Distributed Wired and Wireless Sensors for the Home of the 21st Century Project

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***Abstract*— The George Washington University is collaborating with America Online and Virginia's Center for Innovative Technology to develop the "Home of the 21st Century" in its laboratory in Ashburn, Virginia. The project aims at designing and implementing a distributed network of wired and wireless sensors and actuators that would be capable of sensing and controlling the environment in the house, integrating itself with other network-compatible devices and be accessible from the World Wide Web. The house will be equipped with a certain amount of intelligence to identify the occupants and customize the environment according to their preferences. Other features like voice-activated control will introduce an increased degree of interactivity and be an important step in freeing the user from the familiar mouse-monitor-keyboard model.**

I. INTRODUCTION

With the incredible advancement in computing technology over the last decade, Man today runs the risk of settling into the complacent belief that merely faster and smaller processors would define the future, as suggested by Moore's Law. Consequently, some of the newer scopes and possibilities might not be readily self-evident; requiring as they do, a complete shift in the paradigm that has dictated our understanding of computer applications in the past. One such area is the relationship between the computer and the user. The traditional model sees Man consciously entering an artificial domain (at best defined by a user-friendly graphical interface), while the computer remains largely a passive device allowing itself to be used. In the house of the future, the role of these two may well be reversed; the computer would have to adapt to the human environment, while the inhabitant need not be distracted by artificial props like keyboards, mice and monitors.

It is with this aim in mind, that the George Washington University has embarked on the ambitious "Home of the 21st Century" project, in collaboration with America Online. This project proposes to build a house, equipped with a certain amount of intelligence, to communicate with its occupants in a non-intrusive manner, customizing entertainment to individual preferences and providing increased security by wirelessly connecting devices (including the alarm system) to the Internet. And lest one visualizes the horrors of George Orwell's "Big Brother" scenario, it might be worthwhile to realize that the aim of the Intelligent House is to provide people with easier access to resources, be they computational or otherwise, without forcing her to constantly shift her mode of thinking or interaction.

We have taken up the responsibility of designing and implementing a distributed network of wireless sensors that is capable of sensing the environment in the house, integrating itself with other network-compatible devices, and be accessible from the World Wide Web. While we have been guided by observing how a human being responds to external stimuli, constructing a house that mimics human senses would ultimately be as self-defeating as the earliest aviators' belief that an airplane must be modeled after birds. For instance, the concentration of pressure spots on the human skin is as dense as 200 per square-centimeter (or 1300 per square-inch) on the tip of the tongue. Such a sensor network in the house, imagining it were possible, would provide information at a rate that no known computing resources would be able to process. To allow effective implementation, data should be collected by a limited, but manageable, number of sensors and routed through a series of algorithms to provide a meaningful interpretation. The Department of Computer Science is collaborating in this regard.

An Intelligent House environment has been a favorite topic for science-fiction writers, even predating Arthur C Clarke's HAL by over a decade, but it was not until a few years ago that several Universities, such as MIT [1] and Georgia Institute of Technology [2], began work on independent projects to try and make this a reality. Depending on the scope of their respective projects, the Universities have met with various degrees of success. The aim of the George Washington University is to create a laboratory that would place more stress on wireless devices and aim at seamlessly integrating various household appliances at the lowest possible cost, to make its commercial use feasible. America Online, a company based in Washington DC, was quick to realize the commercial potential, especially in the domestic market, of such an integrated home automation system. In fact, a recent Roper Starch study [3] held at the behest of AOL suggested that 60% of the population expect every room of their home to be wired to the Internet within a decade. So, while this project gives students the opportunity to gain valuable experience in the design, development, and

Fig. 1(a). Office space and meeting area of the GWU-AOL laboratory.

Fig. 1(b). Living room and kitchen of the GWU-AOL laboratory.

implementation of cutting edge technology in wireless home networks and integrated sensors, it benefits AOL by broadening their visibility in this up-and-coming technology.

The laboratory, located at the George Washington University's Ashburn, Virginia, campus (just minutes away from AOL's headquarters), is a 1500 square foot space resembling a contemporary home (Fig. 1). This area has been partitioned and furnished as a living room, kitchen, and three office rooms by the University's Interior Design students [3]. The laboratory is equipped with computers, printers, a fax machine, scanner, PDA, wireless laptop, video cameras, motion detectors and a home entertainment system including a television, VCR and DVD player.

We have envisioned both fixed and mobile sensor platforms connected to each other and to various computing platforms. Typical sensors include, but are not limited to, audio, video, thermal, optical, motion, pressure and infrared sensors. These devices can stream their data through wireless networks to computers, various hand-held devices and networked appliances. The system status will also be available through a home gateway that may be accessed remotely via the Word Wide Web. Once the sensor network is successfully completed, it will serve as a platform and test bed for further research programs in this area.

II. PROJECT OVERVIEW

It is no small matter of pride that in a short duration of time, a number of projects have been designed, implemented and successfully demonstrated before a large and diverse audience. The projects include a music-on-demand server available over the Internet, a sensor network with Web interface allowing remote control of the house and a wireless Personal Digital Assistant (PDA) allowing wireless Internet remote management.

The status and scope of the "Home of the 21st Century" project was presented at the Tech Expo 2001 on April 25, 2001 in the George Washington University, Virginia campus [3]. This was sponsored in part by America Online, Virginia's Center for Innovative Technology, The Washington Post and WashTech.com. The audience included leading experts and representatives of local high-technology companies, Guest Lecturers at the Expo, the press and media representatives, faculty members and GWU students.

A. Music on Demand

Imagine yourself sitting in your room and wishing that you could listen to a particular song that has been haunting your mind—you only need to speak your wish aloud and the music starts playing through your home entertainment system. Thanks to GWU's research, such a scenario is not limited to the imagination. We have developed a music server that enables users to listen to the music of their choice from any web-enabled appliance in the house.

We propose to upgrade this in the near future to allow provisions of video-on-demand, which is likely to become a universal application in the houses of the 21st century. Another area of research is to integrate the server with voice-activated commands to ease the use of the interface [4].

B. Sensors and Actuators

One of the most important goals of home automation is to control all home appliances remotely from a central controller [1]. Sensors are used to collect information (such as movement within a room) and the actuator carries out the corresponding action (such as switching on the light). Given the ubiquity of the Internet, it is logical to allow the management of appliances through the World Wide Web. This would enable an authorized user to check the status or change the controls from anywhere in the world. Moreover, with the gradual convergence of the Internet and mobile telephone technology, control of the home from a Web-enabled cellular telephone would appear quite imminent.

The Web interface that acts as the central controller has been written in Perl, and can run on any Windows-based Web server. Since the microbrowser on most WAP-enabled cellular phones support Perl, the controls can also be operated while on the move. No longer shall a vacation be ruined over whether the oven has been switched off!

Remote management of all the functions was also demonstrated through a Personal Digital Assistant (PDA). Authorized users could listen to any song in the music library, monitor the house via live video, and control all devices in the home from the wireless hand held device. Compaq's ipaq pocket PC (PDA), operating on Windows CE, was used to implement this part of the project. The PDA can be connected to the Internet using different techniques: local area network, IEEE 802.11b or a regular phone line.

C. Intelligent System

The ultimate dream of all science-fiction enthusiasts is a world customized to their preferences. While not yet in a position to change the world, our student researchers are exploring ways to implement such technology within a smaller framework—the Home of the 21st Century.

Picture yourself returning home after an exhausting day at work—as you seat yourself on the sofa, the lights dim themselves soothingly, the coffee-maker starts brewing your favorite blend of coffee and the home entertainment system softly plays *Eine kleine Nachtmusik* to comfort your frayed nerves. If you want to catch up on the latest sports news on television, just say the word—your wish is your house's command!

This no longer need be a work of fiction set many years in the future. Parts of this scenario, including voice-activated commands to control lights and the coffee-maker, have already been implemented and successfully demonstrated at the Tech Expo 2001. Work is now in progress on the identification and localization of the residents, so as to provide a more congenial and "homely" environment within the framework of the house according to individual tastes and preferences.

Several research centers have been working on the aspect of individual tracking within a closed environment. Different technologies may be employed to solve this problem, depending on the accuracy of the position that is desired. Currently we are considering the use of RFID (radio frequency identification) to identify the person at the entrance to the house, followed by a cellular distribution of ultra-sonic or infra-red motion sensors to locate the person within the house. Since RFID would require the person to carry a tag (an active tag, in particular, would help cut down on the size of the RFID reader), a breach of security can easily be spotted if a person without a valid tag attempts to enter the house. There is also a proposal to implement a pressure sensor network to locate residents [5]; while this would have a better resolution and hence provide more accurate localization results, cost considerations will govern which of the technologies will finally be approved.

III. IMPLEMENTATION

A. Network

Two separate networks have already been implemented. The first is the wired and wireless sensor network in which a cluster of switches, relays, RF transmitters, RF receivers, pressure sensors, and motion sensors are inter-networked. This network of sensors, actuators and switches are connected to a home server. This infrastructure enables authorized users to monitor and control almost every function in the house via an Internet browser. A Windows-based web interface program has been developed, employing the Perl programming language. This web-interface is currently the primary controller for the network. Users with access to the Internet can reach this web page and control several automated features of the laboratory, such as turning on and off of the appliances and light, dimming lights, controlling the cameras etc.

The second network is a music server that enables users to listen to the music of their choice from any web-enabled device. A music server has also been installed with the necessary software and a digital audio library of four hundred songs built. Any of the stored songs from the play list can be selected employing any Internet browser and from anywhere in the world. Fig. 2 shows the current network architecture that has been implemented on the project. The implementation of the sensor network, the music server and the primary controller will be discussed in detail in a later section.

1) Sensor Layout

Fig. 3 shows the layout of the Home of the 21st Century laboratory. The laboratory is divided into offices, living room, kitchen and meeting area. The laboratory has four offices. The offices are labeled as Office 1, Office 2, Office 3 and Office 4 on the layout. The electrical devices in the office get their power through home appliance switches. The switches are designated as B1 - B4 on the layout. These appliance switches are connected to the power line and the dashed line in Fig. 3 represents that. The primary control is located in Office 4. For instance, when the central controller sends the information to turn off power in Office 2, the home appliance switch in Office 2 will receive this information and cut off power from all electrical devices in this office.

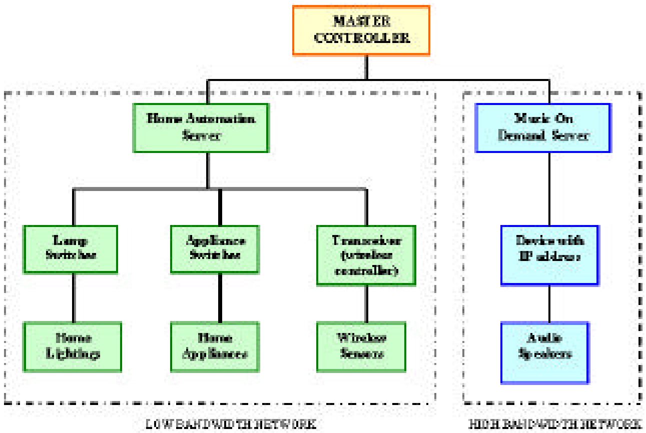

Fig. 2. Network Architecture

We are currently implementing the sensor network on the offices by employing wireless infra red motion sensors and pressure sensors. In addition we also have video sensors and wireless microphone.

Wireless motion sensors are used in the offices to detect motion. These motion sensors are designated as MS1 - MS4 in Fig. 3. Whenever the sensors detect some motion, the information will be sent to the transceiver using HomeRF technology. This transceiver (designated as TR1 and located in office 4) receives the signal and sends it to the central controller for further processing.

2) Living Room
The living room is a very important part of any home since the home entertainment system is usually located there and consequently, people spend most of their leisure time there. We are in the process of installing a network of sensors in the room in order to identify and locate people. Once this task is completed, the home entertainment center will automatically be configured for personal taste. So far, our network of sensors and actuators can control the switching and dimming of lighting, turning on and off the entertainment center, controlling the volume and switching channels of the television. Currently we are developing a system to fully control all the functions of the entertainment system and develop a user-friendly web interface. The commands can be initiated from any web enabled device connected to the Internet. These commands are transmitted to the serial port of the home server to be converted to a wired communication protocol such as x-10 [6] and transmitted through the home power line. A device connected to the home power line converts this signals to infra red in order to control the home entertainment center.

3) Kitchen
At present, we are capable of controlling any device in the kitchen by turning it on and off from any web enable devices. Our plan for the kitchen is to utilize network ready home appliances and incorporate them to our network to fully utilize their capabilities of a network-enabled kitchen. Home appliance switches and lamp

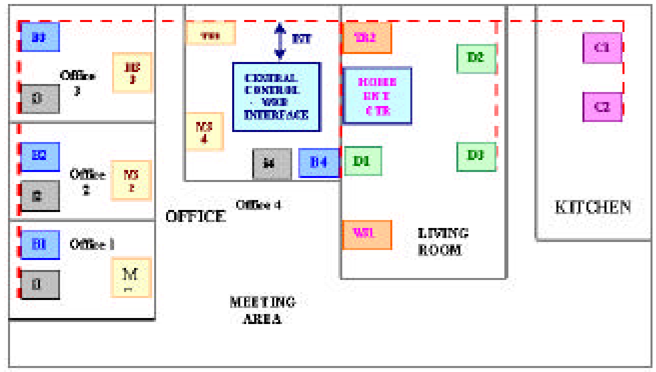

Fig. 3. Sensor Layout

switches are used in the kitchen. The lamp switch (designated as C1 in Fig. 3) is used to control the kitchen lights. The home appliance switch (C2 in Fig. 3) is used to control the coffee maker.

B. Music on Demand Server

The goal of this task is to develop a music server that enables users to listen to the music of their choice from any web-enabled appliance in the house. In the initial phase of this project we have developed the music server, installed the necessary software and built a digital audio library of four hundred songs. The current music server is Unix based; however, the developed software can run on virtually any machine. In the near future, the system will be configured and upgraded such that audio and video can be viewed from any Internet ready device [7]. The music on demand system functions as follows.

1) Operational Overview
Fig. 4 shows the flow-chart of the program. In the start-up phase, the program reads its configuration file and then checks to see if there is already a playlist that is selected. If there is no currently selected playlist or the playlist contains less than 32 songs the server builds a new playlist that consists of all of the available songs in its songs directory. This ensures that any playlist has sufficient variety of songs.

In the next phase, the server selects a song at random from its current playlist. If the selected song is among the last 30 played, it is discarded and another song is selected. This process continues until the program finds a song that is not among the last 30 played. Once the server has found such a song, it updates its database file, where it maintains the last 30 songs played, the currently active playlist, and stored playlists. The program then updates its history file, where it maintains a complete history of all songs that it has played, and how many times. Once the database is updated, the program proceeds to play the song.

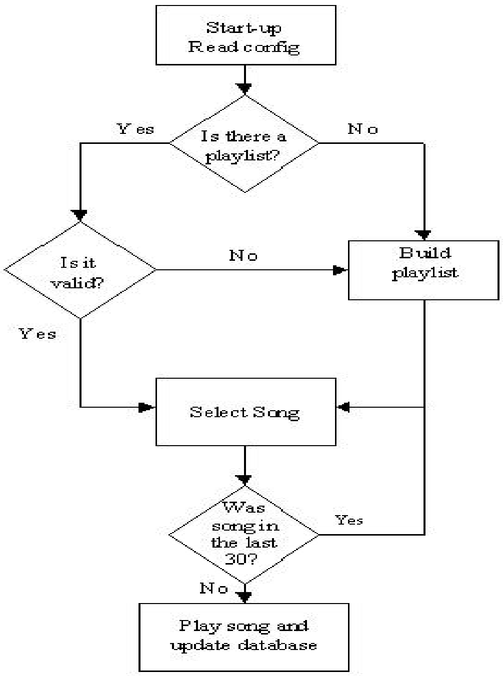

Fig. 4. Flow chart showing operation of the program for the music on demand system.

An external program forked as a child process of the main program handles actual playback of the .mp3 file. The system currently uses the open-source mpg123 program for the reason that it can be run in multiple instances with its output directed to different audio devices, enabling the playback of multiple streams simultaneously

2) Web User Interface
The user interface to the music on demand system is a web interface. The user views a status page that shows the current song that is being played, the last thirty songs that were played, and the next song to be played. This status page is generated dynamically by the program and is updated at the end of each song. The program reads the filename of the song being played, along with the filenames of the last 30 songs that have been played from the status database. It then extracts the ID3 tags (embedded information in any MP3 file that contains detailed information) from those files to generate the data for title, artist, and album information.

A user can generate a playlist by using the custom playlist page. Playlists are stored in the status database as key-value pairs with the value being a list of filenames that comprise the list. The name of the active play-list is stored in a second key-value pair, enabling multiple lists to be stored, edited, accessed and activated independently.

The user can listen to additional songs that are not in the current playlist from a request page. The request page is generated by obtaining a list of all available songs in the songs directory and then extracting the ID3 information from the files. The hyperlinks for making requests are keyed to the filenames. If invalid information is passed to the request handler, it will simply return an error message. Multiple requests for the same file will increase its priority, but requests are subject to the same "not in the last 30" restriction used for playing all songs. The names of the requested songs and the number of votes each song has are kept in the status database. This database is updated after each request in the order of number of requests for each song. Since the list of songs is read from the files in the song directory rather than from the playlist, as soon as a new song is added to the directory, it is instantly available for requests.

3) Playlist Configuration Changes
The users can change the playlist at any given time. In this case, the system will send a hangup (HUP) signal. Since the program which controls the songs is multithreaded, and implements POSIX signal trapping, sending the running program a hangup (HUP) signal causes it to re-read its configuration files and change its running configuration on the fly without interrupting playback of the current song.

4) System Load and Distribution Capability
One complete instance of the music program results in a load increase of approximately 0.07 on the Unix machine running the program. This means that a single machine of the type we are using in the project can support up to 14 simultaneous streams (14 separate instances of the program). This number is probably a low estimate given that all web requests can be handled by a single instance of the web server, so the load placed on the machine by the web server does not need to be factored into the overall performance impact of additional instances.

Distribution of the audio streams is dependent on routing the sound output from the computer through a switching mechanism (there are several commercial solutions currently available) that is capable of routing any individual audio signal to any of the zones in which it controls the speakers. Once these switching mechanisms are in place, different playlists will be played at different zones depending on the location and identity of people in different zones in the house. This feature will be implemented as soon as the localization and identification sensor network is completed.

C. Control with a Personal Digital Assistant (PDA)

For any kind of remote management, access to the Internet is a key component. The goal of this project is to access and control all of the laboratory features remotely from anywhere in the world. This gives the authorized users the ability to listen to any song in the music library, to monitor the house via live video, and control all devices in the home from any devices that is connected to the internet. In order to accomplish this, we have developed and implemented a web-based interface and utilized a PDA to wirelessly connect to the Internet. During the first phase of the project, wireless control of many automated features was demonstrated. This included turning lights on and off, dimming lights, turning on speakers, monitors, etc. Furthermore, live dynamic images were monitored on the PDA, in both wireless and wired connected configurations [3]. A web interface has been chosen as the primary controller and has been written in PERL. The program runs on an Apache web server.

PDAs are becoming more and more popular by the day and as the prices of these devices get lower there will be more of them in use. They are small, mobile, have a long battery life (9 hours), and possess adequate processing power for common purposes. Therefore, it is an ideal platform to build the primary controller interface for the project. For this project we selected the Compaq ipaq Pocket PC that runs on Windows CE and the pocket Internet Explorer (IE) for CE. Therefore, anyone who is capable of operating Windows is capable of operating the PDA.

There are different methods of connecting the PDA to the Internet. For this project we have employed a modem on a telephone line, 802.11b local area network (LAN) and mobile phones. The connection wizard is capable of connecting to any ISP with the same setting as a standard PC. In addition, due to the large demands on communication bandwidth of video streaming, we used a Citrix Client on the PDA to enhance our demonstration. The advantages of the client are:

- it is faster over a 56Kbps modem because it does not use IP;
- it does all of its computing on the remote site (uses small amount of processor resources);
- it mimics all of the programs that are available on the remote site and thus gets rid of the restrictions that are put on the Pocket PC software (for instance, IE on a Citrix Client is fully functional);
- it supports streaming video.

IV. FUTURE WORK

We see the above work as only the beginning of a long-term research collaboration with AOL, CIT and other potential partners on various Home of the 21st Century applications. The wireless sensor network currently being built is an essential platform to base future research projects in this area. Topics that promise to further challenge our student researchers and improve the quality of living in the home will be taken up in a phased manner. These include the integration of wireless broadband entertainment services into the home network (such as WVoD or Wireless Video on Demand) and continuous improvement in network bandwidth and speed based on state-of-the-art network architectures. Moreover, while we have implemented some degree of voice recognition, at this moment it is not an intrinsic part of the infrastructure. Therefore, further development is required for a better integration of voice recognition, command and control into the network. Upon the completion of this, we would like to train the algorithm to recognize a broader variety of speakers [4].

As already discussed, we are interested in automatic personal identification (and hence, customization) and localization using multi-modal sensors, such as video, audio, motion, optical, infrared, ultra-sonic, pressure, as well as the use of active and passive tags that improve accuracy without being obtrusive. Other research topics under consideration include the implementation of multiple pico-networks to increase the size and range of the home network and an optimization of the wireless network, addressing issues such as bandwidth utilization and quality of service.

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