Efficient HVAC Control System

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Sponsored by:
HVAC Development Group
Motivation

- Create a system to reduce the user’s monthly energy consumption
- To implement an HVAC control system based on the control logic and other requirements provided by the sponsors
- The system should reduce “short-cycling”, or the scenario of a unit running for a short period of time, and therefore never reaching its maximum efficiency.

Energy Efficiency Ratio vs. Run Time

![Energy Efficiency Ratio vs. Run Time Graph]
Project Overview

- The system is designed to control an HVAC system consisting of a 1 ton Air Conditioner, a 2 ton Air Conditioner, and a Dehumidifier

- The system gives user the ability to control both temperature and humidity set points

- The system gives the user the option to bring outside air into the building based on either a set schedule, or exterior conditions
The system is composed of the Main Control Unit, Remote Sensing Unit, and LCD touch screen.
Main Control Unit

• The Main Control Unit takes inside temperature / relative humidity readings, wirelessly communicates with both the internet and the Remote Sensing Unit, and controls both the user interface and the relays.

Remote Sensing Unit

• The Remote Sensing Unit takes outside temperature / relative humidity measurements and wirelessly reports the data to the Main Control Unit.
• Since the Remote Sensing Unit is meant to be installed outside where no power source is present, it must be battery powered.

LCD Touch Screen

• The LCD touch screen provides an aesthetically pleasing user interface for easy manipulation of the system.
Objectives

- Accurately read temperature and relative humidity both inside and outside the building.
- Wirelessly transmit outside data from the Remote Sensing Unit to the Main Control Unit.
- The user interface must be a thermostat replacement in the form of a touch screen that is easy to view and intuitive to operate.
- Allow the user to input temperature and humidity high and low set points to create an acceptable range for both conditions.
- Communicate with the internet so that the user can view and manipulate system settings online.
- Be expandable to incorporate additional HVAC components and sensors in the future.
- The system must be able to be installed in an existing building using only the existing HVAC wiring.
Specifications and Requirements

- Must be able to provide 24V AC to control HVAC components (output)
- Wireless transmission of temperature and relative humidity data over a distance of at least 100 feet
- Measure indoor and outdoor temperature (± 0.5 °C) and relative humidity (± 5%) with specific accuracy
- Be capable of measuring realistic outdoor temperature (-20 °F – 110 °F) and relative humidity (0% - 100%)
- Total cost of the HVAC system $1500 or less for initial prototyping
Outside Air

- This system is designed to integrate outside air into the traditional HVAC system.
- Outside air will be blown into the building when it will help bring the inside temperature back within the acceptable range.
- When the inside temperature is not within the acceptable range, the system first checks to see if the outdoor temperature is suitable to either cool or heat the building. This is the least power consuming method of cooling or heating the building.
Comfort Setting

- Another unique aspect of this control system is the ability to select a comfort setting.
- The comfort setting specifies how much the interior conditions can deviate from the acceptable set points before the system takes action.
  - The amount of tolerance associated with each comfort setting is inputted through the “settings” menu on the LCD touch screen.
- When action is taken, it also determines which components will run to bring the conditions back within the acceptable range.
- There are five comfort settings that allow the user to specify emphasis on either “Maximum Comfort”, or “Maximum Savings”
Max Savings Setting Control Example

- **Temperature moves outside acceptable range**
  - The 1 Ton (small) unit runs for a specified hold time (also set by the user on the “settings” screen)
  - Next, the inside temperature measurement is again taken and if the temperature has moved closer to the acceptable range, the 1 ton AC unit will continue to run
  - If the temperature has leveled off or moved further from the acceptable range, the 1 ton unit will turn off, and the 2 ton unit will turn on
  - Only after both the 1 ton, and the 2 ton units have failed to independently bring the temperature within the acceptable range, will they both run at the same time.

- **Humidity moves above acceptable range**
  - Dehumidifier will run by itself until humidity is back within acceptable range
Max Comfort Setting Control
Example

- Temperature moves outside acceptable range
  - Both 1 Ton and 2 Ton units turn on to bring the temperature back within the acceptable range
  - This method uses the same amount of power of a traditional 3 Ton HVAC system

- Humidity moves outside acceptable range
  - Both Air Conditioning units run along with the Dehumidifier in order to bring humidity back within the acceptable range as quickly as possible
# Power Consumption of HVAC Components

<table>
<thead>
<tr>
<th>Component</th>
<th>Energy Use in Watts</th>
</tr>
</thead>
<tbody>
<tr>
<td>Dehumidifier</td>
<td>500</td>
</tr>
<tr>
<td>Air Conditioner [1- Ton Capacity]</td>
<td>1500</td>
</tr>
<tr>
<td>Air Conditioner [2- Ton Capacity]</td>
<td>2500</td>
</tr>
<tr>
<td>Standard 3-Ton Air Conditioning System</td>
<td>4000</td>
</tr>
</tbody>
</table>
Component Overview

- **Main Control Unit**
  - Main Microcontroller (dsPIC33FJ256GP710A)
  - 802.11b Wi-Fi Transceiver
  - 802.15.4 XBee Transceiver
  - Temperature / Relative Humidity Sensor
  - Relays

- **Outside Sensing Unit**
  - Secondary Microcontroller
  - 802.15.4 XBee Transceiver
  - Temperature / Relative Humidity Sensor

- **User Interface**
  - Evervision 7” LCD Touch Screen
  - SLCD5 Controller
Main Control Unit (MCU)

- The Main Control Unit houses several components such as the SHT21 sensor, dsPIC33FJ256GP710A main microcontroller, XBee 802.15.4 transceiver, and the MRF24WB0MA 802.11b wireless transceiver.

Minimum, Maximum, and typical operating voltages for components associated with the MCU

<table>
<thead>
<tr>
<th>Component</th>
<th>Min Operating Voltage (V)</th>
<th>Typical Operating Voltage (V)</th>
<th>Max Operating Voltage (V)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Main Microcontroller</td>
<td>3</td>
<td>3.3</td>
<td>3.6</td>
</tr>
<tr>
<td>XBee wireless</td>
<td>2.8</td>
<td>3.3</td>
<td>3.4</td>
</tr>
<tr>
<td>802.11b wireless</td>
<td>2.7</td>
<td>3.3</td>
<td>3.6</td>
</tr>
<tr>
<td>Temperature and Relative Humidity sensor</td>
<td>3.6</td>
<td>5</td>
<td>5.5</td>
</tr>
<tr>
<td>LCD Touch Screen and Controller</td>
<td>5</td>
<td>N/A</td>
<td>12</td>
</tr>
</tbody>
</table>
Powering the Main Control Unit

The interfacing associated with providing power to the components of the Main Control Unit is shown below. 24V AC is provided from a transformer in the HVAC air handler.
Main Control Unit Components with Connection Types

- MRF 24WBOMB
  802.11b RF Transceiver

- SHT21
  Temperature and Relative Humidity Sensor

- dsPIC33FJ256GP710A
  Main Microcontroller

- XBee
  802.15.4 Wireless Transceiver

- Control Relays

- 7" LCD Touch Screen Display
## Comparison of Main Microcontroller Options

<table>
<thead>
<tr>
<th></th>
<th>dsPIC33FJ64GP206A</th>
<th>dsPIC33FJ256GP506A</th>
<th>dsPIC33FJ256GP710A</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pins</td>
<td>64</td>
<td>64</td>
<td>100</td>
</tr>
<tr>
<td>Flash Memory</td>
<td>64Kbyte</td>
<td>256kbyte</td>
<td>256Kbyte</td>
</tr>
<tr>
<td>ADC</td>
<td>1 ADC, 18 ch.</td>
<td>1 ADC, 18 ch.</td>
<td>2 ADC, 32 ch.</td>
</tr>
<tr>
<td>UART</td>
<td>2</td>
<td>2</td>
<td>2</td>
</tr>
<tr>
<td>SPI</td>
<td>2</td>
<td>2</td>
<td>2</td>
</tr>
<tr>
<td>I²C</td>
<td>1</td>
<td>2</td>
<td>2</td>
</tr>
<tr>
<td>I/O Pins</td>
<td>53</td>
<td>53</td>
<td>85</td>
</tr>
</tbody>
</table>
Reasons for choosing dsPIC33FJ256GP710A

- C compiler optimized instruction set
- 256K bytes Flash memory
- 30K bytes RAM
- 85 Programmable I/O pins
- Supports 2 I²C modules
- Supports 2 UART modules
- The sponsors have stressed their desire to expand the capabilities of the system
Remote Sensing Unit Components with Connection Types

Secondary Microcontroller

- XBee
  802.15.4 Wireless Transceiver

- PIC24F04KA201
  Secondary Microcontroller

- SHT21
  Temperature and Relative Humidity Sensor

- Battery
- Power
- Ground

SPI Interface

I²C Interface
Secondary Microcontroller
PIC24F04KA201

- 20 Pins
- 4K bytes Program Memory
- SRAM 512 bytes
- 3 16-bit timers
- 1 UART
- 1 SPI
- 1 I²C
Functions of Secondary Microcontroller

- Accept input from Temperature and Relative Humidity Sensor (12 or 14 bits)
- Enter these readings into the sensor conversion formula
- Send information to Main Control Unit through XBee 802.15.4 protocol
Secondary Microcontroller Minimum Connections

- This is the PIC24F04KA201 and the minimum required connections as described in the data sheet (EAGLE schematic)
Secondary Microcontroller with other external connections

- The secondary microcontroller with connections to ZigBee RF transceiver, temperature / humidity sensor, and female RJ11 port
# Selected Battery

<table>
<thead>
<tr>
<th>Type</th>
<th>Pros</th>
<th>Cons</th>
</tr>
</thead>
</table>
| Alkaline (AA)             | - Long battery life  
- Has Energy Capacity of 2850 mAh | - Drain rate affects the capacity                |
| Lithium - Ion             | - Produce nominally 3.6 to 3.7 V (very powerful)  
- Generates high current  
- Has an energy capacity of 2250 mAh  
- Relatively low self-discharge rate | - Most expensive in cost                           |
| Nickel Metal Hydride      | - Replace obsolete NiCad rechargables  
- Good all around battery | - High self-discharge rate                         |
| Nickel Cadmium (AA)       | - Decent discharge rate  
- Nominal cycle life of over 1,000 cycles | - Short term battery life  
- Max current is approx 400 mA  
- Being prone to damage by overcharging |
Remote Sensing Unit Power Supply

- The battery pack chosen to power the Remote Sensing Unit consists of 2 AA batteries with an on board DC – DC step up regulator.

- The battery pack outputs 5V DC at a max current of 500mA.

- This pack was chosen because it eliminated the need for a step up circuit to be designed on the PCB, and it provided enough current to power all of the components on the Remote Sensing Unit.
## Comparison of LCD Touch Screens (Sponsor Decision)

<table>
<thead>
<tr>
<th>Company Name</th>
<th>Size of LCD Touch Screen</th>
<th>Controller Name</th>
<th>Controller Specs</th>
<th>Development Kit Price</th>
</tr>
</thead>
</table>
| Evervision   | 7 inches                 | SLCD5 controller | -Power Supply Min 3.0 V to Max 3.6 V  
- 4 MB of flash memory  
-16 bit color         | $499                 |
| Kyocera      | 5.7 inches               | SLCD+ controller | -Power Supply Min 3.0 V to Max 3.6 V  
- 4 MB of flash memory  
-16 bit color         | $499                 |
| NEC          | 8.4 inches               | SLCD5 Controller | -Power Supply Min 3.0 V to Max 3.6 V  
- 4 MB of flash memory  
-16 bit color         | $799                 |
Format of LCD Touch Screen User Interface
Commands Used in Development of User Interface

- **Xi 1 100 200**
  - Places bitmap index 1 at pixel location 100x200

- **Bd 1 x y “text” dx dy bmp1 bmp2**
  - Places a button at x y with text identifier “text” with text offset of dx dy, displays bitmap index of bmp1 in state 1 and bmp2 at state 2

- **T “text string” x y**
  - Places text at (x, y) in respect to the origin point

Display of various bitmaps and buttons
Advantages of the 7” Evervision Development Kit

- The SLCD5 controller was bundled with 7” Evervision LCD screen
- Evervision LCD screen utilizes 4 wire resistive touch technology.
- SLCD5 controller provides easy to use commands to implement bitmaps and macros
The SLCD5 utilizes RS-232 for serial communication to host microcontroller

COM0 is deemed the “Main” port and is connected to the embedded processor to control the display

COM1 port or “Aux” is typically used to update the display of bitmaps and macros

SLCD5 Communication Setup (2 RS232 Ports)
Wireless Protocols

- The protocols that we researched and considered were the ZigBee, Wi-Fi, and Bluetooth.
- The best communication interface for wireless in system communication was ZigBee:
  - ZigBee was relatively simple and would be easily able to handle the readings we had to send.
  - Good amount of sample code available.
- To enable mobile device connectivity we chose a Wi-Fi transceiver:
  - Wireless internet connectivity was required because there is normally not an Ethernet connection wired to the thermostat.
## Wireless Protocols

<table>
<thead>
<tr>
<th>Wireless Protocols</th>
<th>Bluetooth (Class 1)</th>
<th>ZigBee (802.15.4)</th>
<th>Wi-Fi® (802.11 b)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Optimal Range (indoor):</td>
<td>~100 meter</td>
<td>10 – 75 meters</td>
<td>30 meters</td>
</tr>
<tr>
<td>Frequency Band:</td>
<td>2.4 GHz ISM band</td>
<td>2.4 GHz ISM band</td>
<td>2.4 GHz ISM band</td>
</tr>
<tr>
<td>Communication type:</td>
<td>WPANs</td>
<td>PANs</td>
<td>WLAN</td>
</tr>
<tr>
<td>Power required to operate:</td>
<td>100mW</td>
<td>1mW</td>
<td>100mW</td>
</tr>
<tr>
<td>Cost of implementation:</td>
<td>Low Cost</td>
<td>Low Cost</td>
<td>Medium Cost</td>
</tr>
<tr>
<td>Bandwidth:</td>
<td>1 Mbps</td>
<td>0.250 Mbps</td>
<td>11 Mbps</td>
</tr>
<tr>
<td>Encrypted:</td>
<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
</tr>
<tr>
<td>Primary Use:</td>
<td>Data exchange over short distances</td>
<td>Small, low powered devices</td>
<td>Mobile Internet</td>
</tr>
</tbody>
</table>
802.15.4 XBee Transceiver

- The Remote Sensing Unit collects data that needs to be sent to the Main Control Unit wirelessly.
- We had requirements of low power consumption to increase battery life, low data rate and secure networking for communication between the two boards of the system.
- XBee is compatible with Microchip’s Microcontroller Families (PIC16F, PIC18F, PIC24F/H, dsPIC33).

<table>
<thead>
<tr>
<th>XBee 1mW Chip Antenna Key Features</th>
</tr>
</thead>
<tbody>
<tr>
<td>3.3V @ 50 mA</td>
</tr>
<tr>
<td>250kbps Max Data Rate</td>
</tr>
<tr>
<td>300ft Range</td>
</tr>
<tr>
<td>8 Digital I/O pins</td>
</tr>
<tr>
<td>Built-in Antenna</td>
</tr>
</tbody>
</table>
802.11 b MRF24WB0MA RF Transceiver

- The 802.11b transceiver is a 36 pin surface mountable module that has dimensions of 21 mm x 31 mm
- Requires low supply voltage: 2.7V – 3.6V (3.3 V is typical)
- Operates on the 2.4 – 2.483.5 GHz band
- Designed to be used with Microchip’s TCP/IP software stack and microcontroller families
- The MRF24WB0MA module and a PIC microcontroller operating the TCP/IP stack allows for implementation of a web server
MRF24WB0MA  RF Transceiver (cont)

- This module interfaces to the microcontroller via a four-wire SPI interface, as well as interrupt, hibernate, reset, power, and ground signals.
- Offers different modes of operation such as hibernate and sleep to allow for lower power consumption.
- Receive (RX) mode uses 85 mA, Transmit (TX) mode uses 154 mA, Hibernate mode uses < 1 uA, while the Sleep mode uses 250 uA.

CS – SPI Chip Select input
SCK – clock
SDI, SDO – SPI data In and data out pins

MRF24WB0MA interface to microcontroller
The sensor we chose was the Sensirion SHT21 Humidity and Temperature Sensor.

Uses I²C protocol to communicate with the microcontroller.

The SHT21 has a normal operating range from 20 °C to 100 °C (68 °F to 212 °F) at about 8% relative humidity and -20 °C to 60 °C (-4 °F to 140 °F) at 90% relative humidity.

Default digital output resolution of 12 bits for relative humidity and 14 bits for temperature.
I^2C protocol and commands for SHT 21

- Uses two bidirectional lines for the I^2C format: Serial Data Line (SDA), Serial Clock (SCL)
- Data can be sent across the SDA line after a start condition has been met
- The start condition is when the SDA line goes from a high to low while the SCL is high
- When the data is already done sending, a “stop condition” of the SDA going from a low to a high while the SCL is high occurs
- Once the start condition is met, a header made up of 7-bit device addresses and an SDA directional bit is sent and received

Start and Stop Conditions for I^2C protocol
Factors in Calculating Relative Humidity and Temperature Values

- Once the measurement is taken and the bits are transferred, it must be converted into a number that makes sense to the user
- Binary number must be converted to a decimal number (called $S_{RH}$ or $S_T$ for relative humidity and temperature)
- Once converted into decimal representation, the value must be plugged into a formula to get the final output

Formulas for Calculating Relative Humidity and Temperature Values for the User

$$RH = -6 + 125 \times \left( \frac{S_{RH}}{2^{16}} \right) \rightarrow \text{units } \% \text{ RH}$$
$$T = -46.85 + 175.72 \times \left( \frac{S_T}{2^{16}} \right) \rightarrow \text{units } ^{\circ}C$$
Software Overview

- C language used to code compiled with C30 compiler from Microchip
- LCD Interface programmed through microcontroller
- TCP/IP Stack and web server provided by Microchip
HVAC Data Structures

<table>
<thead>
<tr>
<th>HVAC</th>
<th>HVAC_Unit</th>
<th>HVAC_List</th>
</tr>
</thead>
<tbody>
<tr>
<td>Int : NumUnits</td>
<td>uint : state</td>
<td>HVACList : next</td>
</tr>
<tr>
<td>initHVAC();</td>
<td>uint : heat</td>
<td>HVACList : prev</td>
</tr>
<tr>
<td>processHVAC();</td>
<td>insertHVAC(HVAC_Unit)</td>
<td>HVAC_Unit : unit</td>
</tr>
</tbody>
</table>

0..*
Use Case Diagram

Main Control System

- User
- Adjust Settings
- Adjust Power Settings
- Adjust Comfort Settings
- Adjust Venting System
- Power Relays
- Process HVAC Control
- Get Sensor Readings

Wireless Sensor
Humidifier
AC1
AC2
Venting
PCB Design

- PCB design was performed using the EAGLE (Easily Applicable Graphical Layout Editor).
- Two PCB’s were created for this project. One PCB associated with the Main Control Unit and one associated with the Remote Sensing Unit.

Remote Sensing Unit PCB
PCB Design Procedure

- The first step in the PCB fabrication process is to create the circuit needed for the PCB in the EAGLE program’s schematic editor.
- When creating the schematic (.sch file), components need to be selected based on the footprint of the part being soldered onto the final board.
- Many of our components came from the SparkFun website, because they provided a footprint library for EAGLE which contained almost all of their products.
- Once the schematic is complete, EAGLE produces a board layout. This step is where board dimensions are specified, components are placed on the board, and traces are run.
- With the board layout complete, EAGLE then produces the Gerber files needed by the fabrication house.
- The fabrication house we used was www.4pcb.com.
Main Microcontroller, RJ11 Programming Port, and Temperature/Humidity Sensor
Main Control Unit PCB Schematic

Max3232 and Serial Connector for communication with the LCD touch screen
Main Control Unit PCB Schematic

Screw terminals, relays, and transistors
Main Control Unit PCB Schematic

XBee wireless transceiver
Main Control Unit PCB Layout
Hardware Design Issues and Solutions

• The original ZigBee transceiver chosen could not be implemented due to the need for external memory that was not originally accounted for. We changed to an XBee module that was easier to implement.

• Both PCBs contained shorts that had to be located which led to several traces having to be cut and jumper wires soldered onto the board.

• The Main Control Unit PCB had issues with power distribution which also led to traces being cut and jumper wires being soldered to the board.
Software Design Issues and Solutions

- Watchdog timer enabled by default
  - Configuration bits changed to disable
- \(I^2C\) drivers
  - Forced clock tick to clear Ack
- XBee
  - Firmware modified for low power
## Budget and Financing

<table>
<thead>
<tr>
<th>Component Description</th>
<th>Part Number</th>
<th>Manufacturer</th>
<th>Total</th>
</tr>
</thead>
<tbody>
<tr>
<td>7” Evervision LCD Development Kit</td>
<td>52-0102-12</td>
<td>Evervision Reach Technology</td>
<td>$499</td>
</tr>
<tr>
<td>MRF24J40MA PICtail Daughter Board</td>
<td>AC164136-4</td>
<td>Microchip</td>
<td>$60</td>
</tr>
<tr>
<td>MRF24J40MB PICtail Daughter Board</td>
<td>AC164134-2</td>
<td>Microchip</td>
<td>$30</td>
</tr>
<tr>
<td>Explorer 16 Kit</td>
<td>DV164037</td>
<td>Microchip</td>
<td>$299</td>
</tr>
<tr>
<td>MRF24J40MB XBee 1mW Chip Antenna</td>
<td>WRL-08864</td>
<td>XBee</td>
<td>$45.90</td>
</tr>
<tr>
<td>PIC24F04KA201 Secondary Microcontroller</td>
<td>PIC24F0KA201-I/SO</td>
<td>Microchip</td>
<td>$9.20</td>
</tr>
<tr>
<td>dsPIC33FJ256GP710A Main Microcontroller</td>
<td>DSPIC33FJ256GP710</td>
<td>Microchip</td>
<td>$17.08</td>
</tr>
<tr>
<td>Other Miscellaneous Parts</td>
<td></td>
<td></td>
<td>$579.82</td>
</tr>
<tr>
<td><strong>Grand Total:</strong></td>
<td></td>
<td></td>
<td><strong>$1,540</strong></td>
</tr>
</tbody>
</table>
## Production Costs

<table>
<thead>
<tr>
<th>Remote Sensing Unit Production Cost</th>
<th>Main Control Unit Production Quality</th>
<th>Estimated LCD Touch Screen Unit</th>
<th>Efficient HVAC System Total Cost</th>
</tr>
</thead>
<tbody>
<tr>
<td>$124.80</td>
<td>$253.87</td>
<td>$325.00</td>
<td>$703.67</td>
</tr>
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</table>
Questions / Demonstration

Main Control Unit

LCD Touch Screen

Remote Sensing Unit