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Household Energy Aware Real-Time System (HEARTS):
A Capstone Project Design

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Abstract— This paper discusses a design framework and student experiences of a capstone project carried by students at the Department of Electrical Engineering, University of North Dakota (UND). The goal of this capstone project was to provide a "Smart Home" that gathers basic information through various sensors and allows control of devices or loads status of different devices from any computer remotely. Sensors are able to collect data and organize it into an efficient manner for the home owner to process and internet monitoring allows for easy accessibility. A LabVIEW based software interface with remote access enables users to monitor and control appliances and status activities of daily living in their homes for greater independence and improved quality of life. The success of technical framework discussed in this capstone project will benefit the engineering educators.

Keywords – LabVIEW, Capstone Project, Household Energy, Real-Time Monitoring

I. BACKGROUND OF SENIOR DESIGN COURSES AND SYSTEM OVERVIEW

At UND, the capstone courses span into two semesters – EE 480 (Senior Design I) and EE 481 (Senior Design II). EE 480 is offered in the Fall, and EE 481 is offered in the Spring. The students enrolled in EE 480 are asked to form a small team and choose a project based on their interest. A EE faculty member is assigned based on the expertise required to advise such projects. The next paragraph details the technical background and objectives of the project entitled "House Hold Energy Aware Real-time System". For this project, three reports in Fall semester and two reports in Spring semester were submitted. In addition to two presentations each semester, one poster was prepared and discussed in the UND College of Engineering and Mines Engineering Exposition.The overall concept of the project is to provide remote access to a house. This concept was implemented in three major: sensor circuits, central control unit, and user interface as shown in Fig. 1
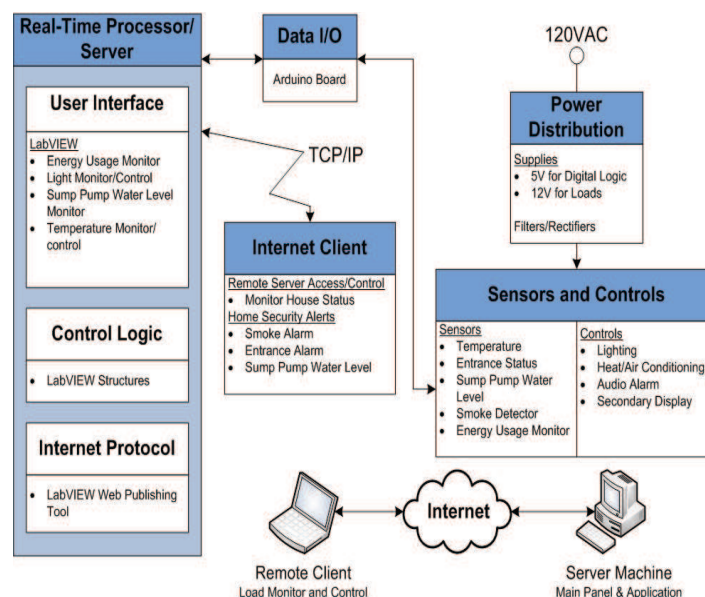

Fig. 1. A HEARTS system block diagram & capstone course elements

The key component in the system is the sensors. The sensor circuits serves for two functions: 1) sending data about the devices and status in the circuit and 2) providing the ability to control devices remotely. Each sensor is able to collect the required data and relay it to the central control unit (CCU). Sensor circuits were designed to control the measured circuit while not interfering with the standard controls found in the house. Each sensor requires a printed circuit board (PCB) to be created to support these functions. The sensor and control modules were incorporated into a model home designed to show product proof-of-concept.

The brain of the system is the central control unit. The main responsibility of the CCU is to receive data from the sensors and issue commands to control the sensed circuits in near real-time. This was implemented by using LabVIEW with an accompanying data acquisition device. The chosen data acquisition device is an Arduino Mega 2560. The Arduino provides many analog inputs and digital I/O and directly interfaces with LabVIEW [1]. The Analog/Digital converter is 10-bit with a maximum sampling rate of 15kSPs. The central control unit is also be able to make simple control choices based on parameters the user has previously defined. Implementing the various functions of the central control unit requires a carefully written program and the effective use of appropriate LabVIEW control structures.
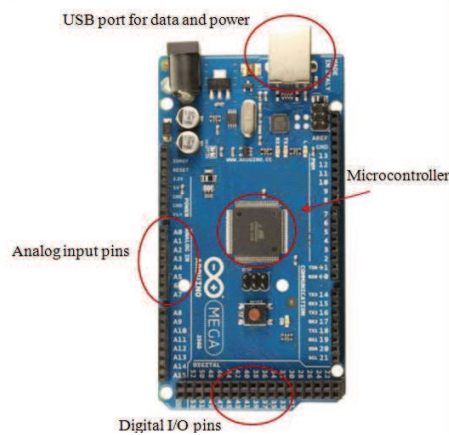

Fig. 2. An example Arduino Mega 2560 [1].

A LabVIEW graphical user interface (GUI) was developed for communication between the user and the house. The GUI allows the user to visually see the status of the monitored household functions and provide the parameters for their control choices remotely [2]. There are several features of LabVIEW and third party applications that can make this possible with reasonable effort. The authors chose to use National Instrument's Web Publishing Tool to develop the remote access [3]. A UND computer acts as a LabVIEW server which hosts the internet functions. This interface also archives and provides an analysis of gathered energy data in spreadsheet format. Text message notifications for select security features have been implemented.

II. SYSTEM DETAILS

A. Project Features, Timeline and Planning

For this project, the group focused on the design of each circuit subsystems during Fall semester. This include initial LabVIEW setup to be able to test each circuits individually. In Spring, the focus was to integrate all of the circuits together, do final testing, building the demo board, and refine all LabVIEW code to function as envisioned. The technical details are listed below.

1. Front Panel

The front panel displays the important information to the homeowner and acts as a user interface to the prototype. The information shown on the front panel was organized into several different groups. The data was represented by LEDs and graphics. Near real-time power usage is also displayed on the front panel. The user was able to directly interact with the front panel. For example, the lights can be turned on or off by clicking the appropriate switch. User commands/requests can be entered into the front panel and LabVIEW will perform the required actions.

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2. Block Diagram

LabVIEW is able to perform the desired actions because of the programming performed in the block diagram. The general algorithm to implement a control is as follows:

Control Procedure
- Initialize the Arduino
- Define digital I/O
- Begin infinite loop structure
    - Read the sensor inputs
    - Display data on GUI
    - Compare to user selections
    - Perform necessary actions
- Close out the Arduino

Initializing the Arduino selects the COM port, determines the baud rate, and selects which microcontroller. This initialization was only performed once each time the program is started. Each of the digital pins can be configured as either an input or an output pin. This is different from the analog pins which are predetermined as inputs. The assigned function of each pin dictates the direction of the pin. The main part of the program is contained within an infinite loop. A while loop is used to provide the infinite loop functionality. The program runs continuously and monitors the house. In order to keep the code more organized and easier to understand, a stacked sequence is utilized. Each circuit subsystem has its own frame. For example, the HVAC sense and control structures are housed in a separate frame from the lights. In each frame, the specific pins for the subsystem are read. The GUI is then updated to reflect the new data as read from the sensors. The sensor data is compared to user settings for certain subsystems. The predominant comparison method is to use logical expression blocks such as AND, OR, IF. The results of these comparisons cause LabVIEW to perform different actions. In the case of the entrances the LabVIEW logic compares the current status of the entrance to open or closed values. If the entrance is determined to be opened when it should not be, then LabVIEW will take the actions of sending the homeowner a text message, sets the alarm on the GUI, and sounds the audible alarm in the house. If the program needs to be shut down, LabVIEW is programmed to close the communication with the Arduino and halt the program.

3. Text Message Alerts

The text message alerts are integrated into the system as an extra security feature for the homeowner. Alerts are sent if the smoke detector is triggered, the sump pump water level reaches 80% or if either of the two entrances are sensed as open. The text messaging alerts are implemented by sending an email to the homeowner's cell phone number as shown in Figure 3. By sending a text message alert as an email to a Verizon cell phone is accomplished by sending the email to CellPhoneNumber@vtext.com. A similar method is used for other wireless carriers [10].
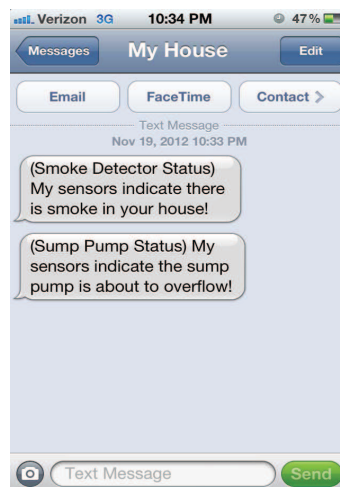

Fig. 3. An example text message alert as viewed on iPhone.

The system was given a Gmail email address to allow access to the Gmail outgoing mail servers. Sending an email from LabVIEW was fairly easy to do because LabVIEW has built in email functionality. Many example VIs are available online [11]. Each part of the email (such as To, From, CC, and Message Body) must be constructed from blocks in the block diagram. An example SMS alert is shown in Fig. 4. The block diagram code is written so only one text messaging alert will be sent per alarm event. When an alarm is triggered, the text message will be sent and a flag is set to indicate the message has been sent. When the code is run through again and the same alarm event is occurring, the flag is checked to see if message was already sent. If so, no message will be sent. The flag is reset when the initial alarm event is no longer active.

4. Internet Functionality

The full professional version of LabVIEW allows for setting up a remote server using National Instrument's Web Publishing Tool. This allows any computer with a compatible internet browser and the correct LabVIEW Run-Time engine to view and control the GUI. The homeowner would be given a website to access the remote LabVIEW GUI in the following general format: <http://IPADDRESS:PORT#/PAGE.htm/>. Basic security is accomplished by allowing only specific IP addresses to access the given remote website.

5. User Modes

If the homeowner is at home, it is not desirable for him (or her) to get a text message notification each time the entrances are opened. To prevent this scenario there are two users modes: *Normal* and *Away*. Normal mode is the default user mode. In this mode, it is assumed users are home. The lights function normally, the sump pump and smoke alarms send text message alerts, and no alert messages are sent when entrances are opened. When Away mode is selected, the lights are automatically turned off and text message alerts are sent when the entrances are opened. The sump pump and smoke alarms function as in the normal mode. Table 1 shows the different actions performed in each mode.

TABLE 1
User Mode Actions

Mode	*Normal*	*Away*
Lights	Normal	Auto-Off
Sump pump alarm	Alert Sent	Alert Sent
Smoke alarm	Alert Sent	Alert Sent
Entrance statuses	No Alert Sent	Alert Sent

B. Circuit Systems
1. Power Supplies

The main household supply voltage is modeled by 12VDC. This is provided by a 120VAC to 12VDC power supply. This AC/DC supply was built for a Junior year project, and is reused for this project. According to our calculations, the maximum current the supply can source is sufficient for our model house. A 5V regulator provides the necessary low voltage for the logic interfaces and some sensors.

2. Heating and Air Conditioning

The heating and air conditioning (HVAC) circuit is comprised of three separate parts. Since the students are unable to actually control and interface with a household HVAC system, students have chosen to model the system. Heating and cooling are modeled by red and blue LEDs, respectively. The HVAC fan is modeled by a 12V desktop computer cooling fan. Household temperature is monitored by a simple thermistor circuit. Each mode has two LEDs in the circuit. Two LEDs were chosen in order to ensure the colors are bright enough to be seen in the model house. Each circuit has a current-limiting resistor to ensure the current supplied to the components are within the specifications noted in their datasheet.

A temperature sensing circuit was designed and provides real-time temperature measurements. Both indoor and outdoor temperatures were monitored. Parameters set in LabVIEW control the HVAC circuit depending on the difference between the desired and actual temperatures. For example, if the HVAC mode is "heat" and the desired temperature is set to 78°F and the

house is 75°F, the control structures in LabVIEW will command the heater and fan to turn on. The heating and cooling were designed to work independently of each other in response to the output of the CCU. The fan will turn on automatically whenever the heating or cooling is on, but it is also able to be turned on independently.

An N-Channel MOSFET is used as a switch to control the heating, cooling, and fan circuits. These MOSFETs were chosen in order to interface with the logic levels of the Arduino and because they provide a solid-state method to control each circuit [4].
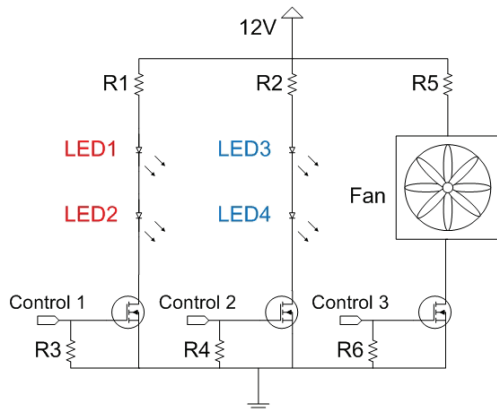
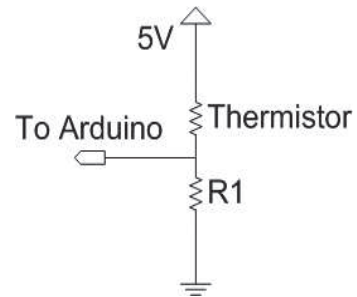Fig. 5. A HVAC control circuit diagram

Fig. 6. A temperature sensor circuit diagram using NTC thermistor.

The thermistor type used is NTC. This means that as temperature increases, the thermistor resistance decreases in a non-linear fashion. The thermistor circuit is designed so the voltage to the Arduino and the temperature are directly related. The thermistor is rated for -40°C to 150°C but homes likely will not be at these extreme temperatures. We are focusing on a range of 10°C to 35°C. This gives a voltage range of 1.67V to 3.02V. At 25°C the voltage output of the circuit is 2.5V. In order to convert the analog voltage level into a comprehensible temperature value, the Steinhart-Hart thermistor equation is used and shown in (1).

$$T = \frac{1}{A + B\ln(R_T) + C(\ln(R_T))^3} \tag{1}$$

where T is current temperature in Kelvin, R_T is the thermistor resistance at temperature T and A, B and C are constants provided by the thermistor manufacturer [5], [6]. The stacked sequence shown in Fig. 5 is used to implement the HVAC system. The user inputs the desired temp and HVAC mode. Depending on the current temperature and the user's inputs, LabVIEW executes the required action to accomplish the task.

3. Smoke Detector

The smoke detector circuit is based on an infrared LED and an optically controlled BJT. The BJT is responsive to infrared light. The LED and BJT are placed close together and protected from ambient light. When smoke is present between the LED and BJT, the infrared light will be obscured and the output of the circuit will change. The circuit shown in Fig. 7 will output a digital high or low to the Arduino. If smoke is detected, the output is high. The output is normally low.
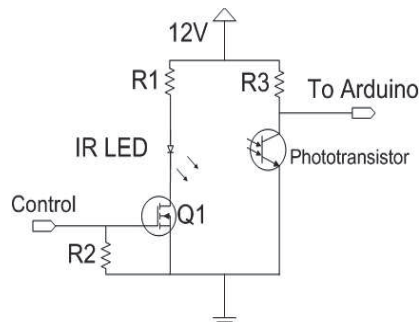
Fig.7. A smoke detector circuit diagram using IR LED and IR BJT in a common-emitter mode.

4. Light Control

The model house has four 12V lights that will all be controlled and monitored individually by the CCU. The power monitoring circuits that are described later serve a dual purpose for the lighting circuits. They are used to measure the power consumption of each light as well as to sense if the lights are turned on or off. This on/off status is shown on the GUI.

Deciding how to control the lights presented an interesting challenge. The authors wanted each light to be able to be controlled both by digital outputs from the CCU and also by a mechanical switch that is found in a real home.

Lights that have two separate mechanical switches are implemented by using two single pole, double throw (3-way) switches. The circuit utilizes one of these 3-way switches that can be purchased from any home hardware store. This 3-way switch is interfaced with two N-Channel MOSFETs as in Fig. 6. The MOSFETs were chosen because of the limited current output of the CCU. The MOSFET allows for voltage control of the circuit instead of current control.
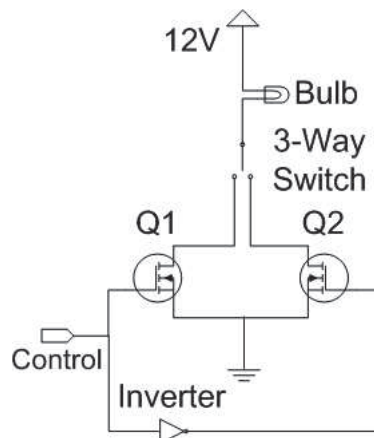

Fig. 8. A light control circuit diagram using MOSFETs and a 3-way switch.

The two transistors will be toggled so that when one is on/conducting the other will be off/not conducting. These are turned on/off by a 5V signal on the gate output from the CCU. An inverter is utilized to produce the required toggling. The two transistors implemented in this way act just like another 3-way mechanical switch. Each incandescent bulb has its own light control circuit as shown in Fig. 8.

5. Water Level Monitor

The purpose of the water level monitor circuit is to monitor the water level inside the sump pump and send an alert to the homeowner if the water level exceeds 80% of capacity. The water level is displayed on the GUI which requires an analog sensor input to the CCU. The chosen monitoring method is a differential pressure sensor. This sensor will sit at the top of the sump pump water tank and have a tube running to the bottom of the water tank. As the water in the tank rises, it will compress the air trapped in the tube changing the pressure that is monitored by the sensor. The recommended pressure sensor circuit layout is shown in Fig. 9. Capacitors are used for proper decoupling of the 5V power supply and A/D input to the

Arduino as well as to filter the sensor output [7]. The sensor will have to be calibrated for each installation in order to find the maximum voltage level the pressure sensor will read.
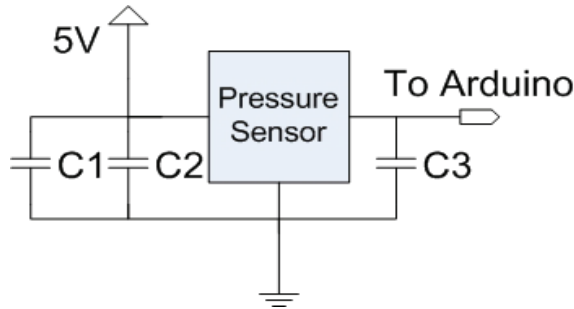

Fig. 9. Sump pump water level circuit diagram [7].

6. Energy Usage Monitor

The power monitoring system uses a resistor to act as a "current sensing" element. This resistor, placed between the load and ground, is small enough to allow maximum current to the load. This current flow creates a small voltage drop across the resistor which will is measured with an opamp. The opamp circuit layout, shown in Fig. 10, was designed to scale this small voltage back to a more usable ratio. This allows for a wider range of values that are better scaled to the analog input range of the Arduino [8].
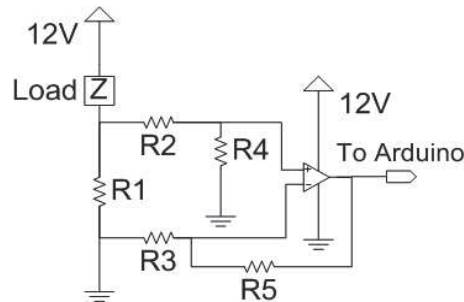

Fig. 10. A power monitor circuit.

The current in multiple circuits is monitored using multiple current sensing circuits. These circuits are integrated into an "electrical box" idea in order to keep everything contained in one area and to keep costs down [8]. These readings are then used to calculate how much power is consumed. This power information is archived in a standard spreadsheet so the homeowner can monitor their power usage over a longer period of time.

Figure 11 shows how the power usage is read and collected. It also determines if the lights are on or off and updates the LED on the GUI. The voltage is divided by ten to account for the opamp gain. This provides a 1 A/V ratio because of the chosen current sense resistor value. Then, the thousandths digit is dropped off to provide a more stable value. Finally, the power is calculated by multiplying by the household voltage (12VDC). This value is then updated on the GUI. Power usage for each monitored load is sampled every thirty seconds and recorded in a Microsoft Excel document. The collected data can be graphed and analyzed using Excel's built-in functionality.

7. Additional loads

Most homes have more loads than just lights and HVAC. Some examples of additional loads could be refrigerators, chest freezers, and washers and dryers. These loads are simulated using variable resistors. The authors wanted to add these additional loads to illustrate the expandability of the system. Each load is able to be turned on or off by the homeowner using

the GUI. An example additional load circuit is shown in Fig. 24. R1 and R2 are used to limit the current through the variable resistor and protect it from dissipating too much power.
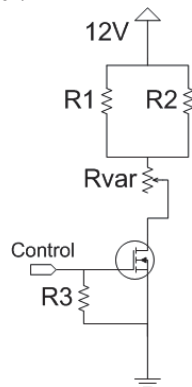

Fig. 11. An additional load circuit.

8. Entrance Status Monitor

A magnetic proximity switch is used to monitor whether an entrance is opened or closed. For example, the switch will be wired to the top of a door frame. The magnet will then be attached to the top of the door. When the door is closed, the magnet will close the switch and the CCU will read 5V. When the door is open, the voltage at the CCU will be low and the CCU will recognize the door is open. A low-pass filter was added to the switch circuit to reduce the voltage spikes and filter the input to the Arduino. A second resistor was also added to drain the capacitor when the switch is open [9]. The circuit layout is shown in Fig. 12.
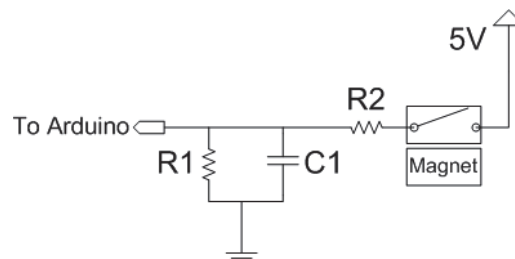

Fig.12. An entrance status monitor circuit.

9. Secondary Display

A secondary display is implemented on the main PCB to provide basic information about of the system in the event a display is not connected to the main server. An example of this would be if the system is installed by a third-party technician using a temporary display and the homeowner is only given the website to access the system. The secondary display has two methods to convey information: three 7-segment displays and ten status LEDs. The 7-segment displays can show either inside temperature, outside temperature, or water level percentage. Information about the individual circuits is shown by the status LEDs. For example, if an entrance is open, the corresponding LED will illuminate indicating its status.
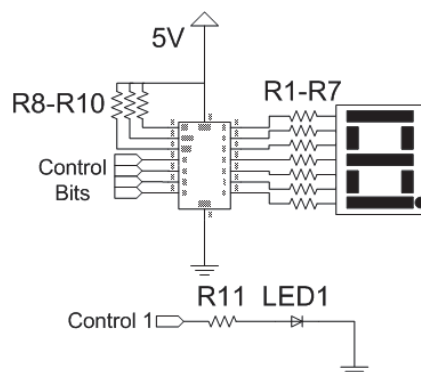

Fig. 13. Typical 7-segment and status LED circuit.

A 7-segment display driver LabVIEW code which controlled by a three position switch on the PCB is read to determine what to display on the 7-segment display. The three possibilites to display are indoor temp, outdoor temp, and sump pump water level percent. Second, the data is seperated into three digits and each digit is written to the appropriate 7-segment display. If required, a negative sign can be displayed to extend the displayed temperature range. A breakdown of what each light represents is given in Table 2.

TABLE 2
Secondary Display Status LEDs Breakdown

Status Light	Description When Lit
LED 1	Entrance 1 open
LED 2	Entrance 2 open
LED 3	Light 1 on
LED 4	Light 2 on
LED 5	Light 3 on
LED 6	Light 4 on
LED 7:8	00 - HVAC off, 01 – Heat on 10 – Cool on, 11 – Fan only on
LED 9	Smoke detected
LED 10	Sump pump level > 80%

10. Audible Alarm

An audible alarm is used in conjunction with the text messaging alerts to notify the homeowner of emergencies or security breaches. The alarm uses the pulse width modulation (PWM) output functionality of the Arduino to create a 440Hz square wave which produces the alarm tone.
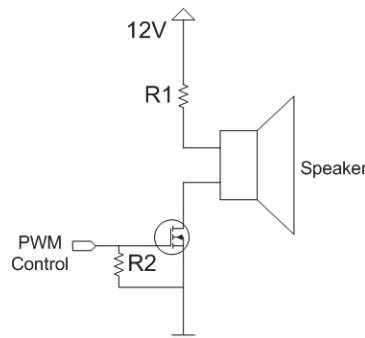

Fig. 14. Audible alarm control circuit.

11. PCB Design

The finished system was implemented using six PCB modules. The main PCB was the largest and included the core functionalities. It also had screw terminals for each Arduino pin to allow for future expansion.

Main PCB module	Sub-PCB modules
The main PCB includes: • Power supply (12VDC and 5VDC) • Arduino connection • Power monitoring circuit • Light control circuit • Secondary display circuit • Audible alarm driver circuit • Entrance status monitor circuit	The five other PCBs are smaller and consist of individual sensor circuits. The five remaining PCBs include: • HVAC/Indoor temperature circuit • Outdoor temperature circuit • Sump pump water level circuit • Smoke detector • Additional loads

III. DISCUSSIONS / EVALUATIONS

A finished product display was created in order to easily present all of the features of HEARTS system. This display as shown in Fig. 15, was constructed with wood and sheetrock. The lower half of the display is meant to represent a house with multiple rooms. It has four lights, additional loads, smoke detector and HVAC. The main PCB, outdoor temperature, household light switches, and sump pump water level monitor are located on the upper half. The main PCB can be seen in detail in Fig. 16. The VAC was set to cool according to the status LED. A short sample of instantaneous power usage data which has been recorded and graphed is shown in Fig. 17 and Fig. 18. When graphed over time, the data shows energy consumption and may be used to help a homeowner find ways to reduce energy use.
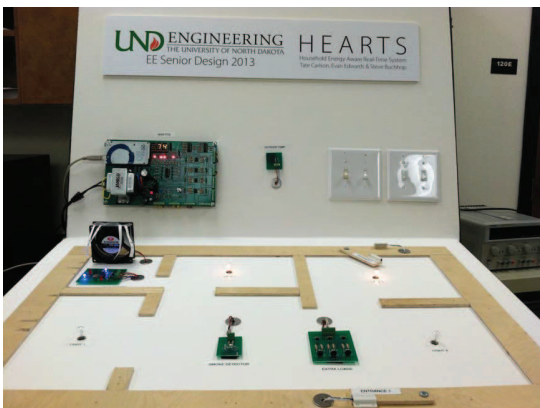

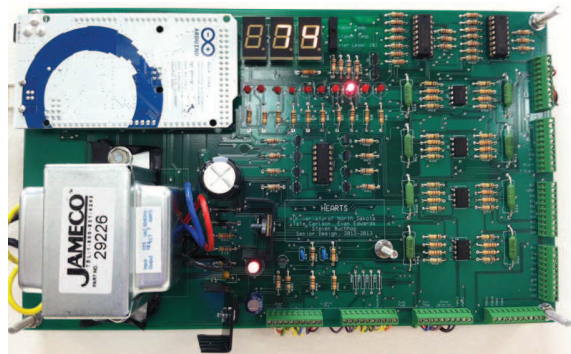Fig. 15. Complete HEARTS Project Station

Fig. 16. PCB with Arduino

Fig. 17. Power Usage Graph

Fig. 18. Data Log of power usage

The capstone project has resulted in various student outcomes, where students faced challenges on design, implementation of the remote monitoring system and identified the learning mechanism to overcome the challenges. The outcome is as follows:

Student Outcome 1: Choosing the right power supply range for LM 741 Monitoring circuit.

For example, the group members identified and rectified problems ranging from component acquisition to troubleshooting full circuits. The power monitoring circuit includes an Op-amp amplifier. We initially selected a LM741 opamp, because we have used it before and it is readily available at UND for no cost to us. This opamp proved to be a poor choice because it was not matched for the very small differential input we are feeding it. We noticed that the LM741 is an outdated technology mostly used for educational purposes only. We investigated different options to replace the LM741 and selected the LM358 for our design. This opamp was chosen because its V_{CC} range is compatible with our 12V system, is available in a dual-package, single-rail device, and is a good general-purpose opamp [12]. The learning outcome of this challenge is choosing the right supply played an important role on functionality of Operational Amplifier.

Student Outcome 2: Compatibility of Sensor ports to Water level sensor

Another problem that the group faced was implementing the water level monitoring circuit. The pressure sensor used in the circuit has ports on it for connecting to a tube. The students initially were not able to find tubing which is compatible with the size of the sensor's ports. We looked at several different types of tubing and eventually found automotive tubing which fit the sensor.

A large section of this project was the remote access to the system. The students implemented this remote access, but they wanted to protect the system from unauthorized users. The initial idea was just do passwords protect the VI and this would take care of it. However, password protecting the VI only keeps the block diagram from being changed; it does not remove control from the front panel. By contacting National Instruments for further guidance, and students learned that it is not possible to keep LabVIEW running while users are logging in and out of the program. Currently, the system is only protected by limiting the IP addresses which can access the server. Future work would be to increase the security of the system by continuing to develop the remote access. This may require switching from the web publishing tool to National Instrument's internet toolkit. The energy usage monitor circuit was not functioning as we expected it to function. When one of the lights was turned on, several of the other lights would read "on" without actually being turned on. The values were fluctuating when they should be reading a constant value or zero. Our investigation concluded that there was a 60Hz noise on the output from the power monitoring circuit op-amp. This noise was not present neither on the 12V DC supply, nor on the input to the op-amp. We were unable to resolve this problem through the hardware, but we solved through in the software approach.

EDUCATIONAL OUTCOMES

Education Outcome 1: Ability to communicate effectively, not only with engineers but also with the community at large In-depth technical competence in at least one engineering discipline. This is done via several written and oral presentations throughout the two semesters at UND.

Educational Outcome 2: Ability to undertake problem identification, formulation and solution. This outcome was accomplished by several refining process of design stages such as preliminary review design (PDR) and other successive weekly meetings with advisor.

Educational Outcome 3: Ability to utilize a systems approach to design and operational performance. For this project, there were several sub systems are integrated to achieve the overall objective of the system.

Educational Outcome 4: Ability to function effectively as an individual and in multidisciplinary and multi-cultural teams, with the capacity to be a leader or manager as well as an effective team member. The team involved in the project has contributed both at individual level and as a group. For example, Evan worked on LabVIEW interface, Steve worked on implementation and Tate worked on sensor integration aspects of the system.

Educational Outcome 5: Understanding of the social, cultural, global and environmental responsibilities of the professional engineer, and the need for sustainable development

Educational Outcome 6: Capacity for independent critical thought, rational inquiry and self-directed learning. The students involved in the project has made effort to research independently on various topics such as type of microprocessor used, sensor types, choosing an application software etc.

Educational Outcome 7: Intellectual curiosity and creativity, including understanding of the philosophical and methodological bases of research activity. The group looked and reviewed IEEE journals and conference papers on existing methods to carry out scholarly work and literature study.

Educational Outcome 8: Openness to new ideas and unconventional critiques of received wisdom. The student received constructive feedback from all our faculty and student groups during various stages of our presentations.

V. Conclusions

The experience of a real time monitoring students in a senior design capstone project was presented in this paper. The capstone project experience through EE 480 and EE 481 courses and the factors such as frequent advisor meetings, preliminary design reviews, team work, multiple presentations and allocated clear budget has helped for a successful senior design capstone experience for undergraduates in the BSEE curriculum. The student felt that by conducting frequent advisor meetings on the project helped achieved the project objectives. The students met with their advisor each week to discuss design progress and to get continuous feedback on our presentations and reports. These meetings helped to keep students on task because students had pending action items to be completed for the subsequent next week's meeting. Meetings held in the Fall 2012 semester helped to define the scope of the project and the implementation phase. This included discussions on methodology and end goals. During the Spring 2013 semester, the meetings have focused on refining the technical aspects of our project and writing a paper for conference submissions.

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