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The easy ADL home: A physical-virtual approach to domestic living

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Abstract. Smart environments worthy of the name need to capture, interpret, and support human activities that take place within their realms. Most existing efforts tend to focus on either real world activities or activities taking place in the virtual world accessed through digital devices. However, as digital computation continues to permeate our everyday real world environments, and as the border between physical and digital continues to blur for the human agents acting in these environments, we need system design approaches that can cope with human activities that span the physical-virtual gap. In this paper, we present such an approach and use it for designing a smart home intended to support Activities of Daily Living (ADL). The easy ADL home is designed based on a wearable personal server that runs a personal ADL support middleware and a set of computationally augmented everyday objects within the easy ADL home. An initial qualitative study of the system involving 20 subjects revealed a highly positive attitude (score 4.37 out of 5) towards the system's capability of co-locating and synchronizing physical and virtual events throughout the everyday activity scenarios, while classical usability aspects in particular related to the gesture-based input (score 2.89 out of 5) leaves room for improvement.

Keywords: Smart environments, ambient intelligence, mixed-reality, context-aware computing, ubiquitous computing

1. Introduction

Smart environments [11] follow the trend of moving beyond desktop computing, where everyday objects, devices, appliances, furniture, mobile robots and even architectural structures are connected forming a massively integrated ubiquitous computing society [57,16]. An important feature of smart environments is the seamless cooperation of its individual entities towards the holistic mission of continuously supporting its occupants. Smart environments are expected to make use of the occupants' abilities and compensate for their limitations in a calm and ambient manner without overwhelming them. In short, smart environments should improve its occupants' experience within such environments. Ambient Intelligence is a term that is often used to describe such a vision [1].

Human agents spend a considerable amount of time at home. This has motivated several research efforts within smart environments to focus on homes. Smart homes are researched with varying themes. Home automation by observing the occupants and learning to predict the occupants' needs is a central theme for much work including the MavHome [10] and the Neural Network House [34]. ThinkHome [33] is an energy efficient smart home that uses a digital ecosystem perspective in facilitating automation. The Aware Home initiated research efforts in investigating issues surrounding computing in a home by serving as a living laboratory for ubiquitous computing in support of home life [29]. The Aware Home is capable of capturing information about itself, its occupants, and their activities. Capturing the occupants' activities and needs is challenging to achieve in practice, which has led to approaches that are semi-automated, thereby giving the occupants more control as in the House_n project [24].

Another central theme is to design smart homes that enable elderly persons to live a longer and more independent life at home (in accordance with the concept of successful ageing) as in the House of Matilda [19] and EU research program like the Ambient Assisted Living [46,55]. The Nursebot project

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[42] is aimed at developing mobile robotic assistants that support elders in performing their activities of daily living (ADL) at home. Smart homes for people with disabilities are an objective of many research efforts. The SmartBo project [15] focuses on elders with mobility impairments and cognitive disabilities while the Gloucester Smart House [2] focuses on people with dementia. An automated hand-washing assistant for people with dementia is researched in [21]. Automated health monitoring and anomaly detection for cognitively and physically challenged people using machine learning algorithms that can model their behavior is described in [26].

There are several research efforts [7,18,33] that attempt to explore the possibilities of human-computer interaction within ambient intelligent environments. According to [12], the "smartness" of a smart home could be related to the occupant's situative interaction possibilities. Physical interaction models using location-awareness and token reading were explored [12], however the virtual counterpart was ignored. Even though many smart homes exist today there have been few attempts to investigate the possibilities of integrating the various physical and the virtual aspects of a smart home. Smart meeting rooms populated with local physical participants and distant virtual participants interacting with each other in a mixed-reality context is described in [38].

The easy ADL home is a smart home designed to provide support for its occupants in performing physical-virtual activities of daily living (ADL). The easy ADL home is not restricted to supporting everyday *physical* activities as is often the case in similar research. Occupants of a home often perform everyday virtual activities like checking emails, paying bills, etc., and we have identified a new class of activities that are neither physical nor virtual, but "physical-virtual" (to be described in Section 3 below) [39]. Many smart-home approaches view smart homes as physical homes augmented with digital technology. Such a bias towards the physical aspects of a home introduces additional cost for its occupants to access its virtual aspects, and to move across the physical-virtual boundary, effectively creating a physical-virtual environment gap [39].

In this work, we propose a perspective that considers the physical and the virtual aspects of a smart home to be equally important. Focus is on the conceptual design of an infrastructure intended to relieve the occupants from some of the extra efforts currently needed when performing activities that make heavy use of both aspects. We propose a physical-virtual design perspective that abstracts from the "user interfaces," leaving only physical and virtual objects. There are at least three motives for adopting such a design perspective: 1) Occupants well acquainted with specific (physical and virtual) environments are typically more concerned with the manipulation of (physical and virtual) objects than the user interface through which they are accessed. 2) Such a design stance facilitates the conceptualization of objects that bridge the gap between the physical and virtual aspects of a smart home. 3) Many existing (physical and virtual) objects already have both physical and virtual manifestations (e.g. a printed photograph within a photo frame and its digital version within a laptop) thereby introducing the possibility of seamlessly crossing the physical-virtual boundary. A comparison of physical and digital mementos in a home environment is described in [41]. Our physical-virtual approach is intended not only to integrate physical and virtual objects, but also to explore the possibilities of integrating physical and virtual situations in which occupants of a smart home might find themselves in the future.

2. Background

2.1. Smart environments

There have been several previous attempts to define and provide a characterization of smart environments. According to the EasyLiving project [8], a smart environment (also referred to as "intelligent environment") is "a space that contains myriad devices (stationary or mobile) that work together to provide users access to information and services. A broader goal is to allow typical PC-focused activities to move off a fixed desktop into the environment as a whole." This definition of a smart environment is restricted to the occupants' virtual activities. The activities that were once performed using desktop computers are now researched in an attempt to move them into the occupants' environment.

According to Coen [9], smart environments are "highly embedded and interactive spaces intended to bring computation into the real, physical world. Such environments allow computers to participate in activities that have never previously involved computation and to allow people to interact with computational systems the way they would with other people: via gesture, voice, movement and context." Introducing computers to activities that were previously performed without their assistance alter the way occupants perform such activities. It calls for an infrastructural platform that allows the occupants to shift between the physical aspects of their activity and the virtual aspects introduced by the inclusion of computers. It also introduces a need to seamlessly integrate computation into the activities performed by the occupants with the possibilities to allow for natural and ambient interaction in a calm manner [57,58].

Many of the smart homes mentioned earlier [10,24,29,34] have a common goal to improve the comfort and productivity of its occupants by predicting the occupants' immediate needs. What would be the occupants' immediate need(s) is an interesting and often difficult question to answer. The occupants' needs vary from home automation, to minimizing the home operational cost, to providing support for everyday home activities, to maintaining safety and security at home, to providing home entertainment, to monitoring the health status of its occupants, to automatic online shopping, to facilitating social interaction, and more. Instead of focusing on the applications that could potentially find its place in a smart home, our focus in this work is to investigate a general-purpose infrastructure that enables its occupants to perform activities that span across the physical-virtual boundary.

According to Cook et al. [11], a "smart environment is one that is able to acquire and apply knowledge about its environment and to adapt to its occupants in order to improve their experience in that environment." The term "environment" is used with a bias towards the physical environment. However, the term environment might also be used to refer to the virtual environment in which the occupants of a home perform everyday virtual activities. Considering our interest in blending the physical and the virtual environments and facilitating activities that span across the physical-virtual boundary, we define "*smart environment as a sensitive, adaptive, and responsive environment with regard to its physical as well as its virtual aspects. It represents a physical-virtual space of activity possibilities and a set of constraints with an overall goal of fulfilling the individual occupant's immediate needs.*"

The term "environment" refers to the surrounding in which an occupant is situated. An occupant might be both physically and virtually situated in an environment if we consider both the physical and the virtual aspects of that environment. For example, an occupant of a home might be physically situated in the living room and in parallel be virtually situated in an online bookstore accessed through a smart bookshelf. The term "smart" refers to the sensitive, adaptive and responsive nature of smart environments and its inherent property of blending physical and virtual aspects.

2.2. Related approaches

There are at least four research approaches that have influenced our physical-virtual design perspective, namely: Tangible Bits, Context-Aware Computing, Mixed Reality and Activity-Based Computing.

Occupants of a smart home live in two realms: a physical environment and one or more virtual environments. Even though the occupants possess dual citizenship, the absence of an infrastructure that allows for easy movement across the physical-virtual boundary restricts the possibilities of reaping the best of both realms. The goal of *Tangible Bits* [25] is to bridge the gap between the two realms by coupling people, bits and atoms. Tangible Bits provide physical form to virtual information such that they are both directly perceivable and manipulable by the human agents. The physical representations are computationally coupled to the virtual information with their physical states more or less corresponding to the system's virtual states.

Providing virtual form to physical entities like physical objects, places and persons is also often useful and is exploited within *context-aware computing* [13]. Context-aware computing focuses on using contextual cues available in the physical environment as a means of improving the richness of communication between human agents and virtual environments. According to Dey [13], context is any information that can be used to characterize the situation of an entity that is relevant for the interaction between a human agent and the virtual environment(s). Typical context-aware systems consider what happens in the surrounding physical environment as contextual cues, but what happens in the virtual environment is often ignored without considering its potential to provide contextual cues. In this paper, we propose an egalitarian stance with regard to physical and virtual context cues.

Mixed reality [32] attempts to merge the physical environment and the virtual environment(s) to produce physical-virtual environments where physical and virtual objects co-exist and interact in real time. According to [32], physical objects are objects that have an actual objective existence while virtual objects are objects that exist in essence or effect, but not formally or actually. Physical objects can be perceived and manipulated both directly and indirectly (through mediators). Mediator is a general name for objects commonly referred to as sensors, actuators, input devices, output devices, interaction devices, interface devices, user interfaces, etc. [39] that act as tools for providing access to the domain objects the human agent wants to manipulate. Virtual objects must first be simulated, since in essence they do not exist, before being perceived and manipulated through mediators. According to [39], objects that seamlessly transcend the physical-virtual boundary by possessing manifestations in a physical environment as well as in virtual environments are referred to as Physical-Virtual Artefacts (PVAs). PVA manifestations in the physical and the virtual environments should complement each other instead of mimicking each other's affordances and appearances, thereby reaping the benefits of both realms.

Smart homes in general are supposed to provide support to the occupants' immediate needs by considering their everyday activities and the context in which such activities take place. *Activity-based computing* (ABC) [6] proposes to consider the occupants' activities as first-class objects in facilitating human-home interaction. The basic computational unit of ABC is neither files nor applications, but the occupants' activities. The essential principles of ABC are [6]:

- Activity-centered: select a range of services needed to support the occupants' activities.
- Activity suspend and resume: allow the occupants to alternate between several activities.
- Activity roaming: allow the occupants to be mobile while receiving activity support.
- Activity support while being adaptive to the resources available.
- Activity sharing: support collaborative activities.
- Activity discovery: recognize activities in varied context.

Occupants of a smart home might perform activities that require constant switching between the physical environment and the virtual environments, also referred to as Physical-Virtual Activities [39]. The strengths and weaknesses of the two realms motivate why occupants of a smart home would do such constant switching and in particular perform physical-virtual activities.

3. A physical-virtual design perspective

3.1. Physical-virtual environments

Physical environments generally possess some basic relations and ordering among self-sustained physical objects, and are governed by the laws of physics. They usually possess rich representations and offer natural affordances. In contrast, virtual environments are dependent on the mediators for their existence and do not have universal laws. Virtual environments introduce inexpensive space navigation and object transportation, allow for making big changes and even reversing operations with ease compared to the physical environments. Virtual environments offer the possibilities of multiple manifestations of virtual objects in distinction to physical environments that only offer one unique manifestation of every single physical object. The fact that physical environments and virtual environments are inherently different introduces the possibility of reaping the best of both environments by allowing them to co-exist and complement each other. However, physical environments and virtual environments are similar in certain respects: they both allow their occupants to be situated in them and interact with objects contained in them, thus providing an arena for their activities. This makes it possible to view them as being alike and merge them together as physical-virtual environments where physical objects and virtual objects co-exist.

3.1.1. Presence within multiple environments

Occupants cannot subjectively be present (in the sense of fully situated or fully attentive) in more than one environment at a time, in parallel. Merging physical and virtual environments will have to take forms that somehow escape that limitation. Making the virtual environments fit into the physical environment and making them subjectively one could potentially be achieved in several ways.

- Time multiplexing: In such an approach, occupants are present in one environment at a time. Their attention switches along with the sequence of environment shifts. The switching should be "natural" and "intuitive."
- Space multiplexing: In such an approach, occupants are spatially present in several environments at a time with varying levels of attention and intention within individual environments.

In both approaches, the merging of the physical and the virtual environments should be dynamic in order to retain the benefits of the rapid changes that the virtual environments allow. Even though in theory there exists a clear difference between time multiplexing and space multiplexing, in practice an occupant might only be able to really focus on one thing at a time, thus all multiplexing ends up being time-based to some extent. The idea with space multiplexing is that an occupant might be able to fully focus on only one task (or environment) at a time, but might still be able to partially perceive information through their peripheral attention. This is clearly an interesting issue, both conceptually and implementation-wise and needs further research.

3.1.2. Mobility

The effect of an occupant's mobility within physical-virtual environments introduces several challenges. Consider a scenario where an occupant is mobile in a physical environment, but is performing actions in a virtual environment. It introduces a challenge in presenting the required virtual environments in a stable manner. The virtual environments are dependent on the mediators that are available in the physical environment in which the occupant is located. This introduces a need for the virtual objects to be flexible and manifest themselves in different modalities (visual, audial, tactile) depending upon the mediators that are available. Mediators that are always on and worn by an occupant offer an alternative solution in maintaining a stable virtual environment. An occupant's movements in a virtual environment often have little consequence for the physical environment. How do we describe an occupant's mobility within physical-virtual environments? When an occupant navigates in the physical and/or virtual environment, his/her physical-virtual environment keeps changing. This introduces a need to maintain stability in an effort to facilitate the ongoing activities across the physical-virtual boundary.

The intensity of an occupant's interaction with physical objects in a mobile context is usually low. For instance, occupants navigate to different rooms, but perform more intensive actions within individual rooms compared to the actions performed (in terms of interaction with objects) while navigating between them. Taking inspirations from the occupants' mobility within physical environments, we propose to facilitate low-intensity interaction with virtual objects while the occupants are moving in their physical environment Such an approach introduces better stability in presenting the virtual environments by ignoring mediators that enter and leave a human agent's physical environment quickly and by focusing on mediators that are more stable within the occupant's physical environment.

3.1.3. Entering and leaving environments

Human agent's mobility in the physical world is often used as a common strategy to enter or to leave physical environments. For instance, human agents leave their home, enter a supermarket, leave the supermarket and enter their home again. In principle, human agents are situated in one physical environment at a time and as they leave one physical environment, they enter another physical environment. Since such environments afford a set of physical activities each, by entering or leaving an environment, a human agent invariably switches between activities as well. Of course there are some activities that span across more than one environment and often introduce a need to shift between different environments. As mentioned earlier, a human agent moves lightly in the virtual world and it is often possible to enter or leave more than one virtual environments at the same time. The traditional approach to entering and leaving virtual environments is by using login and sign out. Research on strategies to facilitate the entering and the leaving of physical-virtual environments has only just started. The vision is to find solutions that are unbiased towards the physical environment.

3.1.4. Centricity

Physical-virtual environments introduce the centricity problem, i.e. to choose an appropriate viewpoint for the observer relative to the objects of interest [32]. Virtual environments can be presented from multiple viewpoints since they do not exist in objective actuality, whereas the physical environments exist in objective actuality and cannot be presented from multiple viewpoints. This makes it simpler to deal with physical environments, compared to their virtual counterpart that might be influenced by the occupants and their viewpoints.

3.1.5. Access and control

The rules for having access to and controlling resources in a physical environment is more well established compared to similar rules within virtual environments. For instance, proximity is often used as an implicit rule to access the resources in a physical environment. The person closer to a chair has a better opportunity to use it compared to someone at a distance. Similarly, ownership could be considered as another implicit rule where a person who owns an apartment has more access and control rights compared to a guest in that apartment. There are rules in virtual environments as well, like guest rights, member rights, moderator rights, etc. But occupants of a smart home might be in the same physical environment, yet access and control different virtual environments. For instance, occupant A might read the

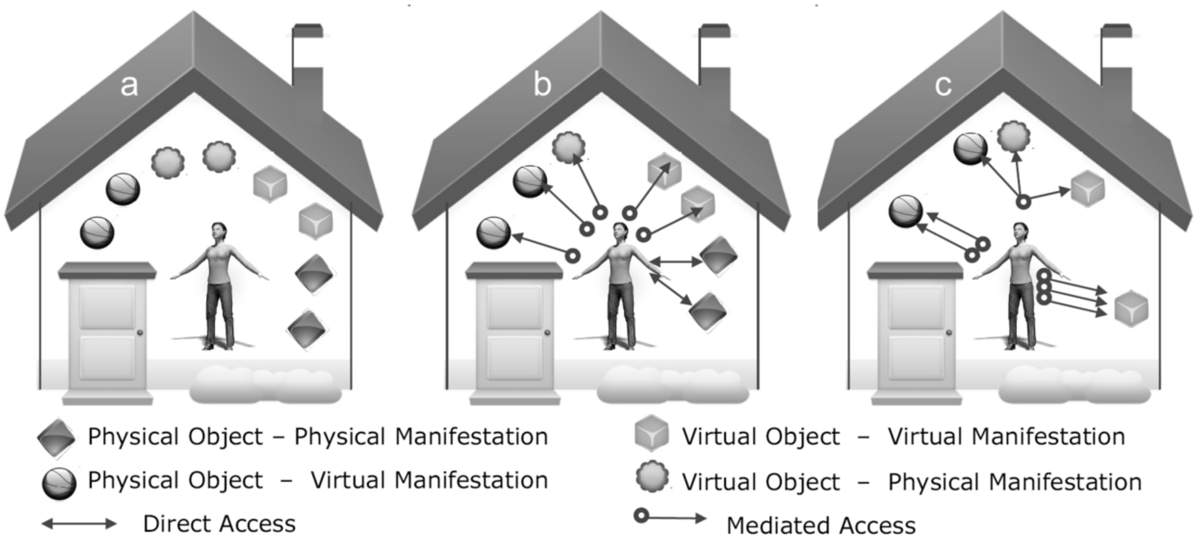

Fig. 1a. Dual manifestation of physical and virtual objects. 1b. Direct and mediated access of physical and virtual objects. 1c. Relationship between mediators and domain objects.

morning news (a virtual object) through the dining table (a mediator), while occupant B might check her emails (also a virtual object) through the dining table. This introduces a challenge to produce access and control rules that span across the physical-virtual boundary.

3.1.6. Privacy

Physical environments protect the occupants' privacy physically, by having doors for instance, so that they can perform both private and non-private activities. The occupants themselves are usually responsible for privacy across the social dimension. Virtual environments usually have access modifiers like private, public, protected, etc., to secure its users' privacy. Within physical-virtual environments, protecting their occupants' privacy can be a challenge. The physical structures that protect privacy quite well within physical environments could be considered as a starting point for facilitating privacy within a physical-virtual environment. However, further research is required to include technological, legislative, and social dimensions to privacy.

3.2. Physical objects and virtual objects

3.2.1. Dual manifestation

Physical objects are physically manifested within a physical environment, while virtual objects are virtually manifested within the realm of a computer screen; this is the traditional view. In a physical-virtual environment, however, both physical and virtual objects possess dual manifestation possibilities, i.e. they can be manifested both physically and virtually. Refer to Fig. 1a.

– Example 1: A physical stove having a virtual manifestation that can be accessed from the living room through the wall display and a gesture recognizer. The virtual manifestation allows the occupants to perceive the state of the stove and manipulate it from a distance through a mediator such as for instance a mobile phone.
– Example 2: A virtual media player having a physical manifestation in the form of a physical candle holder on the dining table. By manipulating the physical candle holder (when not in use), different music play lists can be selected and played. Rotating the candle holder will increase or decrease the sound volume.

Dual manifestation of objects allows the occupants to interact with such objects (irrespective of being physical or virtual) both physically and virtually depending upon the usage context. Such an approach allows for seamless integration across the physical-virtual boundary since the objects exist both physically and virtually. Such an approach introduces flexibility within objects and allows for an appropriate affordance depending upon the usage context. For instance, an occupant located closer to a stove in the kitchen might prefer to turn the stove off using a physical knob considering the handy affordance that it offers; while the same occupant when in the living room might prefer using a virtual knob on the wall display to avoid locomotion.

3.2.2. Direct and mediated access

Traditionally, physical objects belong to physical environments and are accessed directly by its occupants, also referred to as direct access. There are of course exceptions like turning a ceiling lamp on or off through the mediation of a wall switch. However, virtual objects do not exist in objective actuality necessitating the use of mediators to access them, also referred to as mediated access. Mediated access is also required to access the virtual manifestations of physical objects and the physical manifestations of virtual objects. Refer to Fig. 1b.

- Example of direct access: An occupant physically unlocks and opens the entrance door for the evening's guest.
- Example of mediated access to physical object: An occupant while being busy in the kitchen virtually unlocks and opens the entrance door for his everyday neighbor.
- Example of mediated access to virtual object: An occupant uses a speech interface to access her emails while doing the laundry.
- Example of mediated access to virtual object: An occupant takes her daily medication and thereby provides implicit input [45] to the intelligent medication assistant (virtual object).

Considering the lamp and switch example, even though an occupant uses the switch to turn the lamp on and off, the occupant's primary focus is on the lamp and not on the switch. Drawing inspiration from psychology which informs us that expert users of a tool tend to focus on the domain object, instead of the details of the tool, we propose an approach based on mediators to provide access to virtual objects and some physical objects within a smart home. Refer to Fig. 1b. Mediators should be subjectively transparent and invisible in order to facilitate the co-existence of physical and virtual objects within a smart home.

From a human agent's perspective, it is less important to distinguish between physical and virtual objects, more important that the objects (physical or virtual) in an environment should provide the appropriate affordance to perform activities. Hence by introducing the concept of mediators that are transparent, the modeling of a smart home across the physical-virtual boundary is simplified: it only needs to care for the domain objects.

3.2.3. Relationship between mediators and domain objects

The relationship between mediators and domain objects (physical or virtual) can be both one-to-many and many-to-one. Refer to Fig. 1c. For instance, a refrigerator display (a mediator) might provide access to many domain objects like the temperature controller, old food detector and the shopping assistant. Similarly, the shopping assistant (a domain object) might be accessed through many mediators including the occupant's wristwatch, the refrigerator display, and the entrance door display and aurally through the radio.

3.2.4. Perception and action

Occupants of a traditional home environment can (a bit naively) be seen as interacting with physical objects through processes of perception and action. When it comes to interacting with virtual objects, however, the classical HCI concept of input and output is normally used; it is well established within the WIMP interaction paradigm for desktop computers. The input and output concept becomes inadequate within a smart home environment, however, where the occupants are expected to interact with multiple devices, often in parallel. Other issues include the occupants' attention and intention towards interaction with individual devices. The occupants' attention and intention may vary continuously depending upon the context of interaction with individual devices.

Within the proposed physical-virtual design perspective, we consider an occupant's interaction with virtual objects to also be based on perception and action. Such an approach allows for an egalitarian stance in facilitating interacting with domain objects, irrespective of being physical or virtual. It also allows the occupants to interact with multiple domain objects (both physical and virtual) at the same time with varying levels of attention and intention towards the individual domain objects.

In Fig. 2a, two spaces are introduced, namely the perception space and the action space. The perception space contains a set of domain objects that are potentially perceivable by an individual occupant at a particular moment in time. The action space contains a set of domain objects that are potentially manipulable at a particular moment in time. Due to the fact that occupants of a smart home are mobile, the domain objects within the perception space and the action space keep changing dynamically. The processes of perception and action can take place in multiple modalities including visual, audial, and tactile modalities, which means we need to consider the possibility of

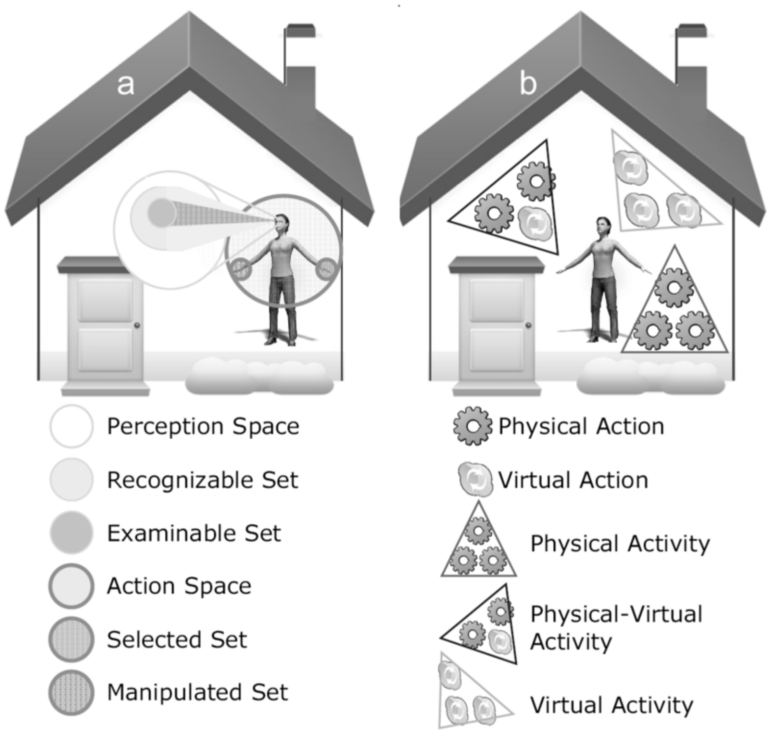

Fig. 2a. A Situative Space Model [40]. 2b. Physical activity, virtual activity and physical-virtual activity.

facilitating distributed multimodal interaction between an occupant and the domain objects within the spaces.

3.3. Situation awareness

Awareness about an occupant's situation is often considered important for a smart home to be able to adapt and respond to the occupant's immediate needs and to facilitate their current activities [31]. According to the Situated Action theory [48], a human agent's activity is emergent and grows directly out of the particularities of a given situation. Traditional approaches to smart homes consider an occupant's physical situation in adapting either the virtual environment (as in context-aware computing) or the physical environment (as in home automation).

- Example of virtual environment adaptation: A virtual cooking guide detects that an occupant is cooking and adapts itself in providing appropriate suggestions based on how well the physical activity of cooking proceeds.

Example of physical environment adaptation: As an occupant wakes up in the morning the coffee maker in the kitchen begins to automatically prepare coffee.

An occupant's virtual situation is rarely used within smart homes in adapting either the physical environment or the virtual environment. For instance, one could imagine that depending upon whether an occupant is sending an email or is watching an online movie the room lighting could adapt and provide an ambient experience. Within the physical-virtual design perspective, we consider an occupant's situational information across the physical-virtual boundary, giving equal importance to the physical and the virtual situation. We are aware of the inherent differences between an occupant's physical and virtual situations. For instance, an occupant's proximity to a set of physical objects might be more stable compared to an occupant's proximity to a set of virtual objects that might appear and disappear as a result of dynamic switching between different virtual environments. Our intention is to handle physical and virtual situations uniformly at a higher level of abstraction in order to better model an occupant's physical-virtual situation.

Situation models that acquire knowledge through observation and evolve during use are important for smart homes. Existing situation models predominantly focus on either the physical aspects of a smart home [31] or the virtual aspects. We propose a Situative Space Model [40] that is centered on a human agent and is based on their perception and action abilities at a particular instance in time. Refer to Fig. 2a. The situative space model spans across the physical-virtual boundary covering the physical as well as the virtual aspects of a smart home. The components of the situative space model are as follows:

- Perception Space: The space around an occupant that can be perceived by that occupant at each moment in time. Perception space can be given a simple geometrical interpretation (like a cone, in the case of vision) as a rough approximation. Refer to Fig. 2a. It contains the set of domain objects that are potentially perceivable. The perception space contains two finer levels of abstraction, namely the recognizable set and the examinable set.
- Recognizable Set: Contains the set of domain objects that are potentially recognizable, where the term recognizable refers to the occupant's ability to distinguish the domain object's type.
- Examinable Set: Contains the set of domain objects that are potentially examinable, where the term examinable refers to the occupant's ability to distinguish the domain object's state.
- Action Space: The part of the space around an occupant where action can be performed at each moment in time. Action space can be given a simple geometrical interpretation (like a sphere, in the case of touch modality) as a rough approximation. Refer to Fig. 2a. It contains the set of domain objects that can potentially be acted upon. The action space contains two finer levels of abstraction, namely the selected set and the recognizable set.
- Selected Set: Contains the set of domain objects that are currently being physically or virtually handled (touched, gripped, selected in the virtual sense, etc.).
- Manipulated Set: Contains the set of domain objects whose states (internal as well as external) are currently in the process of being changed by the occupant.

The information content with regard to the perception space and the action space are considered to represent the occupant's situation. Both the perception space and the action space are occupant-centered and varied continuously with the occupant's movement of body and body parts. The situative space model was used for the wizard-of-oz technique to be described in Section 5.3.

3.4. Activity awareness

Awareness about an occupant's current activity is important for the smart home to support those activities. However, an occupant's activity may span across the physical-virtual boundary introducing a need to recognize activities both in the physical environment and in the virtual environments. Recognizing an occupant's virtual activities is simpler than recognizing their physical activities. We represent human activities using three levels of abstraction: activity, action and operation, inspired by activity theory [36]. An activity has an objective and is comprised by a set of actions that have well-defined goals and are accomplished by largely unconscious operations. Both actions and operations can be either physical or virtual. Activities that contain only physical actions are referred to as physical activities, while activities that contain only virtual actions are referred to as virtual activities. Refer to Fig. 2b. We introduce a third type of activity that contains both physical actions and virtual actions, referred to as "physical-virtual" activities [39]. Such a definition of the term physical-virtual activity was used for the Wizard-of-Oz technique to be described in Section 5.3. Physical-virtual activities introduce constant switching between the physical and the virtual aspects of a smart home and will be the focus of our exploration.

4. The easy ADL home

The easy ADL home[1] is a smart home that is built based on the physical-virtual design perspective discussed in Section 3. As mentioned earlier, it is a home that provides support for its occupants in performing the physical-virtual activities. The first prototype of the easy ADL home [51] was simulated in an immersive virtual-reality (VR) setup. Refer to Fig. 3. The VR model was developed using the Colosseum3D real-time physics platform [5]. Such an approach allowed us to simulate sensors, actuators, interactive devices, physical objects and virtual objects, thereby allowing us to focus on the conceptual and the algorithmic parts of the easy ADL home. The VR-based approach was also useful in updating and exploring concepts at a lower cost since the actual

[1] This work has been partially funded by the EC Target 1 structural fund program for Northern Norrland, Sweden.

Fig. 3. The easy ADL home simulated in immersive VR [51].

physical implementation part can be ignored. We are aware of the limitations of a VR setup: for example, the occupant's mobility is limited by the sensing range of the magnetic tracker, and there is a lack of physical affordances while interacting with objects. This paper will focus on the second prototype of the easy ADL home that was physically constructed as a living laboratory for ubiquitous computing research. A living laboratory home environment [29,47] introduces the possibilities of conducting authentic yet adaptable and controllable experiments in an effort to study and explore the behavior and experiences of its occupants. The easy ADL home is a 54 m^2 apartment intended for providing ADL support for single occupants (of course guests are allowed who might take part in some activities without receiving support from the easy ADL home). The restriction to a single occupant is also helpful in keeping the experimental setup simple and avoids the added challenges of a smart home supporting multiple human agents.

4.1. Augmented everyday objects

Traditionally, physical homes contain physical objects (PO), but by augmenting them with ubiquitous computing technologies, such objects could provide additional functionalities without compromising with their physical affordance [28]. We consider such an object as an augmented everyday object (inspired by sentient artifacts [27]), which is a physical object that contains mediators and provides access to virtual objects implicitly (through sensing or actuating mediators) and/or explicitly (through input or output mediators). Refer to Fig. 4 for the set of augmented everyday objects within the easy ADL home. In total, the easy ADL home contains more than 100 virtual objects that are part of 19 mock-up applications, making it difficult to list them all. We refer to Section 5.1 to get a glimpse of the virtual objects within the easy ADL home. Human agents use such augmented everyday objects in performing physical-virtual activities. The augmented everyday objects are both physical and virtual in nature, and are usually situated within the occupant's physical-virtual situative spaces.

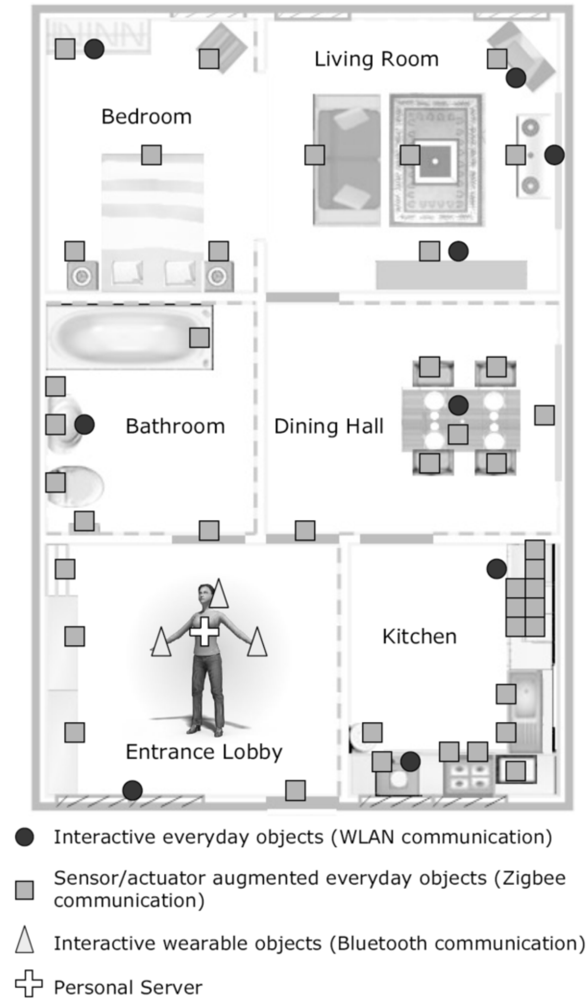

Fig. 4. A floor plan of the easy ADL home, including locations of the augmented everyday objects.

The floor plan of the easy ADL home is presented in Fig. 4. The easy ADL home was populated with more than 300 physical objects of which 9 were augmented with thin clients, also referred to as interactive everyday objects. The interactive everyday objects were equipped with LCD displays (visual output mediator) of varying dimensions, plus a pair of loudspeakers (audial output mediator). A projector (visual mediator) was used in the living room representing an interactive wall. The interactive everyday objects use WLAN technology to communicate with a personal ADL support middleware to be described in Section 4.2. Further details of the wireless infrastructure are reported in [53].The data rate requirement of these objects is usually high and they run a thin client in Java. Several operating systems including Windows and Symbian were used to allow for heterogeneity within the network. Java Speech API was used as a speech synthesizer for facilitating audial feedbacks from these interactive everyday objects.

To complement the interactive everyday objects, 2 wearable wristbands equipped with 3-axis accelerometers (gesture input mediator) for explicit hand-gesture commands and a BTH-8 Bluetooth headset (speech input and audial output mediator) for explicit speech commands and audial output were used by the occupants. Such objects are referred to as interactive wearable objects and use Bluetooth technology (considering the availability of many commercial products that are both interactive and wearable) to communicate with a wearable computer running a personal ADL support middleware. The interactive wearable objects are not equipped with a thin client; the computations are performed in the wearable computer. Microsoft Speech SDK 5.1 API was used for speech recognition and synthesis. A simple hand-gesture recognition engine was developed based on acceleration thresholds along the 3-axis with 5 millisecond time frames at a frequency of 1 KHz. Both left-hand gestures and right-hand gestures are recognized in parallel. In the future, we intend to include complex gestures by using methods like hidden Markov models in order to improve the naturalness and number of gesture commands that could be used by the occupants to manipulate virtual objects. Interactive wearable objects allow human agents to access virtual objects in outdoor environments, such as a lawn behind the occupant's home. Further details about a human agent's multimodal interaction with augmented everyday objects are reported in [54].

The easy ADL home contains 42 everyday objects that are augmented with sensors and/or actuators. Refer to Fig. 4. The sensors (sensing mediator) and the actuators (actuating mediator) were used to keep track of and automatically manipulate the physical aspects of everyday objects. Such objects usually have low requirements of data rate and use ZigBee technology to communicate with the wearable computer. In house sensor/actuator motes were designed using Maxstream XBee 802.15.4 transceiver and Atmel ATMEGA88-20Pu microcontrollers. For further details about the wireless sensor networking of augmented everyday objects, we refer to [52].

The mediators (input, output, sensing, etc.) in the augmented everyday objects provided access to more than 100 virtual objects, most of them part of the 19 mock-up applications built for creating everyday scenarios in the easy ADL home. The mock-up applications, including medicine reminder, old-food reminder, food recipe provider, diet controller, shopping assistant, safety and security manager, weather information provider, clothing assistant, news provider, transportation information provider, day scheduler, office assistant, and more. The everyday scenarios (refer to Section 5) involving various physical-virtual activities were not designed to be extensions of the present, but as provocative explorations of a future that might be, but not necessarily will be realized. The mock-up applications were selected and designed partly on the basis of an informal workshop that was conducted with 8 subjects to understand the needs of an occupant of a smart home, partly on needs we anticipate are interesting to study and explore.

The occupants receiving activity support within the easy ADL home wore a WRT54GL WLAN access point on their chest. A stationary laptop was used to simulate wearable computing. Such an approach allowed us to focus on understanding the physical-virtual approach to domestic living instead of focusing on technological issues such as the battery power that gets drained quickly. The laptop was running the personal ADL support middleware and the mock-up applications. The 9 interactive everyday objects were running synchronized duplicates of the mock-up application software under centralized control.

4.2. A personal ADL support middleware

The augmented everyday objects of the easy ADL home communicate with a personal ADL support middleware. For reasons of privacy, efficiency, reduction in design complexity, feasibility, and cost benefits, we have adopted an approach where the heavy calculations are performed by a wearable computer running the middleware. Refer to Fig. 4 and Fig. 6. Such an approach allows for addressing the issue of "uneven conditioning" discussed by Satyanarayanan [44]. It also provides the possibilities of fu-

Fig. 5. Augmented everyday objects with sensors [52].

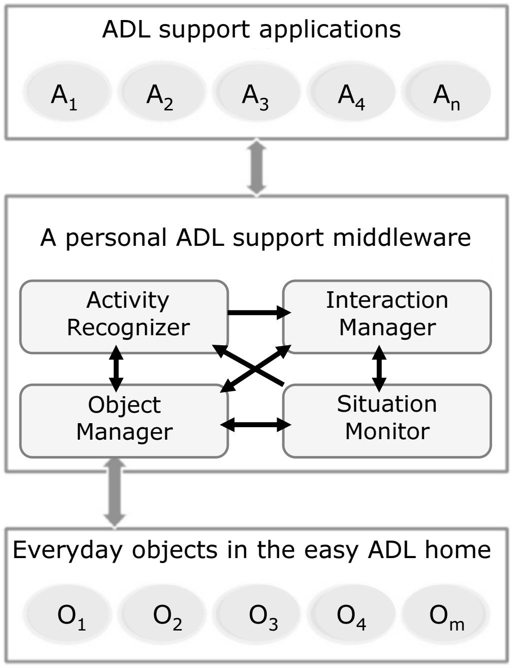

Fig. 6. The easy ADL home system architecture comprising a personal server and a set of augmented everyday objects.

ture extensions where the occupants might use their wearable computer in contexts outside a home, for example in a smart supermarket environment or in a smart airport environment. As in Intel's Personal Server Concept [56], the wearable computer will allow the occupant to readily store and access the data and applications through augmented everyday objects equipped with mediators found in the easy ADL home. The wearable computer does not have any mediator of its own, using wireless technology to connect with the local mediators. A star network topology was used with the wearable computer acting as the central node. Three different wireless technologies are used namely: Zigbee, Bluetooth and WLAN, depending on the augmented everyday object.

In environments with multiple human agents present at the same time (which is common in most human environments), the augmented everyday objects might be more complex than the ones described in this paper, which primarily focuses on a single human agent in an environment as a starting point for exploring the physical-virtual approach to domestic living. There is a range of possible implementation approaches, stretching from purely wearable computing to purely distributed computing where all the computing is distributed over the augmented everyday objects [43]. Our work lies somewhere in between these two extremes, but more close to the wearable computing approach.

The complexity involved in developing ubiquitous computing applications motivates the development of a middleware that encapsulates the low-level sensing and networking tasks, while providing high-level information about the human agent's environment, the augmented everyday objects populating it, the human agent's physical-virtual situation, ongoing physical-virtual activities, etc., to the interested ADL support applications. In our implementation, the middleware is also responsible for managing a human agent's interaction with ADL support applications by communicating with the augmented everyday objects and providing human agents the possibility to access appropriate virtual objects. Considering the variety and number of augmented everyday objects expected in the smart homes, the middleware should meet many of the requirements of traditional distributed systems such as heterogeneity, mob, scalability, security and tolerance for component failures ility and disconnections [20]. The proposed physical-virtual approach introduces additional requirements including the modeling of the situative spaces and the inferring of ongoing activities that span across the physical-virtual boundary.

The middleware is composed of the following four components: object manager, situation monitor, activity recognizer and interaction manager, as shown in Fig. 6. The middleware components run as independent modules and offer a common interface to communicate with the ADL support applications.

Microsoft Message Queues (MSMQ) is used for exchanging objects (the term object is in this case used as in object-oriented programming) and strings among the middleware components, the ADL support applications and the augmented everyday objects. MSMQs are intended for inter-process, inter-program and network communication. It is important to minimize the number of queues required since additional queues introduce additional overhead in exchanging messages. Hence, instead of a queue for each individual communication path, which might reduce flexibility when new components are added, a queue for each individual component is used. The queues work like a mailbox where sent messages are collected and could be read periodically. During the initialization phase, the existing queues are emptied and newly arrived messages are listened to.

4.2.1. Object manager

The Object manager is responsible for managing the physical-virtual environment in which the occupant is currently situated. The physical-virtual world is represented in terms of physical objects, virtual objects and mediators within it. The object manager is responsible for the following: 1) to discover the set of objects (physical, virtual and mediators) present in the occupant's physical-virtual environment; 2) to query a database during the initialization phase for additional information about the objects based on their identities; a mock-up database is used with an assumption that in the future the everyday object manufacturers will maintain such a database online considering the interest shown by the industry and academia in the *Internet of Things* [16]; 3) to initialize and manage wireless communication with the augmented everyday objects; 4) to provide information about the objects to other middleware components and the ADL support applications running on top of the middleware.

4.2.2. Situation monitor

The situation monitor keeps track of the occupant's current situation in the physical-virtual environment in terms of the objects present within the perception space and the action space described in Section 3.3. By keeping track of the objects that are perceivable, recognizable and examinable, the interaction manager can decide on if, when, where and how to present the virtual objects. By keeping track of the objects that are within the action space, it is possible for the interaction manager to decide if an object can or cannot afford a specific task, considering the occupant's current activity. The situation monitor is responsible for the following: 1) to discover the set of objects (physical, virtual and mediators) present within the perception space and the action space; 2) to establish the occupant's physical-virtual situation based on the objects within the situative spaces, their characteristics, and their current state; 3) to communicate with the augmented everyday objects (if necessary) via the object manager; 4) to provide information about the occupant and the objects within the physical-virtual situative spaces to other middleware components and the ADL support applications. Note that the situation monitor was simulated by a wizard in our current implementation. Refer to Section 5.3.

4.2.3. Activity recognizer

The activity recognizer is responsible for keeping track of the occupant's current physical-virtual activity based on the occupant's situational information in terms of selected and manipulated objects. However, objects within the perception space can also be successfully used for activity recognition [49]. The occupants tend to keep objects related to an activity closer to their body, or move to a location (physically and/or virtually) where they could access such activity-related objects. The activity recognizer is responsible for the following: 1) to keep track of the occupant's activities across the physical-virtual boundary; 2) to keep track of so called mandatory action(s) and operation(s) that would mark the possible initiation, interruption, resumption and completion of the occupant's physical-virtual activity; 3) to provide information about the occupant's current activity to other middleware components and the ADL support applications; 4) to allow for training the activity models during the initialization phase (for personal ADL performed by the occupant for the first time). Activity recognition based on an explicitly specified ontology is described in [31]. However, activity models that are learned from the occupant's behavior patterns can be adaptive and we prefer to consider such an approach. The activity models are supposed to be selected in such a way that they are scalable and adaptive to variations in the occupant's activity patterns. The middleware is not dependent on any specific mechanism for activity recognition and can be upgraded with different recognition techniques depending on the type of activities considered. The activity recognizer is intended to include supervised but unobtrusive online learning mechanisms to create the activity models (considering the complexity of ADL, unsupervised learning will be dealt with in future work). For further information about activity recognition, we refer to [49,50]. Note that the activity recognizer was also simulated by a wizard in our current implementation. Refer to Section 5.3.

4.2.4. Interaction manager

The interaction manager is responsible for managing the occupant's interaction with virtual objects (both physical and virtual manifestations) and the virtual manifestation of physical objects. The seamless switching between the physical and the virtual aspects of the smart home are taken care of by this component. As with the other middleware components, it provides information to the ADL support applications and attempts to facilitate natural, multimodal, ambient and calm interaction between an occupant and the ADL support applications. A detailed description of this component is given in [54].

5. Experimentation and exploration

There are many aspects of the proposed easy ADL home that could be explored. The focus of this paper is to understand a physical-virtual approach to smart homes as a concept, its usefulness and the potential for further improvements. We have used a scenario-based exploration of the physical-virtual approach to the design of smart homes.

5.1. Scenario: Another day in Jason's life

Jason is a 42 year old carpenter living in the easy ADL home in Umeå, Sweden. He has reasonable experience and interest in using computers. It is a cold winter morning when Jason is woken up by the bedroom photo frame that begins to sing his favorite song (Fig. 7a). Jason uses hand gestures to interact with the bathroom tub and to fill it up with hot water (Fig. 7b). The photo frame presents the news headlines. Jason has a quick look at it and moves to the bathroom. The bathroom mirror welcomes Jason and continues to present the day's news (Fig. 7c). Jason begins to brush his teeth and the shopping assistant application detects that his toothpaste is used up. The bathroom mirror presents the shopping basket virtual object, now with toothpaste added. Jason's day scheduler detects that Jason has an important meeting with an architect in the morning and informs him about the meeting (Fig. 7d).

It is time for breakfast! Jason opens his refrigerator to check what he has (Fig. 7e). Being clueless of what he could prepare for the breakfast, Jason stands still. The refrigerator informs Jason in a subtle way that the eggs are about to get old. It also presents a couple of recipes that he could try (Fig. 7f). Jason selects a recipe through speech commands and begins to view it. After a while Jason turns on the oven just as his office assistant informs him that he needs to confirm the latest designs sent by the architect before attending the meeting. Jason begins to check the different designs. It is now already 20 minutes (simulated with 5 minutes) since the oven was turned on (Fig. 7g). The easy ADL home informs Jason about the oven that was turned on 20 minutes ago. Jason is busy checking the designs online and does not respond to the oven *ON* status presented virtually through speech. The oven turns off automatically and informs Jason about it (Fig. 7h). Jason moves to the kitchen to continue cooking (Fig. 7i). The breakfast is ready. The office assistant informs Jason about a message from the architect requesting for a confirmation that Jason has the architect's latest edition, through the cutting board everyday object. Jason moves to the bookshelf (Fig. 7j) and grabs the architect's book and begins to check the edition (Fig. 7k). Jason has an old edition (Fig. 7l). Jason informs the office assistant application through speech commands so that the architect can arrange for a copy of his latest edition during the meeting. Jason moves to the dining room, prepares the dining table for breakfast and starts taking his breakfast (Fig. 7m). In parallel, Jason uses hand gestures for manipulating the architect's design (Fig. 7n) and there you go. Jason is happy with an updated design and a copy is sent to the architect. Jason's entrance door informs Jason that he has not taken his medication. Jason takes his medicines, and then leaves the easy ADL home for a meeting with the architect (Fig. 7o).

5.1.1. Discussion

In this scenario, Jason was woken up by the day scheduler application in an ambient way by playing his favorite song which is actually a virtual object. The song was played by the day scheduler application based on time (hard-coded to facilitate the experimentation scenario). Jason manipulates the virtual manifestation of the physical tub located in his bathroom (the physical actuation was simulated) and the bathroom tub virtual object provided him feedback by changing its state from *empty* to *filling-up*. Jason's

Fig. 7. Jason in the easyADL home, performing physical-virtual activities.

virtual activity of accessing the news headlines begins in his bedroom (news presented as text through the photo frame) and continues through his wearable headset (news presented as speech) while he is moving around, and ends in the bathroom (news presented as text through the bathroom mirror). A wizard (to be described in Section 5.3) monitors the changes in Jason's physical situation and selects an appropriate situation from a set of 32 possible situations using his wizard software. Since individual situations were hard-coded with a set of mediators, the news provider application first presents the news headlines through the photo frame object, then through his headset and finally through the bathroom mirror. The easy ADL home recognizes Jason's current physical activity of brushing teeth helped by a wizard (to be described in Section 5.3) who selects this activity in the wizard software. To perform this physical activity next time, Jason will need toothpaste. The fact that the toothpaste is used up was detected by the shopping assistant application using several contextual cues. The toothpaste holder, the waste bin, and the bathroom lamp were equipped with simple state change sensors (light sensors to be precise) that were fine-tuned to detect the following:

IF ((toothpaste holder *is_empty*) AND (waste bin *is_filled*) AND (bathroom lamp *is_on*)) THEN (toothpaste *is_empty*)

Refer to Fig. 4. The logic was selected with the intention of facilitating the subjects to enact the scenarios and experience the easy ADL home. We are aware of the problems with rule-based context inference and we do not attempt to address the problem of context inference, being beyond to scope of this paper. For more information on the sensing infrastructure, we refer to our previous work [52]. The shopping assistant application implicitly adds the toothpaste to the shopping list.

The day scheduler application reminds Jason about the meeting with the architect based on time (hard-coded). This information was presented in an ambient and subtle manner in the bathroom mirror without affecting his ongoing activity of brushing teeth. The old-food reminder application informs Jason about the eggs. The old-food reminder application communicates with the refrigerator through the middleware and gets information about old food in the refrigerator. The physical sensing in this case was simulated. Once the wizard enters in the wizard software that Jason has begun to prepare breakfast, the eggs information was presented to Jason. Jason's virtual status was also kept track of within the easy ADL home and the office assistant application informs him about the need to confirm the architect's design based on time (hard-coded for experimentation purpose). Sensors embedded in the oven detect the rotational position of the oven's on-off knob to know its state. We refer to [52] for more information about sensing. The safety and security manager application waits for 5 minutes after the oven is turned on and detects that no food item has been placed inside (simulated); it informs Jason about the oven status. Since the safety and security manager gets no response from Jason, the oven is turned off automatically (the actuation part was simulated), and the state of the oven virtual object presented to Jason is changed to *OFF*. The easy ADL home affords Jason to both physically turn *ON* the oven and to implicitly turn it *OFF*. The office assistant application requests for a confirmation from Jason that he has the architect's latest edition, based on time (hard-coded for facilitating a realistic scenario). The easy ADL home supports Jason in performing parallel activities (eating breakfast and confirming the architect's design). Natural interfaces like gestures were used to interact with virtual objects. The medication reminder application gets the input from the wizard that Jason has completed the activity of eating breakfast and has started the activity of preparing to leave the easy ADL home. Jason is supposed to take his medication before leaving the home and his current activity information from the wizard triggers the medicine reminder application to present a reminder to Jason.

In this scenario, Jason is often present in physical and virtual environments in parallel. Such physical-virtual situations compel smart home designers in considering the occupants' situation across the physical-virtual boundary. The activity of preparing breakfast was neither entirely physical nor entirely virtual but physical-virtual. The actual breakfast preparation included physical actions and virtual actions with seamless switching between them.

5.2. Experimental setup

20 subjects took part in the experimentation. The subjects were compensated with small gifts (worth around 50 SEK each) and a lot of praise for their commitment to be a subject for this study. The scenario-based experimentation was used to explore and provide insights about the physical-virtual design approach. 14 males and 6 females not part of the research team took part in the experiments. The subjects had limited previous knowledge about our work. Their age ranged from 18 years to 52 years with an average age of 28 years. The subjects were mostly affiliated with our university (student or employee), from different departments including medicine, engineering and social sciences. The subjects were either enacting single occupants (16 of them) or couples (4 of them). In the case of couples, only one person was supported by the easy ADL home at a time, since the easy ADL home was intended for supporting personal physical-virtual activities. The couples swapped roles so that both of them could experience the easy ADL home.

Considering the purpose of the easy ADL home, which is to provide support for the occupants in performing their everyday physical-virtual activities, we created scenarios where the occupants were supposed to perform everyday activities. In an attempt to understand and explore the physical-virtual approach the subjects performed the scenarios as part of two phases. During the first phase, the easy ADL home provided an environment similar to an ordinary home populated with purely physical objects. The mediators embedded in augmented physical objects were turned off so that the occupants could access virtual objects (and the mock-up applications) only through a stationary PC using the WIMP interaction paradigm. (The occupants did not wear the WLAN access point, the wristbands and the headset). During the second phase, the easy ADL home was used as a smart home with the mediators turned on, providing access to virtual objects (and the mock-up applications) and the possibility of manipulating the virtual objects through speech or hand gestures. The easy ADL home in this phase facilitated the co-location of physical and virtual objects. Each subject took approximately 3 to 4 hours to complete both phases of the experiment.

Three scenarios, namely a *weekday morning*, a *weekday evening* and a *weekend* scenario were used for the experimentation and the subjects were free to take part in those scenarios and perform the related everyday physical-virtual activities. Each subject performed at least 5 physical-virtual everyday activities such as *"preparing lunch"* where some parts of the activity would be performed using physical objects (like stove, knife, pasta packet, etc.) and other parts using virtual objects (pasta recipe, tomato sauce recipe, stove on-off status, etc.). The subjects chose physical-virtual activities to perform from a predefined set of 20 physical-virtual activities that we had provided ADL support for. In future versions of the easy ADL home, we intend to include more activities. Some physical-virtual activities like "*having dinner*" and "*watching a movie*" was performed by two subjects together. During the second phase of enacting the scenarios, the occupants were more often simultaneously present in both physical and virtual situations. The occupants used time multiplexing of their hands to manipulate physical objects and virtual objects in such physical-virtual situations. The occupants were speaking to their partners in the easy ADL home and once again used time multiplexing to manipulate virtual objects using speech commands. The perception of physical and virtual objects was space multiplexed for visual virtual objects and time multiplexed for audial virtual objects. The subjects were allowed to perform parallel activities, with the possibility of interrupting and resuming the activities. Our aim was to make the subjects feel at home and act as natural as possible under the circumstances. Human activities in a home environment usually involve mobility, and the subjects were producing a stream of changes to their physical-virtual situations: physical objects, mediators and virtual objects entering and exiting the subjects' situative spaces due to their mobility, observed by a wizard (refer to Section 5.3).

On average, the subjects took 10 min for getting used to gesture commands and 12 min for training the speech recognizer and getting used to commanding using speech. Handwritten notes were made by a non-intervening observer, complemented by log files generated by the augmented physical objects and the wearable computer to understand the occupant's interaction with physical and virtual objects, and in general to understand how they perform physical-virtual activities.

5.3. A Wizard-of-Oz technique

The use of Wizard-of-Oz technique for explorative HCI research is common and was used during an iterative design process in [14]. Considering that the aim of this study is to explore the physical-virtual aspects of the easy ADL home, it is important to understand the occupants' requirements and to obtain their feedback quickly and informally to continue further research in this direction. A Wizard-of-Oz technique [23,4] was used to compensate for the current lack of a fully functional and integrated situation monitor and activity recognizer (essential parts of the personal ADL support middleware); also motivated by the difficulty of anticipating the occupants' user experience while designing the easy ADL home. A simulation of the situation monitor and the activity recognizer was built, managed by two wizards (researchers) in such a way that the occupants of the easy ADL home have the impression of being part of a fully functional easy ADL home. We have addressed the problem of activity recognition in an immersive virtual reality environment [49,50], and sensing the state changes to physical objects [52] in our previous work.

One wizard was engaged in supplying information about an occupant's physical-virtual activity (which is the task of the activity recognizer, see Section 4.2.3). The physical activity context is observed by the wizard, with the aid of a web camera for areas that could not be seen from the wizard's position. The wizard identifies and uses the Wizard-of-Oz software to quickly notify which of the 20 physical-virtual activities (plus a "no activity" choice) the inhabitant is currently involved with. The virtual activity con-

Table 1

Occupant's experience in the easyADL home

Occupant's Experience in the easy ADL home	Score	Number of subjects
Physical-Virtual Activities (PVA)		
1. Convenience in performing PVA	(3.87)	15
2. Seamless integration while performing PVA	(4.45)	20
3. Efficiency in performing PVA	(4.05)	20
Integrating physical and virtual aspects		
1. Match between physical and virtual manifestation of objects	(4.05)	20
2. Synchronization between physical and virtual aspects	(4.37)	19
Interaction with physical and virtual objects		
1. Intuitive usability	(3.65)	20
2. Convenience in the interaction	(3.90)	20
3. Ubiquitous access of physical and virtual objects	(3.80)	20
4. User control	(4.35)	20
Physical-Virtual Environment		
1. Visual perception requirements	(4.32)	19
2. Audial perception requirements	(4.79)	19
3. Motor requirements	(2.89)	18
4. Cognitive requirements	(3.74)	19
Wearability and Ergonomics	(2.00)	20

text was provided by the mock-up applications that were developed to provide a stage for the occupants to enact the scenarios. Note that the virtual activity recognition by the applications was simple and directly based on state changes to virtual objects. The food-recipe-provider application, for example, contains recipes as virtual objects. By tracking the manipulation of those virtual objects (using speech or gesture commands), the occupant's virtual activity context was obtained. A set of 20 physical-virtual activities were hard-coded, including a "no activity" in case the occupant was not performing any meaningful activity from the activity recognizer's perspective (a wizard in reality). The wizard selects the physical-virtual activities in which an occupant is currently involved with through the wizard software. The Wizard-of-Oz software could in principle be extended to allow the wizard to provide information also about an inhabitant's current actions, operations, etc., but that would probably give the wizard too high workload and was ignored in this current implementation for this reason.

A second wizard was employed for providing input about the occupant's physical-virtual situation based on the situative space model described in Section 3.3. 9 stationary physical objects (refer to Fig. 4) like refrigerator, dining table, bathroom mirror, etc. that were augmented with mediators were used as a reference for simulating an occupant's situative space to be tracked by the situation monitor in a fully-functional easy ADL home. An occupant's physical situation is observed by the second wizard. An occupant can move around freely in the easy ADL home and on the basis of their physical location and orientation the second wizard indicates one of the 32 possible physical situations (the occupants can be in one of the 8 possible locations within the home and can be facing one of the 4 possible directions namely north, east, south and west). The number of locations and directions were chosen to suite the size and interior of the easy ADL home. When the second wizard notifies an occupant's physical situation, the occupant's virtual situations is automatically calculated from a combination of the mediators simulated to be within the occupant's situative spaces and the state of the virtual objects that they provide access to.

Any technical approach will have a degree of error: since the wizards were actual researchers of the easy ADL home with experience in handling the wizard software, they made very few mistakes, if at all any. This might affect the scores in Table 1 due to inflation. However, one could argue the reverse too. Computer systems might be more effective in some situations than the wizard (especially if activity context are to be considered at action or operation level). This is usually the motivation for intelligent automation in the first place. Hence, using a wizard might affect the results, but since there are many parts of the easy ADL home that are actually not controlled by a wizard, its influence could be considered minimal. Since WLAN, Bluetooth and Zigbee protocols were used in parallel, there were occasionally latencies of a few seconds (at worst) in the wireless infrastructure deployed. Such technical issues were not considered in this study.[2] The subjects were briefed about the existence of latencies before starting the experiments.

5.4. User experience within the easy ADL home

We are interested in knowing whether human agents would like to live in the easy ADL home designed using our physical-virtual approach. Heuristic evaluation proposed by Nielsen et al. [37] and later adapted to ambient displays by Mankoff et al. [30] was considered as a starting point for marking the user experience factors for exploring the physical-virtual approach to domestic living. We realized, however, that the easy ADL home will not be just a system for providing certain services; it will be an integral part of a human agent who occupies it. This makes it difficult to rely on usability evaluation techniques alone, introducing a need to consider user experience assessment techniques for further exploration. The easy ADL home should be enjoyable and support the fundamental needs of a human agent. Studying user experience was challenging considering the prototypical nature of this work, the complexity of the concepts explored, and the unavailability of a suitable framework for user experience studies. User experience is usually affected by the subject's preconceptions, situation and their internal state. For more information about user experience evaluation we refer to [3,17,35]. Refer to Table 1 for a formalized result of the subjects' experiences in the easy ADL home of interacting with physical and virtual objects and performing physical-virtual activities.

After enacting the three scenarios (both phase 1 and phase 2) mentioned earlier, each subject was given a questionnaire form to be filled out with scores between 1 and 5 for each question, rating how the user experience during phase 2 compares to their experience during phase 1. A score of 5 refers to very good experience during phase 2 in comparison to phase 1; similarly, a score of 4 refers to good experience during phase 2 in comparison to phase 1; a score of 3 refers to experience of equal value in comparison between phase 2 and phase 1; a score of 2 refers to bad experience during phase 2 in comparison to phase 1; and a score of 1 refers to very bad experience during phase 2 in comparison to phase 1. Usually, if the subjects provide a score of 3, then the central tendency bias might occur, but in our case the subjects compare their experience within the easy ADL home during phase 1 and phase 2, and by providing a score of 3, they agree to the non-existence of a real difference between the two phases. Questions like "how convenient was it in performing activities?" were used, where technical terms like "activities" (in our case, physical-virtual activities) were explained. Such a question would correspond to the convenience in performing physical-virtual activities. Similarly, questions like "how easy was it to interact with physical and virtual objects?" corresponds to the intuitive usability in interacting with physical and virtual objects.

Refer to Table 1 for the number of subjects who have answered individual questions. Unanswered questions were not included in the user experience score calculation. Some questions were answered after a personal interview session where the subjects were free to provide their comments and clarify issues made note of while they were enacting the scenarios. The interview removed some of the misconceptions that the subjects had and some of the scores were subsequently modified by the subjects.

One of the primary goals of this work was to explore the physical-virtual approach in supporting physical-virtual activities within the easy ADL home. Even though we have focused on personal physical-virtual activities in this work, the long-term goal is to facilitate both personal and shared physical-virtual activities. Only 75% of the subjects were willing to answer the question of convenience in performing physical-virtual activities. The remaining 25% of the subjects felt that it was inappropriate to speculate about convenience considering the issues of wearability and ergonomics that remain in our current implementation. Those subjects, who answered this question, initially reported the convenience in performing physical-virtual activities to be a bad experience for reasons such as the significant amount of cables in the apartment, the need to wear an access point on their chest, etc. After the interview session where their doubts were cleared and the prototypical nature of our work was clearly expressed, the subject modi-

[2] Evaluation of the wireless infrastructure within the easy ADL home is sent elsewhere [53] for publication during the writing of this paper.

fied their initial opinion resulting in a final score of 3.87 indicating good experience. The subjects began to speculate on the potential ergonomical design possibilities of the future. The importance of human activities and the need to treat them as first-class objects within the easy ADL home have resulted in a very good user experience with a score of 4.45. Thus the idea of seamlessly integrating virtual objects with the ongoing physical-virtual activities is promising. Efficiency in performing physical-virtual activities was given a score of 4.05 (indicating good experience during phase 2 in comparison to phase 1). This is not a surprise since the subjects performing physical activities continued to do so and when they began with virtual activities, they once again began to continue doing it without much switch between the physical and the virtual aspects of their activities while performing scenarios during phase 1. However, the subjects switched between the physical and virtual aspects of their current activity more often within the easy ADL home during phase 2. This is a positive result encouraging further research in the direction of integrating the physical and the virtual aspects of human activities within a smart home.

Integrating the physical and the virtual aspects were explored by checking the synchronization between the physical and virtual aspects of the easy ADL home. This is an important factor to consider for enabling the occupants to feel that both the physical and the virtual aspects are seamlessly integrated and that changes in one environment affects the other thereby creating a feeling that the occupants are part of a meta physical-virtual environment. A very good experience score of 4.37 was obtained for the synchronization factor. Some virtual objects are associated to augmented physical objects while others are not. For instance, the old food indicator virtual object is associated to a physical refrigerator, while an email virtual object is not associated to any specific physical object. Thus there is a need to match the virtual objects and the mediators through which such virtual objects are presented for manipulation by the occupants. A score of 4.45 indicate that our approach of matching the physical and the virtual associations of an object is an important factor to consider for further research. Such an association also introduces the possibilities of offsetting the weakness of an object's physical or virtual manifestation by the strengths of another in various situations.

The occupants' interaction with physical and virtual objects populating the easy ADL home had mixed scores. User control is an important factor to consider and the occupants have given a score of 4.35 indicating good experiences. We followed a mixed-initiative approach [22] where the occupants could control the objects by taking initiatives while the easy ADL home could also initiate and take control, but not in a fully automated manner. In the case of a conflict in interest between the occupant and the easy ADL home, the occupant had the ultimate control. Ubiquitous access of physical objects (i.e. through the virtual manifestation of those physical objects) and virtual objects obtained a score of 3.80 indicating that the user experience during phase 2 is slightly better in comparison to phase 1. However, even during phase 2 the occupants were not able to ubiquitously access all objects. As mentioned earlier, the match between the physical and the virtual aspects of an object is important. We believe that instead of presenting all virtual objects and the virtual manifestation of physical objects everywhere, it is important to have a more systematic way to deploy them. Issues like cognitive overload, perception overload, etc., should also be considered in populating the smart home with virtual objects. Our physical homes usually do not expose all physical objects at the same time. There are drawers, cupboards, and containers to store physical objects in an orderly manner. Perhaps there is something in this to take inspiration from in designing the virtual aspects of a smart home. Of course, the standard approach to provide ubiquitous access is by including additional mediators or by using wearable mediators that are always on. Intuitive usability (score of 3.65) and convenience in interacting with physical and virtual objects (score of 3.90) indicate a need to consider better interaction techniques in the future. For instance, the occupants used their hands both for manipulating physical objects and for hand gestures to interact with virtual objects. A simple time-multiplexing technique was used: explicit gesture commands were used to initiate and terminate interaction with virtual objects. Such explicit initiation and termination could be replaced by a more implicit sensing approach in the future. However, other challenges like understanding an occupant's current intention then comes to the fore and needs to be solved.

Living in a physical-virtual environment could introduce extra demands on the occupant's perception, action and cognitive abilities. A smart home that is well designed should make sure that the capabilities of a human agent are not misused or over-used. Human-centered parameters like visual perception requirement, audial perception requirement, motor requirement, cognitive requirement, and wearability and ergonomics were studied. Before the experiments, we assumed that augmenting a physical environment with virtual objects would lead to additional visual and audial perception requirements from the subjects (since the subjects need to perceive both physical and virtual objects) compared to environments with only physical objects. But to our surprise, the subjects provided a user experience score of 4.32 for visual perception experience and 4.79 for audial perception experience in the easy ADL home. This also shows that virtual objects could be co-located with physical objects within smart homes and that the unobtrusive presentation of virtual objects could be considered as an experience enhancer. The subjects gave a score of 3.74 for their cognitive requirement in the easy ADL home, indicating a more neutral attitude. During the interview session, it became clear that the subjects' moderate experience score was not due to the presentation of too many virtual objects that need to be cognitively processed by the subjects. This aligns well with the earlier mentioned score for visual and audial perception requirements. In fact, the subjects felt that it took some cognitive effort to recall the speech commands and the gesture commands since natural speech and gestures is not supported by the current version of the easy ADL home. Our immediate step will not be to include a natural language processor, but to introduce user-customizable speech and gesture commands. Motor requirements were given a score of 2.89, which indicates that additional efforts were required from the subjects' perspective to perform gesture commands. Both speech and gesture techniques for interacting with the virtual objects were welcomed by the subjects, but should be improved in the future.

5.5. General discussions

The proposed physical-virtual approach in designing smart homes is a general approach useful for non-specific user groups. This is evident in the user group that was selected for the experiments. The subjects were ordinary human agents with few exceptions without any specific health problems, including cognitive problems. One subject had minor problems with his vision and hearing. This subject did not answer the user experience questions related to visual perception requirements and audial perception requirements in a physical-virtual environment. However, the easy ADL home could be used as an assistive home for people suffering from mild dementia, as well as for other specific user groups in the future. The additional improvements that are required to accommodate special user groups within the easy ADL home will not be discussed in this paper, however.

There were some concerns with the wearability and ergonomics of the wearable computer that is part of the easy ADL home (score of 2.0). Refer to Table 1. This is an important issue to consider, especially if mild-dementia patients (one possible application area) are expected to live in the easy ADL home since some mild-dementia patients have the habit of removing wearable objects like wristwatch, belt, etc., when they are frustrated. Since many of the subjects were from the department of public health, there were concerns regarding the health hazards that might arise by living in such an environment over long periods. We are aware of the possible health hazards of radio communication, but our focus is on designing smart homes based on a physical-virtual approach; we leave the health issues to experts in the medical field to evaluate and provide further insights. Some subjects were concerned that living within a smart home might push normal human beings to behave in a certain way if such homes are fully automated. For instance, a smart home might automatically prepare coffee in the morning while its occupant is actually intending to skip coffee because of a stomach ache. The physical-virtual approach is aimed to give the human agents the ultimate control as discussed earlier. We are not intending to introduce automation that would negatively affect human agents' control within the easy ADL home. The virtual objects that are a part of the easy ADL home should rest in the background (similar to physical objects) and only come in to provide support to a human agent if some smart home application believes that some support is required. Some subjects felt that smart homes might be detrimental to human learning and development: the opportunities for human agents to exercise and improve their cognitive abilities. We appreciate the importance of this argument; however, we would like to make it clear that the smart home applications providing support in everyday situations are expected to be configured (set the levels of automation, etc.) by its occupants in the future according to their liking so that they could still exercise their minds if they wish to do so. In the case of mild-dementia patients, we assume that the application configurations will be taken care of by the caregiver or an occupational therapist. Many subjects acknowledged the possible benefits of the easy ADL home in enhancing the everyday life of its occupants. According to those subjects, it was extremely difficult for them to use computers in the kitchen or while having breakfast or while being in the bathroom. However, they were convinced that the easy ADL home would allow them to access virtual objects (virtual information) while being in currently awkward locations like kitchen, bathroom, etc. Even though some people were reluctant to see computers in such locations, they acknowledged the potential benefits in the future, especially when they get older and if there are some useful applications that could help them lead a better life at home.

There are many technical and technological issues that need to be solved before arriving at a fully functional easy ADL home. Modeling and recognizing an occupant's physical-virtual activities and physical-virtual situations are important and interesting challenges. Even if the occupant's situations are individually inferred within different environments at a particular instant in time, there remains a problem of integration. There is no single approach to such integration and it calls for further research. There are other challenges like providing support for collaborative and shared physical-virtual activities. Human beings in general are social beings and any smart-home research should consider scenarios wth multiple human agents. From a technological perspective, the easy ADL home currently facilitates WLAN, Bluetooth and Zigbee wireless communication protocols. Such an approach introduces interference that needs to be handled. Scalability issues with respect to the number of augmented everyday objects, virtual objects to some extent, physical-virtual activities, physical-virtual situations, etc., will be addressed in the future.

6. Concluding remarks

This article has presented our initial efforts in exploring the landscape of a physical-virtual approach to designing smart homes. Such an approach is important since more often the virtual aspects (virtual situations and activities) of the occupants within a smart home is ignored. The concepts of co-located physical and virtual objects, creating physical-virtual situations and enabling human agents to perform physical-virtual activities were studied. The easy ADL home was introduced and the possibilities of providing support for its occupants in performing physical-virtual activities of daily living (ADL) was presented. An architecture for the infrastructure of the easy ADL home, consisting of a set of augmented everyday objects, a personal ADL support middleware and a set of mock-up support applications, was also presented. Two middleware components, the situation monitor and the activity recognizer, were simulated using a Wizard-of-Oz technique because of the prototypical nature of our work. A user experience study involving 20 subjects was conducted in the easy ADL home to understand the physical-virtual perspective. Even though the experiments were conducted in a controlled setup, the easy ADL home acted as a living laboratory where the subjects could enact the scenarios in a fairly realistic manner thereby maintaining the ecological validity of the study. There are many conceptual and technological challenges that remain to be solved, but this work could be considered as an initial step towards the integration of the physical and the virtual aspects of a smart home.

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