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Beyond Four Walls: Towards Large-Scale Intelligent Environments

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Abstract. As Intelligent Environments research continues in its various guises, there is an increase in the scale at which investigation is being conducted. Projects are looking beyond single-room and apartment sized living-labs that have provided us with initial testbeds for early research and are envisioning grander designs on the scale of entire buildings, campus or towns. But now we must ask if the knowledge we have gained previously can scale upwards, or are new methods and models required to break free from the confines of controlled labs and into real-world deployments where multi-user is the norm not the exception. In the discourse of this paper, we describe what Large-Scale Intelligent Environments (LSIEs) are and identify some of the challenges that relate to realizing them. We highlight the importance of security, standards and infrastructure so that human users can roam confidently from place-to-place whilst enjoying a seamless continuity of experience.

Keywords. Large-Scale, Intelligent Environment, Ambient Intelligence.

Introduction

As technology permeates into every aspect of our lives and becomes embedded in the environments that we encounter on a daily basis, the dreams for a world of Ubiquitous Computing (UC) are being realized [1]. Augmented by the deployment of computational / artificial intelligence, the technology rich spaces that surround us are given an Ambient Intelligence (AmI) [2] [3] where software samples the real world, reasons with available information and pro-actively takes action. Such spaces are known as Intelligent Environments (IEs). Thus far, research has specifically focused on creating IEs from the familiar places around us in which a series of interconnected computational devices can be embedded.For example, IEs have been created in: *homes, vehicles, offices, classrooms, shops, libraries, and museums*.

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Much work has been done in the IE area as reflected by the literature, but as the field matures and we delve further, the scale of the environments we envision increases. A trend is emerging where the focus of research is being placed on investigating the challenges related to an increase in deployment size; a community is forming whose intent is to take IE research *"beyond four walls"* and realize the creation of Large-Scale Intelligent Environments (LSIEs) as real-world deployments that surpass early simulation and proof-of-concept work. This has a special relevance in the realisation of real-world applications and is one of the next steps required on the road to widespread adoption of IEs as instances of UC and AmI.

In this paper we first provide an overview of the conventional IE research scale - so called *"living-labs"*. We then provide an operational definition and description to measure what constitutes a Large-Scale Intelligent Environment (LSIE). It follows to explore the various requirements imposed upon them and describe the various forms in which they can manifest. We continue to examine some of the research community projects that are already identifying the shift from small-scale to large-scale.

1. Towards Intelligent Environments

We classify an IE as a logical space that contains a ubiquitous computing deployment (i.e. a set of interconnected computational devices that are embedded in the space itself) and is endowed with an AmI that perceives and affects the real-world through sensors and actuators. This is typically realized by embodying computational / artificial intelligence within agent-based software [4] [5]. Our future world is envisioned to be a set of these IEs through which we roam – each person visiting just a subset of the overall IEs in existence.

The remainder of this section provides some examples of UC and IE works including a case study on one IE in particular – the University of Essex *"iSpace"*. Being rich in interconnected computing devices, sensors and actuators; *"technology rich"* UC environments are example precursors to IEs - lacking only a quality of intelligence that is achieved through the deployment of suitably endowed software, such as intelligent embedded-agents. This subtle difference between UC and IEs has a large impact on the experience of occupants: while a UC is largely reactive to explicit command and control by users, an IE is more proactive and will take actions independently based on decision-making processes.

While not an exhaustive or detailed exploration of the living-labs that exist (or have existed), it is clear that there is a well-established international interest in UC / IE research from hobbyists and students through to academic and industrial researchers.

1.1. Ubiquitous Computing

Circa 2000, the Cisco *"Internet House"* was constructed on a full building scale, but its purpose was to showcase a home with always-on Internet connectivity and appliance automation (where the home and its appliances could be controlled over the internet). Similarly, the Philips *"HomeLab"* [6] was a fully functional apartment whose purpose was aimed more at user experience evaluation through the use of monitoring technologies (such as cameras and microphones). The greater extent of technology deployment in the MIT *"Placelab"* also took place in a dedicated apartment scale space and focused on the space construction, technology deployment and user experience. The Stanford *"iRoom"* [7] and National Institute for Science and Technology (NIST) *"smart space"* [8] have investigated the deployment of ubiquitous computing in the office / meeting room context. The Fraunhofer inHaus-Center run two labs called the *"SmartHome"* and *"SmartBuilding"* for research into many different areas of innovation including user interfaces [9], an area of research also investigated by the *"iRoom"* at LIMSI [10]. The *"Ambient Kitchen"* at Newcastle University [11] examines the application of UC within the specific context of a domestic kitchen, while the *"Classroom 2000"* [12] and *"SCALE-UP"* [13] projects have explored the application of UC in an education setting.

More recently, the Media Interaction Lab at the University of Applied Sciences Upper Austria have engaged in projects centered around the use of technology in collaborative and office based activities. Of particular interest here are the "*Nice Discussion Room"* [14] and the "*Active-Office"* [15]. Similarly, the *"Future Meeting Room"* [16] at Edinburgh Napier University has focused on the deployment of multi-touch technologies and large screen displays built into tables and walls.

Facilities such as the Duke University *"Smart Home"* have been used primarily for student projects, while the more recent emergence of community-lead *"hackerspaces"* around the world have promoted public participation in technology-oriented projects.

1.2. Intelligent Environments

Researchers have deployed intelligence into numerous spaces; the MIT *"Intelligent Room"* [17] was created in order to investigate new modes of Human-Computer Interation (HCI) and relied on the deployment of embedded cameras, microphones and displays. Here, AI was employed to enable the room to interpret and react to users through gestures (from video) and speech (from microphones). This work also incorporated person tracking (from video) for context awareness that reportedly enhanced the operation of other sub-systems such as speech recognition.

At the University of Colorado, the *"Adaptive Home"* used a centralised neural-network based controller that monitored approximately 75 sensors (light, temperature, sound, motion, door/window state, etc.) and then took appropriate action on related actuators in the home [18]. Over the lifetime of this lab, many experiments were conducted and results published regularly. Such a rich publication history also exists for the Georgia Institute of Technology *"Aware Home"* that explores a huge diversity of subject areas including sociological applications such as assisted-living and home-care [19]. The *"PEIS home"* at the Orebro University further extends the capability of environment manipulation that lies within control of software intelligence by deploying and integrating mobile robots into its infrastructure [20]. Elegantly, some labs (such as the iRoom at the German University in Cairo [21] and the MavHome at Washington State University [22]) are used to experiment with populations of software *"agents"* that provide the AmI (this is especially interesting when considering emergent behaviour from populations of agents that compete or collaborate).

The University of Essex *"iDorm"* mimicked single room student accommodation and was deployed with an extensive array of sensors and actuators that were integrated onto a network in a distributed / grid architecture [23]. Many investigations were carried out across several projects and PhD investigations throughout its life, including the use of neural networks, fuzzy logic, embedded agents and genetic algorithms [4] [24] [25]. The iDorm evolved into a larger 3-room space and was succeeded by the iClassroom [26] and the iSpace…

1.3. Case Study: the University of Essex "iSpace"

The *"Intelligent Space"* (known as *"iSpace"*) is a fully furnished apartment that is designed to emulate a typical two-bedroom home and contains a spacious kitchen / living area, bathroom, master bedroom and study / bedroom as shown in Figure 1. The vision became part of the design for a new computer-science and electronic-engineering building on the University of Essex campus in Colchester, UK. This afforded its construction to include unique features not otherwise available as identified by the previous iDorm work – a capacious false ceiling, false walls and an adjoining control room; all of which are hidden from view and can be used to deploy electronic equipment from embedded systems and sensors up to full size computers and control / automation electronics. This is enabled by the pervasive availability of mains power sockets, serial busses, Ethernet sockets, and wireless networks.

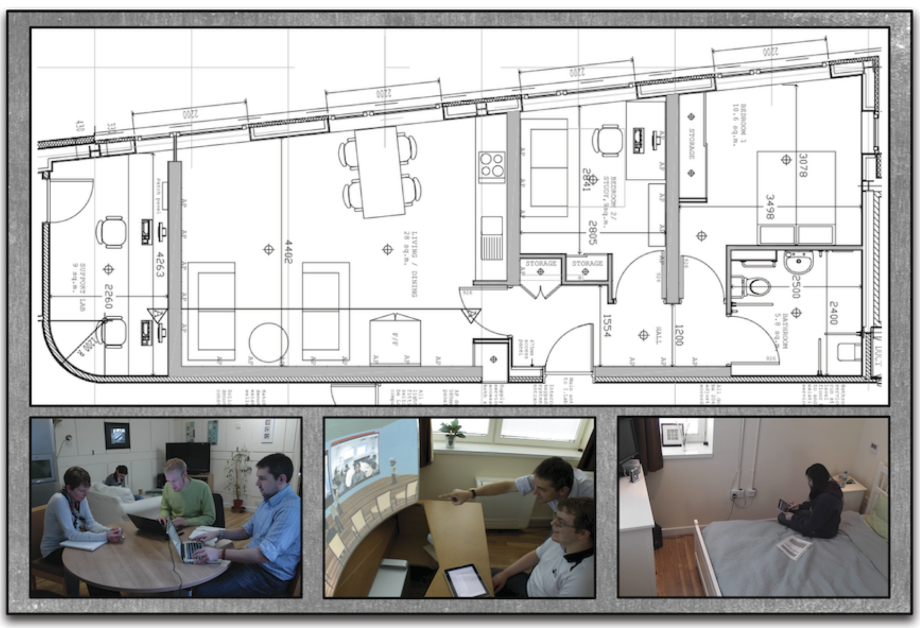

Figure 1. The University of Essex iSpace.

Within the iSpace, a myriad of heterogeneous technology is deployed; An Ethernet / Wi-Fi backbone harbours a distributed computing system that interconnects sensors, actuators and computational devices. For security and privacy reasons, this network is self-contained within the iSpace and is protected by a gateway / firewall that provides an uplink to the University network (and in turn, the Internet). The gateway also hosts certain services such as a DHCP server for dynamic device configuration inside the space and port forwarding for external access to certain resources. Figure 2 shows the general architecture of technology deployment in the iSpace, which builds upon the approach used in the iDorm by adding more technologies and increasing the scale of deployment.

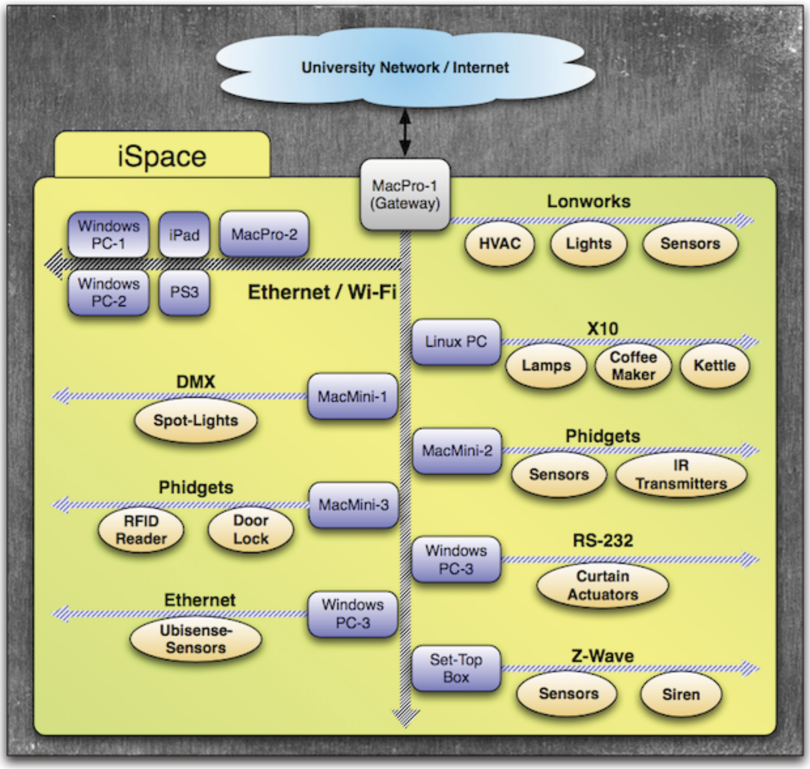

Figure 2. Technology deployed in the iSpace.

To facilitate the discovery and interaction of software components on the network, a middleware layer is deployed that sits on top of the IP network and presents a common *"view"* to the software layer (sometimes called an *"overlay network"*). Each *"peer"* on the network exports its resources through this middleware so that software agents can discover and make use of them. For example, a light-control agent may need to discover and monitor light-sensors and light-switches then discover and manipulate light devices. Thus the heterogeneous network of devices is rendered homogeneous to the software layer for use among different models of distributed computing (service-oriented, multi-agent oriented, component oriented, etc.). Universal Plug and Play (UPnP) has been used as the middleware layer in much of the research that has occurred, but researchers are free to use or develop the middleware that is appropriate to their projects under investigation (in some cases, the middleware itself was the subject of investigation [27] [28]). At the time of writing there are over 100 UPnP devices on the iSpace network, most logically map to some sensor or actuator (such as those shown in Figure 2.) while some are virtual groups (for example, each room has a virtual UPnP device that encompasses a group of individual lights) or higher level sub-systems (such as a user context system that is backed by a Ubisense real-time location tracking system composed of its own gigabit network and 12 sensors). UPnP provides the network with several features that are valuable in such a dynamic and real-time environment. In particular, discovery and subscription allow agents to discover and subscribe to UPnP devices in real-time. This permits an agent to receive asynchronous events when the network topology changes (devices arrive or leave) or when context changes occur (light levels / temperatures change, lights are switched / dimmed from other software sources, etc.).

It is worth noting that software agents can directly interact with all the deployed technologies permitting them to sense, reason and act without human intervention. Thus the iSpace can be placed under AI control (Fuzzy-Logic, Neural Networks, Genetic Algorithms and rule-based systems are most commonly used), where one agent is usually responsible for a particular function (for example security) or sub-system (such as lighting). This kind of relationship between AI and space forms a collective AmI and is a pre-requisite of truly intelligent environments that are required to exhibit user-centric environment adaptation.

2. What are Large Scale Intelligent Environments?

From the literature it is easy to see that a lot of work has been carried out in the IE area, much of it motivated from unique perspectives and investigations. Whilst this work has been proceeding, the need for experimentation has been limited in size to proof of concept work. However, now that the field is maturing and the world is becoming increasingly deployed with networked technology, new opportunities are arising which will allow larger-scale experimentation and real-world deployments to be explored.

The concept of expanding beyond four walls is a defining characteristic of a Large-Scale Intelligent Environment (LSIE); the scale of a LSIE could range from that of a multi-floor building up to an entire town or city, or even up to a country wide or global scale. There are a number of ways in which the vision of LSIEs could be achieved, they could be monolithic or composite systems occupying the physical world but could also exist in virtual reality, or even cross both the physical and virtual worlds using mixed reality. These various forms of LSIE are outlined in the next sub-sections.

2.1. Monolithic Form

In a monolithic LSIE, the whole systems is viewed and governed as a single entity, even though in reality it would most likely contain several sub-spaces. For example, a multi-floor office building could be governed as a single (monolithic) LSIE even though the physical space is separated into multiple floors, each with multiple offices that have their own individual requirements of the LSIE system. This kind of architecture will require extra effort to manage as the technology will cross borders of governance and responsibility, but is well suited to centralised control and therefore may be of use in specific cases despite a probable cost overhead (both for installation and maintenance).

2.2. Composite Form

LSIEs can be realised through the composition of multiple geographically or organisationally separated IEs that are electronically joined to form a larger compound. For example, an organisationally separated building scale LSIE could be decomposed into several individual and independent IEs (in turn of monolithic, composite, virtual or mixed-reality form). This could be useful in situations where each individual component IE requires its own governance (such as an apartment block, or office building). As the links between constituents are electronic, geographic separation could be global. For example, international offices of the same company could transcend their physical separation and be brought together. Similarly, *ad hoc* LSIEs can be formed to host events such as conferences and workshops without the need for participants to leave their parent countries / regions.

2.3. Virtual-reality Form

Entire LSIEs can be simulated / emulated virtually using 3D modelling software or games engines. This form of LSIE has the benefit that it is not restricted by things like the size of the physical space or the cost of equipping the environment with an extensive set of sensors and actuators. What's more, in the virtual world, time can be sped up or slowed making experiments more dynamic [29]. This form offers a safe and cheap way of developing / prototyping / training soft components – an especially useful function for AmI. Other applications of this form include games and social applications in which large numbers of users and non-player characters can interact.

2.4. Mixed-reality Form

As well as entire LSIEs existing in virtual space, they can also be made to span across both the virtual and physical worlds. This form of LSIE has interesting applications in the areas such as eLearning and teleconferencing, in which real-world objects can be linked to virtual representations and manipulated in real time. For example, a lecturer could be giving a talk at the University of Essex in the UK, while a student in another country attends the lecture virtually and is able to interact with the lecturer in real time by raising his hand to ask a question [30].

3. Other Considerations

For LSIEs to become commonplace in the real world, there is a large number of challenges, considerations and requirements that must first be addressed.

A paramount challenge is that of user acceptance, for which many personal concerns of the user and societal-factors must be taken into account. For example, the issue of balancing user-control and system autonomy is a challenge cited by many researchers of IEs [31]. For small-scale IEs, such as a single smart home, this may be a question of user preference (how much control they are willing to delegate to the system), however, for a LSIE that includes multiple different environments or contexts the challenge becomes much more complex. What's more, steps must be taken to deal with the sheer amount information to be processed and work to be done in controlling future LSIE systems, which may simply overload the user. Conversely, a LSIE will also have to deal with an overload of users. The majority of IE research to date has only been focused around single or small groups of users. A city-wide LSIE, however, will have to deal with hundreds of thousands of users, all with individual preferences and requiring different services to be provided constantly and reliably.

Privacy and security are also major challenges that must be addressed in realising the LSIE vision. With an abundance of sensors embedded deeply into many if not all of the environments that we inhabit, many of our personal actions and personal information can easily be detected, shared, and possibly misused by others. In real-world LSIE deployments, every step possible should be taken to prevent this and safeguard personal information. A further security concern, is the potential for malicious use (or abuse) of the system given that LSIE are intrinsically designed to be easily accessible by everyone anytime and via any of a myriad of devices.

4. Community Interest

4.1. Pervasive Computing at Scale (PeCS)

There has been recent attention surrounding the increase in scale of Pervasive Computing (PerCom) applications. Although there is a slightly different focus in the PerCom versus the IE field, they share many commonalities. For instance, much of the PeCS work identifies the increase in embedded / mobile computing with always on network capabilities [32] and examines how systems must scale in order to provide constant and consistent functionality to users that operate with multiple computing devices as they travel through the physical world. The diversity of work examined in this area is reflected by the international attention gained by activities such as the 2011 *"Workshop on Pervasive Computing at Scale"* that was sponsored by the US National Science Foundation. Such is the symbiotic relationship between the IE and PerCom communities that as one field advances, the other inescapably progresses.

4.2. Large-Scale Middleware

As ubiquitous computing deployments, there is a fundamental need for robust and reliable middleware that can securely integrate the various distributed resources of any IE. However, existing approaches have been shown to suffer in terms of both performance and reliability when scaled up. This shortcoming has been identified, investigated and resolved through the work discussed in [27] - co-funded by British Telecom (BT) and the Engineering and Physical Sciences Research Council (EPSRC). The advances made through this work improved the scalability and performance time of distributed middleware for use in IEs by three orders of magnitude and included complex object descriptions that could be queried in a distributed manor reducing the network overhead associated with other approaches.

4.3. ScaleUp

The ScaleUp research project is a collaboration between the University of Essex and King Abdulaziz University. It is focused specifically upon investigating the needs of migrating from current-scale IE research up to LSIEs. The work covers the individual areas of formal methods, infrastructure / middleware, video processing & distribution, intelligent agents and virtual learning environments. The project intends to deploy building, campus and global scale LSIEs through its scope.

4.4. Workshop On Large Scale Intelligent Environments (WOLSIE)

The 2012 Workshop On Large Scale Intelligent Environments (WOLSIE) has been created in response to the inevitable demand for the next phases in development of the IE vision towards real-world adoption. It has been born within the annual Intelligent Environments conference and engages the community of researchers that has emerged through the eight years of conference activity. This will offer a timely exploration of the technical and social LSIE challenges ready for future exploitation in the real world – a world that has been recently primed for the adoption of IE technology by the increasingly widespread infiltration of research that endeavours to create technology-rich buildings, neighbourhoods and cities that operate in a cheaper, greener, safer and more secure way.

5. Conclusions

As the state of the art improves and research in the area of Intelligent Environments progresses, the scale at which those environments manifest increases. We are now at the point when scalability of initial works is being considered and explored by a large community of researchers who share a common motivation to realise larger, multi-user Intelligent Environments in the real-world up to City-scale. The fruit of these investigations will yield a very exciting time as we see not only research, but also practical deployments with real users *"in the wild"*.

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