Efficient HVAC Control System

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***Abstract* — The Efficient HVAC Control System is a control and feedback system that processes temperature and relative humidity data from indoor and outdoor sensing units in order to maintain desired temperature and relative humidity set points in a building. Data is sent from indoor and outdoor sensors to a microcontroller that makes a decision on how to heat or cool the building. The system contains two units: the Main Control Unit (indoor sensing unit) and the Remote Sensing Unit (outdoor sensing unit). The Remote Sensing Unit is designed for outdoor temperature and humidity measurements to be taken, and reported back to the Main Control Unit. The Remote Sensing Unit is powered by a battery so it is completely self-contained, and reports the temperature and humidity data using an XBee wireless RF Transceiver. The Main Control Unit serves as the main thermostat for the user to input the desired temperature and humidity set points through a LCD touch screen. The Main Control Unit uses an 802.11b Wireless RF Transceiver to connect to the internet for the purposes of controlling the system from a remote location.**

***Index Terms* — HVAC Control and feedback system, LCD touch screen, microcontroller, radio frequency transceiver, temperature and relative humidity sensors, wireless communication**

I. INTRODUCTION

Heating, Ventilation, and Air Conditioning Systems use various components to maintain a desirable temperature level inside of a building. During periods of extreme heat or cold, HVAC components are running full time, and become the largest power consumer of buildings. With the recent push toward green technology, a need for a control system to maintain a comfortable indoor temperature and humidity, while being as energy efficient as possible has presented itself.

Our group is proposing to develop an HVAC feedback and control system that consumes less energy than traditional HVAC systems on the market today. It controls the conditions of temperature and relative humidity in the building. As a result of decreased energy consumption, the cost of cooling the building is lowered. It performs the traditional functions of an HVAC system as well as having enhanced options to allow the user to select relative humidity set points, introduce fresh air into the building, and select from multiple energy usage settings ranging from "Max Comfort" to "Max Savings." By selecting a comfort setting, the user has control over the amount of variance from the set temperature and relative humidity points required to initiate heating or cooling. The comfort setting also controls which HVAC components are being used to cool or heat the building. Also, the user will be able to introduce fresh air into the building based on either a set schedule, or current exterior conditions.

The system is designed to control AC1, the main (2 Ton) AC unit, AC2, a secondary (1 Ton) AC unit, and a Dehumidification unit in order to keep the inside temperature and humidity within an acceptable range (or "comfort band") set by the user. As opposed to most systems, where the user has a single set value for the system to maintain, this system allows for a high and low point to be set which creates an acceptable range of temperature and humidity values.

When the temperature or humidity deviates from the acceptable band, the system will first check the current outdoor temperature and relative humidity values that have been recorded by the outdoor sensor. If the outdoor conditions are within the acceptable band, air from outside will be blown into the building in to bring the temperature back within the acceptable range. When the air outside is not within the acceptable set ranges, the conventional HVAC units will be used to control the inside temperature.

The comfort setting is another feature that makes this system unique. The comfort setting is one of five settings ranging from "Max Comfort" to "Max Savings." By choosing a comfort setting, the user is giving the system two inputs. First, the comfort setting specifies how far outside the acceptable temperature and humidity band the indoor conditions must reach before action is taken by the system. These tolerances are set by the user using the touch screen thermostat. For example, the user may want the system to wait until the indoor temperature is four degrees outside the acceptable band when in Max Savings mode, while only one degree of tolerance is acceptable when in Max Comfort mode. Secondly, the HVAC components that are selected by the system to bring the temperature and humidity back within the band will also be based on the comfort setting chosen by the user.

While the Max Savings option is selected, and the inside temperature is not within the acceptable band, the system will first try and use the least energy consuming component (AC2, 1500W) to bring the temperature back to within the acceptable range. After running for a set period of time (called the hold time, and also customizable by the user), the system will reevaluate the indoor temperature. If the temperature has moved back toward the acceptable range, then AC2 will continue to run until the temperature is back inside the acceptable band. If the temperature further deviates from the acceptable range, AC2 will turn off, AC1 (2500W) will turn on, and after the same hold time the conditions will be reevaluated. If the humidity is out of the acceptable range, the Dehumidifier will be turned on until humidity is back within the acceptable range. Max Savings mode is ideal for periods of time where maintaining ideal indoor conditions are not as important as consuming the least amount of energy possible. For example, a user would want to turn the system to Max Savings before leaving for work in the morning.

On the other hand, with Max Comfort selected and the temperature not within the acceptable band, the system will go straight to using both AC1 and AC2 to bring the temperature back within the acceptable range. Another condition occurs when the relative humidity is not within the acceptable set point tolerance range, the system would activate DH. This setting is the equivalent of the standard 3-Ton Air Conditioning System that our system is designed to replace and would be used when it is important to maintain a specific desired temperature for scenarios such as entertaining guests.

The main user interface for the system is a 7” LCD Touch Screen that is designed to replace a traditional thermostat. This is where the user inputs the set points for temperature and relative humidity, as well as choosing the level of energy savings, and customizing the hold time and tolerance levels.

The secondary user interface for the system is a web server that allows the system to be regulated from a remote location. An integrated circuit chip embedded in the printed circuit board inside the Main Control Unit sends and receives information from the router back to the control system. We employed the 802.11.b protocol to connect the system to a network. The web server is optimized to be easily viewable when shrunk to the size of a phone screen, so the system is easily regulated when the user is on the go.

For inter system wireless data communication, there must be a distance of less than 100 feet between the two wireless chips for an accurate and dependable signal due to the finite range capability of our XBee transceiver. The only intersystem communication the system must handle is the transfer of temperature and relative humidity data from the remote sensing unit on the exterior of the building to the main control unit inside.

II. COMPONENTS

A. Microcontrollers

For the design of our project we utilized a main microcontroller and a secondary microcontroller. The main microcontroller is located in the main control unit and is where the majority of the processing will be done. It interfaces with the LCD touch screen interface, a temperature and relative humidity sensor, the XBee and Wi-Fi transceivers, the power supply, and the output relays. During the selection of the main microcontroller we considered several specs such as the number of I/O pins, number of interfacing ports, on-board Flash memory, and read-access memory. We chose the dsPIC33FJ256GP710A because it includes 256 KB on-board Flash memory, 30 KB RAM, 85 I/O pins, and a total of 6 modules for the interfacing ports. These interfacing ports contain 3 wire SPI, I^2C, and UART connections. System expandability is important to our sponsor, and the dsPIC33FJ256GP710A allowed us extra memory and pins to allow for more features to be added in the future.

The secondary microcontroller we picked was the PIC24F04KA201. This microcontroller is only responsible for receiving temperature and relative humidity data and relaying that data to the main control unit. The PIC24F04KA201 microcontroller is a low power consuming component; perfect for our battery powered remote sensing unit.

B. XBee Communications

The wireless transceiver the group decided to use was the XBee RF 802.15.4 as shown in figure 1. With a range of 100ft, the XBee transceiver allowed the group to communicate between the remote sensing unit and the main control unit for most normal applications. The only information that is sent over the XBee transceiver is a 12 or 14 bit temperature or relative humidity value. The data rate of 250 kbps allows the data to be transmitted in a timely manner. It also has a power supply with a voltage requirement ranging from 2.8 – 3.4 V (typical voltage of 3.3V).

Figure 1 – XBee chip from Sparkfun Electronics

C. Wi-Fi Communications

The Main Control Unit for our system needs to be able to connect to the internet so the system can be manipulated when the user is away. Looking at Microchip® wireless solutions, the MRF24WB0MB Wi-Fi radio frequency transceiver module fit our requirements. The MRF24WB0MB has many features that work well with our system and Microchip provides sample code for interfacing the MRF24WB0MB with our main microcontroller. It has a 36 pin surface mountable module that's dimensions are 21mm x 31mm. To test Microchip's ® Wi-Fi radio frequency transceiver module, a PICtail ™ daughter board is a perfect solution for developing and testing because it simply plugs into our development board. This daughter board is compatible with Microchip's ® 16-bit microcontroller Explorer 16 Development Board that we are also using. Figure 2 shown below is a picture of the Wi-Fi RF transceiver with the PICtail TM daughter board being used.

Figure 2 – MRF24WB0MB Wi-Fi RF transceiver with PICtail daughter board from Microchip Direct

D. Sensors

This component of our project was a huge part of our initial design because our temperature and relatively values need to be accurately recorded from inside and outside the building so the system can activate the correct HVAC components. One sensor will be located in the Remote Sensing Unit which is outside the building in order to record current outdoor conditions, while the other will be in the Main Control Unit to record current indoor conditions.

We chose the SHT21 temperature and relative humidity sensor made by Sensirion. The accuracy of the readings for temperature and humidity met the requirements for our project. The SHT21 is currently the world's smallest temperature and relative humidity sensor at a size of 3x3x1.1mm. The sensor has a foot print of 3x3 mm, is pre-calibrated, and uses the I^2C protocol to communicate to the main and secondary microcontrollers. Instead of surface mounting the sensor to our board, we bought it from a vendor that had it already mounted with the minimum connections mounted as well. There is four header pins also pre-mounted to the board. This allowed us to solder on 4 header pins to our board and simply plug in the sensor. This model had the advantage of making the soldering easier for our group since we have limited experience in surface mount soldering and also allowing the sensor to be easily connected to and removed from the board in a matter of seconds. Another advantage of this setup was that the output of the sensor is a digital value. Digital output from the sensor eliminated the need for the use of an Analog to Digital Converter and therefore simplified communication between the sensor and the microcontroller. Figure 3 shown below is a picture of the temperature and relative humidity sensor we used.

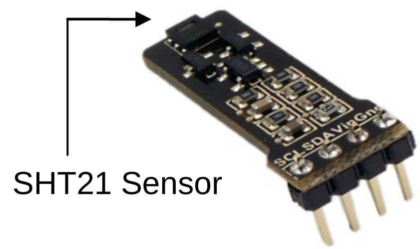

Figure 3 – SHT21 Temperature and Relative Humidity Sensor from Sensirion

E. Relays

In a typical HVAC control system there are two types of relays involved: control relays and power relays. For this project, we are only concerned with the control relays since the power relays are already installed in the existing HVAC system. Normally, power relays are located outside at the HVAC compressor and another also located at the inside air handler. Upon the completion of the project, the sponsors will retrofit this control system to an existing HVAC system. Therefore, the output of our control system needs to be the 24V required to control the existing power relays.

When the power relay is switched to the on position, 220/240V AC line is connected to the compressor or air handler and it runs until the relay is switched back to the off position. The power relays are switched by the control relays which are mounted to our Main Control Unit PCB. The sponsors have specified the number of outputs required for each of the HVAC components. The control relays will provide 4 outputs for AC1, 3 for AC2, 1 for Dehumidifier, 1 for blowing outside air in, and 1 for diluting outside air.

To satisfy these conditions, our group selected the G6RL PCB Relay from Omron. These relays require a 3V coil voltage in order to close the contacts. This was applicable for our use because our microcontroller is capable of producing the necessary coil voltage through the use of a transistor. The contacts in the relay are rated for 400VAC at 10A which is more than enough for our application. Using this type of relay, we designed our printed circuit board for the Main Control Unit so these relays could be soldered directly to the PCB. The outputs of the relays connect to a screw terminal so the existing wires in the building are easily connected to the PCB. Upon completion of the system the sponsors wish to integrate the system into an existing HVAC system. The use of screw terminals allow for existing thermostat wiring to be easily connected to the main control unit. The printed circuit board software that was preferable to use due to its extensive array of electronic parts in their library database was EAGLE CAD. Within these schematic layouts for the microcontrollers, we integrated our relays.

F. LCD Screen

According to the sponsor's specifications, they wanted to have a large color touch screen user interface that was aesthetically pleasing and intuitive to use. We found that in order to program and interface a LCD touch screen with a microcontroller, we needed both a screen, and a controller board. The controller is what takes the command from the microcontroller and displays it onto the screen. For our prototype, we decided to purchase a kit that included both the screen and the controller. The product that we found that provided us both the screen and the controller was the 7" Evervision TFT-LCD Touch Screen Panel development kit. It also included an SLCD5 controller which provides the GUI for the LCD interface. The screen and controller came with software that made it easy for us to add .bmp files and macros to the screen.

Figure 4 below is a picture of the main menu for the touch screen user interface. Through this interface, the user is able to specify the desired set points for temperature and relative humidity, select the desired comfort setting, and view current indoor and outdoor temperature and relative humidity. Also on the home screen, located in the middle, is the "Energy Use Bar." The Energy Use Bar slides from left to right depending on what percentage of the total HVAC system power is currently being used. If no components are running, the bar will be all the way to the left and the entire bar will be displayed green. On the other hand, if all of the components are on and running; the bar will slide all the way to the right and it will be colored red. In the screen shot below, exactly half of the total power of the system is being used. The selection menus on the left of the screen are features specified by the sponsor to be added to the system in the future, and will not be functional upon the completion of the initial system.

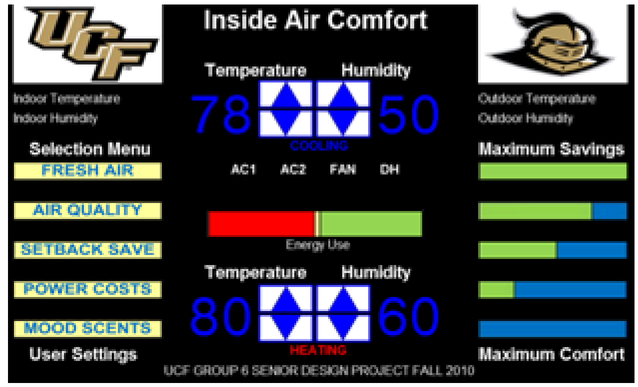

Figure 4 – Main LCD User Interface

In addition to the main screen, the LCD has a "settings" screen. The settings screen allows the user to specify the tolerance level for each of the comfort settings as well as specify the hold time for the system. This is a secondary screen that can be accessed by the user by touching "User Settings" located in the bottom right hand corner of the main user interface screen.

III. Design and Implementation

A. Explorer 16 Development Board

To test and implement our code we are using the Explorer 16 Development Board from Microchip. It provides a low cost modular development system for 16 bit microcontroller families.

The board supports both PIC24 and dsPIC33F microcontroller families that are being used. The development board operates on a 9V DC power input with both 3.3 V and 5 V outputs to test peripheral devices. The board also has an LCD display and several LED's for real time results during testing. On the Explorer Board are socket and edge connectors for PICtail card compatibility. The PICtail compatibility allows us to easily connect the Wi-Fi PICtail Plus Daughter Board to the dsPIC33F for testing purposes.

We are able to also develop and test code for the PIC24 through the use of a Plug-In Module available from Microchip. The use of a Plug-In Module allows the Explorer Board to develop code for more than one microcontroller without having to solder any chips directly onto the board.

The Explorer 16 Development Board is being used with the MPLAB C Compiler from Microchip so code can be written and tested in the C high level language. The C language is ideal for development because it is the programming language we are most familiar with.

B. Main Control Unit

The Main Control Unit consists of the main microcontroller, the XBee transceiver, the Wi-Fi transceiver, the SHT21 temperature and humidity sensor, the LCD touch screen display, and the control relays. Since the Main Control Unit is made up of six different components, care had to be taken to make sure they would all receive appropriate power supplies from the board as well as making sure that all communication lines were properly designed.

In order to make the Main Control Unit a true thermostat replacement, we need to use the 24V AC power source coming from the existing HVAC wiring. This presented a challenge since our components all ran on 12, 5, or 3.3V DC. In order to transform our power to be able to run our components, a multi-stage transformation had to occur. First, the 24VAC input needed to be transformed to DC. To change from AC to DC we use a full wave rectifier along with a smoothing capacitor. The output of the rectifier is then inputted into 12, 5, and 3.3V voltage regulators. The 12V linear voltage regulator powers the LCD touch screen, the 5V linear voltage regulator powers the sensor, and the 3.3V linear voltage regulator powers the XBee chip, Wi-Fi chip, and the main microcontroller. Due to constraints on the allowable input voltage of the 3.3 V linear regulators; a 5 V regulator had to be utilized to provide an intermediate voltage between the input of the 3.3 V regulators and the output of the smoothing capacitor. Research had to be done to confirm each regulator provided enough current to meet the requirements of the devices they are powering.

Communication between the main microcontroller and the XBee chip, Wi-Fi chip, sensor, and LCD touch screen was another design constraint that had to be taken into consideration. The dsPIC33FJ256GP710A has 2 SPI ports, 2 I^2C ports, and 2 UART ports available for communication between the microcontroller and other components.

The components of the Main Control Unit require the connections shown in Figure 5 for communication with a microcontroller. The SHT21 sensor requires an I^2C interface, the XBee and Wi-Fi transceivers require SPI interfaces, the LCD Touch Screen requires a UART (Serial) connection and the control relays require one output wire from the microcontroller per relay. Reliable communication between the components of the system is a crucial requirement for long term dependable and accurate control of an HVAC system.

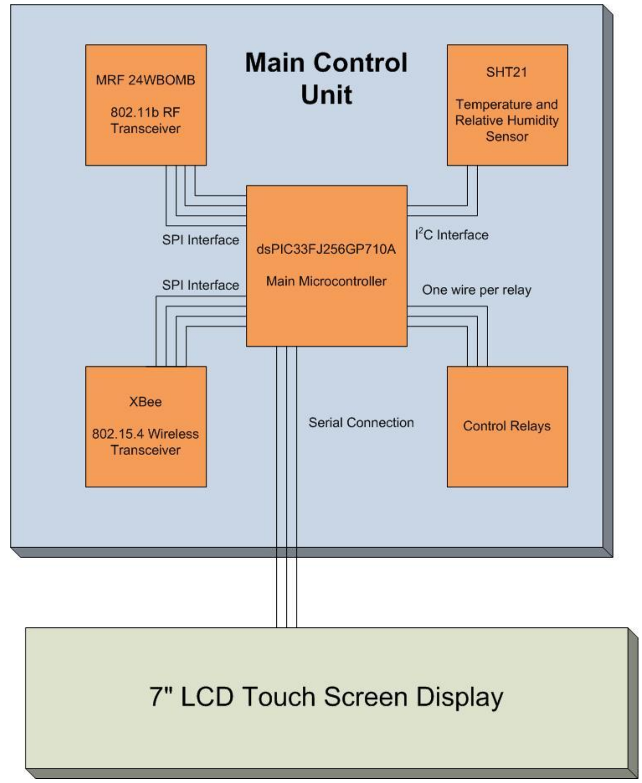

Figure 5 – Main Control Unit Communication Connections

C. Remote Sensing Unit

The Remote Sensing Unit consists of the secondary microcontroller, an XBee transceiver, and an SHT21 temperature and humidity sensor. When designing the Remote Sensing Unit, power and communication were issues that had to be taken into consideration.

The Remote Sensing Unit is designed to be mounted on the exterior of the building, and therefore is required to have its own power supply. The solution to powering the Remote Sensing Unit was to mount a battery inside the unit. A battery holder was found that came with an onboard DC to DC step up regulator that had an output of 5V DC. This simplified the design for the Remote Sensing Unit because a DC to DC step up circuit could be eliminated from the PCB design process. This battery holder is designed to fit 2 AA batteries. AA batteries are a good solution because they gave the Remote Sensing Unit sufficient battery life, and they are easy to buy when replacement is necessary.

The PIC24F04KA201 features 1 SPI interface, 1 I^2C interface, and one UART interface for communication. For the Remote Sensing Unit, the SPI and the I^2C interfaces will be utilized. The SHT21 temperature and humidity sensor will utilize the I^2C interface, while the XBee transceiver utilizes the SPI interface. Figure 6 shown below illustrates the power and communication connections associated with the Remote Sensing Unit.

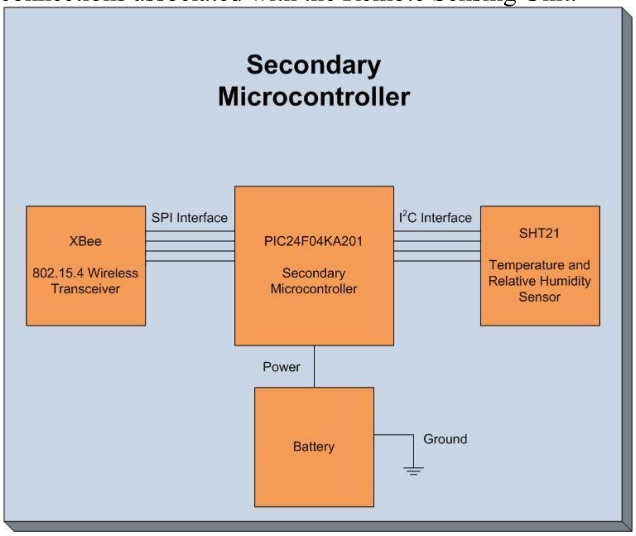

Figure 6 – Remote Sensing Unit Power and Communication Connections

D. PCB Design

PCB Design is a crucial aspect of our project. Since the project has no moving parts, the printed circuit boards make up the majority of the hardware aspect of the system. The PCB design was done using EAGLE 5.7.0 Professional CAD software. The boards were ordered and fabricated through www.4pcb.com. This website was chosen for two reasons. First, they offer a service to check Gerber files through www.freedfm.com before submitting the board for fabrication. The Free DFM check makes sure there are no potentially fatal flaws with the layout of the board's traces and vias. Also, they offer a student only special which allowed the group to order one board at a time for $33 plus shipping.

For the PCB design, the group tried to use surface mount components whenever possible. In general the group found that surface mount parts are cheaper than their through-hole counterparts.

The design of the board for the Remote Sensing Unit was fairly straight forward, since it only consisted of the secondary microcontroller, the temperature and humidity sensor, and the XBee transceiver. There were several components that had to be placed on the Remote Sensing Unit in addition to the main IC's. First, an RJ-11 connector had to be placed. This allows the PIC24F04KA201 to connect to the Microchip ICD3 Debugger for programming. Also, the battery holder needs a JST vertical connector in order to provide power to the board. Lastly, the datasheet specifies a need to disconnect one of the decoupling capacitors during programming so a jumper was placed on the board to allow for a quick disconnect. Figure 7 shown below shows the PIC24F04KA201 with required minimum connections along with power and RJ-11 programming connections.

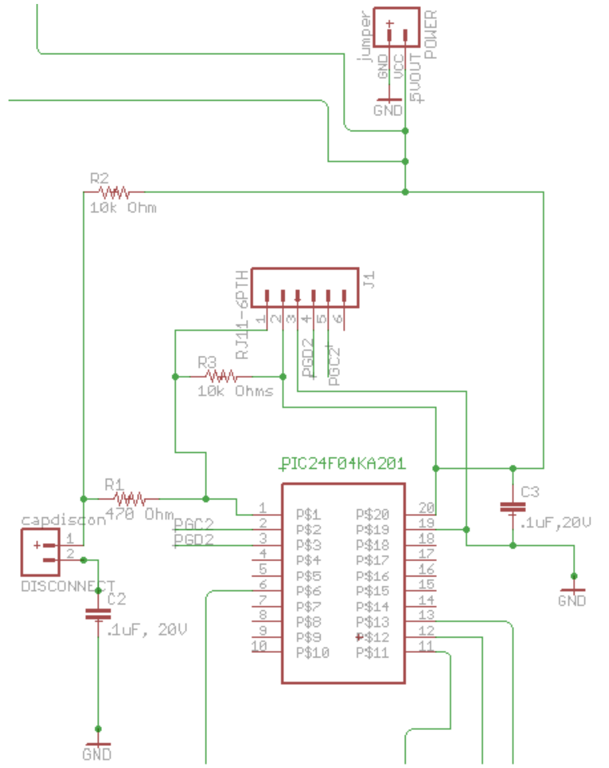

Figure 7 – Power, programming, and required minimum connections for Remote Sensing Unit PCB

The design of the Main Control Unit PCB was more complex. The PCB for the Main Control Unit can be broken down into the three subsections of input, output, and communication. The input to the board provides power to all components; the output provides the correct voltage to control all the HVAC components and communication which allows for the components of the Main Control Unit to interface with each other.

Input for the Main Control Unit PCB is the power supply. As previously discussed, the 24VAC signal is being converted into DC signals of 12, 5, and 3.3 Volts through the combination of bridge rectification and the usage of linear voltage regulators. The 12 volt regulator provides power to the LCD touch screen, the 5 volt regulator provides power to the sensor, and the 3.3 volt regulator provides the power to the XBee, microcontroller, and the Wi-Fi IC's. Figure 8 shown below shows the

EAGLE schematic of the bridge rectifier and the linear voltage regulators for the Main Control Unit PCB.

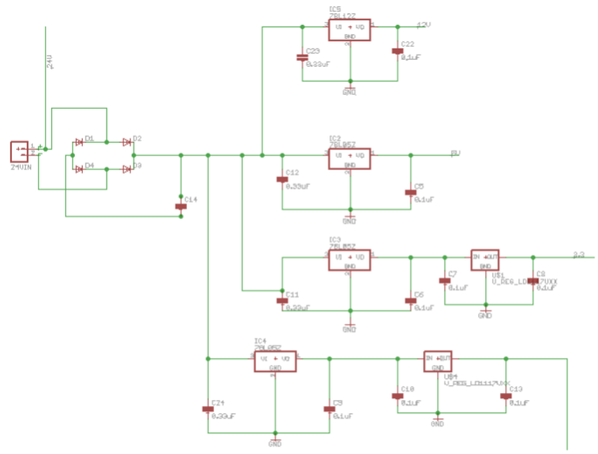

Figure 8 – Power Supply for the Main Control Unit PCB

The output of the Main Control Unit is 24V AC. When the relays close, the 24V AC signal is outputted to the HVAC components, which are turned on. In order to provide the required voltage to the transistor, we found that a 650Ω resistor was necessary between the output of the microcontroller and the base of the transistor using the following equation

$$(3.3V - V_{BE})/R_{SERIES} = 4mA \qquad (1)$$

After solving for R_{SERIES} to be 650Ω, we determined the closest realistic resistor value we could implement was a 649 Ω resistor.

E. Software Design

The main control unit's software design is primarily focused on simplicity. In order to meet our requirements, the unit needs to monitor a wire temperature, control multiple relays to power HVAC units, and to control ventilation systems. In addition to the automated controls of the system, it must have a user interface for which a user can adjust system control settings.

The heart of the control system is a user case that handles all of the HVAC controls. Within this operation we will have our operational conditions checked, and based on adjustable user settings, this user case will pass information to power relays or adjust ventilation system. In making a decision for which systems to enable, the control process must first receive readings from a wireless temperature and relative humidity sensor. With this current information, the system reads the settings that the user adjusted to suit their own comfort and power levels. Figure 9 shown below summarizes the process for the user case diagram for the main control unit.

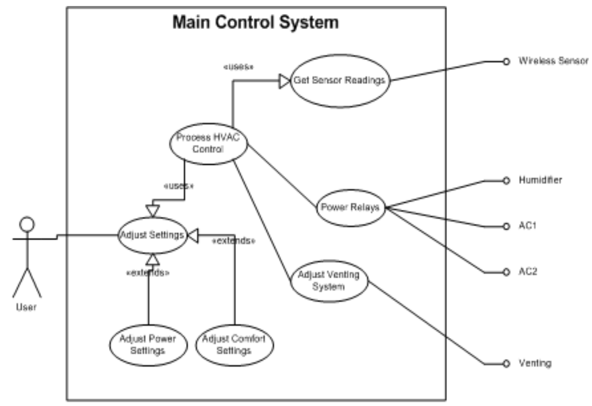

Figure 9 – User Case Diagram for the Main Control Unit

For the wireless sensor, this software design is more basic. The main control unit will transmit a request for information. When this operation is received, the system will gather the current sensor reading. This information is then transmitted back to the main control unit. Figure 10 illustrates the user case diagram for the wireless sensor.

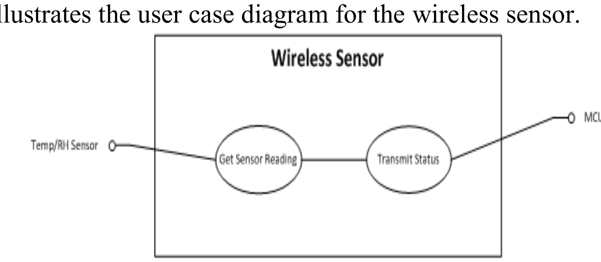

Figure 10 – User Case Diagram for the Wireless Sensor

IV. CONCLUSION

With the increased capabilities of cost effective technologies and the growing demand for energy efficient systems, the need for intelligent control systems is higher than ever. The need for an efficient HVAC control system is particularly high because of two main reasons: First of all because virtually every building has an HVAC system associated with it, and secondly because of the fact that HVAC systems are usually the leading energy consumer in a building.

Our initial system is designed to reduce the energy consumption of the conventional HVAC system. It also makes smart decisions as to which components to be on and running, as well as adding a dehumidification element to the process. An element that makes our system unique is the ability for the system to use outside air to help heat or cool the building when applicable. In addition to outside air being used to heat or cool the building, outside air will help to filter unwanted contaminants out of the building along with the old stagnant air. This system will serve primarily as a replacement to an existing HVAC system that is installed in a residential or commercial building. It will be creatively expanded in a way that makes the system more functional and efficient. This HVAC control system utilizes both inside and outside temperature and relative humidity readings to maintain desirable conditions inside the building.

When combining the user interface of the LCD touch screen and a mobile web server, the user is able to interact with the system either while inside the building, or by using a device with wireless technological capabilities such as a smart phone when away from the building. Internet connectivity and touch screen sensing are new technologies that have only recently been introduced to the engineering field. Advancements in smart phone applications and touch screen sensors have made it possible for consumers to take full advantage of this technology at an affordable price.

As technology advances, features are being added to control and feedback systems such as wirelessly reporting sensor data, and the ability to remotely access system settings. Smart control and feedback systems are becoming more common as technology becomes less expensive and the cost of energy continues to rise. The Efficient HVAC Control and Feedback System is a unique, state-of-the-art product that uses these cutting edge technologies to save energy and therefore saving the consumer money.

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