Ubiquitous computing – a multidisciplinary endeavour

I. D. Zaharakis, A. Komninos

Abstract— **Nowadays, an increasing number of sensors are becoming embedded in the everyday objects or in the environment at a low cost. Accordingly, our living environments are populated by an increasing number of artefacts, i.e., objects enhanced with sensing, computation and networking abilities. In addition, people are increasingly using mobile devices as intermediaries between themselves and the artefacts. As a result of this continuing trend, an elementary Ambient Intelligence (AmI) infrastructure has become installed, though still fragmented, information appliances are commercially available, and Ubiquitous Computing (UbiComp) applications are being deployed. This paper discusses the course of UbiComp evolution since its inception and the inevitable criticality of interdisciplinary approaches in UbiComp. We conclude by highlighting the impact of UbiComp introduction in society and future opportunities that may rise in this exciting field of science.**

Keywords — **Ubiquitous Computing, Ambient Intelligence, Pervasive systems.**

I. INTRODUCTION

AS Norman anticipated [1], with the proliferation of networks, information appliances and artefacts, large amounts of data start being diffused in our living environment and knowledge about patterns and context of human activities are generated. In addition, new generations of mobile devices are being developed having increased capabilities and resources. These devices can now be considered as powerful information processing, storage and access tools, which can be used as facilitators between people and a smart environment, as they can be aware of the artefacts in their vicinity [2].

The concept of Ambient Intelligence (AmI) is used where intelligence pervasively exists in the surrounding environment. Such an environment is sensitive to the presence and activities of people in it, and remembers and anticipates their actions and habits, respectively. It is the overall environment of which devices, applications, services and their interfaces may form part, as do the networks, sensor systems and other technologies that enable it. On the road to realising UbiComp applications and AmI spaces, several technical issues need to be resolved, in order to make these systems adoptable and usable. Some of the major requirements a UbiComp system has to confront are: mask the heterogeneity of networks, hardware, operating systems etc.; tackle mobility and unavailability of nodes; support component composition into applications; context awareness; preserve object autonomy

even for resource constraint devices; be robust, fault tolerant and scalable; adapt to environmental changes; and be usable by novice users via understandable designed models [3]. Furthermore, privacy issues are of utmost importance to UbiComp researchers, designers, service providers, and users. It is prominent that the analysis, design and development of UbiComp systems deal with multidisciplinary areas and require a holistic framework.

The next sections introduce the basics and the vision of Ubiquitous Computing and Ambient Intelligence, define the core properties of UbiComp systems and present architectural approaches. Moreover, we discuss issues of human-computer interaction, context awareness and privacy and conclude by examining the impact of UbiComp in society.

II. ORIGINS OF UBICOMP

Was the course of UbiComp, in the sense of devices and services available to us today, predictable? Mark Weiser, discussed a vision of computing for the 21st century in 1991 [4] where the problem of information overload and the need of specialist training to use a computer are diminished by the integration of the computer into the background of our world. He later discussed his concepts further by describing the Coming of Age of Calm Technology [5]. By coining three core principles of UbiComp, Weiser envisaged not only the embedding of *interconnected*, *context and self-aware* intelligence in everyday objects, but also the *silent integration* and *subtle and natural interaction* that humans should have with technology. Satyanarayanan [6] was amongst the first that attempted to break the vision into solid research questions and directions, by acknowledging the need for *adaptive behaviour*, examining the concept of *local awareness* (context) and whether this can be indeed scaled to produce global awareness. He also proceeded in identifying the computing disciplines from which we would need to draw, in order to materialize the vision of UbiComp [7]. Later work by Hansmann [8] built on the questions of Weiser and Satyanarayanan and proclaim the core properties of UbiComp to be those of *Decentralisation* (of tasks), *Diversification* (of devices), *Connectivity* and *Simplicity*. Much later, in 2009, Poslad [9] added to the principles laid out by Weiser by discussing concepts of *autonomy* and *artificial intelligence* as desirable (but not necessarily core) properties of UbiComp.

Charged with the task of planning research for the European Union's agenda, Ducatel et al. [10] envisaged scenarios for the development of the information society, which they collectively called "Ambient Intelligence" (AmI). This future involved highly embedded, intelligent and adaptive

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computing, located practically everywhere in our constructed environment to support humans in their daily tasks.

Sundmaeker et al. [11] described in great detail the vision of "The Internet of Things" as the Future Internet, were all "things" (entities afforded with computational intelligence) will be networked under common infrastructures and interfaces. IoT focuses on one of the core principles of UbiComp, namely that of connectivity. Though interfaces are mentioned explicitly, the IoT is not concerned with human-computer interaction but rather the way services (and things) interact with one another to request services, share data or collectively combine to solve decentralised problems.

III. UBICOMP TODAY

On the road to realising UbiComp applications and AmI spaces, several technical issues need to be resolved, in order to make these systems adoptable and usable. Some of the major requirements a UbiComp system has to confront are: mask the heterogeneity of networks, hardware, operating systems etc.; tackle mobility and unavailability of nodes; support component composition into applications; context awareness; preserve object autonomy even for resource constraint devices; be robust, fault tolerant and scalable; adapt to environmental changes; and be usable by novice users via understandable designed models [3]. Furthermore, privacy and security issues are of utmost importance to UbiComp researchers, designers, service providers, and users. The intra-disciplinary collaboration needed for UbiComp is thus apparent, with experts from disciplines such as operating systems, networking, security & privacy, computer architecture, software engineering, sensing and actuation and human-computer interaction. Many of these scientists find themselves constrained by their own experience. The spread of availability of powerful personal computers has allowed scientists to focus on very narrow aspects of their domain taking resources as a given. However, UbiComp has forced many computer scientists to go back to the basics of optimisation, operating system concepts, networking protocols. Each attempt at optimising, adapting or re-thinking computing fundamentals for use in UbiComp systems, pushes Computing towards collaboration with other, closely aligned sciences. But even with computing scientists working to the best of their ability to design and prototype UbiComp systems, the fact that these systems are so widely accessible (due to their pervasive nature) to new types of non-traditional users and under so many different contexts and circumstances, brings a layer of complexity to the use of these systems never before encountered by computer scientists.

UbiComp systems have to be usable in the simplest ways possible. Traditional HCI has mostly concerned itself with visual displays, where the majority of interactions takes place under explicit control or instruction from the user. However, the mobility and pervasiveness of UbiComp systems force us to consider not only interaction through multimodal interfaces where non-visual senses play a highly elevated role, but also the nature of implicit interaction which is often instantiated by the user's mere presence, the interaction of intelligent agents

on behalf of the user, or the analysis of other types of interactions (e.g. human-physical) and their interpretation as implicit instructions to an ambient system.

To answer such questions pertinent to the sensory ability, information coding through non-visual stimuli, cognitive abilities, social semantics, emotional responses and reactions etc, we need to resort to sciences normally well away from the field of computing. As such, advances in the physiological and psycho-cognitive sciences can significantly inform UbiComp system development. What is interesting is that while UbiComp can assist with overarching goals led by other disciplines (e.g. energy consumption [12], green transportation [13]), these disciplines often offer significant insights and developments that can further progress the development of UbiComp itself. A recent example is the work done by clinical research to decipher brain activity, which in turn can be used by UbiComp to develop a new modality for interacting in non-clinical scenarios [14].

IV. BRIDGES TO THE INTANGIBLE

Conti et al. [15] discuss a notion of the world where they consider the physical and cyber as two distinct planes, parallel to one another. While the physical world is populated by tangible entities and phenomena, the cyber world is comprised of data, pertinent to their physical counterparts. Additionally, management structures for these data as well as policies and protocols are features of the cyber world. In this vision, UbiComp is the necessary "glue" that binds the two worlds, allowing the physical entities to access cyber entities, but also helping us to understand the hitherto unknown properties of the physical world by examining their cyber representations.

In a sense, this model is not too far off the reality, which we have built for ourselves today. However, an information space has always existed prior to our ability to create cyberspace. In summary, a model of cyber-physical convergence has to consider not only the physical attributes of reality, but also the intangible information space that is created both by natural law and knowledge hidden in our collective or individual conscience. In Plato's description of the *idea*, a perfect instance of any entity exists in an information plane parallel to ours. Interestingly enough, the cyber world, in its attempt to model our own world, considers our physical and logical spaces as the plane of ideas and contains imperfect representations of these, though it also contains representations, which can be entirely artificial, pure figments of our imagination. We might thus consider UbiComp to address the convergence of the *cyber*, *physical* and *logical* planes of existence. We could consider these as distinct planes, but perhaps it's best to think of these as infinitely interwoven threads from different fabrics, akin to the modular constructivism designs of sculptor Erwin Hauer[1].

In Conti's parallel planar view of the cyber-physical world, UbiComp allows us to build ad-hoc bridges, or portals with the cyber world (or is it vice-versa?). Through its pervasive and mobile nature, these bridges are gradually "*democratised*"

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[1] E. Hauer (1926-.) is an Austrian-born sculptor known for his "continua" sculpting notions of infinity using webs of 3D interwoven modules.

as more and more people are enabled by technology and given the capability to build such bridges anytime and any place. Technologies such as mobile information access impart everyone knowledge which would have otherwise remained hidden, inaccessible, or a privilege of the few. One such interesting and upcoming technology bears the name of Augmented, or Mixed reality.

According to Azuma [16], Augmented reality (AR) core properties are the combination of physical (and, according to our prior definition logical) with the virtual (cyber), real-time interactivity and registration in 3D. While AR is primarily a visual art, it cannot be said that augmentation need only involve vision. Researchers in the past have examined haptic feedback and audio for navigation, although the applications of these have been primarily focused on coding information on one or two dimensions. SoNav (Sound Navigation), a project that we are currently trialling, attempts to enhance the user experience using audio augmentation (organic city sounds) in virtual 3D space around a user. If we consider the interwoven planes discussed earlier, one might consider thus UbiComp to be a gravitational force battling to bring together the three interweaved planes, to converge them into single nodes or areas of *maximum knowledge density*. We could as such consider that different UbiComp technologies exert varying gravitational forces upon the fabric of reality. In this respect, AR is probably nowadays the technology that has the greatest impact factor.

V. THE META-SOCIETY

In most research efforts so far, focus has been placed on the individual. Yet the true potential of UbiComp lies with the consideration of use by groups, societies, as democratic access to the planes is its nature. A classical problem in early UbiComp days was "when should a phone ring or vibrate"? This scenario is still not solved today. The social context of the single user must be understood and considered fully and if that wasn't hard enough, so must the social context of other users interacting with her. Ducatel et al. [10] attempted to discuss the impact of Ambient Intelligence in society, through their scenarios. Though their speculations are far from unreasonable, how can we truly understand the impact of UbiComp in society when we don't even understand society itself? The problems of social theory – how the little daily interactions we have with one another shape into big impacts in society. So far we have had little chances of understanding how this occurs but with everyone now being effectively a "sensor", we could in theory mine this universe of social interactions to uncover the secrets of existing social dynamics.

In the grander scheme of things, understanding the world through UbiComp and thus the impact of UbiComp in the world, requires that we employ our best data management, networking, signal processing, pattern analysis and machine learning methods to gain primary data and knowledge. This however cannot be done unless under the careful application of data privacy and security strategies. We need to combine our data acquisition and analysis techniques with mathematical theories on chaos and complexion, borrow from statistical mechanics and combine our best quantitative findings with social theories to leverage outcomes and conclusions that will shape our way forward [17]. Multi-disciplinarity thus is a pre-requisite for the exploration of UbiComp problems.

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