# RESIDENTIAL TELEMETRY APPLICATIONS FOR HVAC CONTROL


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## ABSTRACT

Much of the energy consumed in developed countries is for residential heating and cooling. Substantial savings are possible if one can monitor the indoor environment at many locations, and then actively control the heating, ventilation and air conditioning (HVAC) system. This project uses a wireless sensor array and dedicated microcontroller system to control a residential HVAC system. A low data rate, ad-hoc network of sensors is deployed throughout a residence, with the data sent to a central controller. A graphical user interface allows the resident to monitor the system status, and to set parameters.



## KEYWORDS

Wireless, heating, air conditioning, ventilation, system, sensor, telemetry


## INTRODUCTION

Approximately half of the energy consumed by a typical home in a developed country is used by the space heating ventilation and air conditioning (HVAC) system [1]. Improvements in the efficiency of the HVAC system can yield substantial cost savings, especially as energy costs increase. One way to improve the performance of these systems is to use more advanced automation that is typically available in a conventional thermostat. A programmable thermostat [2] is one step in this direction. These devices change the temperature set point based on some reasonable simple parameter, such as the time of day and/or day of week. However the inflexibility of these devices does not allow them to adapt to the resident's changing usage pattern. Also the limited number of locations at which the thermostat senses temperature can cause significant variation in the temperature where the users are actually located, and cause yet more dissatisfaction with the HVAC system [3].

This paper summarizes a project which investigated the use of wireless telemetry technology to sense and control the temperature at many points within a residence. The project considered a number of factors, including the initial cost to purchase and install the system, energy required to operate, energy saved, lifespan and service costs, compatibility with existing HVAC system components and others.

The proposed system uses an ad-hoc wireless sensor network to communicate throughout a typical residence. Temperature, humidity and occupancy data is collected by the sensors, and relayed to a central controller. The controller combines the sensor data with other information, such as the time of day and day of week, historical occupancy/usage data, pre-programmed user inputs, current user inputs, and other factors to decide how to configure the HVAC system. An LCD user interface shows the current state of the system, and allows the user to modify its behavior. The system is flexible enough to accommodate other information such as weather forecast information, expected cost of energy based on time of day, intermittent energy supplied by alternative sources, and data from electrical "smart grid" systems.

The first iteration of the project is intended to be a drop-in replacement for a conventional thermostat, and uses solid state relays to turn on or off the heating system, air conditioning system, and central ventilation fan. In a more advanced residence, the system would be able to control the flow of air or heating/cooling fluids to allow different temperatures in different rooms of the residence based on occupancy and the heating/cooling load of each room. The system could also control energy storage elements if they were available at the residence.

## AD-HOC WIRELESS SENSOR NETWORK

Installation costs are a concern in any home automation system, especially when retrofitting existing structures. It can be cost prohibitive to install wires between all the possible sensor locations, and a central controller. One way to substantially reduce these costs is through the use of an ad-hoc wireless sensor network [4]. There are a variety of devices commercially available suited for these applications, including ones produced by Z-Wave [5], Insteon [6], ZigBee [7] and XBee [8]. To provide compatibility with a variety of networking devices, this project used the IEEE 802.15.4 standard [9]. The particular product chosen was the XBee modules produced by Digi International.

The network is anticipated to have sensors in several rooms in a residence, all communicating with a central controller, as shown in Figure 1. The sensors may not have access to power from the mains, so they are designed to operate for extended periods from battery power. Powered by a single cell battery, the sensors draw approximately 50 mA of current during the very brief time they transmit, while drawing under 10µA when in the sleeping, or stand-by mode. The sensors allow up to 9 input/output lines for both analog and digital I/O. This will allow them to potentially measure temperature, humidity, light level, occupancy/motion sensors, infrared sensors, audio noise levels, or other parameters. The goal is for the system to develop a detailed model of where users are currently located, how the room is being used, and how comfortable the environment is in the occupied rooms.

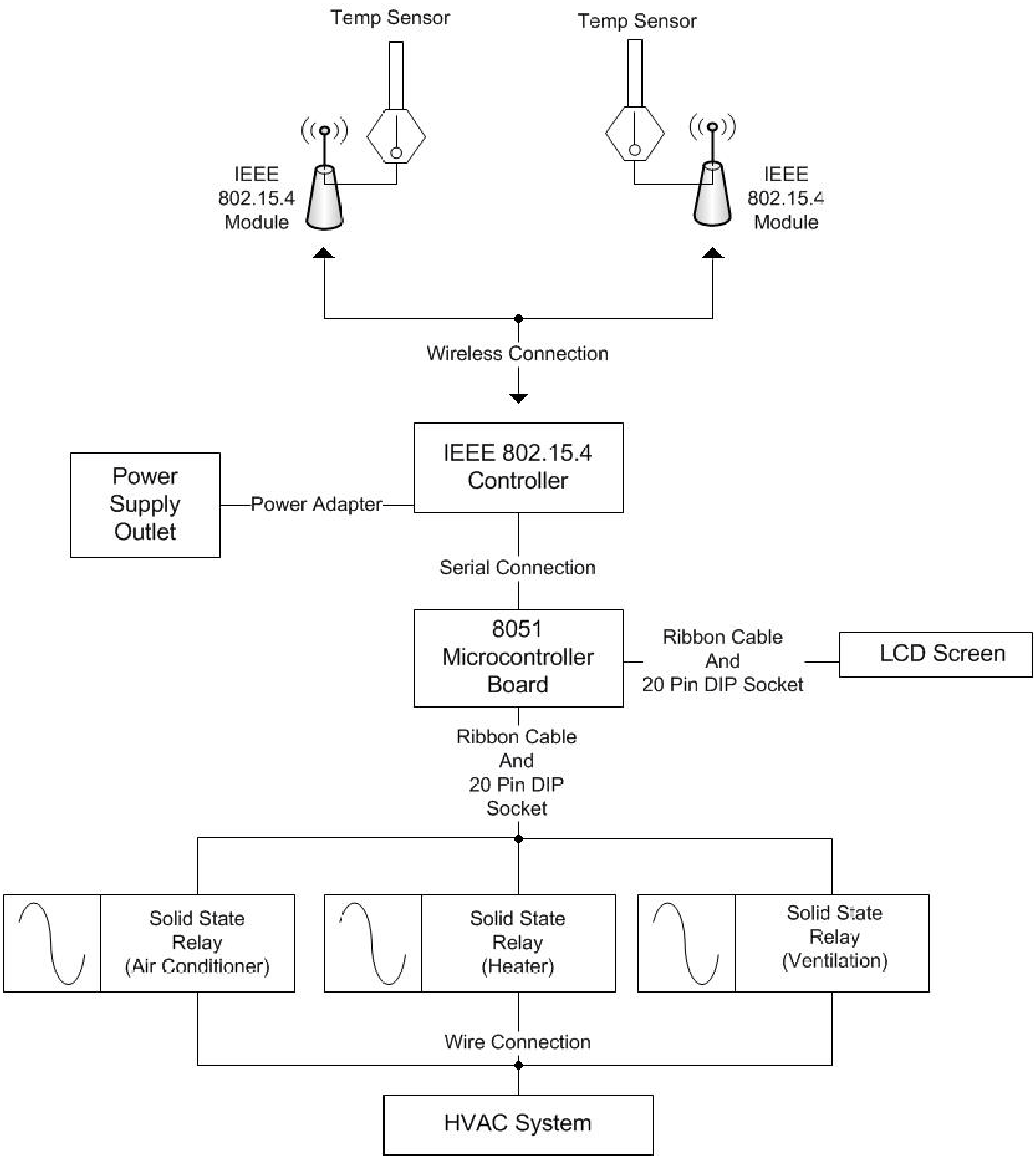


Figure 1. Smart HVAC System Structure

The central controller for the 802.15.4 draws far more power, and is assumed to be located where it will have access to mains power. The system as designed can access over 65,000 unique sensor nodes. This number of nodes is far larger than what is anticipated to be needed for residential applications. However this large number can be useful because it allows for expansion of the system into areas not currently anticipated, and also can be beneficial in environments where there is overlap between adjacent houses.

The central controller can either be connected as a general purpose computer, such as a personal computer – or to a dedicated microcontroller. This project uses a hybrid system. A low-power microcontroller based system will operate the system, and be on continuously. The microcontroller will have a small LCD display to show its status, and allow simple user inputs. When the user wishes to enter more elaborate commands, or receive reports of system status and performance, the microcontroller can be connected to a PC.

The cost of the system will depend on a number of factors, but the target is for each sensor node to be on the order of 10 to 20 USD, and the central controller to be under 100 USD.

## CENTRAL CONTROLLER

The central controller for the 802.15.4 system based on an Atmel AT81SAM7X256 microcontroller featuring 256 kB of flash memory, embedded USB 2.0 interface, and two serial ports [10]. The particular controller selected for this project was sold in a package that was tightly integrated with the 802.15.4 RF interface, and came with supporting software that allowed it to be easily configured using a conventional PC. The 256 kB of flash memory was sufficient to perform the wireless interface functions, but one concern was that it would be insufficient to implement the higher level control functions. In addition the limited digital I/O of the controller was going to make it a challenge to use this device to directly control the HVAC system.

The interface problem was overcome by using an already fabricated microcontroller board based on an 8051 processor as shown in Figure2. This controller uses a P89LPC9321 8 bit microcontroller. The 8051 processor added the following functionality:

- Receive the temperature data serially from the 802.15.4 controller, and convert the data from Open Sound Control (OSC) language to C language.

- Allow the user to use the push buttons to input a desired temperature and tolerance.

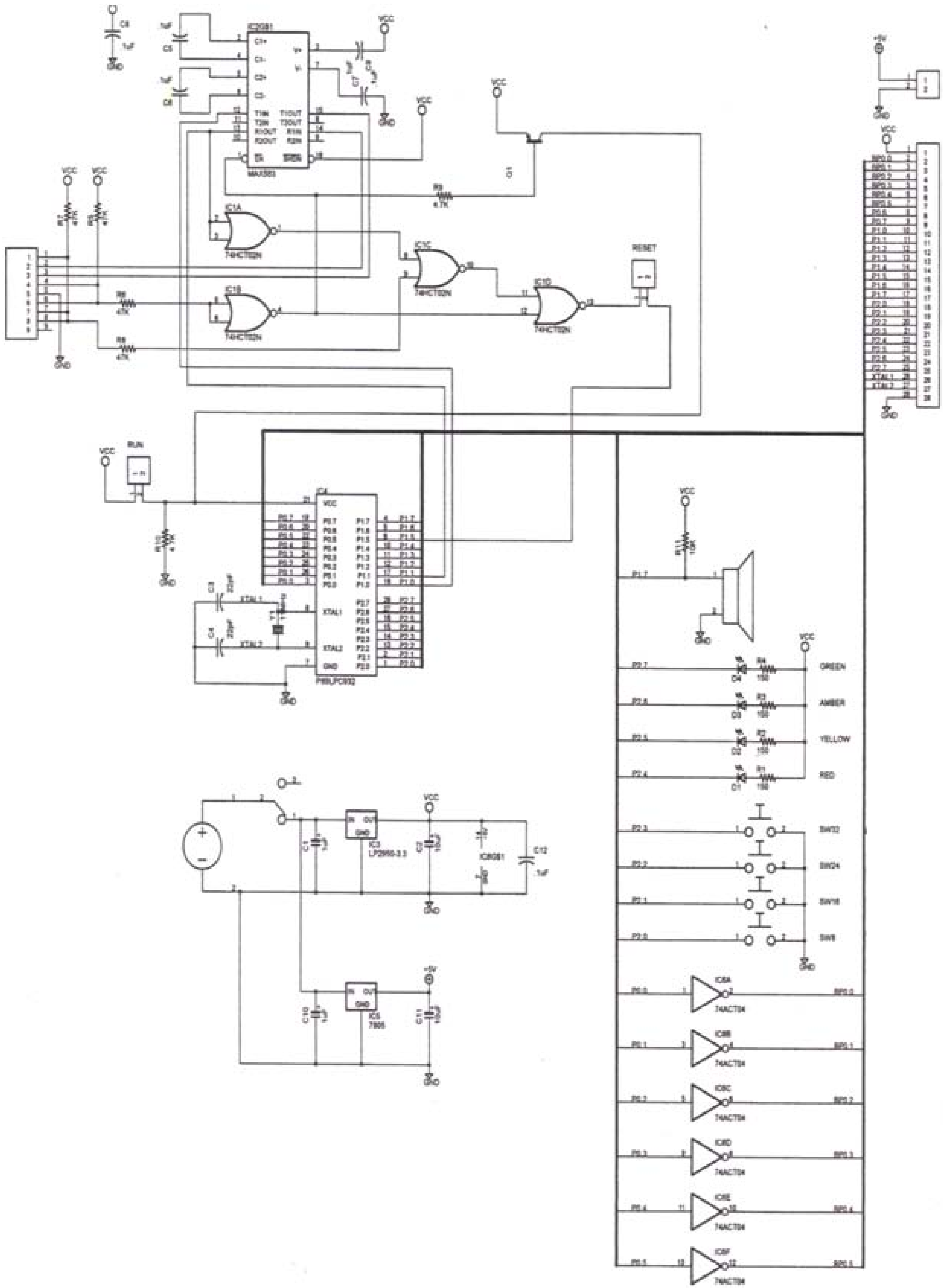


Figure 2. 8051 Controller Schematic

- Compare the desired temperature +/- desired tolerance to the current temperature values received from each temperature sensor in the following matter:

    - If the current temperature from both temperature sensors is greater than the desired temperature plus the tolerance, turn on the air conditioning by sending the correct logic to the appropriate solid state relay.
    - If the current temperature from both temperature sensors is less than the desired temperature minus the tolerance, turn on the heat by sending the correct logic to the appropriate solid state relay.
    - If the current temperature from one of the temperature sensors is within the range of the desired temperature +/- the tolerance and the other temperature sensor value is above or below the desired temperature +/- the tolerance, turn on the ventilation to circulate the air by sending the correct logic to the appropriate solid state relay.

- Provide connections to three solid state relays that will act as 24VAC switches to either turn on the heat, ventilation or air conditioning system when the correct logic is sent.

- Allow the user to see the desired temperature, desired tolerance and current temperature for each of the rooms being monitored via a liquid crystal display (LCD) module and by using the push buttons available on the 8051 controller.

In the initial prototype, the 8051 controller was powered by a 9 volt battery, and connected to the 802.15.4 controller through a null modem serial cable, as shown in Figure 3. The solid state relays and the LCD module are connected to the 8051 controller using ribbon cables and 20 pin DIP headers.

## LCD MODULE

By incorporating an inexpensive LCD module with 16x1 character display, the user will be able to see the current sensor values along with the desired parameters (i.e. temperature, humidity, etc.) and tolerances entered which will provide ease to control the HVAC system. The intent of this display is to simply provide basic health monitoring parameters, so the user can be assured the system is operating and that sensors are operating in a normal range.

It is anticipated the user may want to program the controller with commands which would be too complex to easily enter, or display, on a small LCD. For that purpose, the user will use a USB interface to connect the controller to a conventional personal computer. Custom software on the PC will allow more advanced scheduling information to be entered, along with information about the tolerance the user has for deviations from ideal conditions. The display will also allow the user to interrogate the controller, to download log files which document how the system has performed in the past.

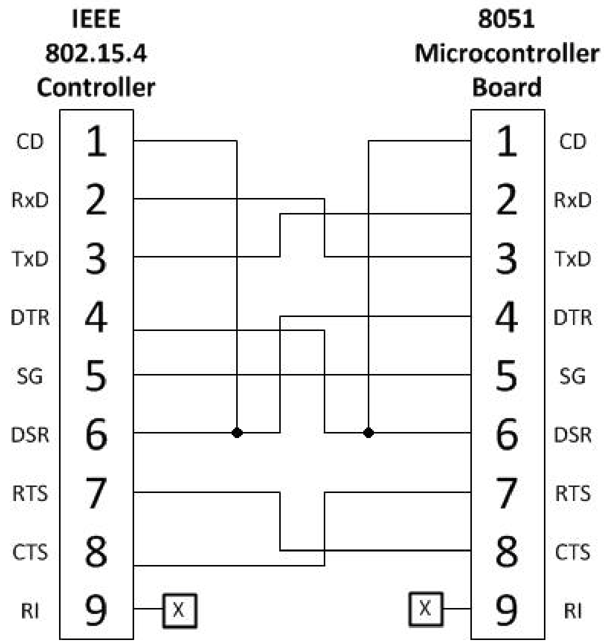


Figure 3. Interprocessor Cabling

## TESTING

A testing and evaluation plan was developed to both validate the system design, and also to be used during operation to monitor the health of the system. Initially firmware needed to be downloaded to the 802.15.4 controller. This was accomplished using the USB interface and driver software provided by the controller's manufacturer. Loop-back test will confirm the software is executing on the controller, and it will be possible to test I/O with the multiport RF interface. In the final version, check sum software will be included, to monitor the integrity of the controller's memory. Any errors will be reported to the PC over the USB interface (assuming it is still operational). The controller will also signal that the system should enter a fail/safe or fail/operational mode. Depending on the user configuration, this safe mode may be either to disable all HVAC operations, or perhaps turn control of the system over to a conventional electromechanical thermostat to prevent unacceptably wide temperature variations.

Each remote sensor node also needs to be programmed. During normal operation, there will be no hard wired connection to these battery powered modules. To conserve battery life, they will spend the vast majority of their time in a low power stand-by state. At times configured by the user, they will wake up and make measurements, to be transmitted to the central controller. The frequency of these measurements will be a function of the parameters being sensed. If the node is only sensing temperature and/or humidity, a sampling rate of 1 sample per minute may be sufficient, since the parameters are anticipated to change slowly. However occupancy information may need to be sensed more quickly, if the user expects the system to conduct some action as soon as someone enters a room.

All remote sensors will respond to loop-back commands whenever they are received. These commands are intended simply to confirm the wireless connectivity of the system. They will be initiated by the central 802.15.4 controller during initial system configuration, or when there has been an unexpectedly long silence from one of the sensor nodes. Periodically, perhaps once an hour, the nodes will execute a self-test. This will involve measuring the battery voltage, or state of charge, verifying the sensor voltages are in reasonable ranges, and calculating a check sum for the node's memory. The pass/fail status of this test will be encoded as one of the bits sent during each interrogation from the central controller. Even if an error is detected, the sensor nodes will continue to make a best effort at determining the correct value of the parameters it is sensing, and relaying that to the central controller – along with an error code. It is undecided at this time how the error code will be cleared. Some of the alternative solutions are:

- Allow the node to self-clear the error code, after a number of self tests indicate the node is now operating normally.

- Allow the central controller to issue a wireless command to clear the error code

- Require a hardware reset of the node by an individual.

The 8051 controller will have error tests which are similar to the 802.15.4 controller. And similar to the 802.15.4, if it detects an error condition, it will place the system in a fail/safe or fail/operational mode. In addition to its self tests, the 8051 controller will also look for error conditions reported by the remote nodes, or the 802.15.4 controller. It will need to assess the seriousness of these errors, to decide if it should execute one of its failure protocols. For example, a failure on a single remote sensor may be an error that should simply be reported to a user, but the system may still be able to operate using the other sensor inputs. However a failure of multiple sensors, or a controller failure, may require more drastic action.

The 8051 controller will also implement a number of watchdog timers. These timers are intended to insure that all remote nodes, and the 802.15.4 controller, are all updating at the anticipated intervals. If any of the remote nodes or the 802.15.4 controller takes a longer time than expected between updates, then that would be sufficient to put the 8051 in a failure state.

Finally, the 8051 will monitor the state of the solid state relays, and the sensor reaction to HVAC activation. For the solid state relays, the 8051 will monitor the current drawn by each relay.

This will allow it to determine if/when the relays have been inadvertently disconnected. The 8051 will also insure that HVAC operation is seen in sensor data. For example, if the 8051 calls for the heating system to activate, then it will check to see some increase in temperature of some of the remote sensors in the next few minutes. If the HVAC commands do not cause the temperature sensors to react, then an error condition will be declared.

The LCD display will be tested every minute or two. This will be accomplished by illuminating all segments of the display, then blinking all elements, before returning to the normal display output. There will be no way for the system to determine if the LCD is operating properly. However a user watching the display should be able to determine if there are any segments which are stuck on, or stuck off.

## FUTURE IMPROVEMENTS

During the initial development phase of this project, we only attempted to measure temperatures from a limited number of sensors. The intent was to provide basic connectivity data, determine the range of the wireless connections, and show simple network multiplexing capability. In addition, the two controllers were programmed to simply measure the sensors and compare the data to fixed set points – and then activate the HVAC system accordingly.

To improve the system in the future, we plan to add

- More elaborate scheduling functions, to allow temperature variation due to time of day, day of week, holiday, etc.
- Data logging
- User specification of tolerance of temperature variation
- More elaborate user interface
- Error checking of nodes, controller and LCD display
- Monitoring of humidity at nodes
- Monitoring of occupancy at remote sensor locations through infrared, or ultrasonic, motion sensors
- Monitoring the state of operable windows, through contact switches, infrared, ultrasonic or perhaps air-flow sensors.
- Activation of remote actuators, to reconfigure heating ducts, turn on circulation fans, turn on/off lighting
- Sensing error conditions, such as calling for heat, or cooling, for an extended period of time with little impact on sensed temperatures
- Integration of 802.15.4 and 8051 controllers into a single microcontroller

## CONCLUSION

Using an 802.15.4 wireless network, and a system of microcontrollers, it is possible to construct an inexpensive HVAC system controller. The system provides far more data on the condition of the environment in a home, and far more flexibility in controlling this environment. The overall cost of the system appears to be a few hundred USD, a cost which can easily be justified if even a small increase in energy efficiency is achieved in the home. The system can be built to detect, and react, to faults – to provide the user time to effect repairs – and to also avoid excessively large energy usage in a structure that is unoccupied for an extended period.

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