Low-Cost Control System Built Upon Consumer-Based Electronics For Supervisory Control Of A Gas-Operated Heat Pump[1]

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ABSTRACT

A preliminary evaluation of the performance of a consumer-based control system was conducted by the Oak Ridge National Laboratory (ORNL) and Southwest Gas as part of a cooperative research and development agreement (CRADA) authorized by the Department of Energy (DOE) (Mahderekal et al. (2013). The goal of the research was to evaluate the low-cost approach as a solution for implementing a supervisory control system for a residential gas-operated heat pump.

The design incorporated two consumer-based micro-controllers; the Arduino Mega-2650 and the BeagleBone (white). Ten five-ton heat pump systems were designed, fabricated, and operationally tested in the Las Vega NV region. A robust data set was produced that allowed detailed assessment of the reliability and the operational performance of the newly developed control system. Experiences gained from the test provided important points of improvement for subsequent evolution of the heat pump technology.

INTRODUCTION

A preliminary evaluation of the performance of a micro-controller-based control system was performed on a new generation of heat pump technology rated at 5 tons (17.6 kW) and designed primarily for residential usage. The heat pump uses a natural gas reciprocating engine to provide power for the

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refrigerant compressor, high efficiency coils, waste heat reclamation, and a high-performance refrigerant loop. The unit performed up to its design expectation but it had a high premium. The cost was too high for potential consumers to recover that high premium in 5 years. As part of the commercialization planning, value engineering study was conducted. Among other reductions, it was decided that the cost of the control system needed to be reduced by at least 70%. The motivations for this evaluation were to assess the feasibility of reducing the cost of the control system and implement a system capable of advanced control strategies.

The evaluation was performed by operationally field-testing ten prototype heat pump units in Las Vegas, NV. The control system was designed around two popular development micro-controller boards; the Arduino Mega 2560 and the BeagleBone (white). The remainder of the control system was composed of interfacing devices and circuits, power supplies, and an engine control board. A commercial fabricator manufactured the ten prototype units. Most of the units were operated in the field for ten months. It was estimated that each heat pump unit would log approximately 4 million data points per day, which resulted in a large repository of data that was used to assess the reliability and operational performance of the developed control system..

An overview of the heat pump technology and details about the control system design are discussed. Test results including operational reliability of the developed control system are presented. Issues and challenges are summarized and possible design improvements are discussed.

GAS-OPERATED HEAT PUMP OVERVIEW

Various electric heat pump systems are used to provide heating and cooling for a wide range of buildings, from commercial facilities to single family homes. The market for heat pumps is significant. For example, according to the U.S. Energy Information Administration’s 2009 Residential Energy Consumption Survey, 9.8 million American homes are heated by electric heat pumps (EIA 2009).

To operate a conventional electric heat pump system, fuel is first converted into energy at a power plant where the waste heat is typically discharged to the environment. Electrical energy is then transmitted over power lines and converted to mechanical energy by the heat pump motor. In this process, energy is converted twice, with energy loss each time. Overall system energy efficiency will increase significantly if fuel conversion is located closer to the site where energy is used to drive a heating and cooling system and if waste heat from the system is captured and utilized.

The project team previously developed an 11-ton packaged gas heat pump system that uses an internal combustion engine to drive a vapor-compression heat pump and utilized the waste heat generated by the engine to enhance the heating of indoor air. The system incorporates a variable speed natural gas engine, which significantly improves part-load efficiency of the system. Accompanying system controls allow the engine to operate at desired design parameters, preventing excessive wear on engine parts and the compressors (Zaltash et al. 2008, and Sohn et al. 2008). On the surface, the design process for a residential unit would not appear to be a big jump from the commercial unit that was already developed. A simple scaling down of the components and a simpler engine package would seem to be an appropriate path. The biggest challenge in the efforts would end up being costs, and that issue confronted the design team from the onset. An initial proof of concept prototype showed that the cost of the system was potentially three times the level that market research identified as a reasonable target for the residential market.

The instrumentation and control package for implementing supervisory controls were originally implemented using a commercial programmable logic controller (PLC). This device alone represented a $1.5K component cost for the system. For this reason, it was decided to attempt to design a new control system that could be realized for a much lower cost. A number of open source micro-controller boards were beginning to debut in 2011 and there were already examples in the literature of how these could be successfully adapted to specific application needs (Zualkernan 2011). Subsequent to our research, numerous other examples of adaptation of open source devices for control have been published (Salamine et al. 2015, Zhuoziong et al. 2015, and Yiheng 2015).

CONTROL SYSTEM ARCHITECTURE AND DESIGN

The operational experience of the previously developed commercial and pre-prototype residential heat pump units laid a solid foundation of expectations for what a new supervisory control system should function like a PLC. Most important features were the ability to remotely monitor the main operational parameters (pressures, temperatures, engine speed, etc) and the ability to remotely program the controller. With this in mind the design effort quickly identified two best-path options for implementing a new generation of controls. The first was to base the controls on a newer and lower cost PLC. The manufacturer of the previous PLC had recently announced a new family of low-cost PLC, and this was identified as a preferred option for a PLC approach. The other path we identified was to adapt a consumer electronics-based micro-controller to this role. Since 2010, dozens of such devices had been introduced as ready to use boards about the size of a credit card. Many could be purchased for less than $100 and the Internet offered many options for peripheral modules and devices to extend the functionality of the main board. After investigating features, costs, and risk, it was decided our design focus would be to adapt an Arduino Mega 2560 to be the controller for the residential heat pump.

The Arduino Mega 2560, shown in Figure 1, was chosen for several reasons. It provides 54 I/O pins for interfacing to discrete devices and high-speed serial communications and it also provides 16 analog inputs. The cost for software development tools was attractive too. The vendor-provided tools for developing software in its native form are free and simple to use and there are many freely available example programs available on the Internet. However, due to the robust nature of multi-loop and multi-state controls it was decided to use the MATLAB/Simulink approach offered by MathWorks since native support for the Arduino board was provided with the baseline product.

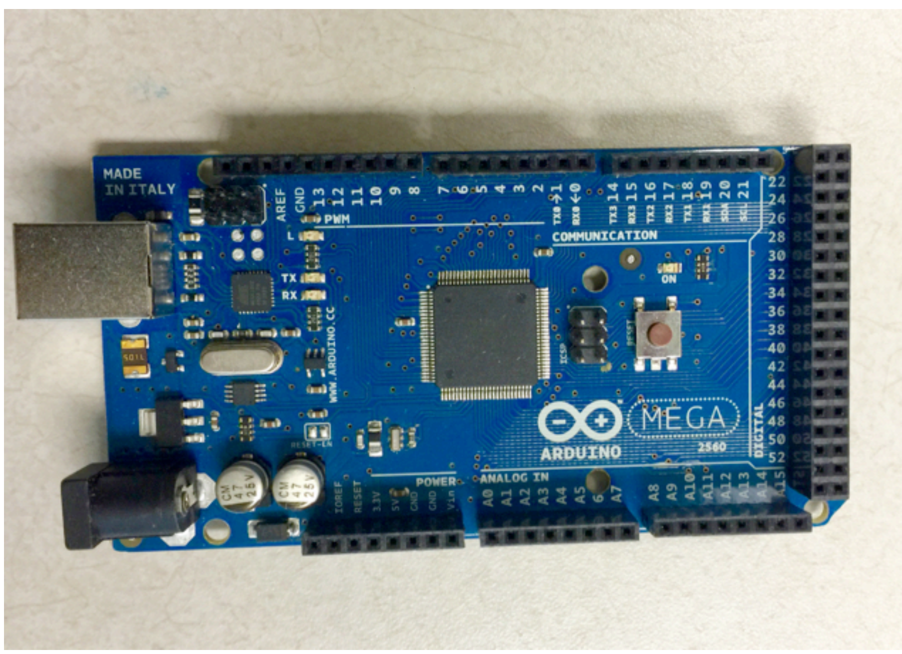

Figure 1 Arduino Mega 2560 micro-controller board.

The Arduino Mega 2560 was an ideal fit because it provided robust performance and copious I/O options. However, its memory is somewhat limited and it lacked a full-featured operating system. This meant adding the capability of network communications and data logging was going to be a challenge. Because of this and the need to plan for flexibility and future enhancements it was decided to add a second micro-controller whose primary responsibility would be network access and data logging. For this device the BeagleBone (white) was chosen and is shown in Figure 2. It was chosen because it offered the functionality and security of a Linux computer and was low cost. The overall topology of the resulting control system is shown in Figure 3.

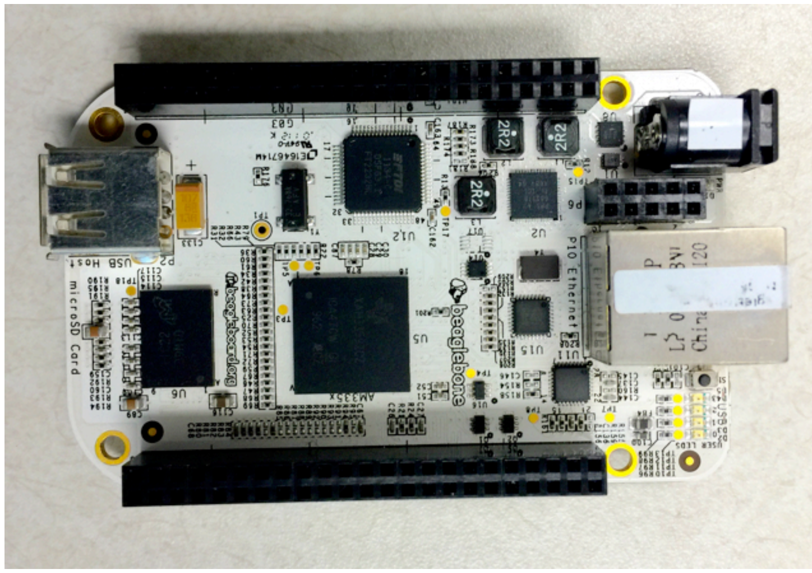

Figure 2 BeagleBone micro-controller board.

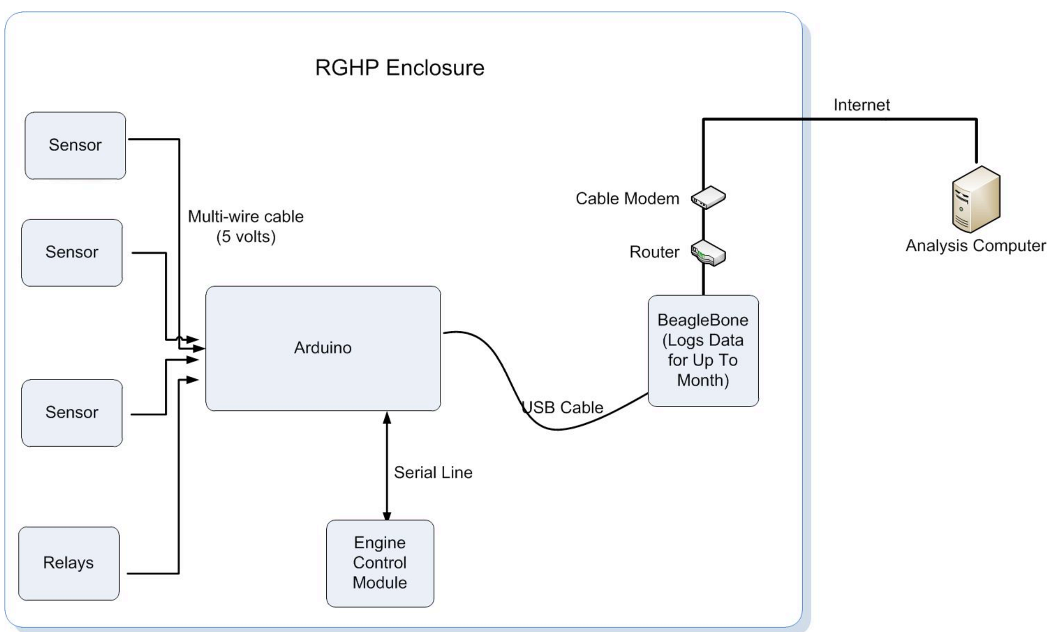

Figure 3 Supervisory control system architecture.

Early in the planning phase of the design of the control system, careful attention was given to operational temperature. The average high and low temperatures in Las Vegas area span a wide range. The average monthly high temperature in July and August is 104 °F (40 °C) and 102 °F (38.9 °) respectively. On the other extreme, the average monthly low temperature in December and January is 39 °F (3.9 °C.) Since it was to be installed in a sealed enclosure, the temperatures the control system would have to endure were even more extreme than ambient. These environmental conditions dictated that the control system had to be able to operate over a wide temperature range; -15°F to 165°F. The documentation available from the manufactures of the micro-controllers did not directly address this important operational characteristic. As a result, a series of test chamber tests were conducted at Oak Ridge National Laboratory with the devices to determine if they would operate over this temperature range. The chamber temperature was taken to each extreme and left for approximately six hours, or overnight in some cases. After this rest period at the target termperature, power was removed for an hour and then restored to verify the units would restart and operate after a power failure at a tempeature extreme. Figure 4 shows one of the setups used for this testing. Temperature data was continuously recorded to log files from the test boards. And, a simple LED light seuence was programmed into the boards such that visual and video monitoring of LED status lights could be done to verify proper operation of the devices when they were at temperature extremes and after simulated power failures.

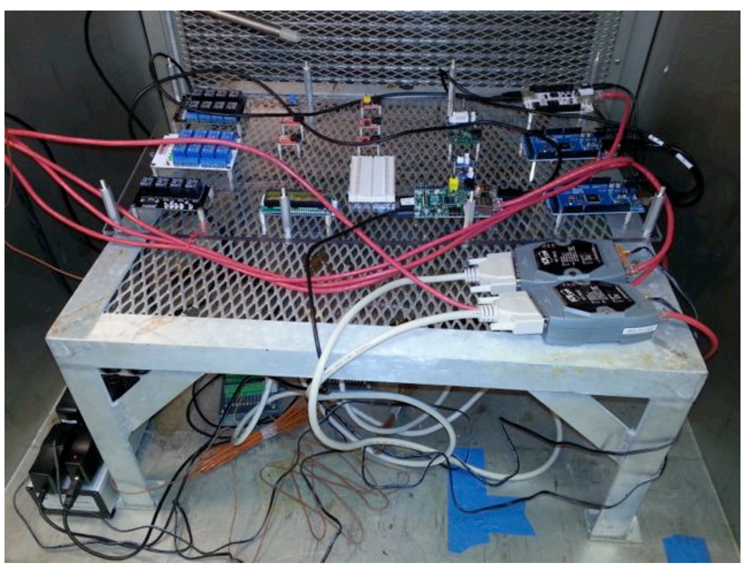

Figure 4 Testing of Arduino and BeagleBone along with several candidate peripheral systems.

In addition to the Arduino Mega 2560 and the BeagleBone the other main components of the supervisory control system were various sensors and interposing relays that were used to activate field devices from the 5-volt I/O pin levels provided by the Arduino.

Software for the system consisted of three main categories. The main control logic that executed on the Arduino was developed with MathWorks Simulink. This allowed for straightforward graphical design, as shown in Figure 5, of some fairly sophisticated control logic and proportional-integral-derivative (PID) controls. Simulink made it easy to implement a large number of state flow diagrams and multi-rate control loops. It also allowed for ease of maintenance of the code, as well as facilitating debug and testing of the code. From the developers standpoint, it was orders of magnitude better than similar experiences developing control applications in C.

The main application software in the BeagleBone was developed in Python including the communications handler that serviced the Arduino data as well as the logging software. Important features such as fault notification by email were also implemented in Python as well as startup scripts that were used to synchronize the clock with the National Institute of Standards and Technology (NIST) time standard. Some of the top-level startup software was implemented in bash scripts that were supported by the Angstrom Linux operating system than ran in the BeagleBone.

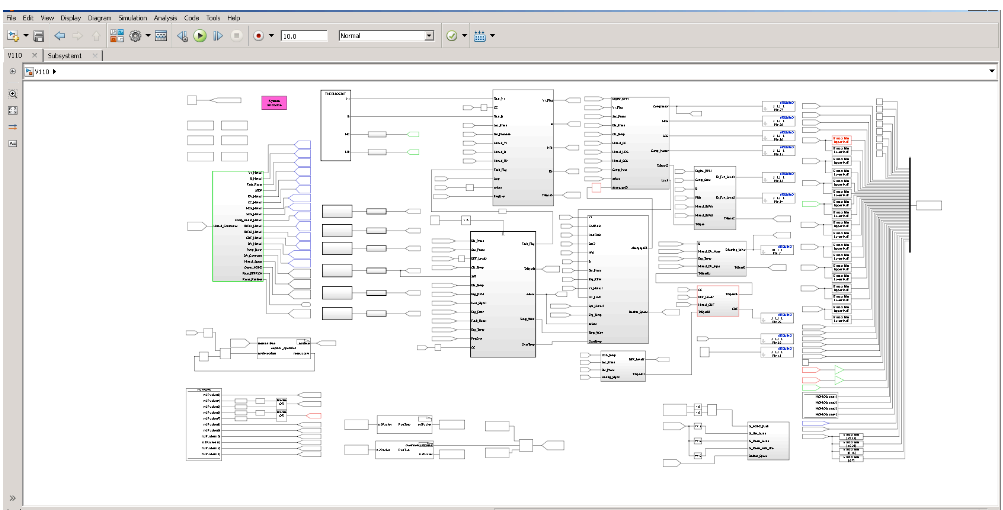

Figure 5 Main control logic implemented in Simulink that executed in the Arduino.

Some additional software tools and capabilities were also developed to support the effort. A graphical user interface was developed in Labview. It allowed easy interaction with the operating heat pump remotely over TCP/IP and locally over RS-232 connection. A typical screen from this tool is shown in Figure 6. Data management was also a key challenge since each heat pump unit produced forty-four operating parameters that were logged to file each second. A python script on the BeagleBone created a new file to store the data each day. Theday files were uploaded to an FTP server at night and subsequently transferred to an ORNL MySQL database. Scripts were developed to automatically transfer and upload data into the database, check its integrity, and provide remote access to off-campus team members.

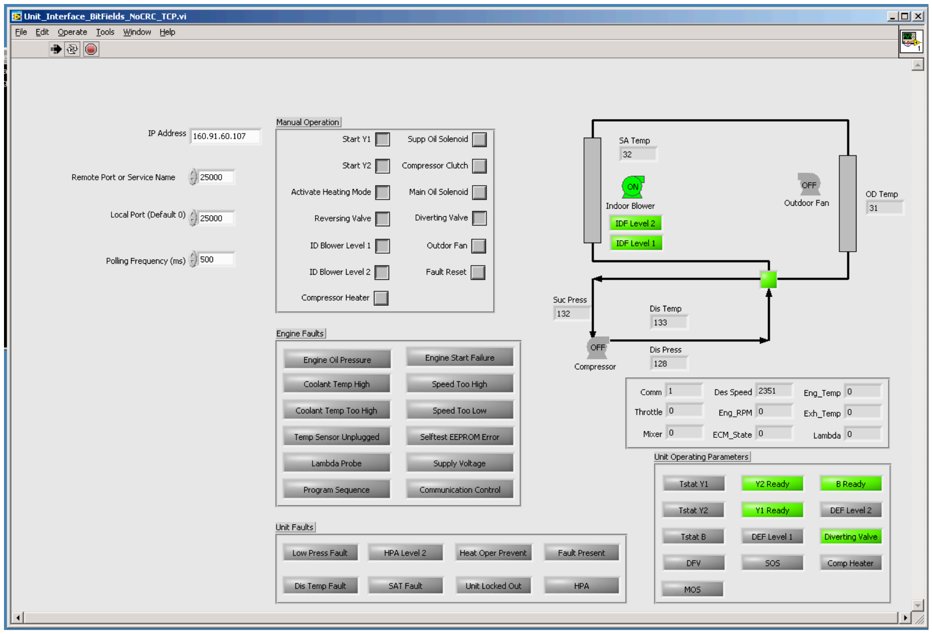

Figure 6 Labview field service tool showing manual command buttons and informational display

OPERATIONAL FIELD TESTING AND AN EVALUATION OF CONTROL SYSTEM PERFORMANCE

Ten prototype residential heat pump units were built using the Arduino-BeagleBone control system. These systems were installed in the Las Vegas metropolitan area and they operated over the period May 3, 2013 through April 14, 2014. Figure 7 shows a new heat pump unit still on its shipping pallet. Over the test period, a total of 2.8 billion field values[2] were logged and loaded into a database at ORNL. This allowed for detailed analysis using tools such as MATLAB.

[2] Subsequent to this testing, and second phase of tests using alternative control architecture produced an additional 43 billion field values.

Figure 7 Residential heat pump ready to install.

Figure 8 shows a representative plot of outdoor temperature for one day during the field evaluation. It shows the temperature trend from several units and the data quality associated with the 10-bit resolution of the analog-to-digital converter that is part of the Arduino. This resolutuion is sufficient to provide a tenth of a percent accuracy for most measurements. Since the topic of this paper is the low-cost control system, specific performace achieved by the overall heat pump system will be addressed in other publications. This plot is included to show the robust data quality provided by this control system approach.

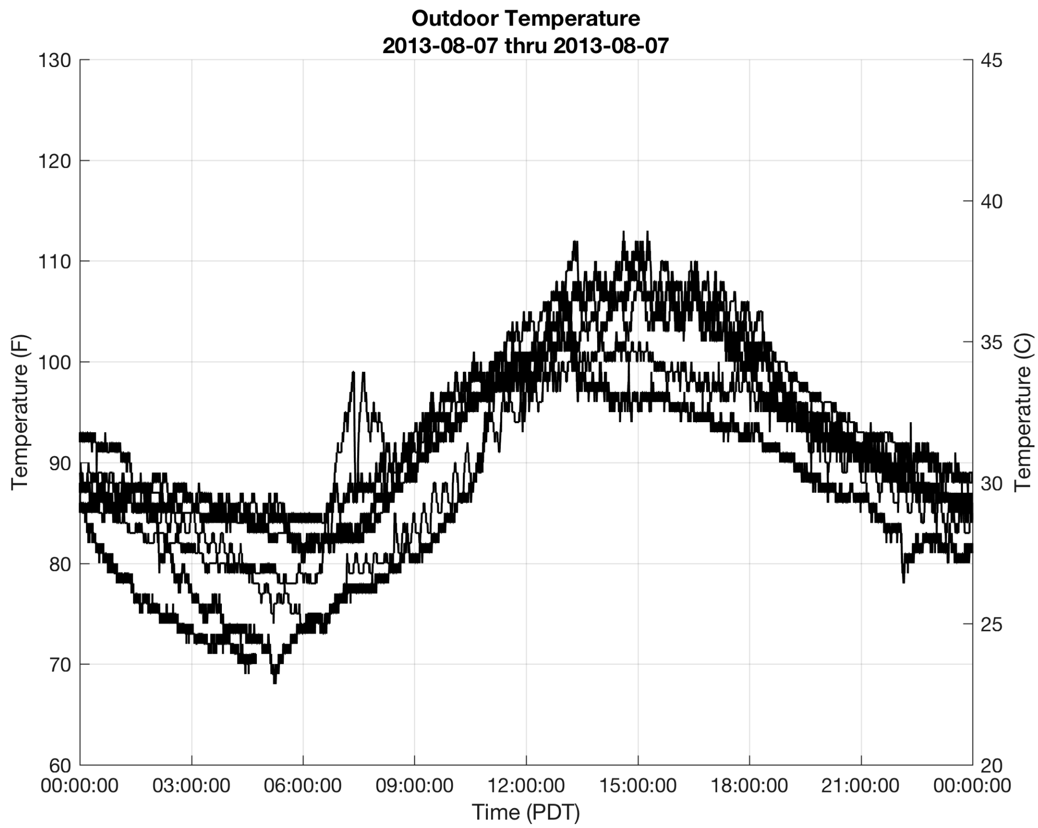

Figure 8 Typical plot of the outdoor ambient temperature over twenty-four hours

ISSUES AND CHALLENGES

Several issues and challenges arose during the development and testing of the control system. Most of the issues were related to wiring field level device voltages to a low-voltage micro-controller, unavailability due to communications failures, and electrical noise caused by inductive kickback with simple relay actions. These are discussed in the following sections.

Wiring to Arduino

The Arduino is manufactured with 0.1" pin headers and without a mechanism for securing the interconnection wiring. This configuration was not suitable for long-term field operation. Wires could easily disconnect from the headers due to vibration especially if the board is mounted in any other position than laying flat on a horizontal plane. Several breakout boards were developed for the different Arduino models and were commercially available. The breakout boards sit on top of the Arduino and provide more robust connection terminal to every I/O pin on the Arduino board. Originally, a breakout board featuring numerous pushpin sets arranged for easy termination of 3-wire cable sets was used. Wiring connections were robust, however, access to different pins was not easy due to the compactness of the pins layout. It was prone to misconnections. Later on, a commercial breakout board was identified that potentially was an improvement. This new board features screw terminal connection for all wiring. In addition, the pin numbers were clearly readable.

Unavailability

Each field site was configured with an Arduino/BeagleBone pair of micro-controllers. The Arduino was used to implement the sensing and HVAC controls and the BeagleBone was used for data logging and communications. It was noticed that sometimes data recording would stop at a field site. No pattern was identified for when the recording stopped. When the recording stopped the Arduino would still execute the control code properly, but remote access to the BeagleBone via Ethernet would fail. On two occasions, the BeagleBone failed and was not able to reboot until a new micro secure data (microSD) card was installed with a fresh operating system image. Figure 9 shows this degradation in data logging from the field sites that occurred over time. The failure rate was so bad, only one month of data from all ten units was realized. It was later determined the microSD cards that were originally installed in the BeagleBones did not have single bit error correction as part of their design. This discovery was made after the field trial was over. A test unit was retrofitted with an microSD with a single bit error correction feature and left running for three months and no loss of data took place. Subsequently, ten similar BeagleBone micro-controllers were deployed as field data loggers on other HVAC equipment in the same geographical area. These new deployments used the better microSD cards and no more unexplained outages were observed over a twelve month operating period. The improved data logging reliability can be seen in Figure 10. The reliailty of the

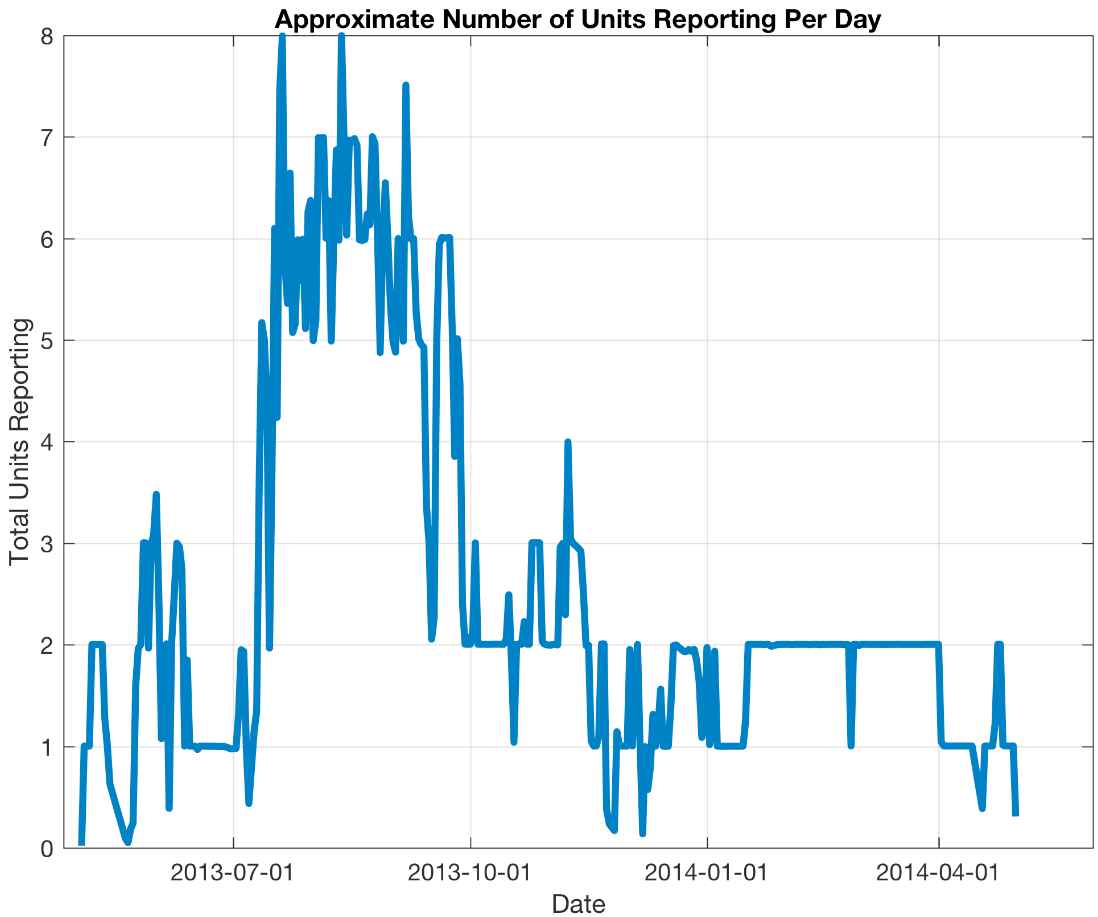

Figure 9 Degradation over time of field site data logging

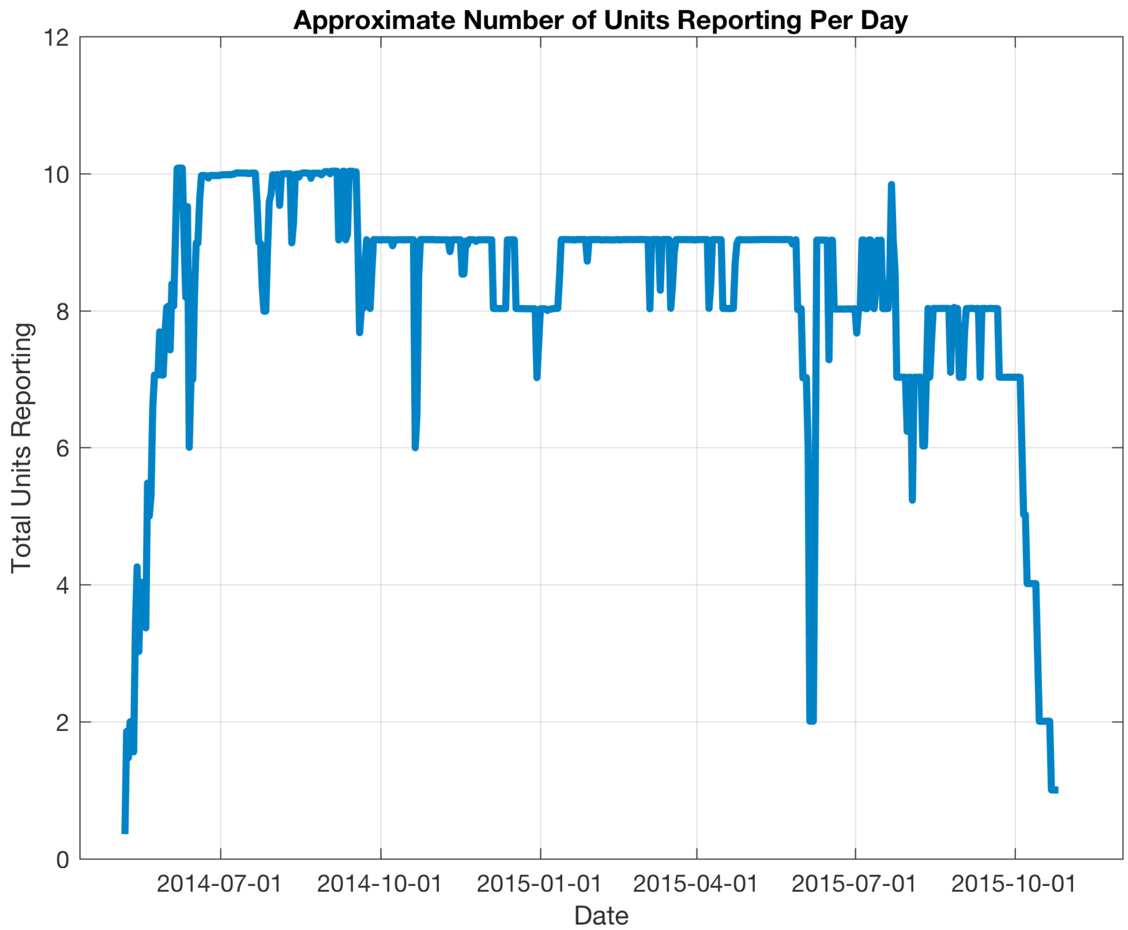

Figure 10 Improved field site reliability after memory card change

BeagleBone data loggers improved so well after the memory card change, they were used to replace several commercial logging devices that were used for similar field tests. The commercial units were failing duing the summer temperature extremes and they could not log data as fast as the BeagleBone units.

Electric Noise

At some installation sites, the recorded pressure and temperature data points had random spikes contained in the data that was logged. The frequency of the spikes was at least the same as the frequency of acquiring the data. The spikes clearly seemed to be the result of electric noise on the analog inputs. The noisy values sometimes resulted in system shutdowns due to false readings of high pressure. At one site, as was evident from the data, the noise was present all the time. At this site, the noise problem was resolved by proper grounding. At the other sites, the noise occurred intermittently over the course of the day. The problem occurred early in the day and from mid-day to mid-evening. Several attempts were made to eliminate the electric noise to no avail. However, it was found that at different sites, different circuits were causing the problem. At one site, disconnecting a 24 V AC circuit eliminated the noise. At another site, a 12 V DC circuit caused the electrical noise. This circuit originated by stepping down and rectifying power from the 120 V AC main. This indicated that the overall electric design of the system was not robust enough in that it made the unit susceptible to various sources of electrical noise. A potential solution involved the addition of isolation circuits on all analog inputs as well as for discrete inputs as well. Unfortunately, this problem went unsolved due to the limited time the units were allowed to be available for maintenance in the hot Las Vegas summer.

Isolated relays

The Arduino is a low voltage micro-controller board. It cannot switch large amounts of current associated with loads. Our design used interposing relays between the Arduino and the actual field load. In the first prototype of the control system development, it was noticed that switching certain relays resulted in the reset of the Arduino. These relays were used to control large solenoids. Apparently, the back EMF originated by the coil of the solenoid caused the reset. This problem was resolved early in the design by using solid-state relays. The solid-state relays would only switch at the zero voltage crossing of the 24 V AC or 120 V AC load power. This eliminated the potential for any inductive kickback from the loads.

CONCLUSIONS

A supervisory control system for a natural gas-operated heat pump was developed using low-cost consumer-based electronics. Twelve units were deployed at residences in the Las Vegas (Nevada) metropolitan area and operated over the period May 2013 through April 2014. Over this period the advanced control algorithms that were developed in Simulink were successfully demonstrated. The overall architecture of using an Arduino for controls and a BeagleBone for logging and communications was validated. A number of operational issues were encountered and most were resolved with simple changes to the design or components. These included the use of more robust mirco-SD flash memory cards and solid-state relay modules. Those that were not resolved during the field testing were related to electrical noise that affected measurement quality of the sensor data. It is believed adding field circuit isolation and minimizing current returns that connected to the Arduino could have resolved the electrical noise issues.

The main reason for developing a control system from consumer-based electronic components is cost. This approach was indeed much cheaper; about one-seventh the cost of commercial grade instrumentation and control technology. The down side to this approach is related to labor. A higher degree of assembly component mounting and wiring are required. Even so, the level of additional assembly labor was not excessive. The project technicians estimated the consumer-based approach required an additional 2-3 man-hours to install which translates to $45 to $135. These costs would likely be reduced by as much as 50% by the efficiencies of mass production and assembly. As a result, it is estimated that the total amount of labor to mount, wire, and interconnect the design to the HVAC system and residence was less than one-fifth what would otherwise be required to deploy a commercial controller system.

The experience gained from the test provided important points of improvement for subsequent generations of the technology, if that opportunity presents itself.

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