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### A Review of Smart Environments for Energy Savings

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#### Abstract

In this paper, we present different papers discussing smart environments for energy savings. Such systems consist of sensors embedded in an environment that allow a control system to perceive its current state. The control system can save energy by turning off devices or put them in a low-power state when they are not in use. The projects discussed in these papers use several different methods for implementing smart environments. We present the approaches used, their advantages and disadvantage, and discuss future challenges in this field.

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#### 1. Introduction

The topic of smart environments, also called ambient intelligence, has been gaining interest recently. The term ambient intelligence refers to the embedding of sensors and actuators within a room or environment that react automatically to the users within that environment. The sensors are hidden from the user so they become part of the environment and should not require the user to explicitly interact with the devices. These sensors could be in the form of thermometers, microphones, cameras, motion sensors, or any device that can provide information to an automated control system regarding the state of the environment.

The control system can then use actuators to alter the conditions in the environment. These actuators could be a furnace or air conditioner to control the temperature, the lights or curtains within a room to control the lighting, etc. The ability of the environment to perceive and react to changes gives the home or office a sort of ambient intelligence.

The recent interest in smart environments can be attributed to several factors. The first is the availability of small and inexpensive network-aware sensors and devices that can be easily embedded in the

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environment. Second is the growing availability of networking technologies in home, such as Wi-Fi [1], Bluetooth [2], and power line Ethernet [3] that allow these devices to communicate. Third is the availability of small computing devices available in homes such as smartphones, tablets and netbooks. This availability of processors and network communication makes it easy to develop and install the infrastructure needed for smart environments.

In Canada, households use energy primarily for space and water heating, space cooling, the operation of appliances and lighting. Among those activities, space heating consumes the most energy in the residential sector according with survey carried out by the Canadian government [6]. According to a recent survey conducted by Natural Resources Canada, the residential sector accounts for about 17% of the national energy consumption.

According to a recent study [7], 20% of energy used within the home is for space heating, 14% is used for lighting, 10% is used for space cooling and water heating uses 8.6%. These 4 factors make up 52.6% of the total energy usage in the home, so it is a good start to focus our energy saving efforts on heating, cooling and lighting. This same study also predicts that there will be a 33% increase in electricity usage between 2006 and 2030.

The rest of the paper is structured as follows: section 2 gives a brief introduction to artificial intelligence used to control a smart environment. This is followed by an overview of papers in section 3 presenting several research projects which have implemented an environment control system, with a focus on the approaches presented in different papers, what advantages they present as well as their weaknesses. In section 4, we present different methodologies for evaluating the performance or effectiveness of different approaches, followed by a brief review discussion in section 5.

## **2. Approaches for Energy Savings in Smart Environments**

There are several approaches to using ambient intelligence for energy reduction. The first rudimentary controllers use rule-based approach that must be programmed by the user. For example, most thermostats can have their temperature settings programmed based on the time of day with the aim of reducing the temperature while the occupant is away from the house. Another example is motion detectors that can turn on lights when they detect the inhabitant's presence.

This is a first step towards energy savings, however these devices only sense one dimension (temperature, motion) of the environment and are not truly intelligent. They do not make decisions on their own but rather just react based on the rules with which they have been programmed.

In order to have a system that truly makes decisions on its own, it needs some sort of artificial intelligence that is capable of deductive reasoning and adaptation. To the best of our knowledge, the approaches used in smart environments include fuzzy logic, neural networks and software agents.

Fuzzy logic is a form of logic that is based on approximate values ranging from 0 to 1, as opposed to traditional Boolean logic, which strictly uses 0 or 1 for inputs. Fuzzy logic is best suited for situations where the input values are approximate, instead of precisely measured. Input values are measured by their inclusion in fuzzy sets, and the fuzzy controller then takes action based on these inclusion values. For example, a temperature can be classified as being a member of the set of cold, warm, or hot. The smart environment can then make decisions such as if the temperature is cold, then turn on the heat. If the temperature is hot then turn on the air conditioner, and if the temperature is just warm then do nothing.

Artificial neural networks (ANN) try to model the neural processing of the brain, by mapping input parameters to one or more outputs. Neural networks typically have to be trained to produce the desired outputs, which can take a long time. There is also no specific rule for how to design a neural network for a specific application, so their design can be more of a trial and error process to get the inputs to map correctly to a desired output. Artificial neural networks are considered more of a "black box" system where the inner workings are not precisely defined, but work well in applications where it is known that a given input should produce a certain output, but it is not known exactly how that happens. The ANN just "learns" that it is the correct output from an initial learning phase.

Software agents are software components that act on the behalf of something or someone else. They have the capability to perceive its environment and take actions to maximize its chances of success. Typically, different agents interact with each other through some negotiation process, or auction, in order to achieve a desired outcome. This process ensures that a particular goal is met, while minimizing some cost or weight associated with that goal. In the context of smart environments, each user in the environment has a comfort agent, which is responsible for providing the environmental settings that are most comfortable to the user. Each room of the house each has an agent responsible for minimizing the energy usage of that room. The negotiation process between these different agents results in a smart environment that minimizes energy while providing a comfortable environment to the user.

### **3. State of the Art in Artificial Intelligence Control in Energy Management Systems for Homes and Small Offices.**

In this section, we present different projects and control systems in the area of smart environments for energy reductions. While this paper covers most projects that are presented in literature, it is possible that some other papers are not mentioned.

#### **3.1 Fuzzy Logic Control**

##### *3.1.1 iDorm*

The iDorm project at the University of Essex [8][9] is a research project that uses fuzzy logic controllers to control a typical dorm room. Their research focuses being able to quickly learn the user's preferences and generating and storing rules on how to reach those settings. This includes the temperature that is most comfortable, the lighting levels desired in the room, etc. The system's rules database also contains pre-programmed behaviours to save energy when the room is unoccupied. In this case, the temperature and lighting levels are set to some pre-set minimum level, which can be adjusted. The system can then restore these levels when the user returns to the room. The iDorm system is controlled by a Compaq iPAQ wireless device. The user can adjust settings in the environment, and thereby enforce the desired comfort settings. To test their system, they had a test subject live in the room for 5 days, and measured how well the system learned the subject's comfort settings. Their results show that their system was able to generate rules which met the subject's preferences within the first 3 days, after which the generation of new rules diminished considerably as most behaviours of the subject were already captured by the system.

This project is a good demonstration of what is possible in smart environments. However, they do not present and results on how much energy was saved.

#### **3.2 Neural Networks**

##### *3.2.1 Neural Network House*

The Neural Network House [10][11] is a project at the University of Colorado at Boulder is a project that uses a neural network for control of a house in order to reduce the energy consumption. They named their system Adaptive Control of Home Environments (ACHE). It has two objectives: to anticipate the inhabitant's needs, and energy conservation.

ACHE uses a neural network to infer usage patterns of the inhabitants. It learns the user's comfort settings by observing when the user must manually adjust the environmental settings. That serves as an indication that the user's needs have not been met and the system learns the new settings.

For energy conservation, when the user is not present, the lights are maintained at the minimum intensity required. The hot water tank is maintained at the minimum temperature needed to satisfy the projected demand. ACHE also occasionally tests the occupant by lowering the energy required, such as lower the temperature or lighting levels and to see if the user notices. If not, then the neural network can use the new settings in order to use less energy.

This project is one of the few in this survey that has actually built a working system. They renovated an old school house that was built in 1905, and installed different types of sensors. However, they did not

present any results showing the energy savings that are possible with such a system. Also, the comfort settings are specific to the house, and cannot be attributed to individual users.

### 3.2.2 Ministry of Education, Nequén, Argentina

Another project that uses a neural network is from the Buenos Aires Institute of Technology, and Comahue University in Argentina [12]. Their goal is to meet the users' comfort settings while using the minimum amount of energy. The building's inhabitants can adjust the temperature and humidity settings using input panels located in different rooms throughout the building.

They reduce energy by trying to apply different pre-defined energy saving rules. If a rule exists for conserving energy, then the system determines the impact that the rule will have on the comfort settings of the user. If it is not affected, then the rule is applied. However, if the environment will be changed so that it is no longer within the user's comfort settings, then the rule is not applied.

They implemented their system in a building of the Ministry of Education in the city of Nequén, Argentina. They conducted a survey on satisfaction in the system meeting their comfort settings and claim that 75% of users were very satisfied, 20% satisfied and 5% not satisfied.

This system uses a central computer for computing comfort values so those settings are only applicable to that environment which is controlled by the system. There is also no mention about storing individual user's comfort settings, and how to track them in the environment. They also do not mention how much energy is saved by this system.

## 3.3 Software Agents

The following section presents different research projects that use software agent for controlling smart environments. They are presented in no particular order.

### 3.3.1 ISES, University of Karlskrona/Ronneby and Stockholm University

The ISES project (Information / Society / Energy / System) [13][14] at the University of Karlskrona/Ronneby in Sweden. The goal of their project is to reduce energy usage while maintaining the comfort settings of the inhabitants. Their system has 3 types of agents: Personal Comfort agents, Room agents and Environmental Parameter agents.

Personal Comfort agents are responsible for capturing a person's comfort preferences. The room agents are responsible for reducing energy within each room of the environment. The environmental parameter agents monitor and control a particular aspect of the environment, such as light levels, temperature, etc. When a person enters a room, the room agent retrieves the comfort settings from the personal comfort agent, and then finds the environmental parameter agents, which can meet the comfort settings with the least amount of energy.

Their simulations show that their multi-agent system controller reduces energy consumption by 40%, while user satisfaction (or comfort satisfaction) is the same as keeping the temperature constant at the user's comfort level. This customer satisfaction measurement is calculated using a simple linear model, where 16° C corresponds to 0% satisfaction, and 22° C corresponds to 100%. Their calculation shows that the multi-agent system is able to correctly meet the user's comfort settings, in other words their environment is at the right temperature when they arrive instead of still warming up.

Their system has the advantage of storing the preferences of individual users. The system's architecture is also quite simple and easy to understand. However, they use computer simulations for testing their system, and their method of testing just uses a sliding scale to represent user satisfaction so their results do not reflect actual user tests.

### 3.3.2 MASBO

The University of Reading in the UK developed a software agent system called MASBO (Multi-Agent System for Building cOntrol) [15][16]. Their system uses agents to control the HVAC (Heating, Ventilation, Air Conditioning) system of a house. Their work builds on the ISES system architecture,

mentioned in section 3.3.1. It uses several different types of agents, each responsible for a different aspect of the environment.

The Local Agent is responsible for monitoring a given room. It acts as a mediator between competing user's preferences and provides information about the room to the user.

There is a Monitor & Control Agent for setting the environment according Local Agent's decisions. It reads and processes sensor data and enforces operational requests from the user.

The Personal Agent (PA) is responsible for learning the user's preferences by passively monitoring the user's interactions with the environment. The PA forwards the user's operation requests, and provides feedback to the user. The personal agent passively learns the preferences instead of having to be programmed. They also provide human-readable feedback on the user's current energy usage.

Finally, the Central Agent has two major functions: decision aggregation and to interface to internal and external services required by agents. Like the name implies, it acts as a central information router, responsible for satisfying information requests from agents within the environment.

The features that set this project apart from others is that the system learns the personal preferences automatically, and passively. Also, the system uses internal information requests that are formed so that they are human readable in order to present feedback to the user in an easily understandable manner. However, their system is a proof-of-concept instead of a fully implemented system, and it only focuses on temperature (HVAC) settings.

### 3.3.3 Multi-Agent System Design for Room Energy Saving

A multi-agent system design for building room energy saving has been proposed by Shen Bin, Zhang Guiqing [17][18]. The architecture of the multi-agent system includes the wireless network, Ethernet network and different agents (Person agent, room agent, environment agent). The characteristic of this multi-agent control system is the communication via wireless network between agents, and the communication with Ethernet network between the agent and the management agent, which act as the controller and the manager for the whole house. The idea of the system is that if a person move from his room to a near room then the room agent will not change the light level. If the room agent cannot detect if the person is around the room or not, then it will ask the management agent to see if the person still in the house or not. However, there is a lack of information regarding the agent types, and they did not talk about the sensors types.

### 3.3.4 XEROX PARC: A Multi-Agent System for Controlling Building Environments

The Xerox Palo Alto Research Center created a multi-agent system for building control [19]. Their system uses agents to model a marketplace to buy and sell hot or cold air in a building. When a room is too warm, then it either tries to sell its warm air to, or buy cold air from, another room agent. The agents are given virtual money in which they can buy heat in an double-blind auction, meaning that the agent that is buying does not know any of the other bids, and the selling agent does not know that the highest bid is. There is an auction held every minute of the day, meaning that there are 1440 auctions held each day.

In evaluating their system, they state that the average deviation of the actual to desired temperature was  $0.74^{\circ}\text{F} \pm 0.11^{\circ}\text{F}$ , as opposed to  $1.39^{\circ}\text{F} \pm 0.43^{\circ}\text{F}$  for a normal thermostat control. This is a 50% improvement in reaching comfort levels, while providing a much closer accuracy to the desired temperature.

They admit that one drawback of their approach are that the control system only works if the temperature settings can be reasonably set. If one room sets their temperature at an unobtainable level, then that means that the demand outweighs supply in the market, and run-away inflation occurs. Eventually the "price" for warm air becomes more than all of the money available to the agents. This means that there are no trades on the market, and thus the system is not controlling the room.

### 3.5 *iHome: University of Massachusetts*

The University of Massachusetts developed a multi-agent system called *iHome* [20]. Their system uses agents to accomplish given tasks, such as a coffee maker agent, water heater agent, etc. The agents wait until the appropriate resources such as hot water or electricity are available to complete their tasks. A given agent can be told to release its resources if another agent with higher priority requires them. Also, an agent can be commanded to stop its task if another agent requires its resources. An agent can also trade off the quality of the task in order to finish sooner. The washing machine can finish cleaning clothes with cold water, or a coffee maker can make coffee with frozen coffee beans instead of fresh ground coffee that must be retrieved from the store.

Also, an agent can stop its task if the results of the task create too great an impact on the environment. For instance, the dishwasher can be stopped if it creates too much noise if it is working at the same time as another appliance.

This system is unique in that it can schedule tasks based on the availability of resources. The amount of electricity available is one of the resources that agents must compete for, meaning that the total energy usage of the system can be constrained. However, in their testing, they use computer simulations to see when agents are able to finish their tasks. They do not focus testing on energy savings or user satisfaction.

## 3.6 Other Approaches

### 3.6.1 *Smart Occupancy Sensors to Reduce Energy Consumption*

This paper [21] presents an approach to energy consumption that uses motion sensors to detect occupancy within a room. They describe a way of calculating the Time Delay (TD) from the last motion detected, and when to turn off the lights within a room. They present the idea that peoples' activity patterns change during the day. For example, during the morning or afternoon, one might briefly go into the living room to vacuum the carpet, or look for their keys, but in the evening, they would stay and read a book or watch television.

Normally, motion sensors would have a pre-programmed time delay from when it last detected motion before turning off the lights, but this system shows that they can save energy by turning off the lights sooner based on how long someone is likely to stay in a given room. By changing the time delay for motion-controlled lights, they achieve a 25% energy savings compared to a 20% energy savings of pre-programmed time delay.

This project is one of the few that has results to show how much energy saving is possible. However, their system is limited to using motion sensors, and therefore does not use an actual artificial intelligence controller for their environment.

### 3.6.2 *AIM Project*

The AIM project [22][23][24] is an energy saving project conducted by several Universities. Their system uses an environmental control system that regulates the lighting and temperature settings within a house. They use wireless sensors throughout the house to monitor the current state of the environment, and to detect a person's presence within a room. They then build up a statistical profile for each user to predict when the person is likely to be home, and what the temperature and lighting levels should be. Using a simulation, they calculated that the maximum error in their presence prediction was 2.55%.

Another feature to their project is the design of a network architecture for the smart environment. Each basic device that is controlled by the environment is abstracted as energy management device (EMD). These EMDs are then members of a home network, which is connected to Internet through a gateway. These EMDs can then be remotely controlled by the inhabitants or by the utility company.

This system achieves fairly good results, however their results are computed using computer simulations. They do not present any tests of user satisfaction with the system, nor do they present results about how much energy can be saved with their approach.

### 3.6.3 Context-Aware Power Management

A paper presented by Harris & Cahill [25] to minimize overall energy consumption while maintaining user-perceived device performance mainly for office environment. The principal context required by their approach, called Context Aware Power Management (CAPM), is to save power by putting a computer (PC) into sleep mode when not in use. They present a method to predict when a user is about to use the computer, so that it can be restored from its low power state so that the user does not have to do it manually.

The CAPM framework is composed of three main components: data capture and feature extraction, context inference, and decision-making. The data capture and feature extraction layer captures the raw sensor events and in most cases pre-processes the data to obtain relevant features. The context inference layer is responsible for inferring more certain, higher-level context from the low-level sensor and feature data. The decision layer is responsible for taking the power-management actions.

Several sensors are used by the PC for building a context. The first is a Bluetooth tag, which is used for coarse location detection. Second are a video camera and microphone that are found on most modern laptop computers. These are used to determine if the user is using the computer. If the user has not moved the mouse or typed on the keyboard for a given time, the system tries to detect if the user is present and looking directly at the screen. If so, then the user is said to be using the computer.

They then collected data on the typical usage patterns of 18 different users to determine which combination of sensors would yield a detection algorithm that is closest to the actual usage (or the oracle approach). They classified 7 of their users as heavy users, meaning that when they were near their computer, then the computer was not being used less than 15% of the time. The other 11 users were classified as light users.

They show their results in terms of false power downs (FPD), meaning that the computer was power down at the wrong time, and manual power-ups (MPU) meaning that the computer was not woken up at the right time. Their testing showed that for both light and heavy users, the Bluetooth tag detection resulted in 0 FPDs, and 0 MPUs meaning that it accurately detected when they were not using, and about to use the computer. The second best approach was Bluetooth detection in combination with idle time, resulting in 0.5 FPDs and 2 MPUs for light users, and 0 FPDs and 0.25 MPUs for heavy users. Using only the Bluetooth tag for proximity detection resulted in energy consumption that was 9.0% from the oracle per day, meaning that the best prediction scheme was 9% from optimal.

This system focuses simply on managing a computer workstation in an office setting, so it is not a true smart environment. However, they obtained their results by studying actual users in an office environment.

### 3.6.4 Location-Aware Power Management

This paper [25] presents a power management system that uses peoples' location to manage power consumption within an office environment. They categorize different devices into three categories: instantaneous resume, sluggish resume, and slow resume. Instantaneous resume devices are categorized as devices that can be instantly brought back from a powered off state. These devices include lights, computer monitors in screen saver mode, etc. The second category is sluggish resume, where devices can be powered within a short period of time, such as a personal computer (PC). The third category, slow resume, includes systems that require some fraction of hours to return to normal state. This includes heating and cooling of a building.

Their system can turn on and off instantaneous resume devices by simply tracking a person's position and turn on the device when they are in the same area. For sluggish resume devices (PCs), they just start resuming the device using a further proximity threshold, giving the computer more time to return to its fully powered state. For slow resume devices (heating and cooling), they argue that reactive schemes are insufficient. Instead, a predictive approach is better suited, where the environment tries to predict when a room in the environment will be in use.

Their paper does not present any measured results for power savings, however their paper is about presenting the potential of a location-based energy control system.

#### **4. Evaluation of Energy Management Systems**

It is difficult to measure the impact of different automated control systems without actually building and installing them. The problem in doing so is that they are both expensive and time consuming to build. However, having a working system lets one make accurate measurements of how much energy was reduced. The Neural Network House and iDorm are two such projects that have built an actual smart environment. They base their results on actual user tests followed by subject questionnaires.

Another approach to testing a smart environment controller is to create a computer simulation of people living and working in a virtual environment. This approach is simple since there is no hardware to install and configure. The disadvantage is that the test results depend on the accuracy of the simulation. The multi-agent system used by the University of Karlskrona tested their system using a theoretical distribution of workers in a building, and then measured their system by how closely they met the comfort settings of these theoretical workers. Although their system would probably work well in a real scenario, it is possible that their energy savings results are not accurate, and it would be useful to have actual customer satisfaction surveys to measure peoples' impressions of the system.

A third approach is to track actual inhabitants of a house or office for a given period of time, and then test different energy management strategies on the recorded data. This way, the only hardware required is a location tracker. The behaviour patterns of the inhabitants are then used as input to each control algorithm, giving the ability to accurately compare the energy savings results.

Another approach, presented in [25] and [26], measures their results in comparison to the optimal approach, or "oracle" approach, where the user's intentions and schedule are always correctly predicted. Their results are then compared as a percentage to the oracle approach. Another way of presenting this type of result is to describe the number of false actions taken by the system, either powering down a device while it was still in use or turning on a device that was not going to be used.

In [27], the authors present a method of measuring energy saved by using a home automation system. They installed their system into 4 different homes and measured energy consumption first without using the home automation, and then again with the home automation turned on. They measured an 18.7% energy savings, however it is not clear how similar the usage patterns were on days with the home automation was used, and on days where it was turned off. A strong point of their paper is that they break down the energy usage by rooms in the house and show that the living room uses the most energy, followed by bed rooms and then the kitchen.

The systems using neural networks have shown that they can adapt over time to a user's preferences without the need for pre-programming. The system build at the Ministry of Education in Argentina showed only 5% of users were unsatisfied with the system. However, the drawback of neural networks is that their inner representation is vague and tailored for a certain set of inputs. This system cannot be trained and then installed everywhere. There is always some adjustment period while it becomes specifically trained for each scenario.

The iDorm system used a fuzzy logic approach, and showed it can adapt quickly to a user's preferences. The fuzzy logic approach creates rules for a user, which can then be used in other scenarios or environments, giving it a possibility of portability. It is also easier than a neural network to inspect the inner workings of the control system and fine-tune different parameters.

Systems using software agents to control an environment are perhaps the easiest to work with, since using agents makes it easy to describe the conflicting goals of saving energy versus user satisfaction. They can be written as competing agents, which reach some agreement based on pre-programmed rules. The user's preferences agent could also be somehow made portable over the Internet so that new environments where the user has never been can quickly access the user's preferences. However, it is not



clear how the individual agent-based control systems learn the user's preferences, but it is possible to use a combination of software agents along with neural network and fuzzy logic systems.

Table 1. A comparison of evaluation techniques.

Evaluation Approach	How are the results compared?	Are the results real or simulated?	Benefits of this approach	Drawbacks of this approach
Testbed System	User satisfaction surveys	Real	The results are accurate, from real people and real scenarios.	Only mentions user satisfaction lacks energy savings data. Also expensive to build a testbed system.
Computer simulation	Calculated energy savings and user satisfaction.	Simulated	Simple and quick to generate results, and test alternatives.	The results don't use real people in real situations. The energy savings and user satisfaction may not be accurate.
User Tracking	Calculated energy savings	Real	Cheaper to build than a full testbed. The location data can be used to test multiple control algorithms	The user tracking data is from a short time period (a few days). The data might be inaccurate.
Oracle Comparison	Number or percentage of false classifications	Real	Easy to compare multiple control algorithms.	Does not mention user satisfaction or energy savings.

## 5. Discussion and Recommendations

There have been many research projects that show the potential for using ambient intelligence to reduce energy consumption. The different approaches use fuzzy logic, artificial neural networks and software agent architectures to allow the smart environment to sense and react to the users. There are several projects that have built a prototype smart environment and have published results showing that they are able to reduce energy without impacting the user's comfort in the environment. Other works present only their proposed architectures and their perceived advantages.

The software agent approach seems to be the most popular perhaps because its architecture is well understood and can be clearly defined. In all of the projects discussed, there is a lack of results showing how much energy was saved. Instead, they focus on their ability to satisfy the user's preferences. What would be best is a quantitative analysis of energy savings based on users' interactions with the environment based on manual versus automated control of devices. This would show a quantitative improvement in energy savings based on smart environments, and would allow for a straight comparison of the different energy savings approaches presented in this paper.

The best way to test different ambient intelligence control methods would be to test them against a standard data set. Perhaps previous smart home projects could publish their location tracking data for this purpose. The standard test could be to see which algorithm could best predict what devices are no longer being used and which devices are about to be used. These results could be compared against each other, and against what actually happened in the data. One problem with this is that the results of some prediction algorithms might be specialized to this specific dataset and might not be accurate to more generic situations.

The field of artificial intelligence for building control will become ever more common. New home appliances and thermostats are being created that have built-in networking capability to display their current energy usage making people even more aware of their energy consumption. We predict that in the near future, we will see commercial systems that integrate some of the research covered in this survey into people's homes and offices.

To be used effectively, however, more research will be needed to make these systems user-friendly and unobtrusive, otherwise they will simply be ignored. As well, more research is required in the security aspect of smart environments. With increased capabilities of networked devices comes an increase in the

possibility of the control of these devices being compromised or personal data being used without their knowledge.

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