A Smart House As Experimental Laboratory For Innovative Environmental Technologies

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INTRODUCTION

The optimized management of energy use remains a central challenge, and is becoming incipient in the current integration of various control and (tele) communication systems in order to assist the building's dynamic and independent fine tuning of thermal comfort.

A group of faculty[1] from the Colleges of Computing and Architecture at Georgia Tech came together to start the planning for the oncampus design and construction of an experimental smart house with fully integrated intelligent systems. In this long term effort, we identified two broad areas of investigation. The objective of the computer science faculty was to provide telecommunication systems for data, audio and video image to monitor the various tasks taking place in and around the building in order to test and evaluate the way these smart technologies influence human performance. The objective of the architecture faculty was twofold: 1) to explore the thermal and daylighting behavior of the smart facade, and 2) to seek the application of these telecommunication systems to remotely monitor and control the building energy consumption via the World-wide Web. With the anticipated participation of the industrial, commercial and governmental sectors in this long term project, the task is to develop proper design practices for the home of the future.

In the collaborative work between faculty from the two colleges to develop the schematic design for this new building, the *total smart house concept* was advanced as the driving force for rethinking the proper design of the future home. Issues of energy efficiency and sustainability became intrinsic to the design challenge. Hence, in this combined effort, the research group at the College of Computing will be involved in the activity to understand and design systems which use intelligence to interact with the house and the world, and in making computer controlled systems more autonomous and ubiquitous. At a time when every home device is equipped with a microprocessor, the expectations that these intelligent systems perceive our needs, anticipate our actions, and learn our habits constitute the research paradigm pursued at the College of Computing.[2]

Research at the College of Architecture will focus on identifying building design practices that properly use intelligence to reduce energy consumption, coupled with a constant monitoring of the users' interface. While these control logic systems are expected to enhance fire safety, security and the automated planning of home activities, the house smartness may remain incomplete if the capability to continuously audit the building at every level is not incorporated, in order to detect and correct potential energy wastes. Consequently, the set of built algorithms must also make the intelligence vested into the building capable of evaluating the influence of each automated action on energy consumption through the building-wide control system. Hence, this laboratory house also presents the opportunity to evaluate how principles of synchronization and interchangeability between various building energy systems may help achieve optimization in energy use. Among the many energy efficient features introduced into this building, the interactive relationship between the HVAC equipment and the building enclosure system to control the dynamic weather variations is presented as the initial domain of investigation. In connection with that, the other identified area of study concerns the ubiquitous sensing devices and their remote control via the web and will be described towards the end of this paper.

DESIGN AND CONSTRUCTION OF THE EXPERIMENTAL HOUSE

The house (see fig 1) comprises two stories and a basement, with the two upper levels made identical for research comparisons. Each of these two stories (see fig. 2a) consists of a master bedroom of 22 m^2 (app. 240 square feet) with bathroom and closet, two bedrooms of 16 m^2 (approximately 180 square feet) each, with shared bathroom. A greatroom of 46 m^2 (approximately 500 square feet) is extended by a kitchen fitted with counter top, track lighting and dimmers. The total floor level area is approximately 186 m2 (approximately 2,000 square feet). The basement will contain a utility room, a laundry room, a home theater and a two-car garage. The 38 m^2 (aproximately 400 square feet) home theater can seat 10 people in either a theater or conference room arrangement, and is purveyed with a rear projection system (see fig. 2b). The basement

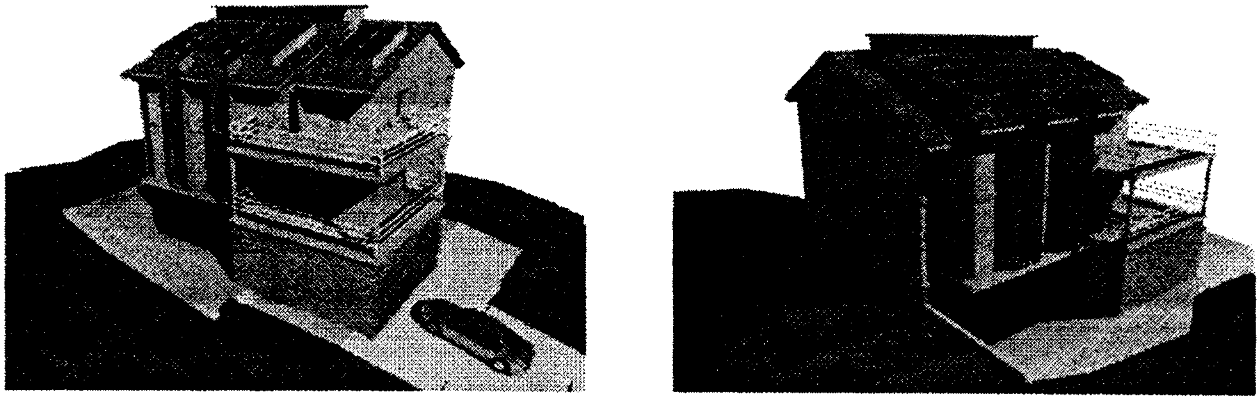

Fig. 1: Smart House Views, (a) east-south sides, (b) south-west sides

also includes a computer room which will hold 10 computers with monitors and 50 others without monitors, as well as the building central control system.

In addition, each of the greatrooms will contain about 20 computers without monitors, and is expected to accommodate 20 people. A deck, located at the south-east corner of the house, extends at each of the two upper floors.

Each room is fitted with in-wall speakers and audio cables originating from the central control system. The room layout provides arrangement for a touch panel and LCD display. In addition, a security system is installed to detect and act on the closing/opening of all exterior and interior doors as well as windows, with motion sensors mounted in each room. The driveway incorporates vehicle sensors, and the house surroundings including the deck are provided with weatherproof power, audio and video cables for the video cameras and the intercom system.

Each closet is fitted with electrical and data outlets and is acoustically insulated to reduce computer fan noise transmitted to the bedroom. All the wiring is run along accessible horizontal chases which are located above the corridor of each floor. These chases are connected to another vertical shaft starting at the utility room. The horizontal chase dimensions are 3 feet wide by 4 feet high, to allow reconnection and rerouting of wires. Each horizontal chase contains stacked trays for wire support. The vertical shafts are of similar sectional dimensions. The main shaft starting at the utility room connects upward to each of the three horizontal chases see fig. 3b) Finally, another shaft located near the kitchen runs through the two upper stories to bring the various communication and data lines to the kitchens and the greatrooms.

DESIGN OF SMART HOUSE ENERGY COMPONENTS

The building envelope is built of 8" Hebel block which has excellent insulating characteristics when the thermal storage effect is taken into consideration. This material also helps also diminish the use of metal in the house, and reduce signal interferences. The roof is built of a wood frame combined with insulation to obtain an R-value not less than 38, with a weather station mounted on top to monitor the climatic parameters. The south side partially incorporates a double-envelope system running from first floor to roof (two 8-foot wide bays).

The outer layer is made entirely of 1/2 inch low-e glass and runs up the full two upper stories and the roof (see fig. 1a, 1b) of the house. In addition, electronically controlled ventilation dampers are incorporated at the top, middle and bottom of the outer layer for ventilation purpose (see fig. 4.) The inner layer is constituted of a spandrel (3.5 feet high) and a strip window. The window at the inner skin of the building, also of .5-inch low-e glass, is operable to permit direct ventilation. The gap width between the two layers is 2 feet wide. Electronically operated, 6-inch wide airfoil louvers are installed inside the gap at three inches away from the inner layer, and braced throughout the cavity height. The inner layer also includes dampers, connected to a duct with a low velocity fan to bring hot or cold air deep into the building. This building envelope sensors and actuators are directly linked to the building's automation system. The two 8-foot wide double envelope bays occupy only part of the south side, and are built to allow easy dismounting in order to test various types

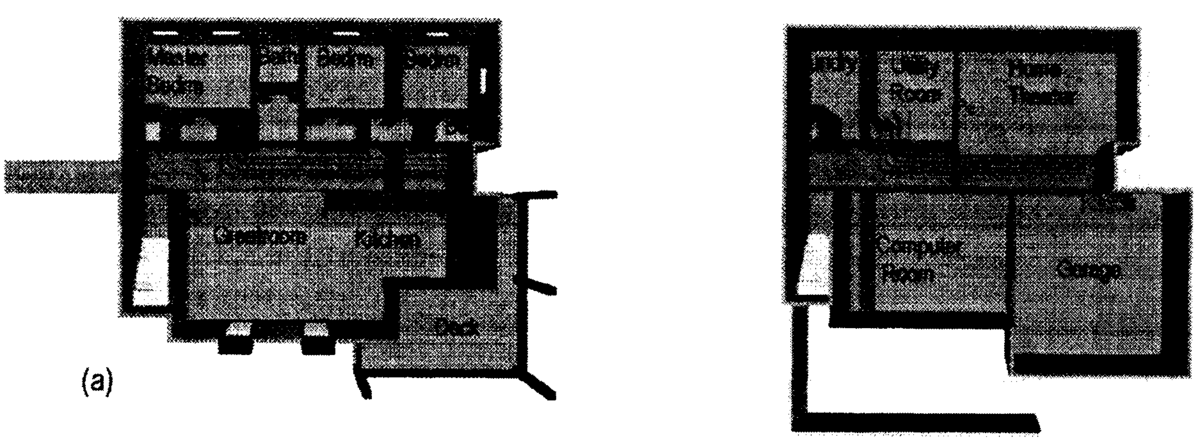

Fig. 2: (a) typical first and second floors, (b) basement

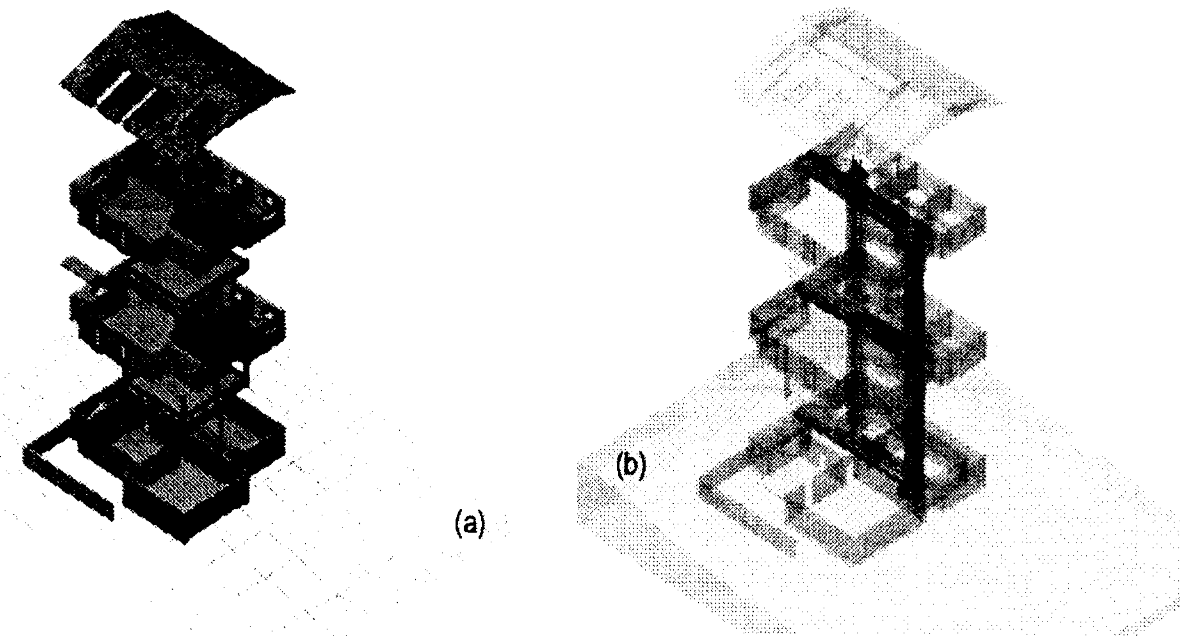

Fig. 3: (a) Exploded view of house and (b) core chases and shafts for wiring

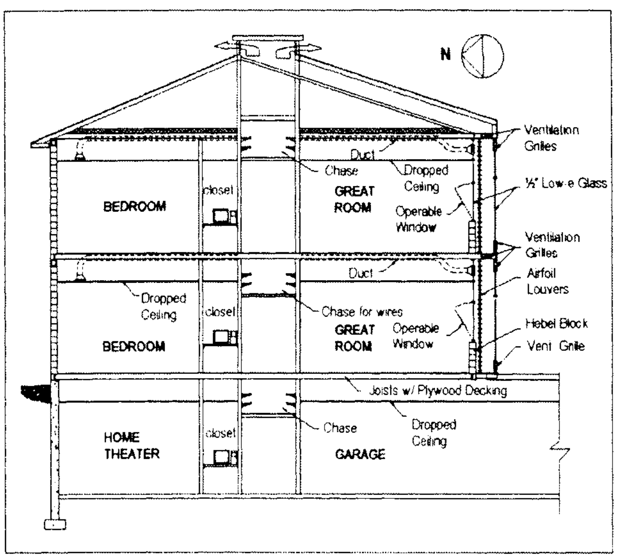

Fig. 4: North-south section through double envelope

of smart facades. Aside from the glazed double envelopes, all other window openings are sized not to exceed 25 percent of the floor area. All windows are built of low-e squared glass.

A motorized flexible ceiling grid is installed to allow either the concealment or exposure of various types of lighting fixtures and their related dimming systems. This setting will permit the comparison between various lighting systems applied to various tasks. All general lighting fixtures are fitted with T32 fluorescent lamps and electronic ballasts. All task lighting fixtures are also fitted with CFL lamps. These fixtures are also connected to the building automation system. This setting allows research into the interactive relationship between daylight and artificial light for potential energy savings.

Finally, in the consideration of an adequate HVAC system, the closed loop geothermal heat pump was the preferred equipment. The run around water loop permits each zone or room to have its own thermostat and control. Each room has then independent control of heating, cooling, and ventilation, with computer controlled dampers and registers. A feed register and return is installed in each room, including closets. The closed loop system permits greater flexibility and minimizes the need for ductwork, which is particularly important if some areas require ventilation and others cooling. A close combustion high efficiency boiler is assigned for water heating, and a variable speed high efficiency Air Conditioner is used for cooling the water.

Areas that contain computers—greatroom and computer room in basement—have economizers as part of the air handling unit. All closets are conditioned to handle the equivalent load generated by two computers without monitors. All parts of the mechanical system are monitored by a central computer. The computer has the capability to control thermostats and economizers, but can be overruled by local controls. The central computer has a display, featuring built blueprints and engineering drawings, to indicate the current conditions prevailing in each room or to display the history of temperature and humidity for each of these locations. To enhance building independence in energy consumption, a system of photovoltaic panels is attached to the south facing slope of the roof (see fig. 1.) The possibility currently under consideration is the installment of an ice storage system.

WEB ENABLED BUILDING CONTROL

One of the novel "smart technologies" in the house concerns the ways that users (occupants and technical services operators) communicate with the environmental components. The basic assumption is that all components of the environmental building system will be LAN wired such that access to these components will be available from every desktop with Web access to the Intranet and a browser. This will offer the variety of controls (e.g. HVAC settings, solar shadings, thermostats, vents, window control, lighting, ...) to all users with Internet access, inside or outside the building (assuming external access to the Intranet is granted to privileged users), as shown in figure 5. A brief explanation of the underlying technology is given below.

Each controllable device in the environmental building system

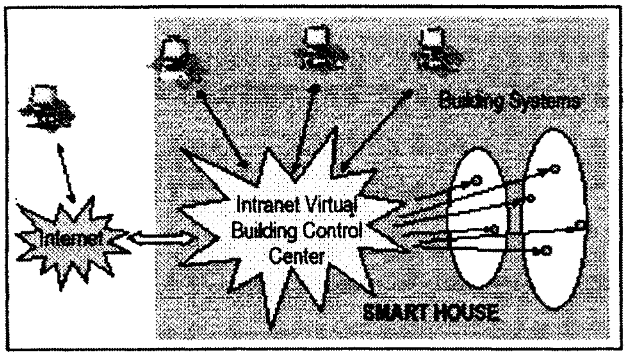

Fig. 5: Smart House with Intra/Internet accessible system devices.

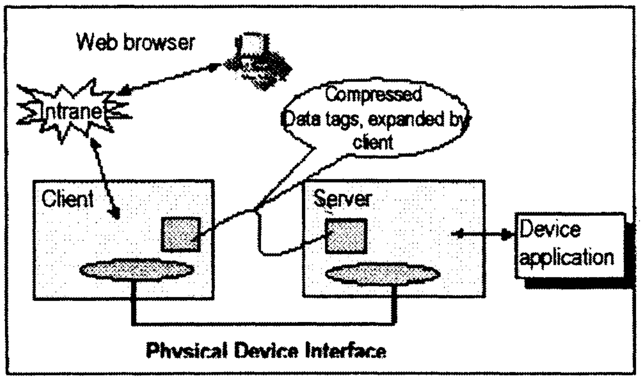

Fig. 6: Embedded device with browser access through client.

will be equipped with a server component addressable over the Web. Device manufacturers have thus far been kept from enabling this because of high costs of controller devices that offer this capability. The device functions (the web server side) could not be stored in average low-cost micro-controller hardware with 4 kB ROM and 100 bytes RAM. The breakthrough is now offered by a "skinny server/fat client" design, which has entered the market recently.[3] The basic idea is to use compacted device tags and event messages passed to the client. Figure 6 shows the basic architecture.

Apart from the controllers/actuators in the environmental system, sensors will be dispersed throughout the building during construction to enable monitoring and input data gathering for model based control. The wiring of these sensors is integrated in the fabric of the external and internal building enclosure systems. Occupants and facility managers will be enabled to monitor and control with certain permissions the system manually. Future stages of the research project will target the definition of control functions that can be fired as JAVA applets to poll sensors for measured data, and issue instructions to control devices based on real time model of control strategies. The challenge of this part of the project is to show that ubiquitous (Web) access and decreased costs of adding Web server functionality to control devices renders the use of this technology a viable proposition for application in larger scale buildings. Return on investment is expected to come from:

- Avoiding the need for a physical central HVAC control station and replace it by a virtual one;
- Saving in wiring, building space, training, manuals, etc. because "it is all on the Web;"
- Integrating building energy management systems in easy to maintain desktop applications.

The ongoing research focuses on: 1) the collaboration with manufacturers in the development of control devices with web server capabilities; 2) testing prototypes in the smart house project; and 3) developing the Web interfaces and client/server software to communicate with the devices.

SIMULATION AND CONTROL

The behavior of a building results from a complex interaction of its passive and active systems, in changing external and internal input conditions and controls actions generated by the autonomous agents of the control system or by non deterministic user interactions with the system. In the first stages of the project, we are concentrating on the thermal behavior of the building in order to define adequate control for energy consumption and maximizing thermal comfort for the occupants.

The study is carried out with a simulation toolbox which was specifically developed to simulate the complex interrelations and control aspects of interacting building systems.[4] The basic simulation engine of the toolbox is based on a discretization of the mathematical physical description for each component. The discretization is based on a particular approximation technique called the finite element method. The system equations are discretized in the space coordinates, leading to a set of ordinary differential equations, which can consequently be solved through numerical time integration. Each component is dealt with as a separate entity (which can be an assembly of other components) that is represented by a set of differential/algebraic equations (DAE).

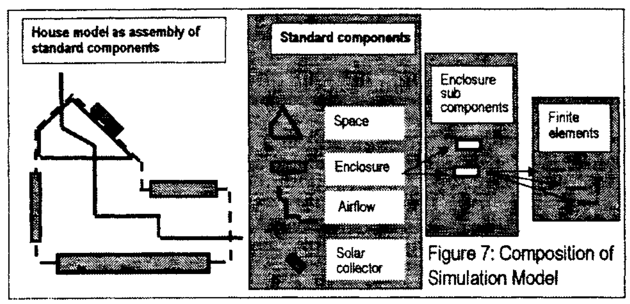

Figure 7: Composition of Simulation Model

Fig. 7

On the lowest atomic level, each component is a finite element that represents the discretized version of the field equation (e.g. heat conduction or mass flow). All interactions between systems are represented as components as well, thus enabling a fully transparent definition of the system as an assembly of components (of either type.)[5] Figure 7 shows the basic idea. All components are treated alike by the system, and assembled in the global system of matrices with the state vector x as the unknown:

$$d\,x/dt = A(x,t).\,x + b\,(t) + B(t)\,u.(x,t)$$

With initial state at $t = 0$ *given:* $x\,(t=0) = x0$

"a" represents the system matrix for the discretized field equations in each component and the lumped inter component interactions, such as long wave radiation exchange between enclosure components, convection heat transfer between room air components and enclosures, and mass flows between room components. "b" is the load vector, whereas "u" represents the control vector. The components of u represent the control variables whereas "b" states the effect of each parameter in the system equations. "u" is assumed to be the result of an external user action (in this case usually a set of rules representing a user response to a certain state) or the result of a computational module that determines an optimal choice of "u," based on a suitable optimization criterion. The control vector "u" represents the control actions activated by the system itself (through a deterministic control rule or procedure) or through human intervention. This set of algebraic differential equations is solved by a suitable DAE solver. The toolbox used in this study offers a variety of robust solvers based on the Runge-Kutta Chebyshev time integrator. The implicit part of the DAE system is computed at each time step using an iterative method.

The observable part of the system state is represented in y which is linked to x by an observation matrix C:

$y = [C]\, u$

The monitoring matrix C translates sensor output (system state information) to an observed state y for human consumption. Typically the user access to the system will show y and u, and the user will have access to change certain components of u within certain ranges.

Based on the global system equations, the following components will be developed:

- Identification of the minimal set of suitable control parameters and the way the user should be given access to them, i.e., based on what subset of the observable state vector and based on what feedback to the user.
- Stability and sensitivity tests of the system aimed at studying the response of the system to user interactions. This will most likely lead to restrictions of the allowed user interactions and the frequency with which they may occur.
- Design of the most suitable control strategies of the system, i.e., in what way the occupant will be given the opportunity to select a model-based control strategy and override parameters of that strategy.

One of the priorities of the ongoing research is to identify controllability range of the system in a given configuration of building systems with device controls. The challenge is to embody the system model in a Web-based "control center" that, based on predictive state simulations, gives advice to the user, whether the system is in near optimal state or needs adjustments.

RESEARCH PHASES

The research agenda will evolve through the following phases, as indicated below.

Phase I: Optimum design and construction of the smart house based on the baseline technologies in (1) energy saving building components, (2) smart building systems, and (3) Web-based access and control.

Phase II: Development of the simulation model that is designed to evaluate the building behavior under different operation modes, calibrate physical variables in component models, and determine optimal control strategies.

Phase III: As new components are being developed or proposed, they will first be studied in small scale test set-ups to determine adequate simulation models for them. The next stage is then to integrate these models in the whole building simulation to investigate their efficiency and controllability characteristics as part of the whole system.

Phase IV: The final stage will be the actual in-situ deployment of the new component in the smart house experimental laboratory. In all of the above studies,

Web access for monitoring and remote control of building systems is concurrently developed throughout all these phases.

FUTURE WORK AND CONCLUSION

The research agenda introduced above will be used to integrate the active building systems into the design of the smart house and prepare the wiring and implementation on-site. The control strategies and user interfaces to it will be developed and implemented in a virtual environmental control center.

The major post delivery follow-ups concern:

- Proliferating the technology for managing building system devices with the Web.
- Monitoring system behavior and registering the way that the users interact with the system. This registration is accomplished through a variety of presence and activity detection and automatic user identification enabled by advanced telecom technology, an elaboration of these aspects is outside the scope of this paper.
- In situ optimization of the system based on the feedback

A major follow-up will be to study the deployment of this technology in other climate zones, where other construction technologies, other system components and other control strategies will be used. The smart house prototype is expected to provide an important benchmark for the combination of telecommunication technology with smart components in the wired energy conscious building. The simulation and optimization of the building control system vis-a-vis user interactions poses interesting challenges on the design of the control algorithms, and the development of adequate user-system interaction capabilities.

ENDNOTES

[1] Professors Godfried Augenbroe, Chuck Eastman, Tahar Messadi are affiliated to the College of Architecture and Professors Gregory Abowd, Chris Atkeson, Irfan Essa to the College of Computing, Georgia Tech.

[2] Chris Atkeson, Assistant Professor, College of Computing, Georgia Tech, Atlanta, Georgia.

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