Defining Smart Space in the Context of Ubiquitous Computing

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ABSTRACT
Ubiquitous Computing (UbiComp), the third generation of computing, has produced many novel computing environments that are dynamic in nature and saturated with sensors, supported by a new breed of computing devices with alternative user interfaces. Although many of these environments have been built, there is a gap between their realisation and the underlying characteristics and principles of UbiComp. Many researchers have focussed on device integration, environmental monitoring, and information availability, and have ignored the need to support user mobility and the potential of using pseudo intelligence. This paper identifies core principles and characteristics of UbiComp environments and maps these to the domain of Smart Spaces in UbiComp. Specific Smart Space examples are critically analysed to determine if they truly meet the criteria to be part of UbiComp. From this analysis a novel definition of Smart Spaces in the context of Ubiquitous Computing is presented.

Keywords: Ubiquitous Computing Environments, UbiComp, Smart Space, User Mobility.

1 INTRODUCTION
Ubiquitous Computing, UbiComp, is a paradigm that was first defined over a quarter of a century ago by the seminal paper of Weiser in 1991 [1]. However it is only recently as technology has provided sufficient levels of miniaturisation and integration that true UbiComp environments can be deployed. In this sense UbiComp is still an emerging computing paradigm with the aim of supporting users in and intuitive manner. This emergent computing paradigm is very different to first generation mainframe computers and second generation desktop computing as it aims to support computation for anyone in anyplace at anytime. A fundamental aim in this emergent paradigm is the provision of services to users in an intuitive manner such that the end-device is not perceived as a computing element. End-devices such as smart mobile phones were not designed as computer devices but as a by product of integration and miniaturisation provide significant computational power that can provide additional services to end users.

This paradigm is characterised by; disappearing computers, where computational power is not provided in a manner such as by a traditional computer; and context-aware applications; that understand and react to their environment appropriately. Further key principles are support for user mobility and seamless integration of computing power.

UbiComp environments are unlike traditional desktop computing environments, they are highly dynamic, saturated with sensors, use emerging computing devices and utilise novel user interfaces.

Researchers in UbiComp have developed many UbiComp environments to address specific problem domains. However, we propose that many of these applications have a gap between implementation and underlying characteristics and principles of UbiComp. The majority of research in UbiComp has focussed on issues such as device integration, environmental monitoring, and information availability. In accomplishing this they have ignored the need to support user mobility, where computation power and network support is available, to provide services in an anytime, anywhere fashion and predict user needs.

This research gap does not fully leverage the power of UbiComp to support our daily tasks in an unobtrusive and mobile manner. A better understanding of UbiComp environments and their underlying principles and characteristics will open alternative opportunities to UbiComp research community.

This paper explores characteristics and principles of UbiComp environments with a particular emphasis on environments that are context aware, permit end-devices to collaborate, and provide suitable reasoning mechanisms to react to users needs. This focuses the domain of interest to the area of Smart Spaces within UbiComp. However we have noted, through our research, that
the term Smart Space is widely used to describe any environment that has some form of reasoning included. We identify that many such Smart Spaces do not adhere to the principles and characteristics of UbiComp and as such cannot be classified as Smart Spaces in Ubiquitous Computing. To confirm this we analyse a variety of Smart Spaces with the aim of identifying and mapping their underlying characteristics to those of UbiComp environments. We then provide key components and attributes that a true Smart Space in the context of UbiComp must possess. This incorrect use of the term Smart Spaces has lead to confusion among researcher and needs to be addressed. To resolve this confusion we propose a new definition for Smart Spaces in Ubiquitous Computing.

The rest of this paper has been organised as follows: Section 2 provides a review of UbiComp focusing on key principles and characteristics of UbiComp environments. Section 3 explores general views of Smart Spaces as applied by the UbiComp research community. In section 4 we present a discussion regarding Smart Spaces. Section 5 provides characteristics and the working definition of Smart Spaces in UbiComp. Section 6 presents conclusions and future work.

2 BACKGROUND OF UBICOMP

The root of UbiComp can be traced back to 1991 when the late Mark Weiser wrote his seminal article [1] about the 3rd generation of computing Ubiquitous computing, as opposed to 1st generation; mainframe, and 2nd generation; personal computers. Ubiquitous computing aims to minimise human interactions and intuitively integrate them with computing power at anytime, anywhere fashion [1]. Ubiquitous means being everywhere [2], however, in the context of UbiComp this too limited. It is necessary to describe it based on two perspectives; computing being hidden and being everywhere.

To accomplish UbiComp visions, many research communities have been established focusing on different themes. These themes include Pervasive computing, Disappearing computers, Invisible computers, Ambient Intelligence, Context-Aware computing. Although each theme focuses on its specific area, sometimes they are interchangeably used to mean UbiComp. This brings about a huge confusion the UbiComp research community. In this section we try to resolve this confusion by explaining each theme and their relationships with UbiComp.

- **Pervasive Computing:** As described by IBM [3], Pervasive computing refers to the computing infrastructure that enables the availability of computational power in an anywhere, anytime manner. This research theme utilises existing computer networking technologies to utilise computational power within the current environment. The ability to use a Virtual Private Network (VPN) facility from a Smartphone to connect to an office network is a good elaboration of this research theme.

- **Invisible/Disappearing Computers:** A good description of Invisible computers comes from Norman [4] and for Disappearing computers Streitz and Nixon [5], which focus on deployment of another breed of computing devices. Devices that are physically unseen and not perceived as computational devices. This research theme focuses on building novel technologies such as embedding computing power into to real objects. The long existing concept of Roomware [6] is a compelling example of this research theme, where objects have embedded computing that can communicate locally to users or over wireless networks.

- **Ambient Intelligence:** Ambient Intelligence [7] is a theme that is closely related to the previous theme though it focuses more on intuitively integrating users with the computation power. As with Invisible/Disappearing computers, this research theme focuses on building new forms of user interfaces. However, Ambient Intelligence focuses on reducing user interaction time. The recognition technique used in IBM BlueBoard [8] is a good example of this research theme.

- **Context-Aware Computing:** In a similar manner to Ambient Intelligence, Context-Aware (CA) computing [9] emphasises the reduction of user interaction time with computation power. However, the distinction between these two research themes is their approaches. While Ambient Intelligence deploys new forms of user interactions, CA computing relies on information captured by sensors to predict users’ intentions and act on their behalf [10][11].

As UbiComp emphasises computing being hidden, everywhere, with seamless integration, each of the above research themes can be readily classified as UbiComp environments. Pervasive computing facilitates the availability of computing power everywhere, while Invisible and Disappearing computers address the aspects of being unseen and devices not being perceived as computers. Ambient Intelligence and CA computing, on the other hand, facilitates seamless integration of users and computing power. However, both Ambient Intelligence and CA computing depend on pervasiveness and the disappearance of computing power to accomplish their goal it is clear that each
of these research themes are subsets of UbiComp.

Each of these research themes focus on accomplishing the underlying aim and principle of UbiComp; to support humans in their everyday activities. To achieve this goal, however, we have summarised these research themes in three phases; proliferation of computing devices, natural interface development and application-centred research [12], as in figure 1. The initial phase is characterised by computing devices which are of different sizes, particularly miniaturised, and most importantly capable of knowing their locations [1, 13]. Network infrastructures to support interconnection of these devices is a core requirement of this research [1]. Work performed by Want et al [13] on integrating palm-sized computers into an office network is a compelling demonstration of this research.

![Figure 1: Evolution of UbiComp research](image)

Unfortunately, these technologies did not work well with traditional keyboard and mouse input technologies, and demand for intuitive user interaction devices was identified [12]. This led to a new shift in UbiComp research, natural interfaces, that focus on human speech, gestures and movement. UbiComp research considered capturing these natural actions using custom built UbiComp devices. The development of Pen-based input device is a good example of this research [14].

The third phase, which we are currently in, is research on designing and developing of infrastructure and applications to leverage existing and novel UbiComp technologies. Abowd and Mynatt [12] refer to this phase as application-centred research. Its main focus is to better support everyday tasks and observe the effect UbiComp has on our lives. The work on the Cyberguide application [15] which involves providing a PDA to assist in guiding people is a good example of this research. It is this theme of better supporting life that has driven the focus on implicit and intuitive user inputs.

2.1 UbiComp Environments

Unlike traditional computing environments, UbiComp environments are highly dynamic and saturated with computing devices embedded in everyday objects that gracefully integrate with human activity [16, 17]. Such smart objects include interactive whiteboards, tables and smart walls that we can interact with. These environments are characterised by many sensors that perceive the physical environment [18]. Unlike other computational spaces, UbiComp environments are highly dynamic and heterogeneous [19]. Computing resources keep on changing as devices enter and leave, and users within these environments experience different contexts. Consider the following scenario:

“An employee wants to show a set of figures to his manager. As he approaches her office, a quick glance at his tab confirms that the boss is in and alone. In the midst of their conversation, the employee uses the tab to locate the data file on the network server and to request a printout. The system sends his request by default to the closest printer and notifies him when the job is finished.” [13]

This employee-figure scenario depicts what it is like being in a UbiComp environment. Services move with the user without requiring any interactions, hidden computing everywhere.

Three elements are fundamental in these environments; UbiComp devices, sensors and network infrastructure [13]. UbiComp devices can be compact, mobile and provide functionalities that were previously difficult to be supported in 1st and 2nd computing generations. The employee’s palm-sized mobile computer, referred as a tab, exemplify these devices, as in figure 2.

![Figure 2: Palm-sized mobile computer](image)

Additionally, sensors are mandatory to perceive the current state of the physical environment. This perception, referred to as context [20], is an
important aspect for understanding the environment. In the employee-figure scenario above, context includes the unique identity of the user and devices around him, and the location of the user. Finally, network infrastructure is mandatory for device connectivity as well as for routing computational resources within the environment.

With these core elements in place, UbiComp environments require the following capabilities;

2.1.1 Support for User Mobility
Mobility is an integral part of our everyday life, and so UbiComp environments must support mobility [16]. Mobility in this sense means the ability to support users’ computational needs while moving from one point to another within the environment. These needs must consider both the computational tasks and resource availability [21]. Consider the ability of an environment to move a computational task, such as editing a document, from their desktop computer to a Smartphone. This is an example of supporting true user mobility. To achieve this, however, an appropriate network infrastructure is required. This permits continual interaction of a user with an end device within the UbiComp environment [1].

2.1.2 Seamless Integration
As UbiComp focuses on minimising manual human interaction and integrating computing devices into the environment, the provision of seamless connectivity is an important attribute [22] of a UbiComp environment.

For example, consider a mobile phone, and the number of cellular base stations it automatically connects to and disconnects from in a particular day in order to ensure continuous service. This is a complex task that requires significant management. Likewise in UbiComp environments, services should follow users whenever they go within network range of a UbiComp environment without demanding user interaction.

<table>
<thead>
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<th>Definition</th>
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<td>A region of the real world that is extensively equipped with sensors, actuators and computing components [23].</td>
<td>This research does not explicitly involve reasoning (intelligence) or mobility which are significant elements for Smart Spaces in UbiComp.</td>
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<td>Work environments with embedded computers, information appliances, and multi-modal sensors allowing people to perform tasks efficiently by offering unprecedented levels of access to information and assistance from computers [27].</td>
<td>Although this definition clearly shows the underlying meaning of mobility in UbiComp, it ignores the need of demonstrating intelligence in these environments.</td>
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<td>A well-defined area that is embedded with computing infrastructure that enables sensing and controlling of the physical environment [16].</td>
<td>This research does emphasise the need to proactively act on user’s behalf however only provides some support for user mobility in this environment.</td>
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<td>Sentient, information-rich environment that sense and react to situational information to tailor themselves to meet users’ expectations and preferences [18].</td>
<td>The degree of intelligence is limited to individual agents and does not encompass intelligence in the environment as a whole.</td>
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<td>An environment stipulated by intelligent agents, services, devices, and sensors to provide relevant services and information to meeting participants on the basis of their contexts [24].</td>
<td>This research focuses on using abstract semantic models and context brokers to provide appropriate service. It partially supports user mobility though it depends on centralised computational model.</td>
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<td>An environment that acts as an intelligent agent that perceives and acts on the environment through sensors and actuators to reason about and adapt to its inhabitants [25].</td>
<td>This project, MavHome focuses on using agents to collect information about users to predict users’ mobility, the focus is on location algorithms.</td>
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<td>An assistive environment that can sense itself and its residents and enact mappings between the physical world and remote monitoring and intervention services [26].</td>
<td>The key attribute of this environment is the ability to change its state. In particular the GatorTech Smart Home uses numerous independent local Smart Spaces to address specific user needs.</td>
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Table 1: Selected Definitions of Smart Spaces

Although the employee-figure scenario illustrates the look-and-feel of UbiComp environments, a Smart Space provides enhanced functionality. In a Smart Space scenario the employee would not have to be near their manager’s office for notification as to whether they were in or not. Moreover, the employee should not require to manually search for data files. In other words, a Smart Space should understand the context and the users’ needs and act on their behalf.
3 SMART SPACES: GENERAL VIEWS

Smart Spaces, at an abstract level, can be identified as UbiComp environments that can understand and react to human desires. The research into these environments is motivated by continual miniaturisation of computing devices and the possibility of augmenting humans’ everyday tasks [5]. Moreover, the possibility of converging UbiComp technologies with machine learning techniques have boosted the research interest in Smart Spaces [28].

Unlike a typical UbiComp environment, Smart Spaces incorporate processes to make the environment smart or pseudo-intelligent. These processes can be categorised as a bottom-up and top-down cycle [29]. Sensors monitor and collect physical information in a bottom up, low level, process while decisions are made by a reasoning mechanism and the resulting actions are implemented from a top-down, high level, manner.

While many researchers claim to have built Smart Spaces in UbiComp, these environments actually do not comply with UbiComp principles. While the majority of these environments facilitate seamless device integration, environmental control and information availability they ignore need to support user mobility. Other Smart Space definitions overlook the necessity of understanding and reasoning about an environment as a whole unit. Due to this inadvertent misuse of the term, the definition of Smart Spaces in the context of UbiComp is vague.

To demonstrate these deficiencies, we have reviewed existing research in order to understand how these environments operate and see if they map to fundamental principles of UbiComp and then determine if they fit into Smart Spaces in UbiComp context. Key limitations of the following sample environments are analysed in section 4.

3.1 EasyMeeting

EasyMeeting [24] is a smart meeting environment with the aim of providing appropriate services and information to participants and the speaker within its perimeter. This environment exploits the distributed nature of intelligent agents, computing devices, services and sensors, integrated by a context-aware broker (CoBra) to provide a coherent view of the environment. In addition, CoBra mediates sharing a coherent view of the environment with intelligent agents.

The current state-of-the-art for EasyMeeting is the exploitation of meeting context to deliver appropriate services and information. By meeting context Chen et al. [24] mean meeting related events such as identity of participants, speakers, the start time of the meeting, slide presentation and other related tasks. To achieve this, however, the environment uses sensing devices to detect Bluetooth-enabled devices, such as phones and PDAs, of participants, and a speech recognition system to recognise and respond to speaker’s voice.

3.2 MavHome

“MavHome is a multidisciplinary project with the aim of developing a smart environment that acts as an agent of its inhabitants” [25]. The ultimate goal of this environment is to provide maximum comfort to its inhabitants with minimum operational costs. Ideally this environment will be able to predict, based on daily movement patterns, where the inhabitant goes and automatically do things that were previously performed manually.

MavHome leverages integration, artificial intelligence, multimedia and database systems to meet its goals. The environment monitors activity through sensors then the information is transferred to an agent that selects appropriate commands to effect the environment. The captured information from sensors, along with the proposed decision is stored in a database for future reference. Additionally, the environment monitors users’ mobility by periodically searching for terminal sensors worn by inhabitants.

3.3 GatorTech Smart Home

“Programmable pervasive spaces” or “Smart home in box” are common synonyms for GatorTech project [26]. This project aims to develop a smart environment that is assistive to its inhabitants, particularly elderly or disabled people. Ideally, this environment will be able to sense its surroundings and monitor its inhabitant and automatically establish communications with remote monitoring and intervention services.

The GatorTech Smart Home is saturated with novel computing devices, referred to as smart technologies, which are sensors and actuators integrated to accomplish specific pseudo-intelligent operations. The current state-of-the-art of the GatorTech environment is its generic middleware which facilitates automatic integration of system components for collaborative actions.

Apart from these specific Smart Spaces examples many researchers have used the term Smart Spaces in many different ways. For instance, based on the definition proposed by Satyanarayanan [16], any UbiComp environment can be regarded as a Smart Space, but this does not take into account the availability of a suitable reasoning mechanism. While, the definitions proposed by Al-Muhtadi [18] and Nixon [23] describe Smart Spaces as a computing environment distributed with intelligent agents integrated to accomplish a common goal. Although many of these environments may demonstrate some degree of global or unified intelligence, their reasoning capability is limited to individual devices or localised areas. Additionally, they do not provide flexibility for utilising mobile computational devices that are within the

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environment. As a result they are not capable of continuously supporting computational task mobility for a user. In effect, these environments are more similar to the work of Mozer [30] focussed on building a self-learning smart environment, ACHE, which primarily involves automation of home appliances.

4 DISCUSSION
In this paper we argue that the Smart environments reviewed in the previous section do not qualify as being Smart Spaces in UbiComp for three specific reasons, openness, dynamism, reasoning.

4.1 Lack of Openness
In this aspect we identify the openness of the environment to supporting computational task mobility and supporting the arrival of mobile devices with high computational power.

While some Smart environments partially utilise mobile devices brought in by their inhabitants, the majority do not fully utilise their capabilities. For instance, in EasyMeeting [24] mobile devices are limited for identification of participants at the meeting. Additionally, MavHome [25] and GatorTech [26] projects focus on integration of sensors, agents and actuators which are stationary and predefined. These environments do not appear to accommodate additional mobile devices introduced by their inhabitants. In effect, lack of openness hinders the ability of these environments to continuously support user mobility.

4.2 Limited Dynamism
The key difference between UbiComp and desktop computing is the dynamic nature of their environments. In other words, users in UbiComp experience different contexts as they move, as opposed to desktop computing users who operate in a single environment; the context and resources remain unchanged. Although the majority of Smart environments reviewed utilise UbiComp technologies, still they operate under the same norms as desktop computing. They focus on integrating computing devices and ignore the dynamic nature of the environment. In many cases they use static sensors and devices to monitor the environment and the inhabitants.

4.3 Global Reasoning
Smart environments reviewed provide limited reasoning capability. This reasoning capability is often limited to agents that act locally. As Smart Spaces are saturated with many heterogeneous computing devices and sensors, this requires a general environment reasoning mechanism in order to mediate between these devices and provide decisions that proactively support human desires.

In this paper, we contend that most of the Smart environments research is based on intelligent automation of devices to support their inhabitants and not true Smart Spaces in UbiComp. These environments do not provide true integration of devices with support for user mobility. In effect, they provide limited support for continuous access to computational tasks and resources for their inhabitants. For example the research in Gator Tech [26] and MavHouse [25] is similar in concept to the ACHE [30] work, even though they differ in technology and approaches.

5 SMART SPACES IN UBICOMP
UbiComp environments are open and dynamic, and the support for user mobility is a basic principle and crucial. Therefore, Smart Spaces in UbiComp need to be both predictive and highly integrated to take advantage of the nearest devices to support what we refer as true user mobility. By true user mobility we mean the ability of an environment to continuously provide access to computational tasks and resources anywhere and everywhere in that environment.

5.1 Attributes of Smart Spaces
To reflect the basic principles and concepts underlying UbiComp, we argue that Smart Spaces in the context of UbiComp must have four components that will also support true user mobility; UbiComp devices, wireless networks, sensors and a reasoning mechanism, as in figure 3. Although these components have been used in previous incomplete definitions, in this paper we emphasise their capabilities in the support of true user mobility.

5.1.1 UbiComp Devices
UbiComp devices go beyond desktop computing to perform tasks that were previously considered computationally difficult. There are many devices that have a range of sizes and costs
that allow them to be everywhere and almost be invisible [1, 13]. The employees’ palm-sized mobile computer, shown in figure 2, is an example of such a device. UbiComp devices require support for both intuitive user interactions and user mobility.

5.1.2 Wireless Networks

UbiComp environments are saturated with computing devices and sensors that are interconnected with wireless networks. Wireless networks in Smart Spaces support user mobility and facilitate integration of computing devices and sensors to form sensor networks. It is these sensor networks that are responsible for acquiring and distributing information from individual sensors to a reasoning mechanism in Smart Spaces [29]. Collecting situational information, context-awareness, is a key attribute of Smart Spaces provided by sensors.

5.1.3 Sensors

Sensors can be widely defined as a physical device that augments the physical sensing of the environment [31]. Based on this definition, audio microphones and video cameras are regarded as sensors, though are only now becoming sufficiently miniaturised to be unseen. Smart sensors go further to include limited reasoning of the sensed information [29]. Sensors provide real-time data about the environment that allows it to effectively react to user’s desires. Regardless of their capabilities, sensors, when connected with a wireless network, enable Smart Spaces to model and communicate the current state of the physical environment to the reasoning mechanism.

5.1.4 Reasoning Mechanism

Smart Spaces need to be highly integrated with sensory and computing devices. This means that these environments collect vast amounts of information on a daily basis. In order to fully utilise this information, Smart Spaces must deploy reasoning mechanisms to filter and manage the information. The role of the reasoning mechanism is twofold; modelling of collected information into abstracted useful knowledge, and reasoning with this to effectively support users’ activities [29].

5.1.5 User Mobility

In addition to these elements Smart Spaces in UbiComp must support true user mobility within the well defined and constrained environment of UbiComp and seamlessly integrate computing devices to provide transparent and intuitive user interaction. Most of the reviewed research has fulfilled the latter aspect, while the former, mobility, is still elusive. The majority of research is limited to the view of providing information rich environments. Their focus is to provide information effectively and efficiently to their inhabitants and ignore the aspect of mobility of users by supporting the mobility of computational tasks.

5.2 Smart Space: Definition

For a Smart Space in UbiComp we have clearly identified the key components required such as UbiComp devices, wireless networks, sensors and reasoning mechanism. In addition we identify the need to support true user mobility to fully define a Smart Space in UbiComp. From these components and the true user mobility attribute we propose the following definition for a Smart Space in UbiComp as;

“A highly integrated computing and sensory environment that effectively reasons about the physical and user context of the space to transparently act on human desires”

By highly integrated we mean an environment that is saturated with UbiComp devices and sensors that are fully integrated with wireless networks; by effectively reason we mean a pseudo-intelligent reasoning mechanism for the environment as a whole, not just to an individual device or component; by user context we refer to an individuals profiles, policies, current location and mobility status; finally by transparently act we mean an environment that is responsive to human and supports user mobility without user awareness or requiring user interaction.

6 CONCLUSION

In this paper we have identified basic characteristics and associated principles for environments to be classified as UbiComp environments. This has been done to address the issues of researchers claiming to develop Smart Spaces in UbiComp that clearly do not match these characteristics and principles. Specific examples have been reviewed and critically analysed in order to support the case for clarification of the use of the term Smart Spaces in the context of UbiComp.

As this 3rd generation or wave of computing emerges from research environments and become deployed in the real world many researchers want to place their research under the banner of Smart Spaces in UbiComp. However it is necessary to fulfil both sets of criteria for ubiquitous and smart in order to use this term appropriately.

In the paper we have identified the issues with these Smart Space definitions and propose a new definition for Smart Spaces.

6.1 Future Work

The paper identifies specific examples of Smart Spaces that are not classified as being truly a subset of Smart Spaces in the context of UbiComp. In a future paper, currently under development, we are developing a taxonomy of Smart Spaces that will provide a suitable classification for these examples.
7 REFERENCES

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