The Vision and Technical Foundations of Ubiquitous Computing

Friedemann Mattern

Continuing technical advances will soon lead to an abundance of very small and very cheap microprocessors, which are equipped with sensors and have wireless communication capabilities. Information processing will then become ubiquitous and will permeate almost every type of object. We illustrate the vision of Mark Weiser, the visionary behind ubiquitous computing, and describe its technical foundation and current trends. We also give a brief overview of its implications for privacy and outline possible applications.

Keywords: ubiquitous computing, pervasive computing, sensors, embedded processors, networking, information appliances.

1 Towards Smart and Interconnected Things

Today, the Internet connects almost all of the world's computers. From a technological point of view, one could describe "ubiquitous computing" as the prospect of connecting the remaining things in the world to the Internet, in order to provide information "on anything, anytime, anywhere." Putting it in another way, the term "ubiquitous computing" signifies the omnipresence of tiny, wirelessly interconnected computers that are embedded almost invisibly into just about any kind of everyday object. Using small sensors, such embedded processors can detect their surroundings and equip "their" object with both information processing and communication capabilities. This adds another, completely new dimension to such objects – they could, for example, find out where they were, what other objects were in their vicinity, and what had happened to them in the past. They could also communicate and cooperate with other "smart" objects and, theoretically, access all sorts of Internet resources. Objects and appliances could thus react and operate in a context-sensitive manner and appear to be "smart," without actually being "intelligent".

Due to the continuing advances in the fields of computer science, microelectronics, communication technology, and materials science, this vision of a comprehensive computerization and interconnection of everyday objects could become a reality in the not-too-distant future. Since ubiquitous computing could trigger a completely new set of applications where, for example, cooperating objects created new emergent functionalities, this vision could in time also be successful from a business point of view. This would doubtless have enormous economic and social implications. It would also raise issues relating to technology acceptance and the creation of a world in which reality gets closely coupled to – and in some respects even merges with – our information-based cyberspace.

2 Moore's Law and Weiser's Vision

Constant advances in microelectronics have become commonplace: Moore's Law, formulated in the sixties by Gordon Moore, states that the computing power available on a micro chip doubles approximately every 18 months and, in fact, this has proved to be an extraordinarily accurate prediction of chip development since then. Comparable exponential growth can also be observed in other technical areas, such as storage capacity and communication bandwidth. Seen the other way around, prices for microelectronic functionality with the same amount of computing power are falling radically over time.

This continuing trend will lead to an abundance of very small computers in the not too distant future, heralding a paradigm shift in computing applications: processors, memory devices, and sensors will be assembled to form a wide range of cheap "information appliances", which will be wirelessly connected to the Internet and custom-built for specific tasks [Want/Borriello 00]. Such microelectronic components could also be embedded into almost any kind of everyday object, thus adding "smartness" to it, for example by modifying its behaviour dependent on the current context of the object. Eventually, information processing and communication capabilities will be integrated into objects that, at least at first sight, do not look like electrical appliances at all – "computing" capabilities thus become ubiquitous.

The term "ubiquitous computing", denoting this vision, was coined more than ten years ago by Mark Weiser, a researcher at XEROX's Palo Alto Research Center [Weiser 91]. Weiser sees technology only as a means to an end, which should take a back seat in order to allow the user to fully concentrate on the task at hand. In this respect, the Personal Computer as a universal information technology tool would be the wrong approach, since its complexity would take up too much of the user's attention. According to Weiser, the computer as a dedicated device

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should disappear, while at the same time making its information processing capabilities available throughout our surroundings.

While Weiser sees the term "ubiquitous computing" in a more academic and idealistic sense as an unobtrusive, human-centric technology vision, industry has since coined the term "pervasive computing" with a slightly different slant [Hansmann et al. 01]: Even though its vision is still to integrate information processing almost invisibly into everyday objects, its primary goal is to use such objects in the near future in the fields of electronic commerce and Web-based business processes. This pragmatic variant of ubiquitous computing is already beginning to take shape: IBM Chairman Lou Gerstner once described his vision of the "post-PC era" as "a billion people interacting with a million e-businesses through a trillion interconnected intelligent devices…"

Figure 1: Mark Weiser (1952–1999), the visionary behind ubiquitous computing

3 Technical Foundations

The driving force behind these dynamic technological developments is the field of microelectronics, where progress has truly fulfilled Moore's Law during recent decades. Recent achievements in the fields of microsystems and nanotechnology are also of increasing importance. One example is tiny embedded sensors suitable for detecting a multitude of environmental parameters. Another interesting development is that of radio sensors that can transmit pressure or temperature changes across several meters without any explicit source of power. The energy required for transmitting the measured data, and also for adding an individual identification code to the data, is obtained through the measurement process itself using piezoelectric or pyroelectric materials.

So-called "smart labels" or "radio tags" also operate without a built-in source of power. Such labels contain transponders that receive a high frequency signal from a distance of up to two meters. The energy of the signal is used by the transponder to decode the message, power its internal information processing capabilities, and send back its reply. This allows up to several hundred bytes to be transmitted and received "over the air" within the space of a few milliseconds. The transponders have form factors of a few square millimeters, are as thin as a sheet of paper, and are available as flexible address labels for less than one Euro apiece.

Complete computer systems on a single chip measuring only a few square millimeters and including several kilobytes of memory (enough for a simple operating system) can already be manufactured for a few Euros. This technology is mainly used for smart cards, but can also be found in embedded systems, where processors are integrated into all sorts of appliances to carry out control tasks. These processors – together with suitable sensors, I/O-interfaces and communication capabilities – are the primary components that could make real world objects "smart". For objects that communicate with each other, research is underway to create processors that also contain appropriate communication components on the chip itself.

Significant advances have also been made in the field of wireless communications. For ubiquitous computing, short-range communication technologies that use very little energy are extremely relevant. One such example is the already well-established WLAN technology (with a range of about 100m and data rates of about 10Mbps), but even more relevant are wireless room networks. For the latter, the emerging Bluetooth standard (10m range, 1Mbps data rate) is currently becoming a de facto standard. Bluetooth modules are presently available at form factors of about half a the size of a match box, but by integrating memory, high-frequency, and digital components on a single chip, much smaller sizes are expected in the near future. Improved methods for determining the position of mobile objects (for example, using satellite-based systems such as GPS or the radio-based methods used by mobile phones) are also being developed.

Another exciting development is the field of "Body Area Networks", where the human body itself is used as a transmission medium for electrical signals of very low current. Simply by touching an object, an individual identification code can be transmitted. (This could, for example, be supplied to the body by a wristwatch). This could be used for simplified access controls, customized device configuration, or billing of services. Another target for experimentation is the field of "wearable computing", where clothing made from special fabrics is able to conduct electrical currents. Fibers that can change their electrical resistance when they are stretched or bent will certainly make for interesting man-machine interfaces.

Recent developments in the field of materials science will give computers of the future a completely different shape, or even mean that computers are no longer recognizable as such because they blend into their surroundings. One important example in this context is light-emitting polymers, which enable displays consisting of highly flexible, thin and bendable plastic foils to be created. Research is also taking place into "electronic ink" and "smart paper", which will enable pen and paper to become truly mobile input/output media. However,

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this technology is still a number of years away from becoming usable in practice, for example in the form of a computer as a foldable road map. Another significant option currently under development is laser projection from within eyeglasses directly onto the retina, as a replacement for traditional output media.

4 Applications and Effects

From a technological point of view, simply by extrapolating Moore's Law, one can estimate what could – theoretically – be possible within the next few years. Which of these developments will be economically viable, however, is much harder to predict. It is equally difficult to predict how such personal information and communication technology will be accepted: the satellite-based mobile phone system Iridium proved to be a spectacular failure, whereas the European short-message-system (SMS) for mobile phones has recently been a completely unexpected success.

In any case, the potential of applications using smart everyday objects seems immense, especially if one assumes that objects could, theoretically, use spontaneous networking technology to cooperate with each other, access information stored in online databases or on the Internet, or use any suitable Internet-based service available. The limits are less of a technological nature than economic or even legal: what kind of information should an object remember, and to whom should it be allowed to pass it on? It also remains unclear which, if any, of the oft-cited stereotypical examples will ultimately play a role in the future: the refrigerator that automatically reorders milk before it runs out? The communicating umbrella that warns of an approaching shower if a recognized pair of shoes leaves it behind on the way to the front door? Or even "intelligent" clothing that reports pulse and breathing rates to one's general practitioner if they deviate from individually-customized norms?

The first objects that might benefit from a ubiquitous connectivity and "collective intelligence" will probably be higher-priced devices that can offer substantial added value by using sensor-based information processing and communication capabilities: an automatic lawn sprinkler will profit not only from being networked with humidity sensors in the ground, but also from obtaining the current weather forecast free from the Internet. Similarly, parents might appreciate it if their kids' shoes or hi-tech jackets reported the current location of their loved ones. And if all cars knew both their own position and that of neighbouring cars, many collisions might be avoided.

The ultimate vision of ubiquitous computing, however, extends well beyond such applications, towards scenarios that verge on science fiction. We are talking here about ordinary things such as pencils that digitize (and process) everything that is written with them, or suitcases that remember the places they travelled to and the objects that were carried in them (or even recall conversations they overheard?). Apart from being an extraordinary technical and organizational challenge in itself, extending the Internet into everyday objects also raises the question of how we would communicate with our smart objects, and how we could put this new technology to good use for society as a whole.

Taken to its ultimate conclusion, a world made up of such communicating smart devices will most certainly lead to a significantly changed perception of our surroundings, triggering substantial social and economic changes that will ultimately be of political relevance as well. The social and cultural consequences of such developments are still very unclear, but our personal privacy will certainly be affected, since cheaper, smaller, and more effective sensors and processors allow for a much more comprehensive automated surveillance of the environment, including what we do and say [Mattern/Langheinrich 01].

If the age of ubiquitous computing extends the Internet into everyday objects, this alone will result in enormous challenges for our privacy: whereas until now only a relatively limited view of a person could be obtained by rummaging around in data, a much more comprehensive picture can be painted in the ubiquitous vision, including a person's interests and inclinations, as well as their weaknesses. Previously, the "informational surveillance" of a person was clearly limited to the time he or she spent using the PC and the WWW, but in a world full

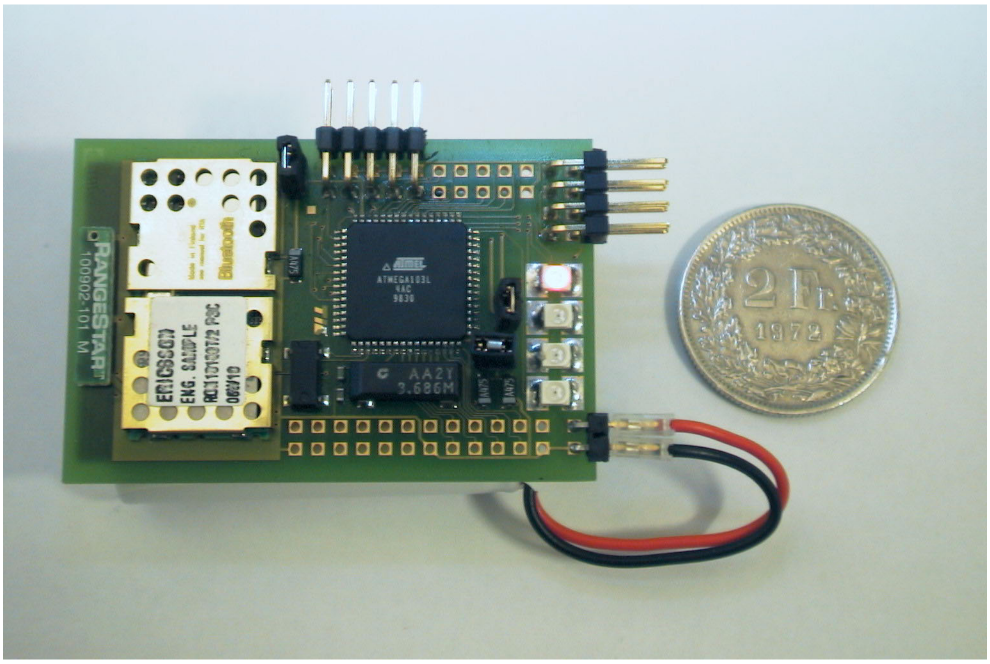

Figure 2: A "Smart-Its", a universal sensor platform with Bluetooth support (ETH Zürich)

of smart and talkative everyday objects, a clear distinction between "online" and "offline" will often no longer be possible. Clearly, a substantial amount of effort needs to be expended in order to prevent this brave new world of smart, interconnected objects becoming an Orwellian nightmare.

Despite all the difficulties that remain to be overcome, it seems clear that the trend towards computerizing and interconnecting almost all objects will continue. Completely new applications will be created around such smart devices in the future, and the maintenance and ongoing development of the necessary infrastructure could give rise to a whole new industry. However, how such a radically new technology will affect us personally, as well as society as a whole, remains unclear. Only time will tell!

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