, chemical, and toxic material pollutants. Each of these will be discussed in the following sections.

Figure 5: Different pollutant sources inside a house [12]

3.2.1 Biological Pollutant Sources

Biological pollutants include viruses, bacteria, pet saliva, molds, and dust mites. These pollutants can cause serious health issues. Contaminants like bacteria can trigger allergic reactions such as pneumonitis and asthma. Viruses can cause infectious illness such as influenza. A common source for biological pollutants is mold. It grows in the dark and humid areas around the house. Mold can trigger an allergic reaction in some people, including eye or throat irritation, coughing and headaches. Pets are a major source of indoor air pollutants [13]. According to the U.S. Environmental Protection Agency (EPA) [13], pets can be significant triggers for different diseases because of dead skin, hair, feces, urine and saliva. All of these biological contaminants are a direct risk to occupants' health. Since it is difficult to eliminate the sources, using an HVAC control system to control and manage the air quality inside enclosed areas will decrease the probability of health issues. By introducing fresh air, contaminants will be reduced through dilution.

3.2.2 Chemical Pollutant Sources

Some of the common indoor chemical pollutants can be in the form of gases such as CO. CO is odorless and dangerous. It stops the body from using the oxygen to work normally, which causes fatigue, headaches, dizziness, and high heart rate. If the concentration of CO is high enough, it can result in death.

Radon is another common source for indoor pollutants. It's a radioactive gas that comes from the rocks and soil. Radon is odorless, colorless, and tasteless, which makes it particularly dangerous. Long-term exposure to this gas at elevated levels can result in lung cancer [1].

3.2.3 Toxic Pollutant Sources

The Environmental Protection Agency classifies toxic air pollutants as those pollutants that may cause cancer or other serious health issues [14]. Examples of toxic pollutants include benzene (e.g., found in gasoline) and perchlorethylene (e.g., found in dry cleaning facilities). Lead is also a common source of indoor air pollutants. Lead is a soft metal that can be very toxic if consumed. It was widely used in paint in the 1970s.

Lead particles and dust can become airborne, leading to dangerous indoor air pollution. Exposure to lead can damage the brain and nervous system. It can also affect and delay growth in children [13].

3.2.4 Indoor Particulates

Most people in the U.S. spend 90% of their time indoors [11], resulting in greater exposure to indoor pollutant sources such as particulate matter. Particulates are tiny airborne particles of various materials such as dust, soot, and other materials. Particulate matter (PM) includes a wide range of different particles that are small enough to be carried by air and can be breathed in by people. Dust is the biggest source of indoor particulates. It’s generated from outside sources, house dust, and tobacco smoke. Wood stoves and furnaces can generate a huge number of particulates in the air. The particulates in an enclosed environment can cause different health issues, such as irregular heartbeat, aggravated asthma, decreased lung function, and non-fatal heart attacks.

The relative importance of any single source depends on the amount of a given pollutant it emits and hazardous level those emissions are. In some cases, factors such as how old the source is and whether it is properly maintained are significant. For example, an improperly adjusted gas stove can emit significantly more particulates and CO than one that is properly adjusted.

Some sources, such as building materials, furnishings, and household products like air fresheners, release (outgassing) pollutants more or less continuously. Other sources related to activities carried out in the home release pollutants intermittently. These include smoking; the use of unvented or malfunctioning stoves, furnaces, or space heaters; the use of solvents in cleaning and hobby activities; the use of paint strippers in redecorating activities; and the use of cleaning products and pesticides in housekeeping. High pollutant concentrations can remain in the air for long periods after some of these activities.

3.3 Controlling Indoor Air Quality

Indoor air quality in a semi-enclosed environment needs attention. As shown in the previous sections, there are numerous sources for indoor pollutants. These have direct effects on indoor air quality and occupants' comfort, health, and productivity. Most occupants don't notice when indoor air quality is good, but most people will recognize when the air is not good. Indoor air quality is a problem when there is a high number of particulates in the air, when the temperature and humidity levels are not within the comfort zone of occupants, and when CO_2 levels are high in the enclosed environment.

Acknowledging that air quality inside an enclosed environment is worse than outside is critical to manage and control air quality inside these enclosed environments. Moving the air in and out of an enclosed environment, using filtration, and controlling the temperature and humidity levels are essential in keeping the indoor air quality at acceptable levels and keeping occupants healthy and comfortable.

3.3.1 Ventilation and Circulation

Controlling the particulate matter, CO_2, temperature, and humidity inside an enclosed environment can be accomplished with minor modification/redesign of an HVAC system. The objectives are to use sensors to sense when circulation and ventilation are needed. With the use of filters and the introduction of fresh air using regulated valves and vents, pollutants can be removed and diluted. Using sensors, vents, fans, and control systems can be very effective in ventilating enclosed places and minimizing sources of indoor pollution. Places adhering to guidance from ASHRAE standard 62.2 for home ventilation will have better indoor air quality.

The rate at which outdoor air is supplied to an enclosed area is specified by the ASHRAE standards. Supply rates are based primarily on the need to control the air quality inside an enclosed place. The supply rates dictate how to control odors, CO_2, and indoor contaminants. CO_2 is a component of the air, but excessive amounts of CO_2 indicates inadequate ventilation. ASHRAE refers to supply rates as ventilation rates which are expressed in units of cubic feet per minute per person (cfm/person) [15].

Control of pollutants at the source is the most effective strategy for maintaining clean indoor air. Unfortunately, it’s not always possible or practical to control pollutants at the source. Ventilation and circulation are the next most effective methods to control and manage good air quality inside any enclosed environment. The common practice in the past was to open windows to air out a stuffy room. Also, the air pressure differences between indoors and outdoors provided ventilation through leaks that allowed fresh air from the outside to get inside an enclosed place.

Natural ventilation, unlike forced ventilation, uses natural forces of wind to deliver fresh air into buildings. Some enclosed places use only natural ventilation or exhaust fans to remove odors and contaminants. In these places, thermal discomfort and unacceptable indoor air quality are likely to occur when the occupants keep the windows closed because of extreme hot or cold temperatures. According to the National Institute for Occupational Safety and Health (NIOSH), under-ventilation is also likely to happen during swing seasons [16]. Keeping the air quality inside an enclosed environment within an acceptable level is difficult when natural ventilation is used, especially when natural ventilation affects the temperature and humidity levels without proper control or regulation. This requires the use of a controlled system that manages the heating ventilation, circulation, heating, cooling, and air conditioning.

HVAC system refers to the equipment that provides heating, cooling, filtered outdoor air, and humidity control. This will maintain the comfort condition for occupants inside an enclosed environment. Traditionally, HVAC is controlled with just a temperature sensor. The proposed HVAC system for this work will depend on several factors, specifically CO_2, temperature, humidity, and particulate matter.

The quality of air inside workplaces, offices, and homes is important for the occupants' health and comfort. With a leaky structure, outside air was introduced (unintentionally) to the enclosed space through cracks. However, this is problematic as the uncontrollable introduction of fresh air can cause increased energy usage. With spaces being built tighter for high energy efficiency, mechanical ventilation seems to be the best solution for managing air quality.

ASHRAE Standard 62.1, Ventilation for Acceptable Indoor Air Quality [17] sets the minimum ventilation rates for indoor air quality. The standard applies to all types of buildings such as hotels, retail stores, schools, sport facilities, and other commercial buildings. ASHRAE specifies rates at which outdoor rate must be supplied to each room within the enclosed environment from 15 to 60 cfm/person [17].

Table 1 shows the minimum ventilation rates established by ASHRAE Standard 62.1 2004 for some common places, interpreted per person and per area. The occupant density, used when the number of people is not known in a specific area, refers to the default number of people in 1000 ft^2. The combined outdoor air rate is the minimum ventilation required per person for 1000 ft^2, based on the default occupant density.

Table 1: ASHRAE Standard 62.1 2004 minimum ventilation rates in breathing zone [17]

Occupancy Category	Outdoor Air Rate per Person		Outdoor Air Rate per Area		Occupant Density	Combined Outdoor Air Rate	
	cfm/ person	L/s* person	cfm/ft^2	L/s* m^2	#/1000 ft^2	cfm/ person	L/s* person
Educational Facilities							
Day Care	10	5	0.18	0.9	25	17	8.6
Classroom	10	5	0.12	0.6	25	15	7.4
Lecture Hall	7.5	3.8	0.06	0.3	150	8	4
Science Laboratories	10	5	0.18	0.9	25	17	8.6
Food and Beverage Service							
Restaurant dining rooms	7.5	3.8	0.18	0.9	70	10	5.1
Cafeteria/fast food dining	7.5	3.8	0.18	0.9	100	9	4.7
Bars	7.5	3.8	0.18	0.9	100	9	4.7
Office Buildings							
Office Space	5	2.5	0.06	0.3	5	17	8.5
Reception Areas	5	2.5	0.06	0.3	30	7	3.5
Entry lobbies	5	2.5	0.06	0.3	10	11	5.5
Public Spaces							
Courtrooms	5	2.5	0.06	0.3	70	6	2.9
Libraries	5	2.5	0.12	0.6	10	17	8.5
Museum	7.5	3.8	0.06	0.3	40	9	4.6
Retail							
Mall Common Areas	7.5	3.8	0.06	0.3	40	9	4.6
Supermarket	7.5	3.8	0.06	0.3	8	15	7.6
Coin-operated Laundries	7.5	3.8	0.06	0.3	20	11	5.3

Additionally, ASHRAE Standard 62.2, Ventilation and Acceptable Indoor Air Quality in Low-Rise Residential Buildings [18], specifies the minimum ventilation required for homes based on the number of rooms and the total area of the house. ASHRAE Standard 62.2 allows local ventilation exhaust (e.g., bathroom fan or kitchen exhaust fan) and whole building ventilation. This means that simple exhaust fan or supply fan or a combination of both can be used to ventilate homes and increase quality of air inside semi-enclosed areas. ASHRAE Standard 62.2 provides a specific equation to calculate the minimum ventilation required for homes. Equation (1) shows how to calculate the minimum ventilation required for homes. Q_{fan} stands for the minimum ventilation required measured in cfm. A_{floor} stands for the air conditioned floor area measured in ft^2 and N_{br} stands for the number of bedrooms in the house.

$$Q_{fan} = 0.01\ x\ A_{floor} + 7.5\ x\ (N_{br} + 1) \qquad (1)$$

For example, if the area of a house is 3000 ft^2 and it has 3 bedrooms and 2 bathrooms, then the calculations for the minimum ventilation required will be as in Equation (2).

$$Q_{fan} = 0.01\ x\ 3000 + 7.5\ x\ (3 + 1) = 60\ cfm \qquad (2)$$

Equation (1) specifies the minimum ventilation required for acceptable indoor air quality in a home, excluding the exhaust ventilation for kitchens and bathrooms. ASHRAE Standard 62.2 does indicate that the minimum ventilation required for kitchens is 100 cfm and 50 cfm for each bathroom. This means the total ventilation needed is 260 cfm.

3.3.2 The HVAC System

Figure 6 shows the overall layout of the proposed HVAC system. The semi-enclosed environment could be a single-family home or a commercial building. The sensor in the figure represents a sensing system that has the ability to measure different types of environmental conditions. The sensing system can measure sensor data such as temperature, humidity, CO_2, and airborne particulates. This system will send these sensor data to the control system, which will make decisions to manage the indoor air quality and control the environmental conditions inside the semi-enclosed space.

The sensing system will communicate wirelessly, using Bluetooth, with the HVAC control system. The HVAC control system will receive sensor data from the sensing system. The control system will then make decisions to control four different devices. It will control a fan, which simulates the fan in the HVAC unit. It will also control a damper, which acts as the ventilation device. Whenever the damper opens, it allows fresh air from the outside to get pulled into the enclosed environment.

The ventilation and circulation process will control the air quality inside the enclosed environment. For example, when the CO_2 concentration inside the enclosed place is higher than a certain level, the HVAC control system will run the fan and open the damper to allow fresh air with acceptable air quality to enter the enclosed area. Another example is when the particulate counter from the sensing system measures high levels of particulates, the HVAC control systems will turn the fan ON. Turning the fan ON will allow the air to circulate inside the enclosed environment. The circulated air will be filtered, which reduce the number of contaminants inside the enclosed area. This approach leads to better air quality in the enclosed environment.

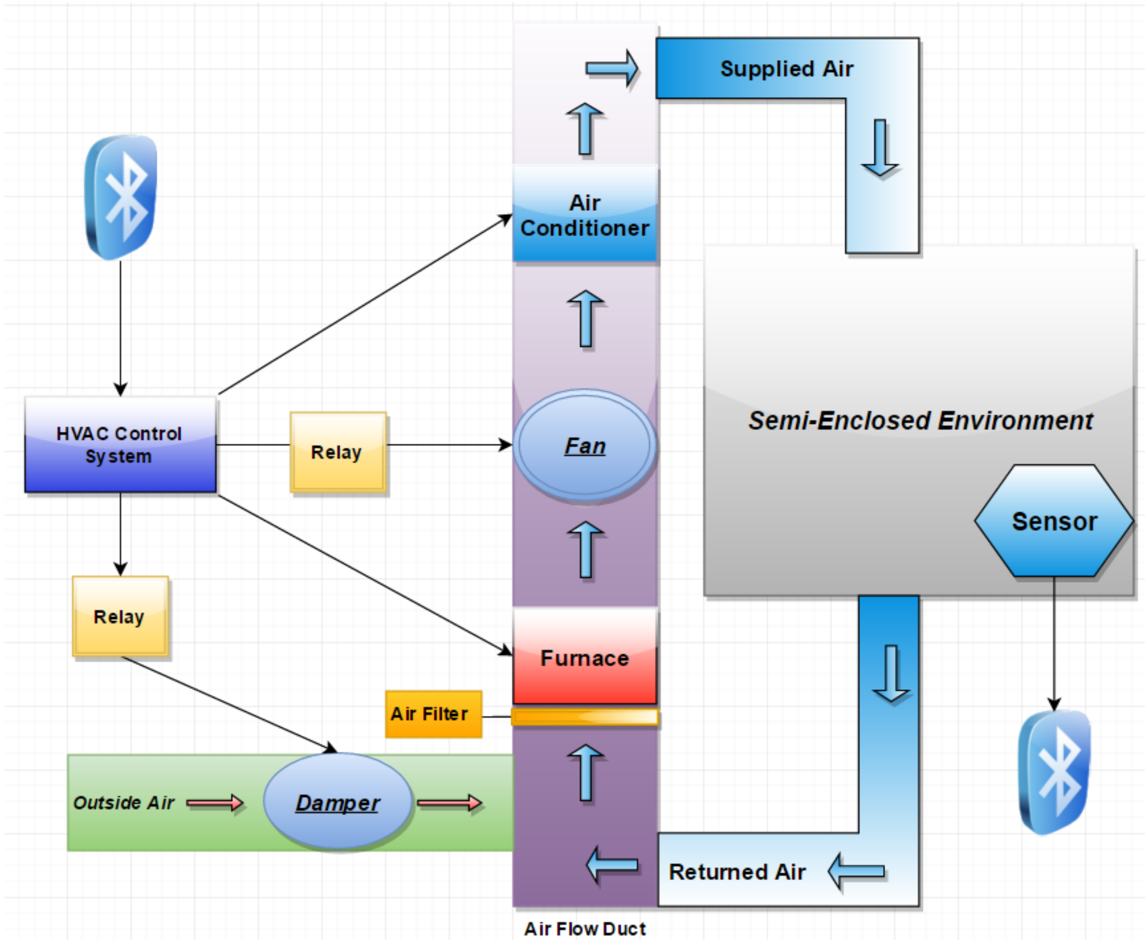

Figure 6: Overall Layout of the Current Research Plan

The third element is the air conditioning unit, and the fourth is the furnace unit. These two will only be simulated through the device using Light Emitting Diode (LED). Table 2 shows a list of the simulated physical and simulated devices used during the work of this thesis.

Table 2: Phyiscal and Simulated Devices list

Physical Devices Used	Simulated Devices using LEDs
Ventilator Circulator	AC Furnace Humidifier Dehumidifier

CHAPTER 4: HARDWARE DESIGN

The hardware used to prove the feasibility of the air quality management can be divided into two major parts: the control system and the sensing system. The control system refers to the system that controls ventilation, circulation, air conditioner, furnace, humidifier, and dehumidifier. This system manages all the devices while receiving sensor data from the sensing system. The sensing system (refers as IHAQ) is the sensing system that monitors sensor measurements changes and send them to the control system.

4.1 HVAC Control System

The key design aspect of an HVAC control system is the motherboard. The motherboard must be designed so it can provide a sufficient number of interfaces for controlling valves and turning devices/appliances on/off. Power consumption for the control system is important, as it will be on 24 hours/day and 7 days/week.

Figure 7 is a block diagram of the control system. The microcontroller is the brain of the control system. There are interfaces for appliances and devices. Bluetooth wireless transmission has been selected to wirelessly connect the sensing system to the control system. The use of wireless connection allowed the sensing system to be placed at any desired location without the limitation of wired connection. With the received sensor data, the control system can make a decision on what to activate (cooling, heating, damper, ventilator, circulator, humidifier, or dehumidifier).

Cooling or heating requests from the control system will cool or heat the air, respectively, in the semi-enclosed space. The role of ventilator is the control of a damper that allows fresh air (e.g., outside air) to be introduced into the semi-enclosed space. The ventilator's damper is activated when a high CO_2 level has been detected and will continue to be active until CO_2 is within an acceptable range.

The purpose of the circulator is to circulate air within the semi-enclosed environment. The circulator can be used with or without activation of the ventilator. Usually, the circulator will be activated when there are no requests for cooling or heating for an extended period of time. The objective is to mix the air.

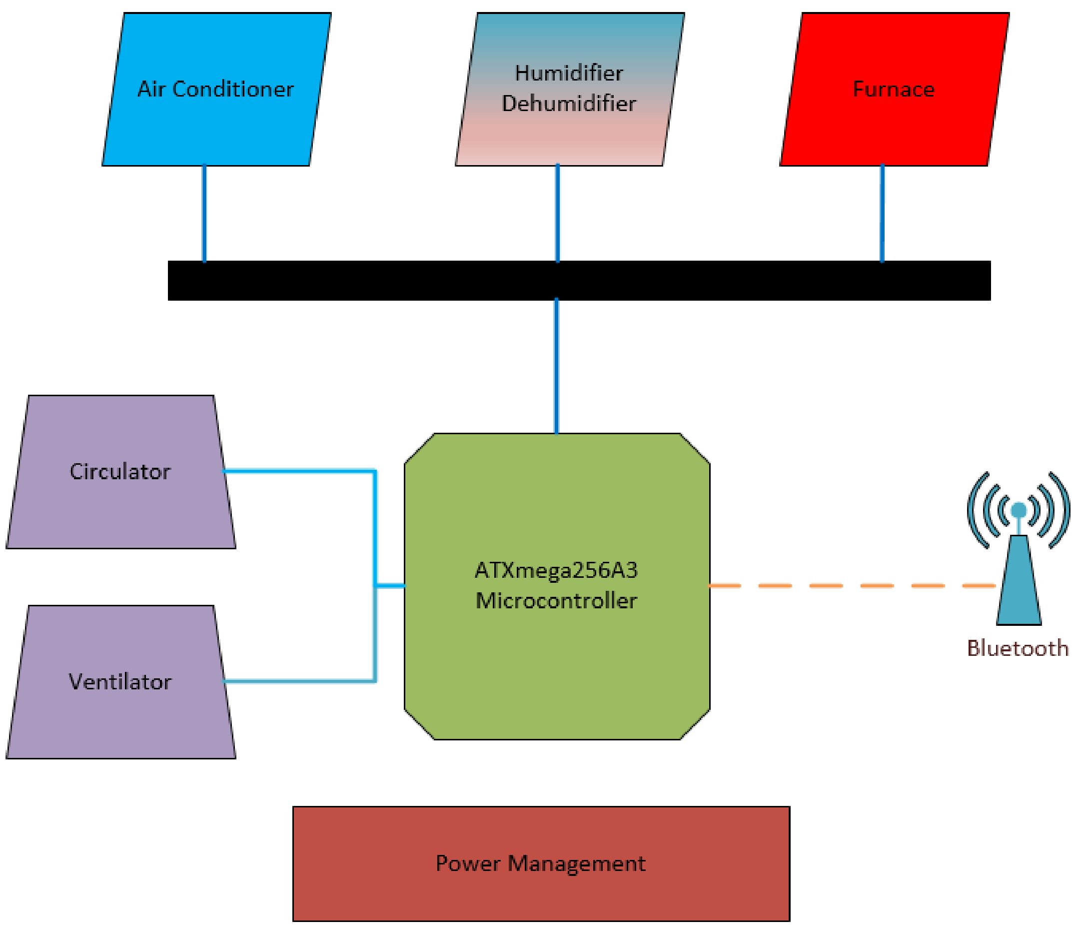

Figure 7: The connection of the different parts on the HVAC control system

Figure 8 shows a prototype. The board has been populated with the ATXmega256A3 microcontroller (#1) and RN-42 Bluetooth transceiver (#2) as shown in the previous figure. The power management circuitry (#3) is placed on the bottom portion of the finished board. The connectors for relays (ventilator and circulator) and LEDs used to simulate temperature and humidity control (air conditioner, furnace, humidifier, and dehumidifier) are #4 and #5, respectively, in Figure 8. The area designated as #6 is the programming connection required to program and debug the microcontroller.

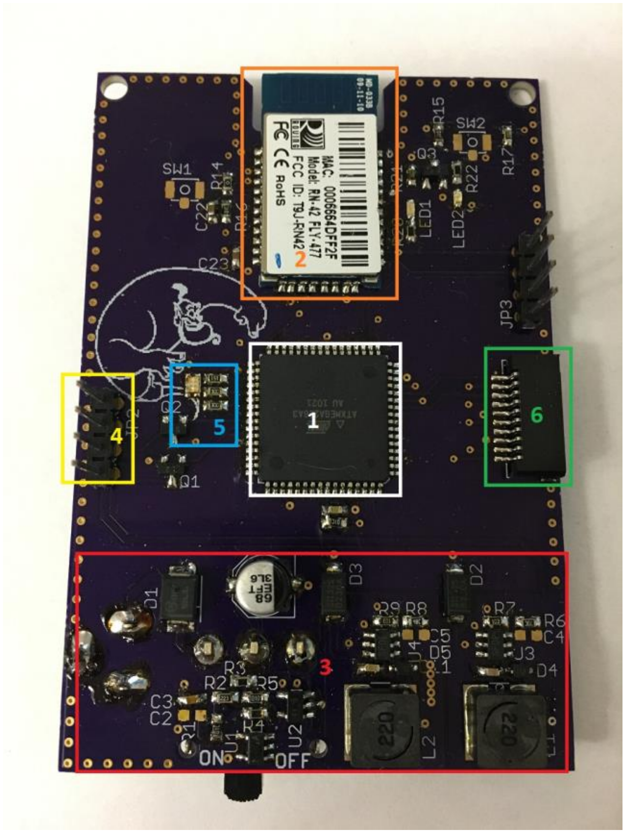

Figure 8: The HVAC control system board

4.1.1 The Microcontroller

The HVAC control system is designed around an Atmel ATXmega256A3 microcontroller. This Atmel microcontroller is based on an 8-bit RISC CPU. The microcontroller includes 256 kB of flash memory and 16 kB of SRAM. It can be clocked at up to 32 MHz [19], and has enough input/output interfaces (pins) for interface with HVAC appliances and devices.

There are multiple UART communication transceivers. UART can be used for system debugging and communicating with appliances/devices. The microcontroller also has different timers and counters that can be used to control the system. This microcontroller contains a Real-Time Clock (RTC) function for time-stamping, and for overall operation and management of the HVAC control.

This particular microcontroller was chosen for the implementation of the HVAC control system due to its rich peripheral set, adequate internal memory, performance, and available software framework. This allows a good portion of the HVAC control system to be implemented within the microcontroller without the need for external devices/circuitry.

4.1.2 Power Management

The availability of various voltage levels for any HVAC control system can be a limiting factor for the type of appliances/devices it can control. Various voltage regulators can be built into the design of the control board to meet these requirements. The board must also supply power (usually 3.3V) to devices such as the microcontroller and the communication interfaces. The ventilation and circulation controller device requires 5V for their operation (relays). For these reasons, the HVAC control system motherboard has been designed with 3.3V and 5V regulators.

The design goal for the HVAC control system dictates that the device should be able to function reliably for extended periods of time. With this in mind, the HVAC control system board was designed to run off an external wall transformer. Figure 9 shows the design power circuitry. The outlet on the figure represents the wall transformer that powers the control system. The control system board can be powered using a voltage range of 7.3V-20V. The design in this thesis utilized a 12V wall transformer. The power circuit has a voltage supervisor circuit that automatically shuts down the system when the external voltage is below 6.3V. The voltage supervisor circuit is represented by the comparator shown in Figure 9.

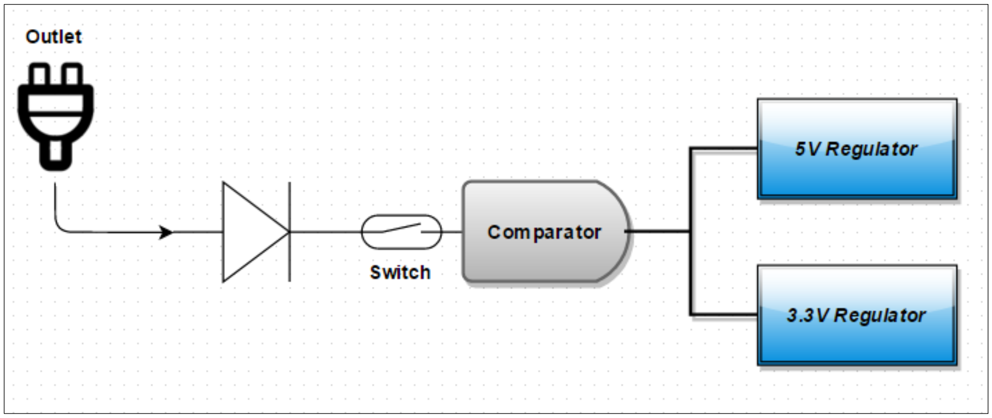

Figure 9: The power circuit of the HVAC control system board

4.1.3 Wireless Communication

The sensing system communicates wirelessly with the HVAC system board, which requires some type of wireless transceiver. Designing a quality system requires understanding the differences between the numerous wireless transceivers that can be used. Various wireless devices were evaluated to choose the most suitable device for this research. Since different wireless transceivers use different communication protocols, the evaluation included the type of communication protocol used for each transceiver.

Table 3 summarizes the advantages and disadvantages of each wireless device. Wired communication between the sensing system and the HVAC control system has traditionally been hard-wired. The length of wired communication can create signal quality issues, which is one reason that traditional HVAC systems use 24V AC rather than 24V DC.

As a proof of concept, a Bluetooth device was used for wireless communication. Prototyping using Bluetooth made the process quicker than using Wi-Fi. Granted, wired communication would have been quicker, but using wireless communication between the control and the sensing systems is part of the current work for this research.

Using Bluetooth class 1 increased the range needed for the communication between the sensing system and the control system. Bluetooth uses a simple UART communication between the microcontroller and the Bluetooth device. This type of communication protocol does not require much overhead from the microcontroller. Since UART does not check if a packet has been received, this can be done by the software.

Table 3: Comparison between the different type of devices and methods that can be used for communication

Method/Device	Explanation	Advantages	Disadvantages
Wired Connection	Uses wire connection to connect the sensing system and the control system.	• It's simple • Least expensive	• Can take a lot of wires to connect the full system. • Sensing location is fixed
Wi-Fi with TCP/IP	Uses Wi-Fi with TCP/IP protocol to communicate among different systems.	• It can be a reliable system when designed correctly. • The guarantee of the commands reaching a specific module. • TCP/IP automatically breaks the data that needs to be sent.	• It's much more complicated than the other methods. • TCP/IP requires much processor overhead. • TCP/IP requires specific connection to each module to be able to communicate with it. • Wi-Fi is energy inefficient
Wi-Fi with	Uses Wi-Fi with	• Much faster than	• No guarantee of

UDP	UDP protocol to communication among different systems.	TCP/IP • Can be used to broadcast a message to all the other systems.	transmission • UDP requires some overhead to communicate with other modules. • Wi-Fi is energy inefficient
Bluetooth	Uses Bluetooth transceiver to communicate among different systems.	• Energy efficient • Little processor overhead.	• Shorter range • Not very reliable

4.1.4 Ventilator and Circulator

Understanding the required ventilation rate for indoor air quality allows the system designer to size the ventilator to supply that air. The minimum ventilation required by the ASHRAE standards was discussed in Chapter 3. In this research, we selected an 8" inch damper as the ventilator (see Figure 10) to simulate supplying fresh air into the enclosure space. A duct fan is also used to simulate the furnace fan (see Figure 11). This fan is being controlled by the HVAC control system to manage the circulation. Since the fan by itself does not allow outside air to replace the inside air, a ventilator (damper) was integrated into the HVAC control system design.

Dampers are commercially used to regulate the flow of air in HVAC control system. For this thesis, a damper was integrated with the HVAC control system to manage the fresh air intake from outside and work with the ventilator. Figure 10 shows the damper used on the HVAC control system. It is being controlled by the microcontroller on the HVAC control system board through a relay.

Figure 10: 24VAC Damper used on the HVAC control system board

Figure 11: A duct fan to simulate furnace fan from VenTECH with 400 cfm

The HVAC control system is a DC system, while both the fan and damper are AC devices. Thus, a relay was used to allow the HVAC control system to control the fan and the damper. A relay is an electrical device that controls the flow of current through it in one circuit, and is switched ON and OFF using a different circuit. The diagram shown in Figure 12 illustrates the connection between the microcontroller and the relay through a

MOSFET. The microcontroller sends an enable signal to the relay to turn it ON. Turning the relay ON will enable the AC circuit that has the fan or the damper connected to it. Thus, the relay works as the interface that allows the microcontroller to control the fan and the damper. Figure 13 shows the connection between the HVAC control system board and the two-channel relay used to connect to the fan and damper.

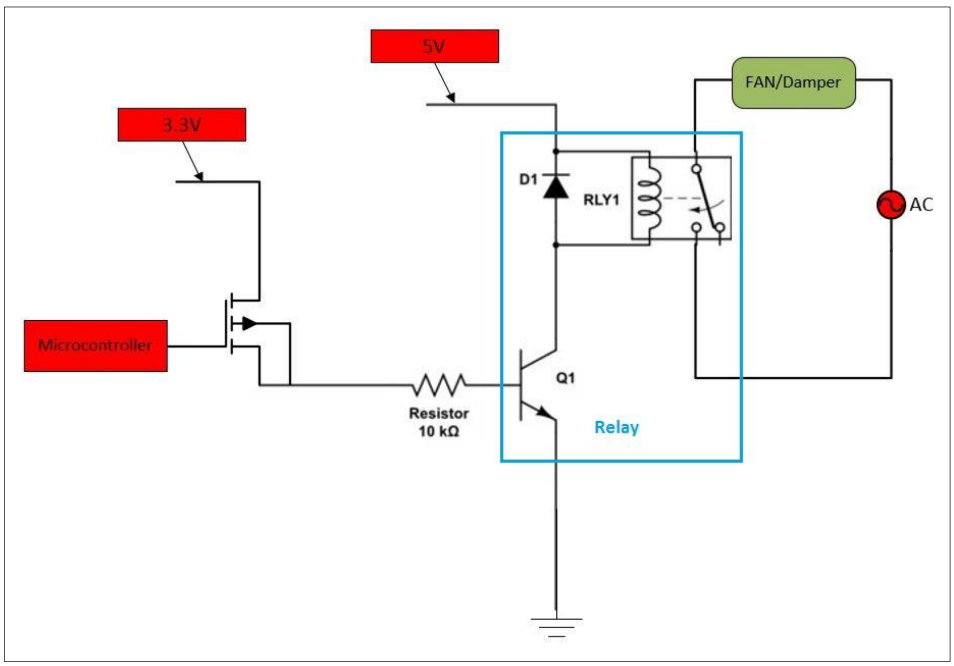

Figure 12: The HVAC system control connected to a relay then to the AC power

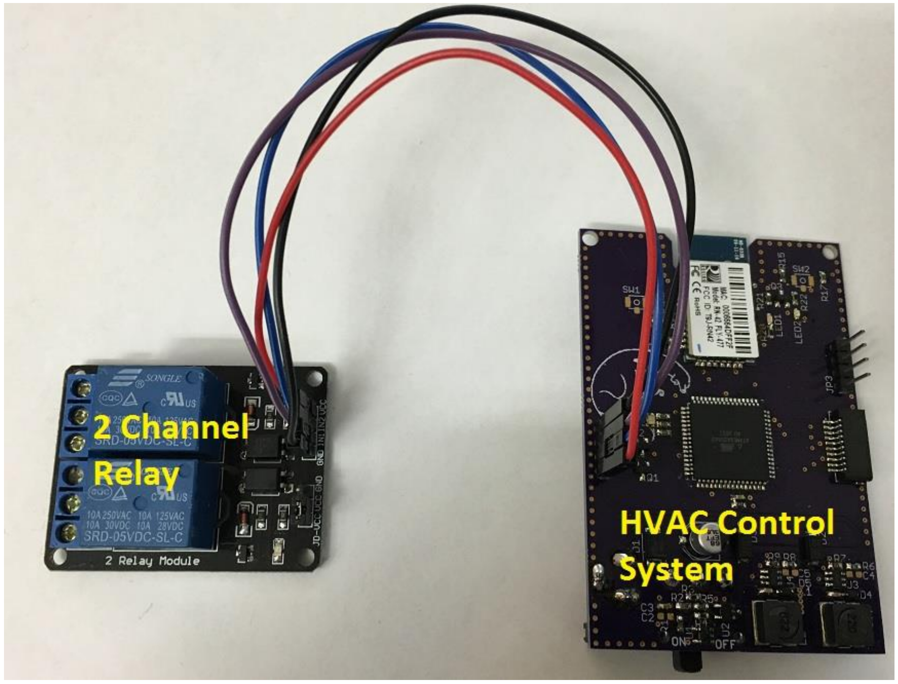

Figure 13: HVAC control system connection with 2 channel relay

4.1.5 Air Conditioner, Furnace, Humidifier, and Dehumidifier

HVAC control systems are designed to keep occupants comfortable within a semi-enclosed environment. Occupants have different comfort levels, e.g., 70°F is considered as comfortable by some and others may find that to be cold. There is no specific temperature or humidity setting for comfort. ASHRAE Standard 55 prefers temperature and humidity settings between 68˚F to 72˚F and 20% and 60%, respectively. Thus, the HVAC control system must control the temperature and humidity and keep them within the recommended ranges. Due to the complications and the requirements needed to actually connect an HVAC system to an air conditioner, furnace, humidifier and dehumidifier, these appliances are simulated on the HVAC control system board using LEDs.

4.2 Sensing System Unit

The previous section discussed the design and implementation of the HVAC control system. The control system requires measurements from sensors (e.g., temperature, humidity, CO_2, and airborne particulates) to manage indoor air quality and keep the semi-enclosed space within the occupants' comfort level. For this reason, a sensing system unit is needed for sensor measurements. The IHAQ system was designed and implemented by the Hartman Systems Integration Laboratory.

The IHAQ sensing system is a wireless sensor platform. It was designed to be a flexible and modular sensing system. It has been designed for environmental monitoring. The flexible hardware and firmware design allows for future development and adaptation for different application. The flexible design allows for sensor change and upgrade whenever needed for different sensor(s), without the need to redesign the full sensing system.

The IHAQ sensing system hardware includes a powerful 32-bit Atmel microcontroller. The system has a real-time clock with a coin cell battery backup in case of power loss by the system. It has I^2C, SPI, and UART communication interfaces for communicating with the different sensors. These communication protocols are also used to communicate with the wireless devices on the IHAQ sensing system. Wireless devices, such as ZigBee, are used to communicate with other IHAQ systems or with a coordinator for data transfer.

The IHAQ unit also includes USB and UART ports for data transfer and debugging. With the USB interface, the sensing system can be connected to a computer using USB to receive live sensor measurements. The system also has an SD card for data storage. It allows the sensing system to save all the sensor measurements, and to debug information on the SD card. The system also includes a user interface LCD that allows the user to see the different sensors measurements in real time. Figure 14 shows the internal view of the IHAQ sensing system. It also shows the different boards for the sensing system.

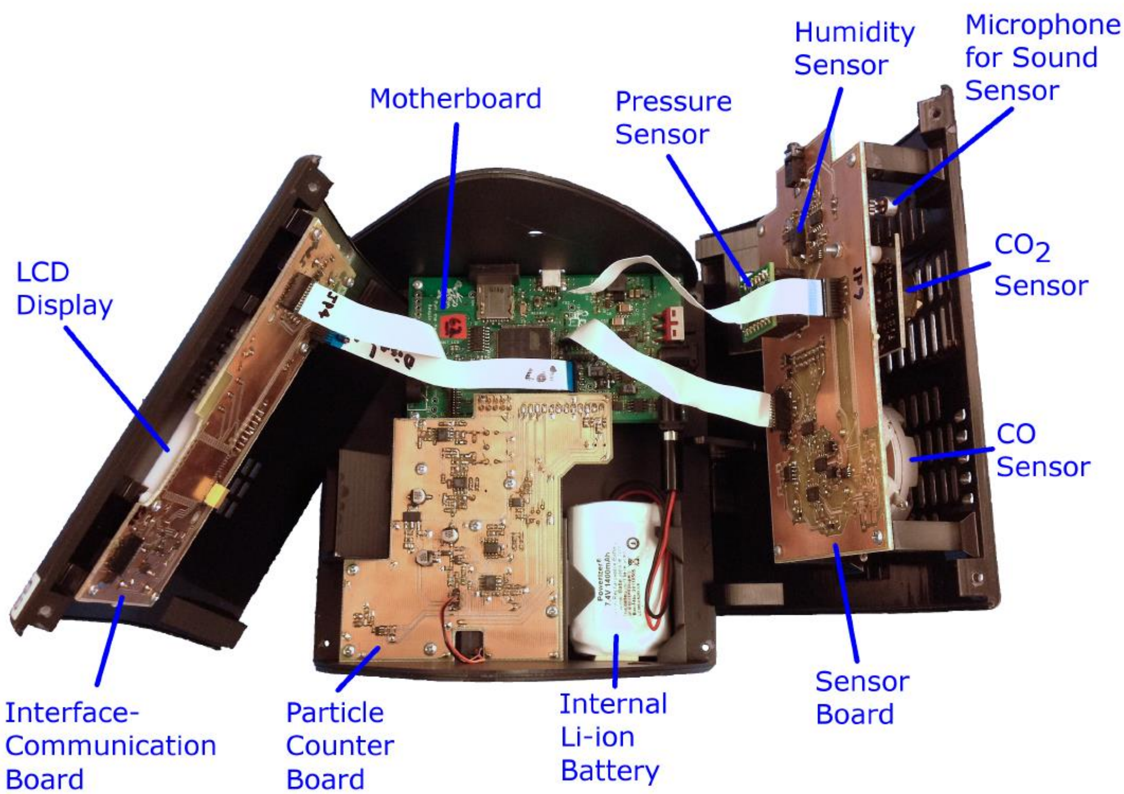

Figure 14: The IHAQ Sensing system Internal View showing boards and interconnections

4.2.1 Sensors

The IHAQ sensing system includes different types of sensors. The sensor set includes CO_2, CO, particle count, temperature, humidity, pressure, and sound levels. These sensors allow the system to monitor diverse environmental conditions that are related to the air quality and the comfort of occupants in a semi-enclosed area. Table 4 lists the sensors incorporated in the IHAQ sensing system design with their parameters. The ranges for these sensors were chosen to cover ranges expected during normal activity in any semi-enclosed environment. The sensing system take measurements for each sensor every five seconds except the particulate counter, which gets new data every 10 seconds.

The number and types of sensors on the IHAQ unit make it a perfect fit to be integrated with the HVAC control system. The sensing system measures all the different sensor data that can be used to manage the indoor air quality and the comfort of occupants.

Table 4: IHAQ Sensing system sensors and some of the parameters

Sensor	**Technology**	**Range**	**Accuracy**
CO	Electro-chemical	0-500 ppm	2 ppm
CO_2	Infrared	0-2000 ppm	10% of reading or 75 ppm
Humidity	Capacitive	0-100% RH	+/- 3%
Pressure	Diaphragm, capacitive	30-120 kPa	+/- 150 Pa
Sound	Electret microphone	48-110 dBA	--
Temperature	NTC thermistor	-40oC - +125oC	5% of reading

4.2.2 IHAQ Design Changes

The various sensors used in the IHAQ sensing system and its flexible design made the integration with the HVAC control system relatively easy. There were relatively minor hardware changes needed to adapt this IHAQ as a sensing system for HVAC. The only change was made on the interface board part of the IHAQ sensing system. The interface-communication board shown in Figure 14 is the original design for the system. It was designed to work with Zigbee wireless transceiver rather than

Bluetooth. The new board design added a Bluetooth module to the board. The new interface board has the same dimensions and placements for most of the components such that it will still fit in the original enclosure. Figure 15 shows the new interface-communication board. The top part shows the Bluetooth device added to the new board. The bottom shows the LCD display and the buttons.

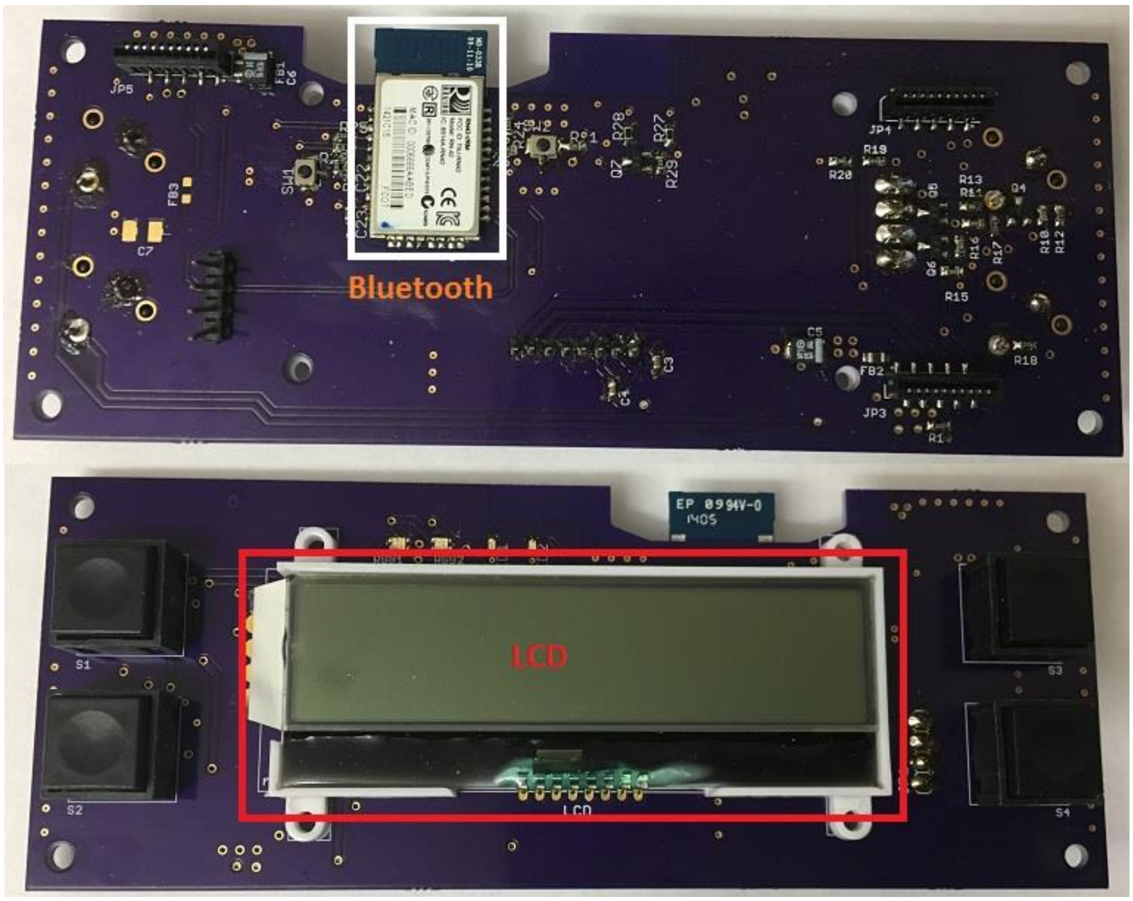

Figure 15: The new interface-communication board. Top picture shows the Bluetooth with the Connections Bottom picture shows the LCD display and the buttons

CHAPTER 5: SOFTWARE DESIGN

Firmware is software that is embedded in a piece of hardware (e.g., microcontroller). Firmware can be simply explained as the software for the hardware. Firmware gives the hardware instructions on how to operate. It cannot be altered or deleted by an end user without the aid of special programs. It is usually programmed into non-volatile memory.

The sensing system and the control system have two separate codebases. The firmware for the sensing system was written by members of the Hartman System Integration Laboratory, funded by FAA and NIH. Modifications to the existing codebase for the sensing system were required to integrate the two systems together. The firmware for the control system was written for the purpose of the current research.

5.1 Sensing System Firmware

The development model for a sensing system can dictate frequent changes to the sensors and system components. These changes can be to the sensors, communication interfaces, and/or microcontroller. Systems may require specific customization for a specific application, leading to multiple unique instances of the base system.

The Hartman Systems Integration Laboratory team developed a layered firmware architecture for the IHAQ sensing system. The firmware code was developed using the C programming language. The low level firmware of the sensing system is the device drivers. It is responsible for interfacing with the hardware of the system. The device drivers create a firmware layer between the actual hardware and the higher level code to simplify the programming process. A timer-based scheduler is on the top of the device drivers. It provides essential high level timing for the sensing system and the rest of the software modules. The sensor manager collects data from the different sensor and passes it on to the data manager. The data manager passes the sensor data to other communication modules or to be stored on an SD card. The top of the firmware architecture is the application layer that controls the overall functionality of the system. The full architecture of the sensing system is shown in Figure 16.

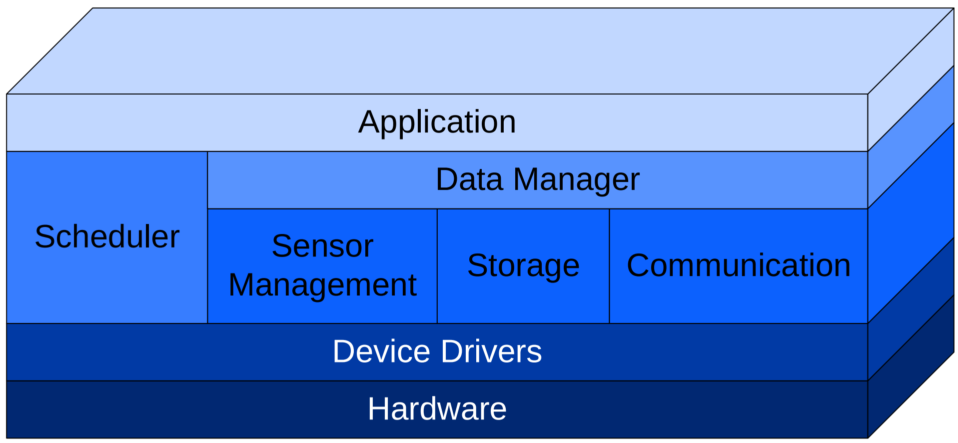

Figure 16: Firmware architecture diagram [9].

The sensing system starts with initializing all the timers on the microcontroller. It will also initialize the low level communication interfaces and the device drivers. The scheduler is enabled to provide the timing required for each task. The data manager and the sensor management part of the software will be initialized after the scheduler, and will be ready to add the sensors and receive the data. All the enabled sensors will initialize and be ready to get data from each sensor. Figure 17 shows pseudo code for the sensing system.

```
Initialize Timers
Initialize low level communication interfaces and device drivers
Initialize the scheduler
Initialize the data manager and sensor management
Initialize all enabled sensors

Running Code
{
    Data Manager Task
    Log File Task
    Communication Interfaces Tasks
    Sensors Task
}
```

Figure 17: Sensing System Pseudo Code

The firmware for the sensing system is split into multiple tasks, with each task handling a different part of the system. This multitasking system runs as a simple loop with tasks executing sequentially. To avoid starvation of other tasks in the system, all tasks are designed to be non-blocking. The amount of processor time for each task is limited such that the tasks won't affect the overall processing time.

The sensing system has two types of data strings that it can send out. The first is the identifier string, as shown in Figure 18. This string includes the name of the sensor, the units for the measurement, and the time of the current measurement. The current time is read from the real-time clock in order to set the current real time. The second string is measurement string, as shown in Figure 19. This measurement string can be saved or transmitted. The system will be continuously recording measurements at a specific interval for all the enabled sensors (e.g., temperature, humidity, CO_2, and particulate counter). The sensor data is stored on a removable storage device (e.g., SD card) and also transmitted to the control system for further processing.

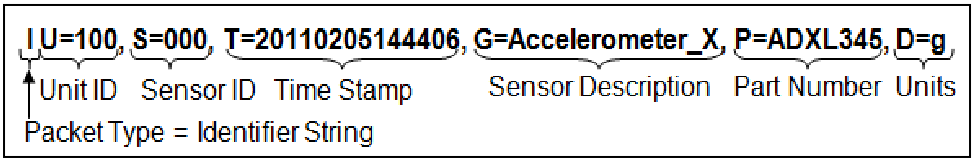

Figure 18: Sensor Identifier String Format

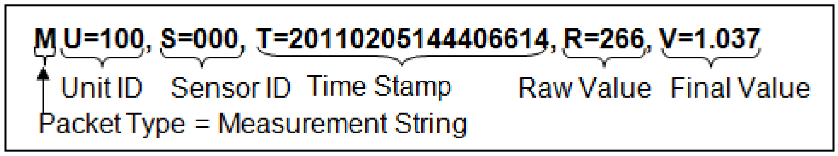

Figure 19: Sensor Measurement String Format

The sensor identifier and measurement string formats shown in Figure 18 and Figure 19 were developed for the sensor network. The decision to create a separate identifier string for each sensor was made to reduce the amount of information that had to be transmitted with each sensor measurement. The sensor measurement string gives the important information needed, such as the type of the sensor, the units it measures, the sensing system unit ID, and the sensor ID. The system unit ID is a unique number given to each sensing system unit on the network. This can be used if there are different sensing system units running at the same time and the base node is receiving data from different sensor nodes. The sensor ID is another unique number that identifies each of the sensors. Each one of the sensors on any sensor unit will include the information in the sensor measurement string. Thus, each measurement can be matched using the identifier and the information in the identifier will only be transmitted once. For this research, we may or may not use some of the information. The most important information for the control system is the sensor values provided by measurement strings. The sensor measurements will dictate what the control system will and won’t do.

5.1.1 Bluetooth Setup

Within the firmware is the Bluetooth transceiver setup code. The setup for the Bluetooth transceiver is only executed once during startup. Once completed, it will be ready to connect/reconnect automatically to the paired Bluetooth device on the sensing system. Once the Bluetooth has been powered up, the module can be configured to operate in different modes. The command mode for the Bluetooth can be accessed by sending “$$$” from the microcontroller.

The Bluetooth transceiver has four different modes. In *slave* mode (default mode from factory), the module will be waiting for connection requests. The Bluetooth can either accept or deny these requests. The Bluetooth module cannot initiate connections by its own in slave mode. *Master* mode is the opposite of *slave* mode. The device can initiate connections to other Bluetooth transceiver, but it cannot receive any connection requests. The third mode is *trigger master* mode. The module connects to the previously paired Bluetooth transceiver whenever it receives a character from the microcontroller. The fourth mode is the *auto connect*. In this mode, the Bluetooth transceiver can initiate connection to the previously paired module. The current firmware setup for the HVAC control system uses the *auto connect* mode. This will allow the sensing system and the HVAC control system to connect to each other automatically. In this mode, the Bluetooth requires a previously saved Media Access Control (MAC) address. The remote MAC address can be set using “SR, <MAC Address>” command when the Bluetooth transceiver is in command mode. This setup step only needs to be completed once. Whenever the HVAC control system and the sensing system are turned on, the Bluetooth transceivers will establish communication automatically.

5.2 Control System Firmware

The firmware design for the control system was developed to be modular firmware. It is similar to the layout used for the sensing system. The lowest level of the firmware is the device driver to interface with the hardware. A listener is implemented in the firmware to receive and parse the sensor data coming from the sensing system. A data manager sits on top of the device drivers. It provides critical decision-making to control the different devices on the control system.

The firmware starts by initializing the Hardware Abstraction Layer (HAL) for the ATXmega256A3 microcontroller. Upon startup, the system initializes all communication interfaces and the device drivers needed for the control system. The firmware resets all controlled devices (e.g., damper and fan) by turning them OFF. The firmware establishes communication with the sensing system using Bluetooth. The control system will be connected to the sensing system and ready to receive sensor data. Pseudo code of the firmware is shown in Figure 20.

```
Initialize Timers
Initialize low level communication interfaces and device drivers
Establish Bluetooth connection with the sensing system
Initialize all the control devices
Running firmware
{
  Listener Task
  Data Process manager  Task
  Controller Task
}
```

Figure 20: Control System Pseudo Code

The control system will use the sensor measurements to make the decisions for air quality control and the control of environmental conditions (e.g., temperature and humidity) in the semi-enclosed area. The control system will enable or disable one or more of the controlled devices depending on the received sensor data. For example, if the CO_2 measurements are above a certain level, the control system will enable the circulator and/or the ventilator. For all the various sensors, the control system processes the changes in the data after three consecutive measurements to minimize the system response to spikes in the sensors.

5.2.1 Indoor Air Quality Control

The control system is responsible for making decisions to manage the indoor air quality and keep the indoor environment comfortable for the occupants. As shown in Chapter 3, CO_2 and airborne particulates can be used as a measurement for indoor air quality. The indoor air quality is managed by controlling the levels of CO_2 and the airborne particulate inside the enclosed environment. The control system manages the CO_2 and the airborne particulates by controlling the ventilation (damper) and circulation (fan) of air inside the enclosed environment.

Figure 21 shows the decision tree used by the control system unit after receiving a new CO_2 measurement. When a new measurement arrives, the control system checks whether the CO_2 level is higher than the threshold level of C1 and C2, set at 600 ppm and 800 ppm, respectively, to demonstrate the function of ventilator and circulator. Using the two levels C1 and C2, the control system determines the correct response for the HVAC system. C1 is the threshold where the air quality is still considered good, but where the circulator would be triggered to mix the air. (This scenario happens during the change of seasons when furnace or cooling isn’t operating as often.) C2 is the level where the ventilator will be triggered. This scenario often happens during the change of seasons.

The higher level of CO_2 can occur when there are more occupants in the semi-enclosed environment. In order to reduce the CO_2 level, outside air will be introduced into the space.

For every new CO_2 measurement, there are three different possible actions. The first is when the current CO_2 is less than C1 (which is less than C2 as well). The control system checks whether the ventilator and the circulator are enabled and makes sure they are disabled. Making sure the ventilator and the circulators are turned OFF when they are not needed decreases the power consumption of the HVAC control system.

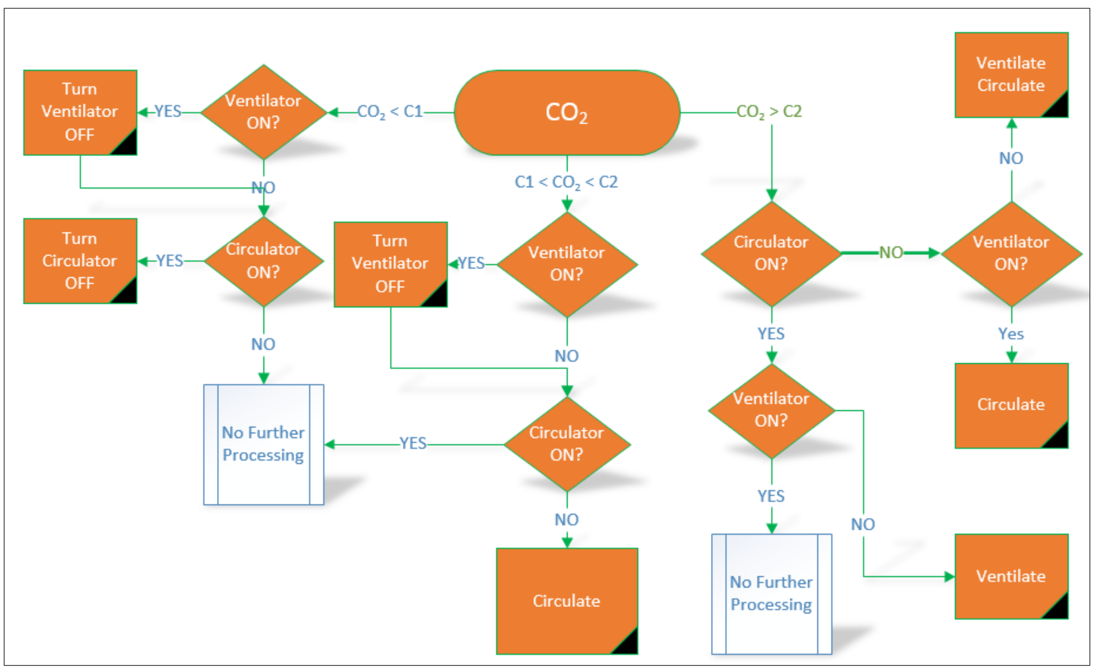

Figure 21: Indoor air quality management by controlling CO2 levels, where C1=600 ppm and C2=800 ppm.

The second possibility is when the CO_2 measurement is between the set points for C1 and C2. This means that the indoor air quality is still at an acceptable level, but the indoor air must be circulated to decrease the amount of CO_2 build-up inside the semi-enclosed place. The control system will first check whether the ventilator (the damper) is enabled and, if so, will disable it. In this scenario, it will enable the circulator (the fan).

The third possibility is when the CO_2 level is above C2. In this situation, the control system will activate both the circulator and the ventilator. The control system will open the damper and keep the fan running to replace the inside air with fresh air from outside. These actions will reduce the CO_2 level and will lead to better indoor air quality.

The sensing system also monitors airborne particulates in the semi-enclosed environment. The airborne particulate readings are sent to the control system. The control system checks the most current reading for the particulate in the air and makes decisions based on Figure 22. When there are low levels of contaminants in the air, with airborne particulates less than the threshold, the control system disables both the ventilator and circulator. This will reduce the power usage of the HVAC control system. If the airborne particulates are above the first threshold level, the control system will only enable the circulator. This will allow the indoor air to circulate, and fine particles are captured by the high-efficiency filter. With the filter and circulator, the number of particulates will decrease since the filter is capturing the particles. When the airborne particulate level is higher than the second threshold level, the control system will enable both the circulator and ventilator. In this situation, the HVAC control system will filter the indoor air and allow fresh air intake from outside. The filtration and fresh air intake will increase the air quality level in the semi-enclosed environment.

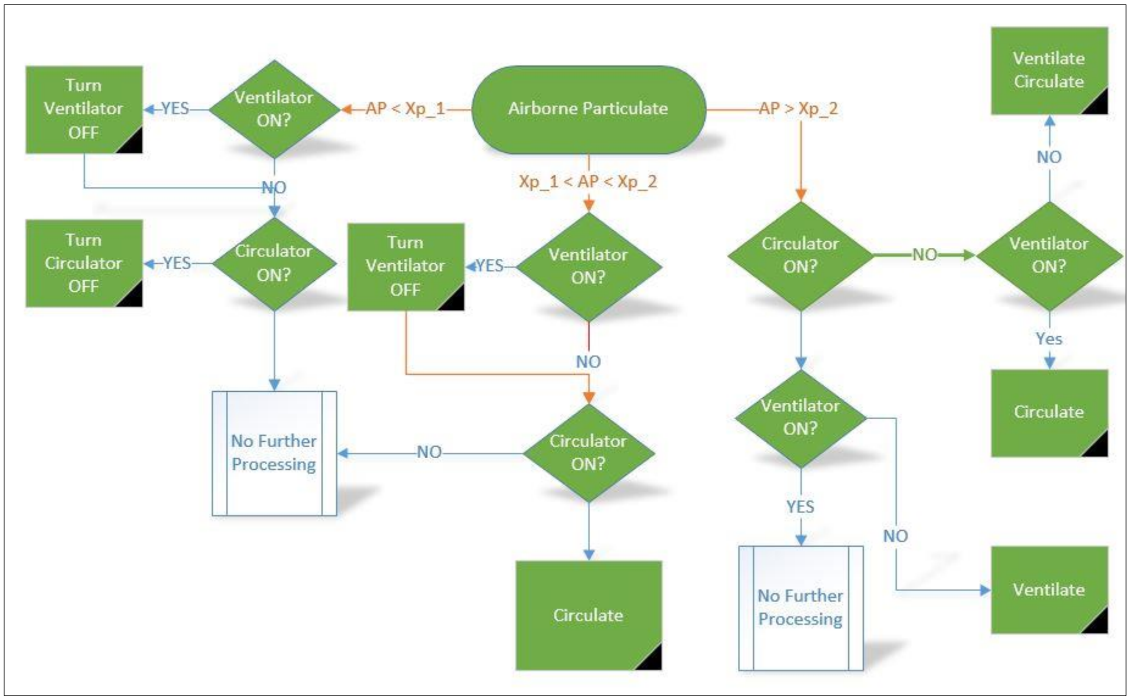

Figure 22: State Diagram for Airborne Particulate monitoring and control

5.2.2 Heating, Air Conditioning, and Humidity Management

The management of indoor air quality is essential for an occupant's health. For occupants, a comfortable environment is a necessity. This means that it is necessary to control the temperature and humidity levels. In the current research, the control of temperature and humidity is being accomplished by a sensing system through humidity and temperature readings. The readings are used by a control system to control the furnace, air conditioner, humidifier, and dehumidifier.

The control system will receive the most current temperature readings from the sensing system. It will make the decisions shown in Figure 23 and Figure 24. The system will decide if the current temperature is above the set cooling temperature or below the set heating temperature. It will decide if the air conditioner needs to be turned ON to decrease the temperature, or to turn the furnace ON to increase the temperature in the semi-enclosed place.

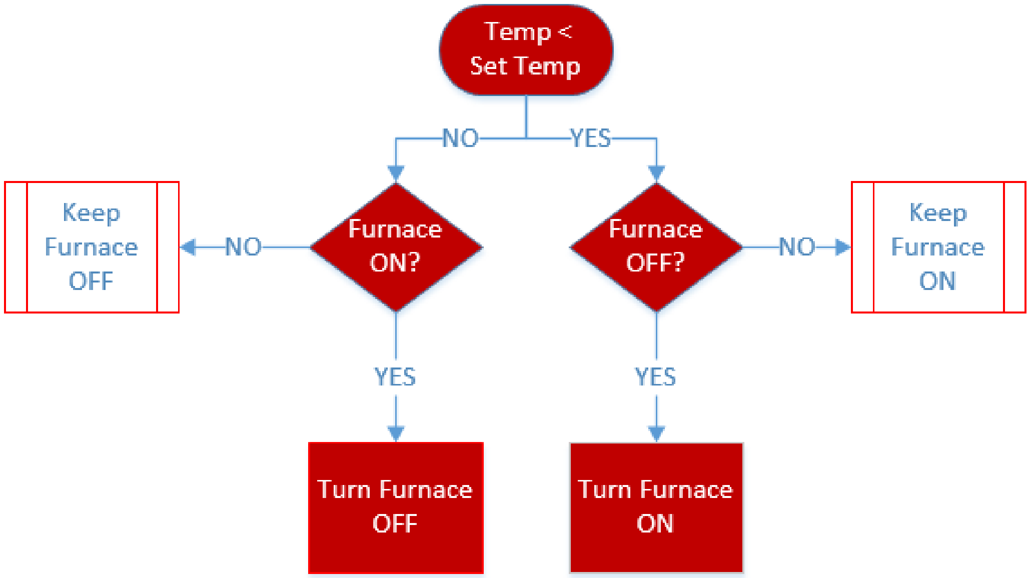

Figure 23: Furnace Control Decision Diagram

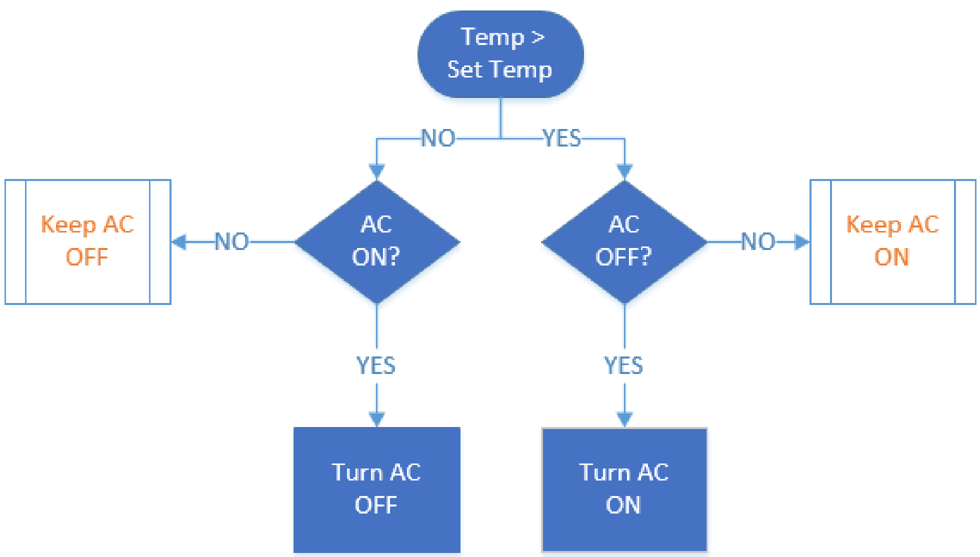

Figure 24: AC Control Decision Diagram

The control system will also receive the current humidity data. Humidity is preferred to be set between 20% and 60% for occupants' comfort. The control system will manage the humidity levels and make the necessary decisions (shown in Figure 25) to keep the humidity within the preferred range. For example, when the humidity is below the threshold of 20%, the control system will turn the humidifier ON to increase the humidity in the semi-enclosed space. When the humidity level is higher than the threshold of 60%, the control system will turn the dehumidifier ON to decrease the humidity level in the semi-enclosed environment.

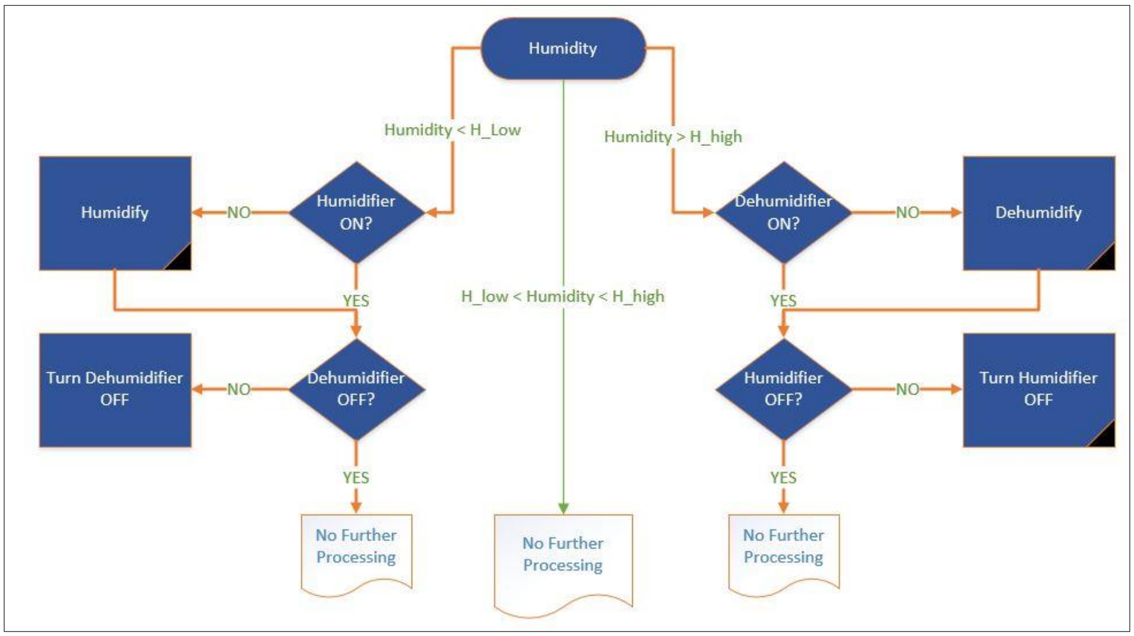

Figure 25: Humidity State Diagram Control

5.3 Computer Software

The sensing and control systems are fully automated. They work together and manage the indoor air quality, as well as controlling the environmental conditions without any interfacing from the user. If the user would like to display the current sensor measurements, a computer is available to display the current sensor data measured by the sensing system.

The Boise State University (BSU) Sensor Monitor Lite Program was designed as a simple tool for experiment data analysis. It was designed by the members of Hartman Systems Integration Laboratory. The program reads the measurement and identifier strings from a file stored on the IHAQ's SD card for post-experiment data processing. The BSU Sensor Monitor Lite program also allows the user to receive data (via either wired connections, or wirelessly) in real-time from the IHAQ sensing system. The strings are parsed and the data is organized by sensor IDs. The user has the ability to choose any of the available sensors, by selecting the description and sensing system unit ID from a drop-down menu, as shown in Figure 26. A graph of the data for the selected sensor is generated and displayed within the axes limits such that all the measurements are visible.

One other feature of this program is its ability to be generated in a data format for processing on any platform. Although the graphical interface will only work in Microsoft Windows, the data collection and ".csv" creation will work on any operating system. This portion of the program can be launched and controlled from the system's command line without the need for any graphical interface.

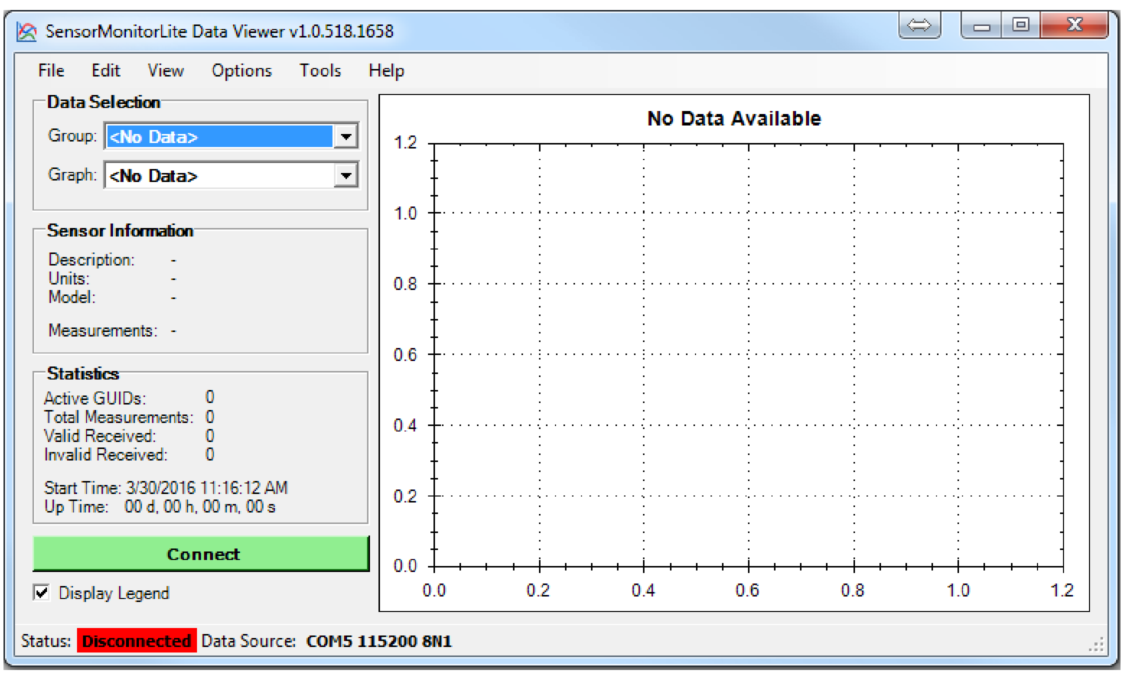

Figure 26: BSU Sensor Monitor Lite Program Screenshot

CHAPTER 6: RESULTS AND ANALYSIS

The hardware and firmware discussed in Chapters 4 and 5 have been vigorously tested. The performance of the overall system was evaluated, and the results are outlined in this chapter. The tests performed were designed to test the functionality of the sensing system and the control system. The focus of the tests was to introduce different environmental changes to the sensing system and monitor the response of the control system. The loss of wireless communication between control system and sensing system was also tested. This is to evaluate the default settings on the HVAC control system. The overall tests are divided into two major sections: air quality settings testing and comfort settings testing.

6.1 Air Quality Setting Testing

Multiple tests were performed on the sensing system and the control system in order to prove their viability for air quality management. The control system is responsive to air quality changes depending on the changes of the CO_2 levels and the airborne particulates. It checks both CO_2 and particulate levels continuously.

6.1.1 CO_2 Testing and Results

The overall system response to CO_2 level changes was tested by introducing CO_2 calibration gas. The full system was tested by applying the CO_2 gas to the sensing system and observing the response of the HVAC control system. The HVAC control system is set up to enable the circulator when the CO_2 level is above 600 ppm and to enable the circulator and ventilator when the CO_2 level is above 800 ppm. The test started with ambient levels of CO_2 (~500 ppm). The test was started by introducing CO_2 calibration gas to increase the CO_2 to a concentration above 600 ppm and below 800 ppm. The level was around 750 ppm (between 600 and 800 ppm). As expected, the HVAC control system enabled the circulator while keeping the ventilator disabled. Enabling the circulator will enable air circulation in the semi-enclosed space along with air filtration. This reduces contaminants in a particular area or areas through dilution.

The next stage of the test involved increasing the CO_2 level to over 900 ppm with the use of CO_2 calibration gas. With the CO_2 above the threshold of 800 ppm, the HVAC control system enabled both the circulator and ventilator. Since the circulator enables filtration of indoor air (by running air through a filter) and the ventilator will introduce fresh air from outside, the circulator and ventilator will decrease the level of contaminants and improve the indoor air quality. The different stages of the test data collected are shown in Figure 27.

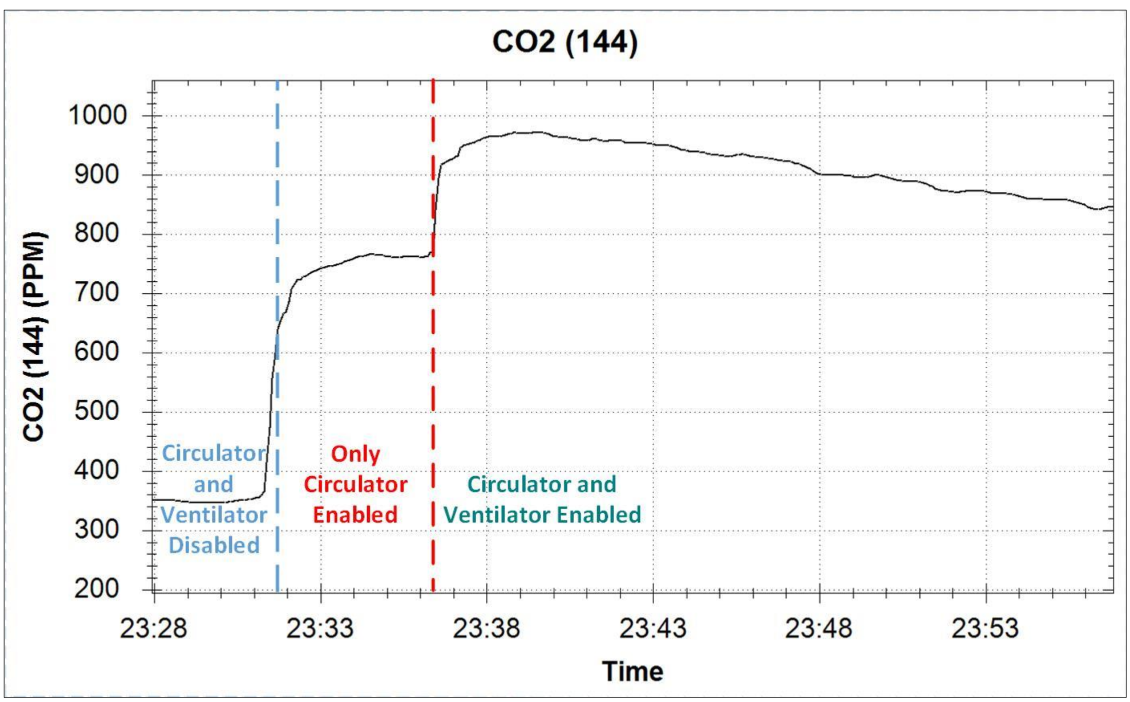

Figure 27: The different stages of CO2 testing to manage indoor air quality

Figure 28 shows another set of test results. Before the system was powered up, CO_2 between 600 and 800 ppm was introduced to the sensing system unit. In this cold start test, the HVAC control system recognized that the CO_2 was above the first threshold level (600 ppm), and it enabled the circulator on startup. The next test was whether the system would disable the circulator or ventilator as programmed. This test is shown starting at 23:23:30. As CO_2 ppm dropped to less than 600 ppm, the HVAC control system disabled the circulator as it was programmed. The next two stages were to test the circulator and the ventilator when CO_2 levels reach 600 and 800 ppm, respectively. These tests happened at 23:31:30 and 23:36:30 as shown in Figure 28. The HVAC control system responded as it was designed, enabling the circulator when the CO_2 level exceeded 600 ppm and turning the ventilator ON when the level passed 800 ppm.

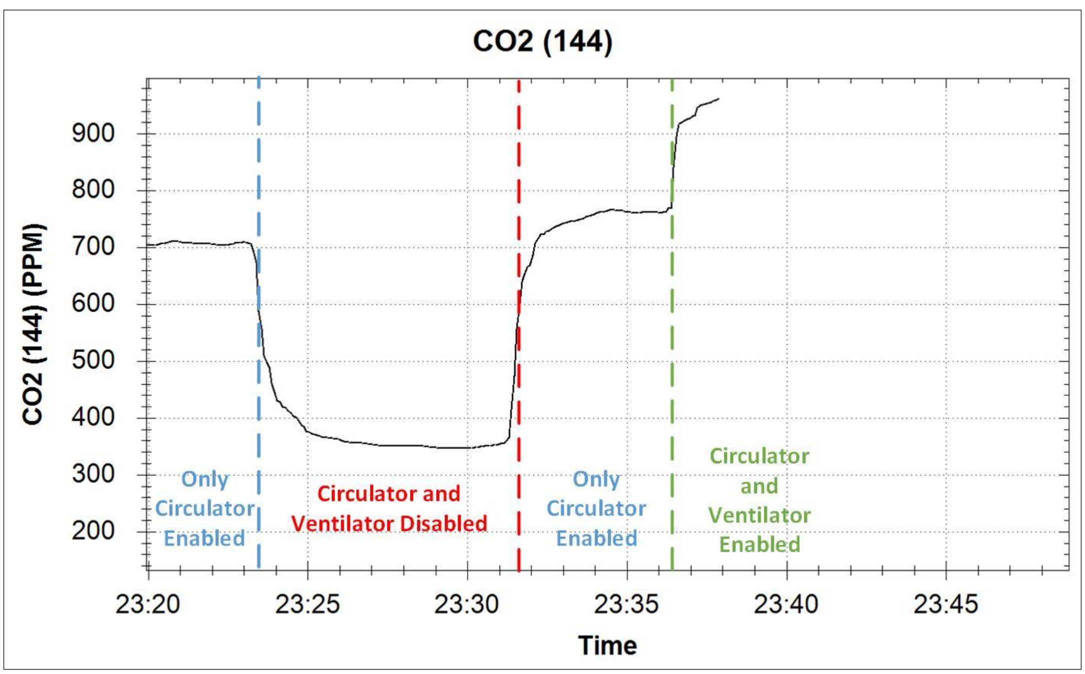

Figure 28: CO2 testing with a different starting stage

6.1.2 Airborne Particulates Test Results

The next phase of testing was the system's response with changing particulates counts. In these tests, the sensing system measured the changes in the particulate counter and sent measurements to the control system. The control system is set up such that it will enable the circulator when the airborne particulates are above 20,000 particles per liter (ppl). The system enables both the ventilator and circulator when the particulate levels are above 30,000 ppl. When the airborne particulates are below 20,000 ppl, the control system idles the circulator and ventilator.

The airborne particulates test was done inside a research lab. The lab has multiple occupants with some entering and leaving at different times. This test was performed over a period of four hours. The sensing system measured the changes in the airborne particulates during that period. The responses from the control system were monitored throughout the same period of time. Figure 29 shows the airborne particulates measurements and the response from the control system.

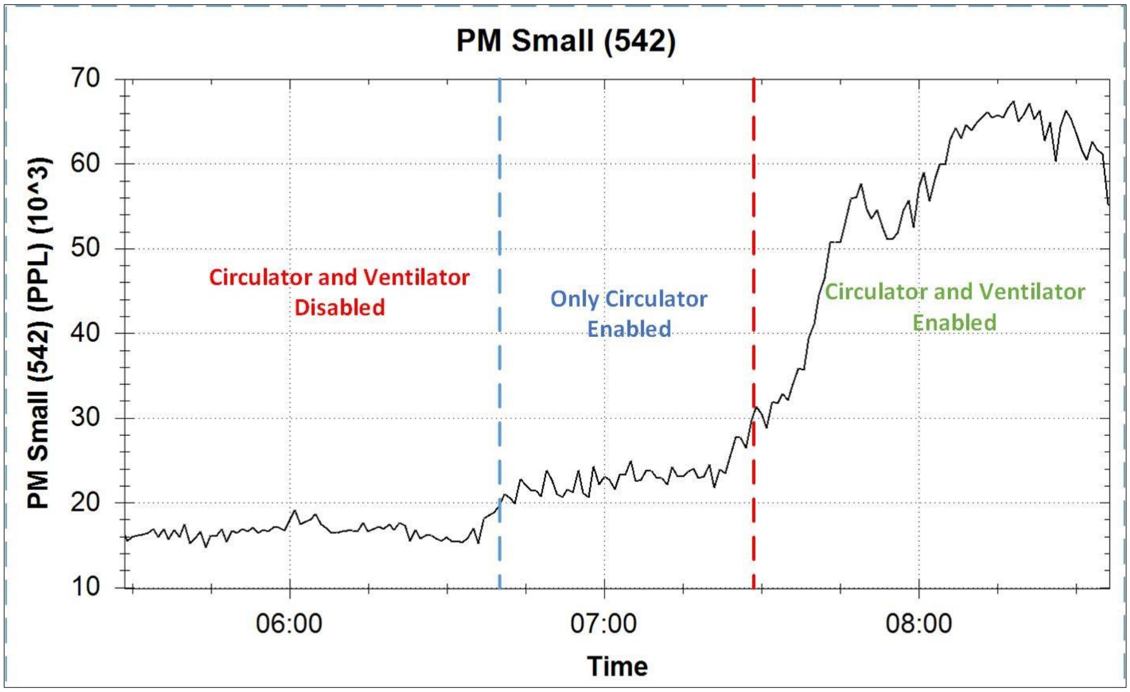

Figure 29: Airborne Particulates Test

During the first two hours of the test, the particulates were below 20,000 ppl. Thus, the circulator and ventilator were both disabled by the control system. Starting at around 06:40, the airborne particulates increased because the number of occupants inside the lab increased. There are more occupants moving around in the room and disturbing the particles that exist on different surfaces. In the next two hours, the control system enabled the circulator because the airborne particulates were between 20,000 and 30,000 ppl. At around 07:30, the airborne particulates increased to a level above 30,000 ppl, and the control system enabled the circulator and ventilator.

If the circulator and ventilator were connected to a complete HVAC system with filter, the number of airborne particulates would have been reduced by the filtration system. In our setup, it is not possible to show the reduction of particle counts.

6.2 Comfort Settings Testing

The comfort settings testing refers to the tests that are related to the comfort of the occupants inside the semi-enclosed area. Comfort settings can be divided into temperature and humidity. Temperature and humidity levels do not directly affect the indoor air quality, but they influence the amenity level for occupants. When the temperature or humidity levels are higher or lower than a certain threshold, occupants start feeling discomfort, e.g. dry skin, dry eyes.

6.2.1 Temperature Control

The temperature control on the HVAC control system was performed by simulating the air conditioner and furnace using LEDs. When the air conditioner is enabled, the control system turns the blue LED ON. When the furnace is enabled, the control system turns the red LED ON.

The sensing system monitors and sends the latest temperature readings to the control system. The control system checks whether the current temperature value is above or below the set temperature for cooling and heating. For the different tests, the air conditioning temperature is set to 72°F and the furnace temperature is set to 68°F. Whenever the temperature is higher than 72°F, the air conditioner will be enabled. Whenever the temperature is lower than 68°F, the furnace will be enabled. With the above setting, the semi-enclosed space will have temperature range of 68°F to 72°F.

Figure 30 shows the temperature changes and air conditioner management by the control system. The test was done throughout two days. The x-axis runs from 06:00AM on March 4th to 06:00AM March 6th. Between approximately 06:00 and 10:00AM, the temperature is around 71°F. The air conditioner and furnace were disabled, since the temperature was within the programmed temperature settings of 68°F-72°F. At a little past 10:00 AM, the temperature rises above 72°F. The control system enabled the air conditioner by enabling the blue LED on the HVAC controller board. The AC stays enabled as long as the temperature is above 72°F. In the last stage of the test (at 4:00AM), the temperature drops below 72°F, and the control system disables the air conditioner.

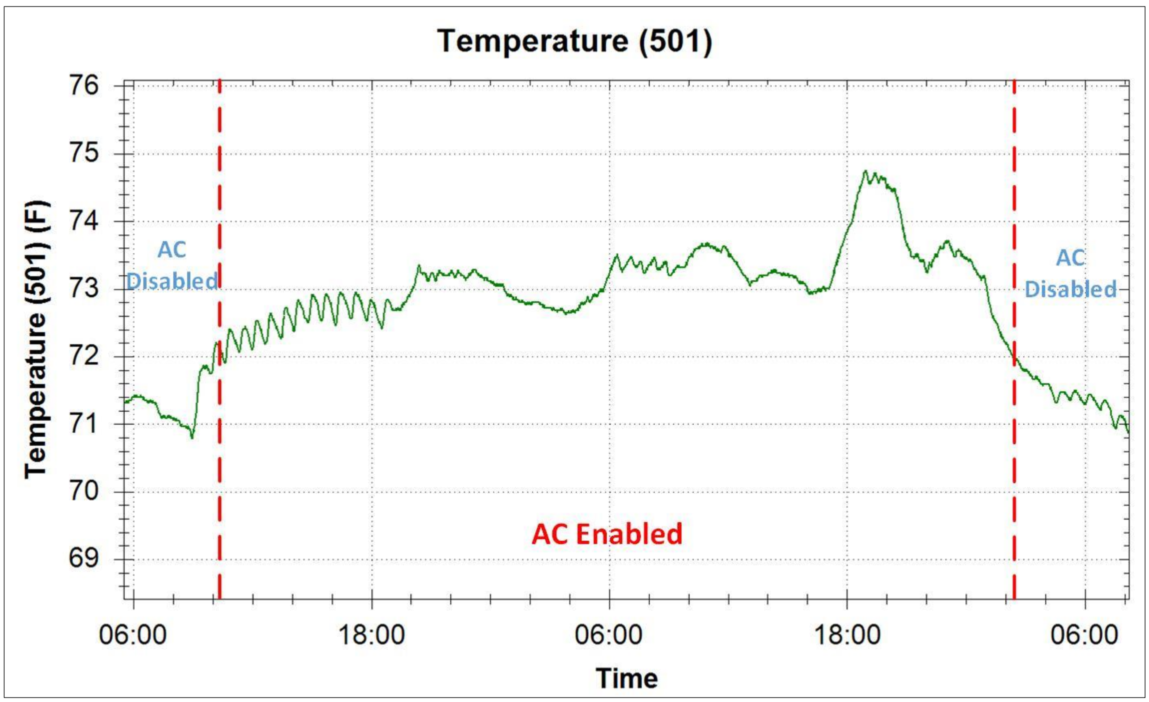

Figure 30: Temperature AC Test

The second test related to temperature is testing the sensing and control systems with the simulation of the furnace. The control system is set to enable the furnace when the current temperature is below 68°F. The first stage of this test (shown in Figure 31) started with the temperature below the set point of 68°F. The control system enabled the furnace by activating the red LED on the HVAC control board. The simulated furnace remained enabled until the temperature rose above 68°F.

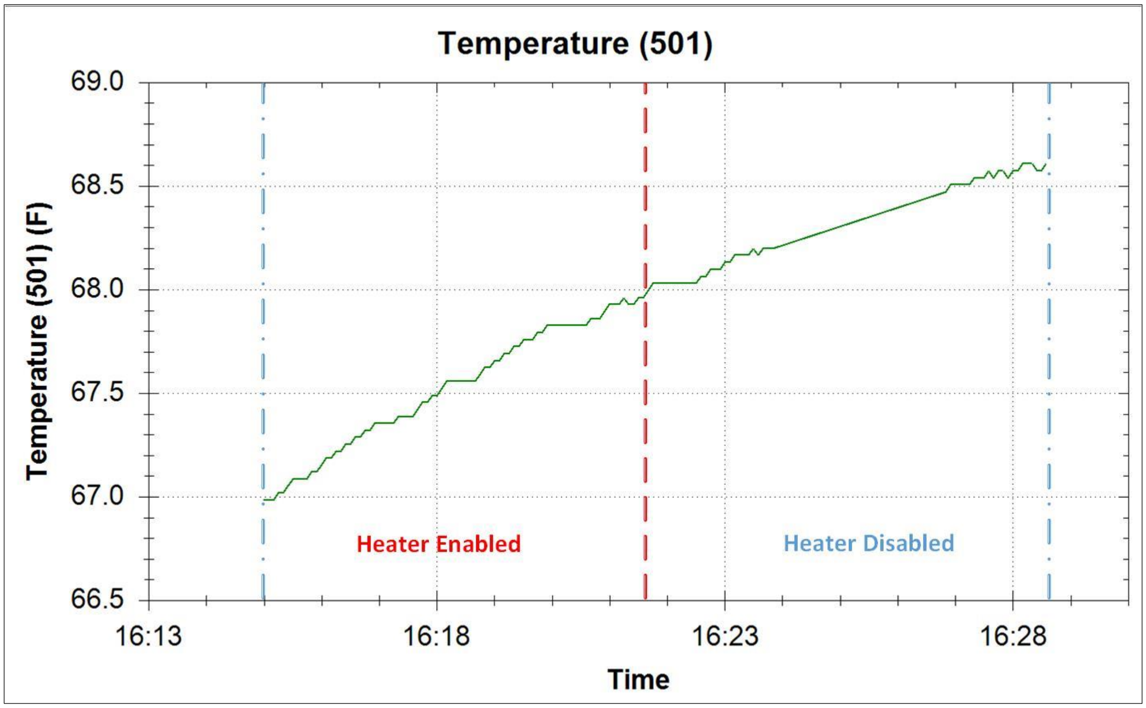

Figure 31: Temperature Furnace Test

The two different tests made for the temperature control testing verified the functionalities of the sensing and control systems of the HVAC system. It showed that the system is responsive to temperature changes below or above the set thresholds of 68°F and 72°F, respectively. It has been shown that the sensing and control systems have the ability to control the temperature within the pre-programmed range.

6.2.2 Humidity Control

The second type of comfort setting testing is humidity. The humidity was also simulated on the HVAC control board using LEDs. Different light sequences of LEDs correspond to the humidifier or the dehumidifier being enabled.

The optimal humidity for occupants' comfort has been determined to be between 20% and 60%. The sensing and control systems monitor and control the humidifier and dehumidifier to maintain the humidity levels within the settings.

There were two tests performed to verify the humidifier and dehumidifier functionalities of the HVAC control system. The first test performed was to check the control system response to high levels of humidity. This was performed by simply breathing on the sensing system. This increased the humidity level above the threshold of 60%. Figure 32 shows the humidity levels throughout the test, and the control system's response. Between 22:19 and 22:23, the humidity level was around 24%. Since it is within the pre-programmed range, the control system kept the dehumidifier disabled. When the humidity was increased, at 22:23, the control system enabled the dehumidifier as soon as the humidity passed 60%. The dehumidifier remained enabled by the control system until 22:26:45 when the humidity was decreased below 60%. The sensing and control systems were able to monitor and control the humidity levels whenever it exceeded the threshold of 60%.

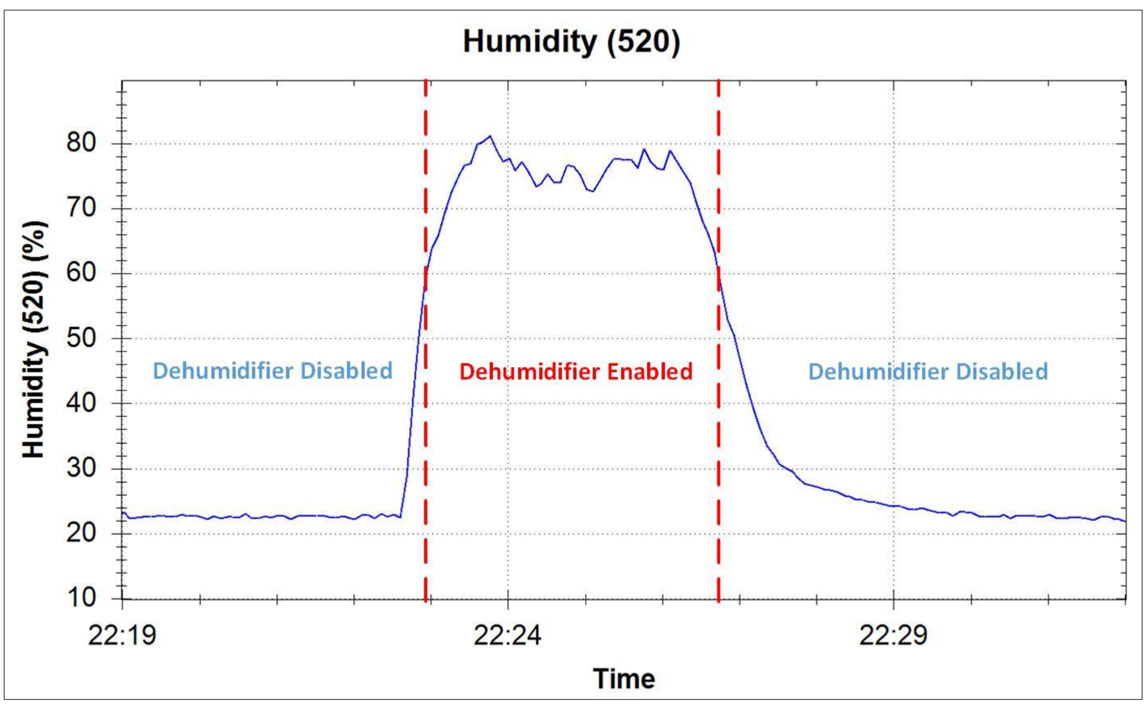

Figure 32: Humidity test to verify the response of the system to high levels of humidity

The other test was to verify the low humidity level functionality of the HVAC control system. In this test (shown in Figure 33), the system was tested over multiple hours where the humidity level is around 18%. Higher humidity was introduced to the sensing system by breathing on the sensing system. The humidity increased to between 30% and 50%. Since this level is within the set humidity range, the control system disabled the humidifier. When the humidity level dropped below 20%, the humidifier was enabled again. This shows that both the sensing and control systems have the ability to monitor different humidity levels and control the humidifier and dehumidifier.

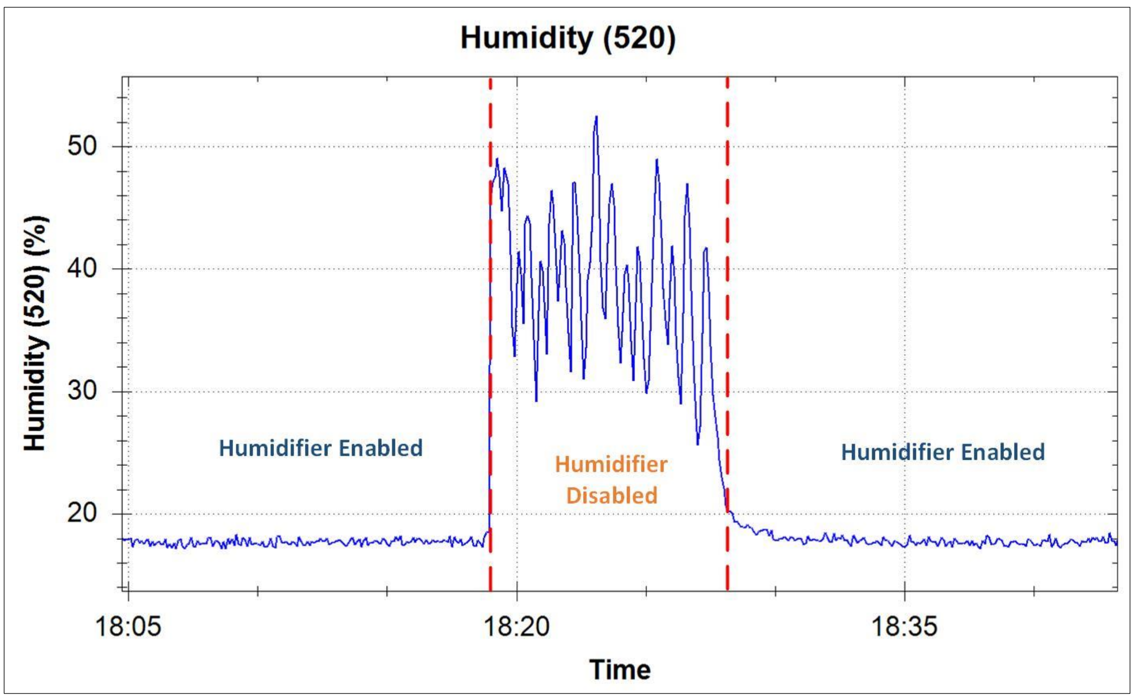

Figure 33: Humidity test to verify the response of the humidifier

CHAPTER 7: CONCLUSIONS AND FUTURE WORK

The thesis has successfully completed the design and implementation of an HVAC control system for management of indoor air quality. The laboratory tests show the objectives have been met. The current design has been proven to be capable of managing indoor air quality by decreasing the number of contaminants in a semi-enclosed area and controlling of environmental conditions.

7.1 Sensing System

The ability to easily modify the sensing system and communicate the sensors data to the control system is a major component of this thesis. The flexible design of the sensing system unit (IHAQ) made it possible to integrate the sensing system with the control system. In addition to the ease of integration with the control system, changing and/or increasing the number and types of sensors will be possible with the flexible hardware and firmware design. The wireless design allowed for easier testing and will make the implementation of future applications easier. It made the sensing system portable and able to be installed at any locations.

As the design stands, the sensing system is more than adequate for the needs of the current research, but it can be improved in the aspect of using multiple sensing systems to communicate with the control system. The addition would be using different IHAQ units in various locations inside the semi-enclosed environment. For example, if the current research would be used in a house, two different sensing systems would be used. One of them can be placed in the living room, and the other can be placed in the kitchen or the master bedroom. Using this setup will allow more sensor data from multiple locations. It will also improve the indoor air quality and make the environmental conditions more comfortable for occupants.

The current design works on the assumption that outdoor air has less contaminants, low CO_2 levels, and better air quality. There is a possibility that outdoor air can have more contaminants or worse quality than indoor air. Therefore, adding a sensing system located outside the semi-enclosed environment can help make better decisions. The ability to receive sensor data from the outside will change the decision-making of when to enable or disable the various controls. For example, if circulation and ventilation are called for by the indoor sensors, the control system will check the outside air quality and make a decision as to whether the ventilator should or should not be opened.

Research into more efficient ways to transmit data could be beneficial by increasing data throughput. The current firmware design transmits data in a string format. This makes the transmissions easy to read by the controller system. Simpler format (e.g., binary representation) could greatly decrease the packet size for this application.

7.2 Control System

The system has proven its ability to receive sensor data from the sensing system and manage circulator, ventilator, and devices appropriately. For future studies, the controller system firmware can be changed to accommodate using multiple sensing systems. The Bluetooth transceiver on the control system is capable of connecting to multiple sensing systems, but the firmware must be updated to make decisions depending on the location of the sensing system.

The hardware for the HVAC controller system could also use more work. The full system was not physically connected to the air conditioner and furnace to control the environmental conditions. Adding the ability to actually connect the HVAC controller board to the air conditioner, furnace, humidifier, and dehumidifier would be a great addition. This will give the system the ability to control the different environmental conditioners in any semi-enclosed area. Connecting the circulator and ventilator used for the current research to a duct system for a house would improve the system by allowing it to manage the indoor air quality for the house.

The current research controls one circulator and one ventilator. Adding the ability to control multiple fans and dampers will make the management of indoor air quality even better. It will allow for more fresh air intake and it will also filter the indoor air more frequently. Another improvement would involve changing the control of the ventilator such that the system can control the amount of ventilation allowed by the damper. This can be done by using a damper that has the ability to be controlled using pulse width modulation. In this case, the system will give the ability to control when and how much to ventilate.

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