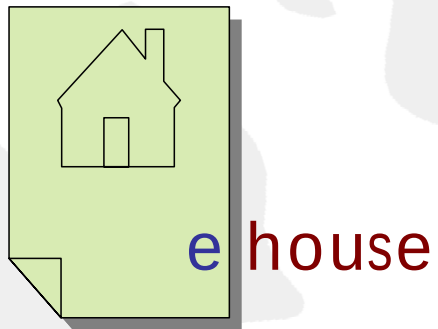


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Windows Student Embedded Challenge





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1. Abstract

The Earth's natural resources are among the most important assets bestowed upon mankind. Human beings however, are consuming these resources more quickly than they can be restored. Conventional energy extraction processes are depleting natural resources and disturbing the balance of nature. They are polluting the environment with waste and non-degradable byproducts that contribute to harmful effects such as global warming. Not only do these processes harm the environment, but these sources of energy will soon run out. This realization has spurred significant effort in the last few decades to develop solutions to resolve the energy crisis. There are two approaches to this problem: (1) looking into alternate sources of energy and (2) developing methodologies to reduce energy consumption. Our approach focuses on the latter.

Energy consumption continues to increase each year. According to the U.S. Department of Energy, energy consumption has more than tripled since 1949 [1]. Households alone contribute to 21% of total U.S. energy consumption [2]. Thus, lowering household energy consumption would have a significant impact on the global scale and help protect and preserve the environment.

The e-house is an intelligent home automation system designed to lower household energy consumption. This would in turn reduce energy-related costs that homeowners incur on their electricity bill each month. The e-house accomplishes this by monitoring and regulating air conditioning, heating, and lighting. The system can be set to automatically control home appliances based on information collected through local sensors and internet data. Manual control will also be available through a local interface and remotely available through a device connected to the World Wide Web. Additional design considerations are as follows:

- Low Cost
- Ease of Installation
- Ease of Use
- Customizability
- Reliability
- Extensibility
- Efficient Power Management Algorithm
- Real-time energy consumption monitor

The functionalities and purposes of the e-house extend beyond serving as an environmental and cost saving solution. Other benefits that come with all home automation systems such as user convenience and security are included in the e-house as well. The e-house could be considered a revolutionary system that would make life more comfortable while serving a greater cause.

2. System Overview

The system consists of three major hardware components: the home automation unit, the mobile control unit, and the in-house control unit. The e-house runs on Windows CE family with .NET Compact Framework 2.0.

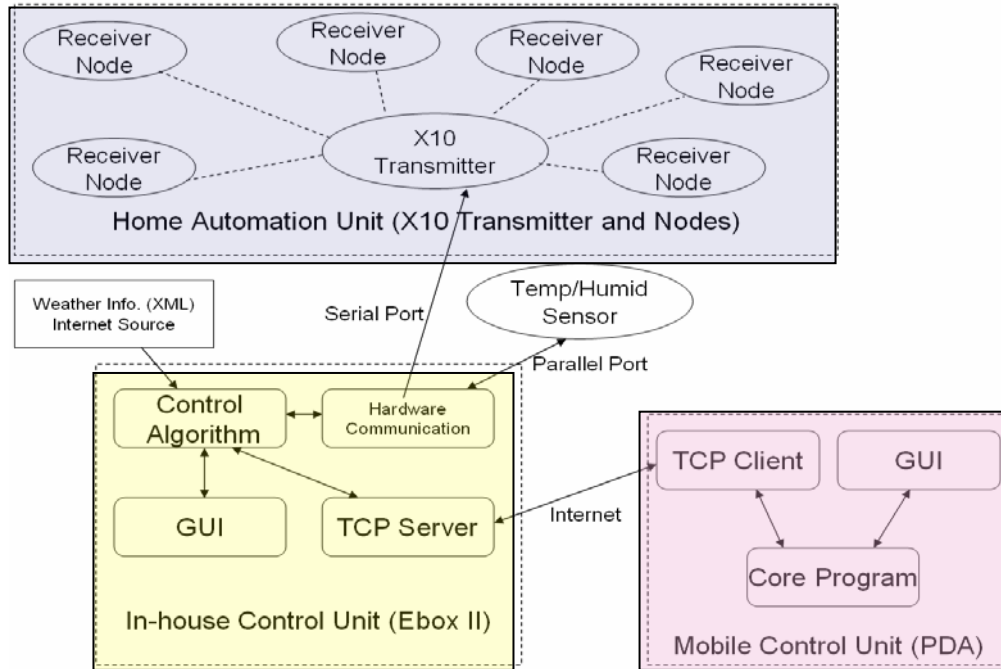


Figure 1. System Overview.

2.1 Innovations

While a number of commercial home automation products are currently available on the market, none incorporate energy saving methodologies. Using information from the Internet and in-house temperature and humidity sensors, the e-house has been designed to maximize energy efficiency while maintaining a comfortable home environment. The system also enables remote control through any mobile device that supports the .NET framework.

The e-house allows the user to monitor energy consumption and provides the user with a monthly expenditure forecast based on current settings. This helps the user define settings to maximize efficiency. This functionality is unique to the e-house.

Another unique feature presented by e-house system is that it uses the “real feel” temperature to control temperature-based appliances. The real feel temperature is the temperature perceived by human beings. It takes into consideration both humidity and dew point apart from the measured temperature value.

2.2 System Components

In-home Control Unit

The Ebox serves as the central control unit for the e-house system. It interfaces to the home automation unit through the serial port and to local sensors through the parallel port. It is connected to the Internet in order to gather current weather conditions and forecast and to allow for remote access. Home automation is accomplished by feeding Internet and local information to the control algorithm.

Mobile Control Unit

A .NET application developed for the mobile control unit allows remote control of the system. The software makes use of .NET TCP/IP connection ability to communicate with the in-home control unit.

Home Automation Unit

This unit consists of the X10 transmitter and receiver nodes. The X10 transmitter is connected to and controlled by the Ebox. It uses signals transmitted through power lines to communicate with the receiver nodes. The nodes connect electrical appliance to their respective wall outlets. These nodes can then be used to trigger different devices remotely.

2.3 Performance Requirement and Failure Countermeasures

The e-house is designed in order to be compatible with any household. The low cost, ease of installation, and ease of use would make the e-house a viable option for all. The e-house also allows devices to respond to manual operation, and therefore by attaching a device to the system, the user does not relinquish control over the device.

Reliability is also an important factor for a home automation system. The e-house is designed in such a way that it would revert to its last state after a power outage. In the case of loss of internet connectivity, the system will switch to local sensor control. If the homeowner is away and loss of internet connectivity at the in-home control unit disables remote access, the e-house will still control appliances based on the energy saving algorithms. Therefore appliances will not be left on indefinitely.

2.4 Design Methodology

In order to design a safe and reliable product, careful planning, bulletproof design, and thorough testing was implemented. This project required recognizing tasks, dividing the tasks among team members, testing and development of each module, and finally integrating each module and testing the system as a whole.

The project was divided into individual components, which were assigned to team members based on their fields of expertise. The team then came together to integrate the various components and develop the central control algorithm.

3. System Implementation and Engineering Considerations

3.1 Design Considerations

3.1.1 Marketing and Cost

The notion of intelligent home automation systems has long been discussed, but serious integration and development of these ideas has just recently begun. For instance, mass-market home builders met in San Diego on April 10, 2006 for a digital home conference in San Diego [3]. Due to growing popularity, this is a perfect opportunity to market the e-house as not only a convenient home automation system, but as an environment-friendly, energy saving asset.

The e-house incurs a one-time cost that will yield an excellent return on the investment. Statistically about 60% of an average family's household energy goes to heating, cooling, and lighting [4]. Efficient regulation of air conditioning and ambient moisture content would easily reduce energy consumption. This, along with lighting control, translates into significant savings for the consumer.

The cost breakdown for a single e-house unit is as follows:

Component	Cost
Ebox II	\$180
SHT75 Humidity/Temperature Sensor	\$ 24
X10 Active home System + 6 Nodes	\$ 80
Total Cost	\$284
Table 1. System Cost Breakdown	

3.1.2 Energy Conservation Analysis

The total annual energy saved by an average household can be calculated with Equation 1 below.

$$E_{AS} = C_{EH} \cdot P_{ES} \quad (\text{Eq. 1})$$

E_{AS} represents total the annual energy savings per household, and C_{EH} is the average household energy consumption per year in kilowatt hours (kWh). P_{ES} is the percent savings.

The e-house focuses its energy savings on two main factors: (1) efficient regulation of temperature and (2) lighting control. The calculations for percent savings per day depend on many different factors, several of which are listed below:

- Dimming lights during the day
- Regulating heating/cooling during sleep hours



- Remotely turning off unused appliances
- Outside weather awareness

It is not feasible to include volatile factors for the calculation of energy savings, so for the purposes of this example, only concrete data is included in the calculation. It is very likely for actual energy savings to be higher. Equation 2 below shows percent energy savings based on dimming lights and lowering heating/cooling during sleep hours where P_{LD} is the percentage of light dimmed, P_{LT} is the percentage of time the lights are dimmed, P_{LC} represents the percent of energy use that lighting contributes, P_{HS} is the percent savings from lowering heating/cooling, and P_{HC} is the percentage of energy use that heating/cooling contributes.

$$P_{ES} = (P_{LD} \cdot P_{LT} \cdot P_{LC}) + (P_{HS} \cdot P_{HC}) \quad (\text{Eq. 2})$$

Based on deduced and statistical data, the following parameters will be used in this example: $P_{LD} = 0.75$, $P_{LT} = 0.30$ (assuming there is adequate sunlight 6-8 hours a day), $P_{LC} = 0.10$, $P_{HS} = 0.15$, $P_{HC} = 0.50$ [4][5]. Plugging in the parameters yields energy savings of at least 9.75%. With the average residential annual electricity expenses of \$977.04 [6], average savings from automated features of the e-house would come out to at least \$95.26 per year. For larger homes, savings would be significantly higher.

According to 2004 statistics from the US Department of Energy, the average annual energy consumption per household is 10,896 kWh. Using this figure in Eq.1 shows that the e-house would save at least 1071.1 kWh per year. If the system were implemented all 120 million homes in the US, over 129 billion kWh of energy would be saved just in the residential sector alone. This amounts to at least 11.5 billion dollars of annual household electricity bill savings. To put this amount in perspective, the government energy efficiency branding program ENERGY STAR saves 12 billion dollars annually from thousands of products they have ever been registered [11]. The e-house can alone save at least that much annually.

3.1.3 Home Automation Technologies

The primary requirements for the home automation system are economic feasibility and ease of installation and maintenance. The X10 Active home system perfectly satisfies these requirements. However advancements in the field of home automation may offer more viable alternatives in the future.

Technologies such as ZWave, Bluetooth, and ZigBee protocols might enable a more efficient method of integrating devices without having to use the AC power line for communication. ZWave technology uses RF signals to communicate between nodes, effective to about 100 feet. ZWave devices are however much more expensive and complicated to implement than X10 devices and were thus not considered.

The ZigBee protocols use a series of small low power digital radios to establish wireless personal area networks. These devices are optimal for networks that require low data rates and with low power consumption. However, this technology

is still in a very early stage of development and not as freely available as X10 based devices. These technologies may be considered alternatives to the X10 system in the future as they develop further.

3.1.4 Expansion Considerations

Temperature Control

While the X10 system provides a convenient method for controlling devices across a household, this control is limited to turning devices on and off. While it is slightly more versatile in handling lights, the system would benefit greatly by more intricate X10 interfaces with heating/cooling devices. The automation system could exercise a finer degree of control over the temperature of the household and this would translate into greater savings.

Health Benefits

Incorporating air purifiers along with existing humidifiers and evaporators to the automation system would further alleviate health concerns and provide for a cleaner living environment. These could be triggered by on site sensors and internet sources detecting pollen and dust content resulting in an appropriate response. Apart from reducing molding caused by damp conditions, this would alleviate other health concerns related to asthma and allergies.

Energy Alert - Early Warning Systems

The internet connectivity offered by the e-house would also make it convenient for blackout/brownout warnings. In the case of anticipated power outages, the service providers could send blackout/brownout warnings through the internet, which could in turn be interpreted by the e-house to warn homeowners. Under these circumstances, the system could be used to minimize consumption during the peak hours thereby reducing the likelihood of a power failure. This may be practical if enough homes implement the system.

3.2 Hardware Components

3.2.1 Ebox II

The Ebox II is a compact computer which runs on the Windows CE operating system. At its core is a Vortex86 processor that operates at 200MHz. It also includes 128MB DRAM memory on board. The 10/100Base-Tx Ethernet interface allows the Ebox to connect to the network or the Internet. The Ebox also includes VGA output, PS/2 keyboard and mouse interfaces along with serial and parallel ports to attach peripheral devices.

3.2.2 X10 Home Automation System

The X10 home automation system provides a convenient means for interfacing the appliances in the home with the Ebox. The X10 system was chosen over others

primarily for its ease of installation. The system was also well documented online, which made developing software for it significantly easier.

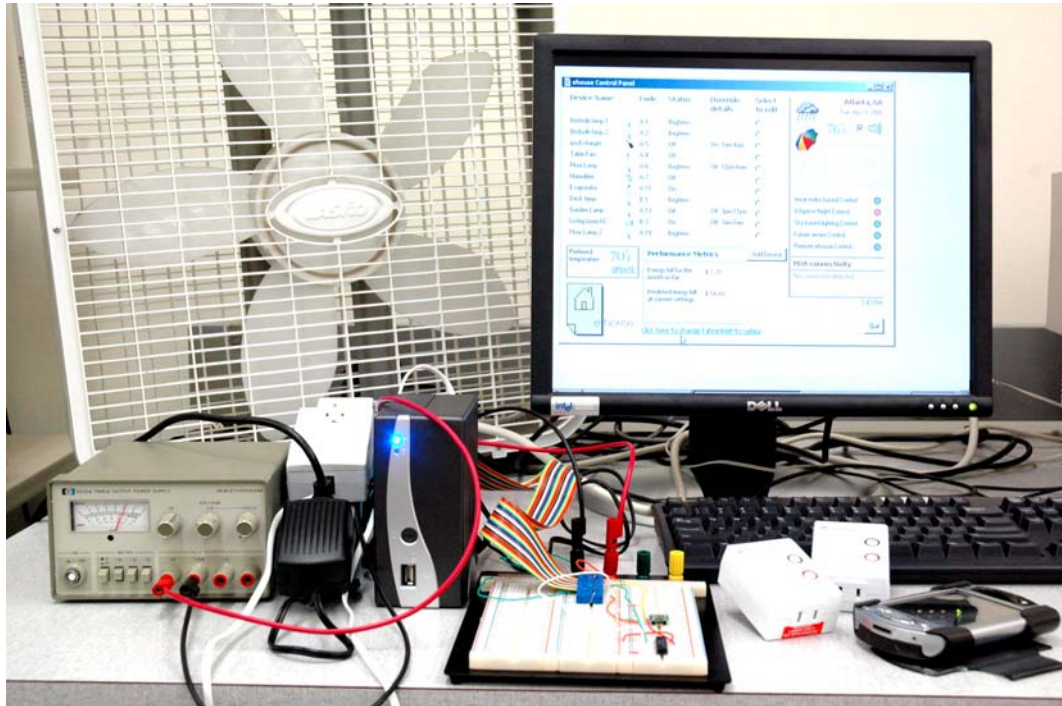


Figure 2. The e-house Prototype

The X10 system consists of a transceiver (the CM11A controller) which is connected to the Ebox through the serial port. The system also consists of a number of individual nodes that receive the signals transmitted by the CM11A. They interpret these signals to turn the devices connected to them on or off. The nodes are currently available in two distinct varieties;

- the appliance module, which accepts only on / off commands
- the lamp module, which can be used to adjust the intensity of incandescent lamps apart from turning them on and off

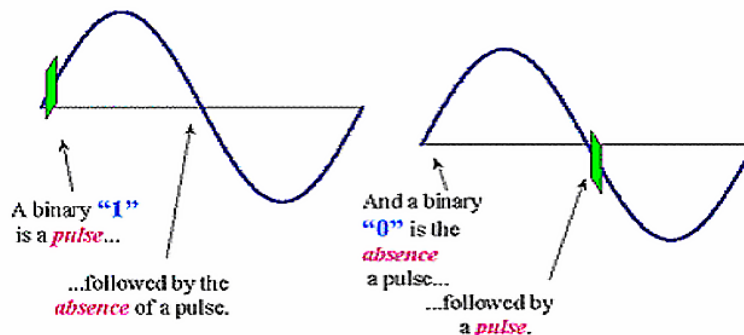


Figure 3. X10 Transmission Signal

The CM11A controller transmits signals to the nodes using existing electrical wiring. The X10 transmissions are synchronized to the zero crossing point of the AC power line (Figure 3). Every node has a zero crossing detector that is used to detect

signals transmitted by the controller. The receivers look for the signal within 0.6 microseconds of the zero crossing point.

Initiation Signal											
1	1	1	0	0	1	1	0	1	1	1	0
Start Signal				House Code "A"				Device Code "2"			

Command Codes											
On = 00101				All Lights On = 00011				Bright = 01011			
Off = 00111				All Units Off = 00001				Dim = 01001			

Figure 4. X10 Communication Codes

The CM11A controller initiates communication by sending a start packet followed by the house code and the device code. This initiation signal is followed by a command signal that is used to control the specified node. The command codes (Figure 4) include options for toggling nodes on/off and for dimming/brightening lamp modules.

By installing a series of nodes any home can be automated to a reasonable degree. The installation would only require setting a house and device code on a node and attaching the X10 node between a device and the wall outlet.

3.2.3 SHT75 Temperature/Humidity Sensor

Sensirion's high precision SHT75 sensor is utilized to measure local humidity and temperature data. The 2-pin serial interface allows for ease of communication with any programmable digital device. The SHT75 includes an input SCK (serial clock) pin, and a bi-directional DATA pin. These pins are interfaced to the parallel port of the Ebox as shown in the schematic below.

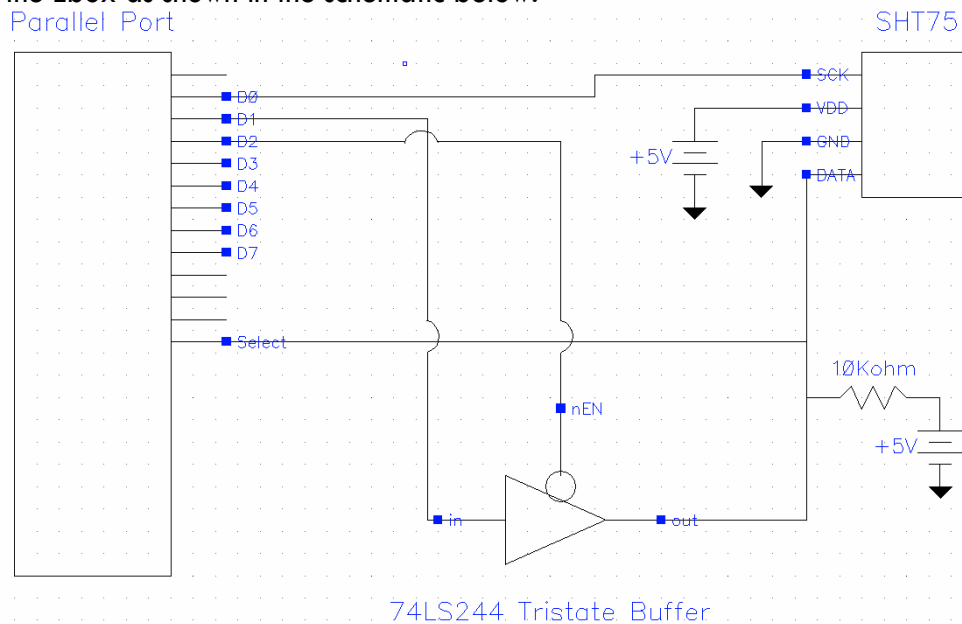


Figure 5. Sensor Interface Schematics

The first bit, D0, of the parallel port drives the SCK input of the SHT75 chip. The second bit, D1, drives output to the DATA line through a tri-state buffer. Input from DATA is received through the SELECT line of the parallel port. The tri-state buffer is necessary to avoid line contention on the DATA bus. When the parallel port is driving DATA, the buffer is turned on, and when input is received from DATA, the buffer is turned off. The 10k Ω resistor in the circuit pulls DATA high while control of the bus is exchanged from one device to the other.

To initiate a measurement, a transmission start signal must be first sent to the SHT75 chip. This is done by driving the DATA low during two pulses of SCK, and back high again before the falling edge of the second SCK pulse.

Following a transmission start signal, an 8-bit command is sent through the DATA line. Each bit is clocked in by one SCK cycle, so DATA must remain stable while SCK is high. If the command is accepted by the sensor, then the chip will drive DATA low, signaling acknowledge, on an additional 9th clock. Figure 6 shows a waveform capture of a transmission and command sequence from a logical analyzer.

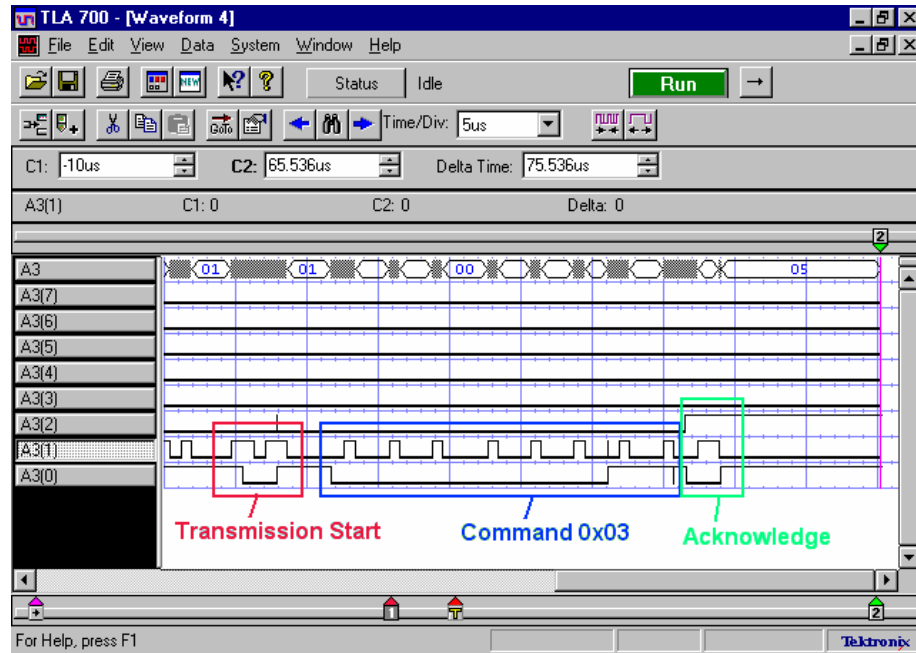


Figure 6. Waveform Capture

Depending on which command is sent, if successful, the SHT75 will send back the digital measurement one byte at a time. The 12-bit temperature and 14-bit relative humidity readings are converted using the following equations where T_{C} is the temperature in Celsius, T_{reading} is the 12-bit temperature value, RH_{L} is the linear humidity, RH_{reading} is the 14-bit humidity reading, and $RH\%$ is the relative humidity.

$$T_{\text{C}} = 0.01 \cdot T_{\text{reading}} - 40 \quad (\text{Eq. 3})$$

$$RH_L = -0.0000028 \cdot (RH_{\text{reading}})^2 + 0.0405 \cdot RH_{\text{reading}} - 4.0 \quad (\text{Eq. 4})$$

$$RH\% = (T^{\circ}\text{C} - 25) \cdot (0.1 + 0.0008 \cdot RH_{\text{reading}}) + RH_L \quad (\text{Eq. 5})$$

3.2.4 Pocket PC

The mobile control unit can be implemented on any Pocket PC device that supports the .NET Compact Framework 2.0. Other requirements include TCP/IP support and an active internet connection through WiFi or Bluetooth. Our prototype system includes a Dell Axim running Windows Mobile 5.0 as the mobile control unit.

3.3 Software Components

3.3.1 Windows CE Image

A custom Windows CE 5.0 operating system was developed for the in-house unit. The kernel image was created using Windows Platform Builder 5.0 incorporating the ICOP_EBOXII_50DVS:X86 board support package. The kernel includes the components listed in Table 1. The release version of the kernel image is approximately 18.9MB.

Modules	Purposes
Serial Port Support	X10 Transmitter Control
Parallel Port Support	In-house Sensor Communication
TCP/IP Support	Info. Gathering and Network Communication
.NET Compact Framework 2.0	C# .NET Program Support
Standard SDK for Windows CE	Embedded Visual C++ 4.0 Support

Table 2. Kernel Components

3.3.2 Backend Components

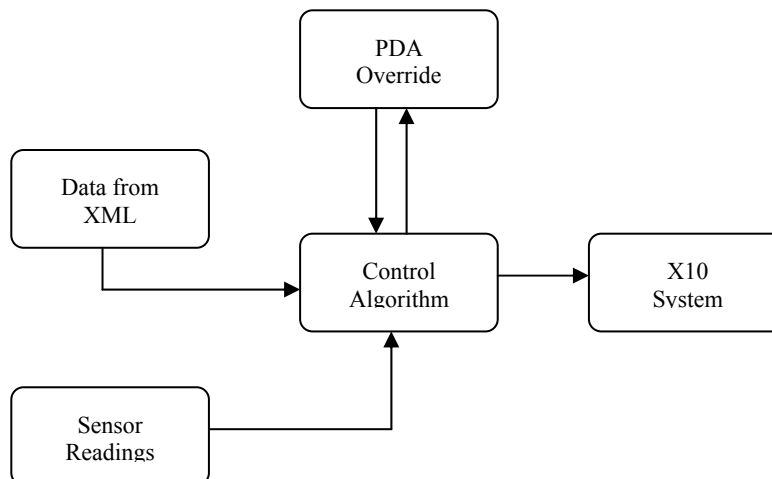


Figure 7. Backend Communications

Ebox – Pocket PC Communication

Communication is established using the TCP Listener class from System.Net and System.Net.Sockets classes of the .NET Compact Framework 2.0. With this Listener class, the Ebox acts as a server offering remote control service for the Pocket PC client. The server program starts a new thread to constantly check for any incoming requests. Once the connection is established, the Ebox transmits the current status of the e-house system, receives override values from the Pocket PC, and configures the devices correspondingly.

XML Parser

The XML parser reads through the Yahoo! Weather XML page every 5 minutes and extracts temperature forecasts, humidity levels, and current temperature for any area based on a user input zip code. This data is utilized by the control algorithm to manage the devices connected to it.

Sensor Readings

Sensor readings are taken every 5 minutes. Temperature, humidity, dew point, and real feel temperature are calculated from the readings and fed to the main control algorithm to trigger heating and cooling devices.

3.3.3 Main Algorithm

The e-house implements a detailed algorithm for the control of devices to conserve energy. The algorithm is divided into three sections based on the type of device or control.

1) Lighting control

Data for sunrise time, sunset time, and sky condition description is extracted from XML data. Between sunset and sunrise, all lamp devices controlled by the e-house are set to full brightness. It is expected that the user manually turns lights off before sleeping. There would be no point to automate this since it would probably vary according to the user. The user also has the option to set a manual off-time within the system. Between sunrise and sunset, the e-house controls the brightness of lamps connected to it according to weather or sky information. For instance, if someone had a desk lamp lit during the day, the e-house will monitor brightness, dimming the lamp if it is sunny or brightening it if it is cloudy. This feature is referred to as *Sky-based Lighting control*.

2) Temperature Control

Since undoubtedly the greatest part of household energy consumption goes into heating and cooling, the e-house attempts to optimize temperature control to a high degree. The block diagram on page 12 outlines the steps involved in the process. Items within a block in the diagram are executed sequentially. Items preceded with right arrows represent conditional execution, but are also executed

sequentially. The table below can be used as a key to understand the process block diagram.

LEGEND

Tn	Temperature from the Net
Hn	Humidity from the Net
Ts	Temperature from the sensor
Hs	Humidity from the sensor
Tp	Preferred temperature
Hp	Preferred humidity
HI	Humidex calculation function (Eq. 6)
Tnn	Predicted temperature of next hour from the Net
Hnn	Predicted humidity of the next hour from the Net
TCD-enable	Temperature Control Device (AC and Heater) Enable
ΔT_{ps}	Difference between preferred and room temperature
ΔT_{pn}	Difference between preferred and internet temperature
ΔT_{sn}	Magnitude of difference between room and internet temperature

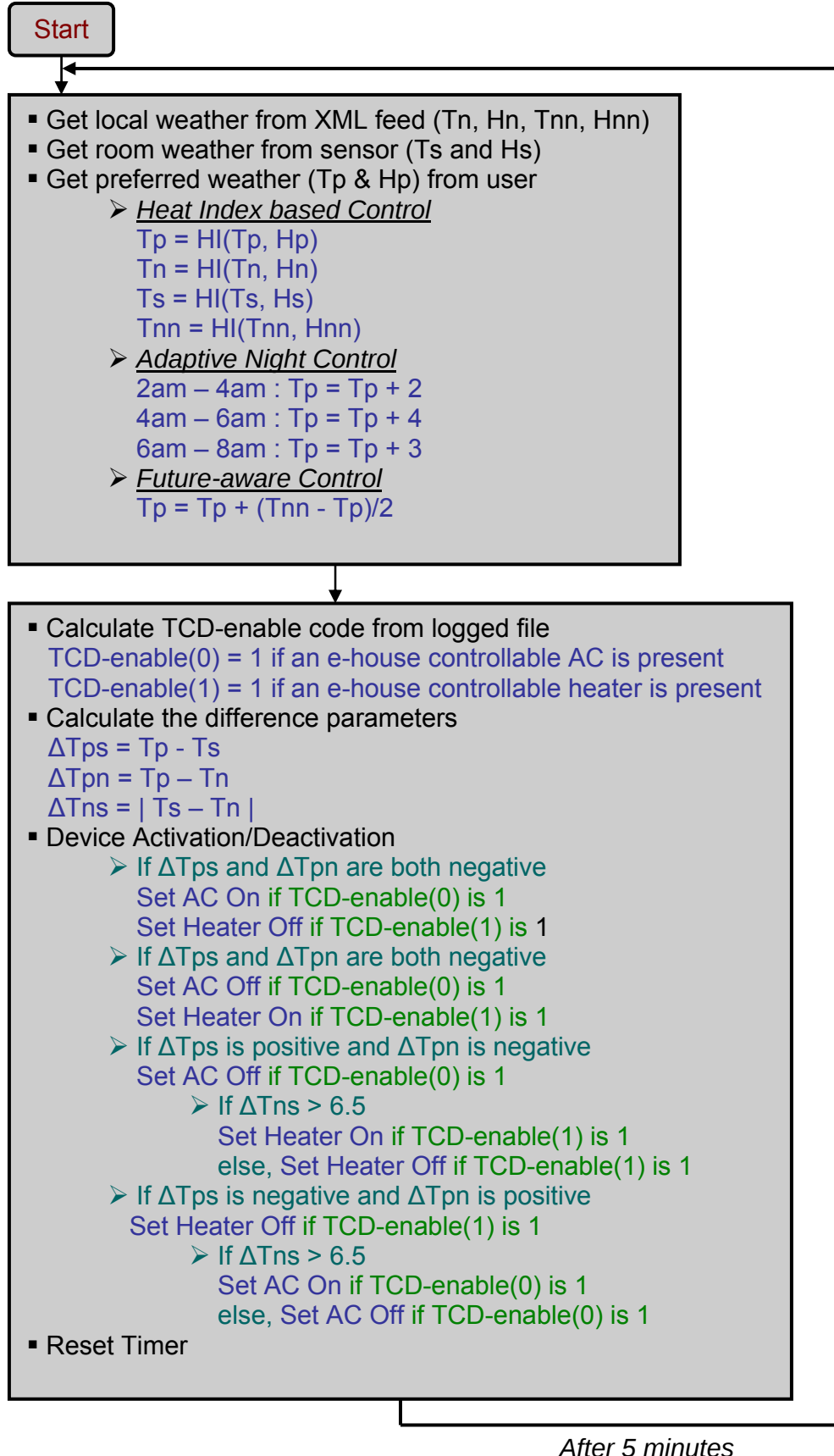
The e-house control algorithm receives data from the local sensor and XML feeds regarding outside and inside temperature and humidity level. It also receives data input from the user regarding preferred temperature and humidity level. For the remaining calculations, the e-house uses “humidex” [7] or “real feel temperature” calculations (Eq. 6) so that the temperature measurements accurately represent the degree of warmth and coolness. This is referred to as *Humidex based Control*. Dew point is calculated from humidity and temperature values [8].

$$T_{\text{humidex}} = T_{\text{actual}} + 0.5555 \cdot (6.11 \cdot e^{(5417.7530 \cdot (1 / 273.16 - 1 / \text{dew point}))}) \quad (\text{Eq. 6})$$

Yet another feature provided by the e-house is *Adaptive Night Control*. This mode is based on the common observation that it feels colder in the middle of the night and early morning. This is used to reduce the preferred temperature by a few degrees (Fahrenheit) during the night depending on time.

Last but not the least, the e-house provides capability to automatically adjust cooling and heating conditions based on predicted data for future weather. For instance, this provides the capability to reduce air-conditioning if it is known that temperature will be dropping in an hour. This is incorporated by adding half the difference of the predicted and preferred temperature to the preferred temperature to get a new estimate. This facet of the system is called *Future-aware Control*.

The next step involves controlling the hardware. Based on logged information, enable signals are created for an air-conditioning and heating component. An enable is set high if e-house has the capability to modify the component. After that a number of conditions are run through to set the devices to the right state. For instance, if it is cold inside a house and hot outside, the e-house checks to see if the humidex difference is significant enough to turn the heater on. If not, it turns the heater and the AC off depending on whether these devices are enabled to be automatically controlled.



3) Humidity Control

The algorithm for humidity control is similar to the algorithm for temperature control. The e-house monitors humidity levels inside the house and turns humidifiers and evaporators on and off based on humidity levels. This control prevents molding, maintains a healthy living environment, and contributes to the upkeep of the house.

3.3.4 GUIs

Control Panel GUI

The in-house unit control panel offers the user the ability to configure and maintain control over the various aspects of the e-house system. After the user inputs zip code, preferred temperature, and preferred humidity level, the in-house unit displays the e-house control panel (Figure 8). The user then has options to add devices, set preferred temperature, and toggle different modes of automated operation of the e-house. The system also gives the user the option of setting devices to automatically turn on and off based on time.

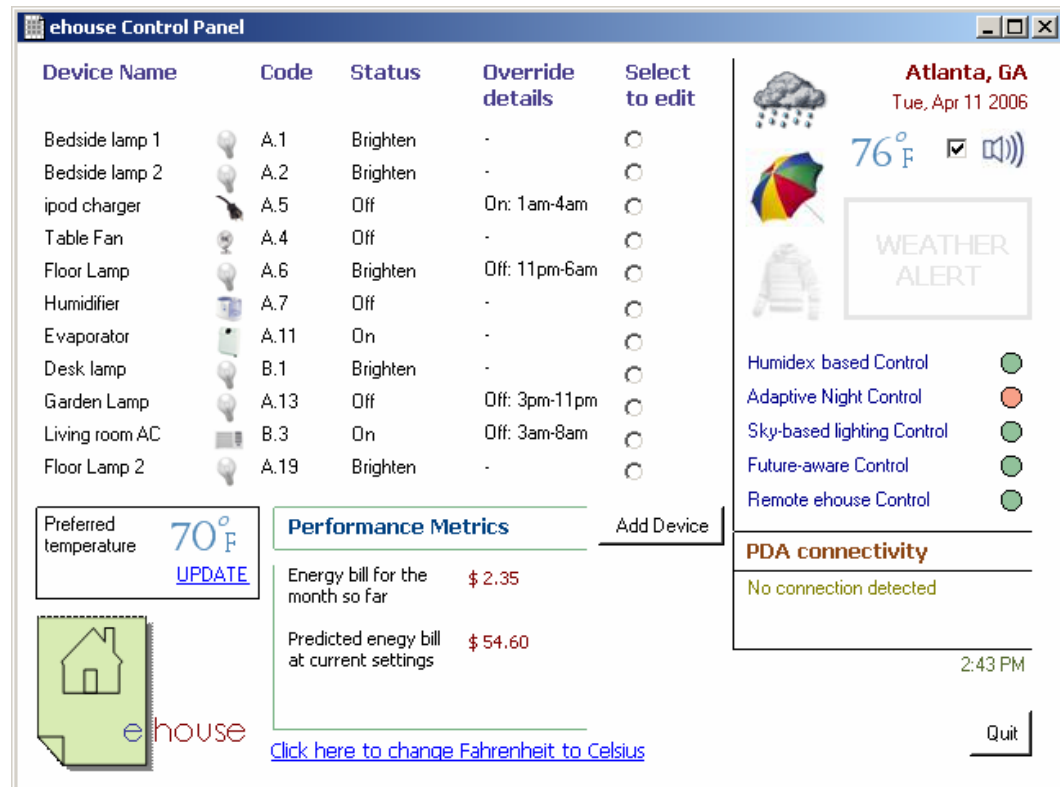


Figure 8. In-house Unit GUI

Another feature of the interface is that it displays weather forecasts. If the forecast shows rain or low temperatures the GUI notifies the user to wear warm clothes or carry an umbrella. Dedicated lights can be added for visual notifications of these

features. A final characteristic of the GUI is the weather alert system. If severe weather conditions are forecasted for the given zip code, then the GUI flashes the alert signal. If the user has voice alerts enabled, then the e-house will give an audio warning of the actual alert as well.

The control panel also logs and displays real-time energy expenditure to assist the user in estimating monthly bill. The real-time electricity bill estimate further helps users to set the appropriate settings on the e-house to achieve budgeted expenditure.

Mobile Unit GUI

The mobile unit provides the user the ability to monitor and control home appliances.

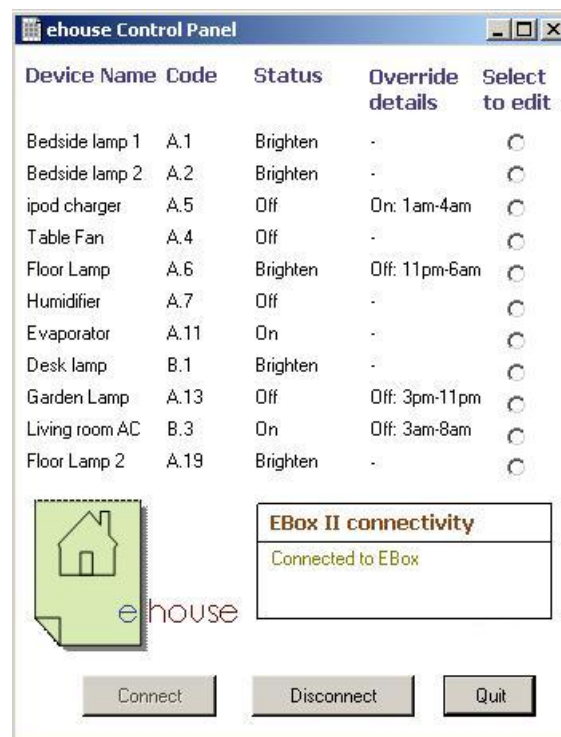


Figure 9. e-house Remote Access GUI

3.4 Development Tools

In order to establish the foundation of the e-house, Platform Builder 5.0 was used to generate a kernel for the in-home unit. Development was then carried out in Embedded Visual C++ 4.0 and Visual Studio 2005. Embedded Visual C++ was used to develop parallel port communication with the SHT75 temperature/humidity sensor. Visual Studio 2005 was used to develop GUIs, backend interfaces, serial port communication with X10, and the central control algorithm in C#.

3.5 Verification and Testing

Functionality

The functionality of the individual components was tested rigorously to ensure that the system would perform as expected when the e-house was assembled together.

Device	Testing Methodology
Sensors	Monitored control and data traffic with a logic analyzer and outputted sensor readings to a console.
X10 Transceiver	Controlled single LED device with simple GUI input on the Ebox.
XML Parser	Developed a GUI wrapper for using the parser DLL and extracted data from the Yahoo! Weather page based on an input zip code.
PDA	Monitored, transmitted and received text stream from the PDA to the Ebox and vice versa.
e-house System	• Developed a GUI control panel to monitor the control and response of a lamp and a cooling device individually. • Tested the different conservation modes individually. • Extended system to test performance with multiple devices under multiple modes.

Table 3. Testing Procedures

Performance

The performance of the system was tested by comparing automated control versus normal usage of appliances over a period of 24 hours. The e-house was connected to a lamp, a mini-heater, and a fan to simulate the lighting and cooling aspects of the algorithm. The hours for which the e-house lights remained illuminated and the fan and heater operational were logged and compared against normal usage. A difference of a couple of hours was noted for the lighting and cooling. While this data may not seem significant on its own, extrapolation for all devices on an average household shows significant reduction in power consumption. Since the performance of such a system would vary based on housing setups and personal preferences, data is currently being collected under various scenarios.

4.0 Summary

The e-house is a system that aims to provide much more than mere home automation for comfort and whim. The e-house concerns itself with global environmental issues and provides a solution for energy reduction apart from economic advantage and comfort.

The e-house is more intelligent than contemporary home automation systems. It uses internet weather forecasts and in-house weather conditions to control lighting and heating or cooling devices. Automated features namely humidex based control, adaptive night control, future-aware control and sky-based lighting control serve to reduce energy consumption by about at least a tenth every day. In other words if the e-house gains



popularity and is implemented on a large scale, it is not difficult to save about a years worth of energy every decade for households.

The e-house also provides a groundbreaking energy consumption monitor which allows people to see for the first time ever what their electricity bill is shaping up to be. Such a real time monitoring system encourages people to reduce electricity consumption to prevent the electricity bill from ballooning. This helps customers set up devices to minimize the monthly expenditure. This capability of the e-house could alone make it sell successfully.

The e-house, however, is more than only an energy consumption monitor or cost reducing device. The weather alert feature warns homeowners through audio-visual outputs about official weather alerts. This replaces presently used expensive weather radios, reducing the need of additional weather monitoring devices. Lamps or LEDs can be connected to the e-house to warn users to carry umbrellas or wear warm clothes without requiring them to check the weather report on TV or online. The Adaptive Night Control further adds to comfort through better adjustment of night temperature. Finally the ability to control home appliances from anywhere provides a convenience desired by many.

As of now a prototype system has been developed that provides for all discussed functionality. This prototype is useful for demonstration purposes, but there is a world of advancements possible to make the e-house a successful market product. The look and feel of the system can be drastically improved by using an ICOP embedded CPU touch screen [9]. The system could also be synched with a power company RSS feed, perhaps available in the future, to control devices efficiently during a brownout. The e-house could be updated to incorporate new energy savings techniques. Control for more types of devices can be provided as and when home automation interfaces are developed to support them. Since the e-house would perform better in larger environments, a corporate version of the system can be developed. Therefore, the e-house represents a visionary breakthrough in home automation technology.

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