The Challenge

The field of ubiquitous computing and some key computer science research challenges that it entails were described more than a decade ago by Weiser [1]. He defines ubiquitous computing as a phase in the development and use of computer systems in which they permeate our environment and are integrated in most artefacts, adding useful information services in an unobtrusive manner. One of the most important goals is to ensure that information services remain in the periphery of users’ consciousness until the need for them brings them to the centre. This is what is meant by ‘calm’ technology [2].

Many of the goals of ubiquitous computing are encompassed by a challenge to create a sentient building on a large scale (1000-10,000 people). Such a building would be equipped with sensors and associated processing machinery integrated into systems that simplify and enhance its everyday use. This poses a Grand Challenge because the construction of mobile and ubiquitous systems on this scale and with this degree of complexity and universality has many unresolved problems.

The ubiquitous computing research community has already made significant advances towards this goal. Research teams across the world have produced sentient spaces [3] encompassing one or two prototype rooms that detect the locations of people and devices and sense lighting, sound, temperature and other signals. Handheld or wearable computers with attached sensors and wireless connectivity provide users with continuously updated contextual information relevant to their current activity. Appliances and everyday artefacts sense and respond to changes in their human and physical environment. To expand to larger scale deployments and environments populated with non-specialist users requires a coherent effort from the Computer Science community to develop robust, convenient and efficient methods for the use of such sensory data and its integration with the digital environment.

Purposes

In order to elucidate the problem and facilitate the evaluation of a Sentient Building, we propose a series of sub-goals, each with well-defined criteria for accomplishment:

- **Environmental awareness and control** – The Sentient Building uses sensors to determine its environmental state and occupancy and takes steps to reduce pollution and to optimise the use of energy and of physical resources. This involves continuous adaptation to the mode of use of each part of the building. For example, providing lighting, and air conditioning only for areas where humans are currently working, and using automatic shutters to minimise light pollution.

- **Adaptive utilisation of space** – By adapting to a user’s state, the Sentient Building supports and enhances the working modalities of its users. Spaces can reconfigure dynamically according to the context inferred from sensor input. A basic but powerful example is the teleporting of information contexts - that is, the reconfiguration of idle computers to reflect the current information context (the desktop and other sensory inputs) of an approaching user. This promotes dynamic co-operation and collaboration between colleagues and is a supporting component of hot-desking – the dynamic allocation of desks to optimise the utilisation of space – although hot-desking demands more sophisticated contextual support if its deployment is to conform with the calm technology perspective.

- **Interruption and interaction management** – The Sentient Building uses context information from sensors and communication devices to evaluate the current interaction state of a user. It must provide for users who need to be contactable in any space that they occupy, and others that do not wish to be available because of the task they are currently performing (perhaps they are in a meeting). Specification of this context can benefit from predictive analysis based on user behaviour but it will probably also involve some user participation.
• **Navigation** – In dynamic working spaces with changing occupancy, dynamic routing assistance is needed in order to reach new locations and other personnel. Sensors must be capable of sensing the building shape and contents and modelling it with sufficient accuracy to enable detailed route planning. A user may, for example, wish to find Bob while following a route that takes him past Steve, but avoids Alice. As Bob approaches a lift, the algorithm should aim to have the lift waiting at the correct floor, and preparing to move in the correct direction. Having available such a-priori information about potential users adds a new dimension to the standard algorithms used to control elevators.

• **Crisis Management** – Sensor systems and information dissemination channels would be included that greatly enhance user safety. Algorithms should exist to efficiently and safely route people out of the building in the event of a crisis. A detailed state report should be available to emergency services that provides information such as accurate maps, fire spread extent, the positions of remaining personnel, structural integrity, etc. The auditing of safety on a continuous basis could be another function of the system. (The need for effective social, as well as official, auditing will be a major issue brought to the fore by the deployment of sentient and ubiquitous systems.)

• **Public Policy** – The Sentient Building offers an opportunity to ascertain policy approaches that ensure public participation in the benefits and safeguards against the risks in a world that is permeated with sentient information systems. It can assist in developing the equivalent of the Data Protection Registrar for sentient systems.

**The Research Issues**

Here are six major open research issues that will have to be resolved before the Sentient Building can be achieved:

• **Modelling and providing access to the state of the physical world:** The construction and distributed storage of a world model together with the notification of changes in its state to interested system components are challenges. This includes the fusion of sensor data and the development of methods to infer the state of people and physical objects. For example, systems should be able to infer the physical state of a person (sitting, standing, lying, kneeling) with a similar accuracy to humans. (Note that we do not demand advances in artificial intelligence, but rather the development of specialised approaches to each inference problem.)

• **Spontaneous interaction and self-configuration for mobile and user-installed devices:** A building’s configuration, information services and occupants are in a state of continuous flux. Yet users should have continuous access to all of them. This poses a major computer systems challenge – to provide access to new system interfaces without manual intervention.

• **User interaction in a ubiquitous computing environment:** Ubiquitous systems are often described as ‘invisible’ and for most of the time this is the desired state, but when there is a need for interaction users will need cues and operational interfaces in a form that is compatible with their physical context.

• **The design and management of security mechanisms that address users’ privacy concerns:** Many location-aware services and functions can be delivered anonymously; the anonymity should be manifest and guaranteed to users.

• **Effective operation with limited resources:** Computers that are deployed in the physical environment or worn by users must be capable of operating effectively with limited electrical power, processing, storage and networking capacity. Approaches to be investigated include ‘cyber-foraging’ - the use of computing resources in the local environment to augment those in mobile devices.

• **Scale and dependability:** Research on dependable real-time systems has focussed on smaller systems with much more limited functionality. The Sentient Building project will demand a major step forward in this area.
A Grand Challenge in Computer Science: 
The Sentient Building (Part II)

Answers to submission questions.

Why the UK?

The UK houses research institutions that are near the top of the fields identified in this position paper. Interdisciplinary projects such as the EPSRC Equator project have demonstrated that careful co-ordination and co-operation can yield advanced results within relatively short timescales. Moreover, the UK already has substantial experience in the deployment and use of sentient systems at several universities and industrial research labs.

Significance

Is it driven by curiosity about the foundations, applications or limits of basic Science?  
The Sentient Building offers the chance to amalgamate many research concepts from a wide range of fields, along with exciting new innovations, and asks what can usefully be achieved by doing so. It investigates new scientific challenges, and the opportunity to implement the results on a truly large scale.

Is there a clear criterion for the success or failure of the project after fifteen years?  
The sub goals identified in Part I have clear success criteria, which can be quantitatively measured.

Does it promise a revolutionary shift in the accepted paradigm of thinking or practice?  
If the challenge goals are achieved, we expect that it will induce a major change in the way computers are built, communicate, and are used. It calls for revolutionary new interfaces that will change the way we work for the better.

Does it avoid duplicating evolutionary development of commercial products?  
Current ubiquitous computing research is conducted in research laboratories. The radical shift in computing approach that the sentient building demands means that any company producing commercial products would be taking a large business risk since there are many open research issues and widespread implementations can only pay dividends in the long term.

Impact

Will its promotion as a Grand Challenge contribute to the progress of Science?  
The challenge presents a futuristic vision that promises to change the day-to-day lives of people, whilst demanding exciting scientific achievements. It favourably promotes the impact Computer Science can have on society.

Does it have the enthusiastic support of the general scientific community?  
Many respected scientific institutions already have groups researching ubiquitous computing issues. Ubiquitous computing always captures the interest of scientists and the public alike.

Does it appeal to the imagination of other scientists and the general public?  
The challenge offers the opportunity to integrate and advance many branches of computer science. It can implement concepts from highly specialised areas in a ubiquitous manner, and is limited only by imagination.

Because the challenge deals with integrating complex machinery into familiar surroundings, the benefits of meeting it are easily put in context for the general public. The challenge carries with it ideas previously found only in the realm of popular science fiction, and will easily capture the public imagination.
What kind of benefits to science, industry, or society may be expected from the project, even if it is only partially successful?

Achievement of any of the sub-goals identified in Part I will each significantly advance an important field within computer science. For example, improvements in self-configuring systems will improve the world in which we live regardless of whether or not they are implemented in a sensor-equipped environment.

Industry will need to cultivate stronger links to ensure device interoperability, and the field is fertile for innovation. Society will benefit from new modalities of working, and an increased confidence in using technology. We will see greater safety, and the emergence of new multi-user communication streams.

**Scale**

*Does it have international scope?*

The sub-goals span different computer science fields and are potentially cross-disciplinary. Achieving each requires input from research institutions that lead the relevant field, which clearly has an international scope.

*How does the project split into sub-tasks or sub-phases, with identifiable goals and criteria, say at five-year intervals?*

Part I identifies a series of sample sub-goals.

*What calls does it make for collaboration of research teams with diverse skills?*

Sentient systems can be realised in many different ways. Teams may use centralised or distributed approaches, ad-hoc or integrated communications, existing or revolutionary software design, and stateful or stateless architectures, to name a few diverse approaches.

**Timeliness**

*When was it first proposed as a challenge? Why has it been so difficult so far?*

The challenge has not stood for a lengthy period because technology has only recently reached a stage where devices can be deployed in any manner approaching ubiquity. Current difficulties stem from the research issues identified in Part I.

*Why is it now expected to be feasible in a ten to fifteen year timescale?*

The Sentient Building needs small, low powered, but high specification devices and sensors. Advancement in sensor technology is currently proceeding at a fast pace, and miniaturisation of electronic devices is continuing in a similar fashion. The ubiquitous computing field can already exhibit small environments with limited capabilities. Integrating results from the related fields will provide the foundations to achieve the goal within fifteen years.

*What are the first steps? What are the most likely reasons for failure?*

The diverse set of research issues identified above suggest that the problem is unlikely to yield to a purely frontal attack. But research efforts aimed at the integration of smaller-scale ubiquitous systems are the best way in which to evaluate progress and highlight deficiencies. Such integration efforts, even on a relatively small scale are complex and require substantial support.

There will be many and varying degrees of failure before success is achieved. Some of the sources of failure will be technical, but others will derive from an incomplete understanding of the human requirements.
References

