

A Survey of Ubiquitous Computing Technology and Application Prospects (Postprint)

Authors: Zhu Zhenmin

Date: 2017-03-10T00:00:00+00:00

Abstract

“From each according to his ability, to each according to his needs” is a great ideal of humanity. Ubiquitous computing highly integrates information space and physical space, precisely seeking to provide people with the “computing” services they need most. This paper analyzes and surveys the development, key technologies and challenges, application prospects, etc., of ubiquitous computing.

Full Text

Ubiquitous Computing Technology: Overview and Application Prospects

Abstract

“From each according to his ability, to each according to his needs” represents a great human ideal. Ubiquitous computing, which deeply integrates information space with physical space, aims to provide people with precisely the “computing” services they require most. This paper analyzes and synthesizes ubiquitous computing from the perspectives of its development, key technologies and challenges, and application prospects.

Keywords: ubiquitous computing, context computing, middleware, ubiquitous devices, human-computer interaction, sensor networks, Internet of Things

Introduction

In 1987, the Electronics and Imaging Laboratory (EIL) at Xerox PARC began developing a large wall-mounted tablet computer system that could function as an electronic pen, image scanner, electronic whiteboard, and especially as a networked device that could connect with other similar devices. This “wall” inspired a research philosophy fundamentally different from the “one computer

per desktop” model: embedding computers ubiquitously and invisibly throughout the entire environment. At that time, PARC anthropologists observed that people’ s actual use of technology often diverged from their stated preferences. For instance, when using computers, people rarely focused on technical specifications like memory capacity, pixel count, or processor frequency; instead, they concentrated on how computers could be utilized in specific contexts—particularly how computers could be embedded within complex frameworks of daily social activities and how they could interact with the real world.

Against this backdrop, Mark Weiser and his technical team initiated research on Ubiquitous Computing (UC) in early 1988, later also termed Pervasive Computing (PvC). For Weiser, there were no clear boundaries between society and technology, art and science, or work and play. He envisioned creating a technological world that reflected human and social spirit, steadfastly challenging and harnessing contemporary concepts in computer science, human-computer interaction, and computer-mediated work environments. Weiser’ s ubiquitous computing philosophy involved embedding computers into everyday objects people encounter, creating a new human-centered world of information services. In 1991, he published the influential paper “The Computer for the 21st Century” in *Scientific American* [2]. Alongside the convergence of computing, communication, and content, coupled with the miniaturization and embedded development trends of computers, computing paradigms are evolving toward human-centered ubiquitous computing. Computing and communication capabilities have begun integrating into people’ s daily living environments, with information space and physical space achieving substantial fusion.

This paper introduces the origins and development of ubiquitous computing, its key technologies and challenges, and analyzes its application prospects, concluding with a summary and outlook for future work.

2.1 Overview of Ubiquitous Computing Research Development

Since the mid-to-late 1990s, research programs centered on ubiquitous computing have proliferated widely, with the vast majority of renowned universities and research institutes in the United States and Europe launching related initiatives. These include MIT, Carnegie Mellon, Stanford, UC Berkeley, University of Illinois at Urbana-Champaign (UIUC), and Georgia Tech (GIT) in the U.S.; the German National Research Center for Information Technology (GMD) and University of Karlsruhe in Germany; Cambridge and Lancaster Universities in the UK; and the University of Tokyo in Japan. Since the new millennium, China has also embarked on related research, receiving comprehensive support from national research programs in 2006.

To secure technological dominance, governments worldwide have provided extensive support for ubiquitous computing R&D. In the U.S., DARPA, the National Science Foundation (NSF), and the National Institute of Standards and Technol-

ogy (NIST) have all funded ubiquitous computing research. DARPA specifically established a Ubiquitous Computing program and funded five related projects: MIT's Oxygen, Carnegie Mellon's Aura, the Oregon Graduate Institute of Science (OGI) and Georgia Tech's InfoSphere, UC Berkeley's Endeavor, and the University of Washington's Portolano. In Europe, government-funded projects include the EU's IPTS (Institute for Prospective Technological Studies) Ubiquitous Computing in Europe program and the UK's Engineering and Physical Sciences Research Council (EPSRC) Equator program. Cambridge and Lancaster Universities in the UK have undertaken EU-funded projects related to the Disappearing Computer and FP6 programs, alongside Berkeley's Endeavour and IBM's DreamSpace.

In Asia, initiatives include South Korea's u-Korea and Japan's u-Japan. In China, notable projects include Tsinghua University's SmartClassroom, Zhejiang University's SmartShadow, and the Institute of Computing Technology's INAP protocol.

Ubiquitous computing promises numerous business opportunities, and industry has embraced it enthusiastically. The IT industry's pronounced downturn at the end of the 20th century led major IT corporations to recognize that desktop computing had entered a mature phase, hoping that ubiquitous computing could drive continued industrial growth. Consequently, IBM, Microsoft, Sun, HP, AT&T, Sony, and others have invested heavily in ubiquitous computing research. IBM has been a particularly vocal advocate, with its research labs conducting dedicated studies. The concept has even reached the company's product marketing level, with the 2008 "Smarter Planet" initiative aiming to push ubiquitous computing and its technological achievements to new application heights. Microsoft launched the EasyLiving program to research key issues in information device interconnection in ubiquitous computing, along with its WCN (Windows Connected Now) and UPnP applications.

As research has deepened, two journals dedicated specifically to ubiquitous computing have been launched: *Personal and Ubiquitous Computing* (established 1997) and *IEEE Pervasive Computing* (established 2002). Two major annual international conference series have also emerged: UbiComp (The International Conference on Ubiquitous Computing, published in the LNCS series by Springer-Verlag) starting in 1999, and PerCom (IEEE International Conference on Pervasive Computing and Communications) starting in 2003. Additionally, many international conferences now include ubiquitous computing topics.

2.2 Notable Research Programs

Over the past two decades, several prominent research programs have shaped the field:

2.2.1 Xerox PARC' s Ubiquitous Computing Program

In early 1988, Xerox PARC' s research center initiated pioneering research on Ubiquitous Computing (UC). The UC program comprised three intersecting components: (1) Large wall displays called LiveBoard (later commercialized as LiveWorks), which could be networked using traditional methods; (2) Note-sized devices called ParcPad (later MPad), book-sized tablets that maintained constant network connectivity through a unique near-field radio system and featured a window-and-pen interface system. ParcPad validated an important platform for research on radio, protocols, mobile networking, user interfaces, and workplace studies; (3) Palm-sized devices called ParcTab, which used a location-aware, agent-based, enterprise-wide infrared-sensitive network. It employed a Unistrok system for alphanumeric input and selection via touchscreen and three ergonomically designed buttons. Additionally, there were identity badges—the Active Badge system. Together, Board, Pad, Tab, Badge, and a flexible computing infrastructure could identify not only devices but also their locations, contexts, connections in use, and owners.

PARC' s UC program produced numerous foundational technical achievements across an independent domain of computer science, encompassing physical transmission, network protocols, operating systems, windowing systems, file systems, user interfaces, power management, and input methods. It established a new field in computer science and proposed a pioneering vision: creating a physical world fully and invisibly interwoven with various sensors, actuators, displays, and computing elements, seamlessly embedded into our daily objects and connected through a continuous network, thereby merging our physical and information worlds into one. Xerox PARC' s research was constrained by the computer hardware and network technologies of its time, focusing primarily on developing various forms of ubiquitous computing devices and building entire systems from scratch, with insufficient consideration for multi-faceted integration. Nevertheless, it profoundly influenced ubiquitous computing research and embodied computing characteristics distinct from desktop computing: continuous services and contextual usage.

2.2.2 Indoor Positioning—AT&T' s Bat System

The AT&T Laboratory at Cambridge University focused on making location a resource for ubiquitous computing applications. In 1992, the Active Badge system, which had significant impact on ubiquitous computing research, was developed. This project implemented the first indoor positioning system, using wearable identity badges to transmit beacons while network sensors monitored the badges to locate wearers. The Active Badge system also spurred new context-aware applications in ubiquitous computing, with early context-aware applications all utilizing active badges. To provide precise location and orientation information, they also pioneered the introduction of ultrasound into indoor positioning systems, developing the ultrasound-based positioning system Active Bat. The Bat system became the research foundation for Sentient Computing

(2000), which maintains a software model of the real world containing location and status information. Its research focus aims to provide systems with the ability to update data based on users and locations through user interfaces, sensors, and resource data, enabling seamless extension throughout entire buildings.

2.2.3 Outdoor Positioning—Lancaster’ s Guide System

PARC and AT&T’ s research was limited to developing infrastructure and applications for home and local area ranges. However, with the massive deployment of mobile computing facilities and the development of outdoor positioning technologies (such as GPS), ubiquitous computing system research expanded beyond office environments. In 1996, some systems began providing mobile, continuous services and contextual usage in application domains such as tourism guides and navigation systems, offering prospects for ubiquitous computing applications among the general public. A typical representative was the Lancaster Guide project, which provided guide services for visitors to the city of Lancaster. Users employed handheld devices as endpoint systems, connecting to information servers via 802.11 networks. Users could effectively navigate information space while moving through physical space. However, positioning systems were not universally available, and user interaction was limited by infrastructure capabilities.

2.2.4 MIT’ s Oxygen Project

MIT’ s Laboratory for Computer Science began the Oxygen project. This program represents a typical pursuit of the ubiquitous computing ideal. The researchers believed that the future world would be an environment saturated with embedded computers, with embedded systems integrating into people’ s daily lives. The Oxygen project’ s metaphor was to make future computing as ubiquitous and freely accessible as oxygen. Traditional computing paradigms are computer-centered, whereas the new paradigm should be human-centered and adaptively respond to user needs and work changes. The Oxygen program includes three elements: E21 (Embedded 21), N21 (Network 21), and H21 (Handy21). E21 refers to embedded computing devices incorporated in physical spaces such as offices, buildings, homes, and automobiles, whose function is to transform physical spaces into intelligent spaces. E21 provides numerous interaction points between humans and computer systems, allowing users to exchange information using natural human interaction methods (such as speech and vision) while hiding the interaction interfaces. N21 is the network that connects various devices in the environment and supports collaborative work, supporting different protocols while providing unified naming and security mechanisms. H21 provides users with a portable interaction interface that can receive voice and video input, self-configuring to support multiple communication protocols or complete various functions (e.g., serving as a cellular phone, radio, television, geographic location device, camera, personal digital assistant, pager, etc.). E21 is embedded in various living environments and occasions, H21 can

be carried with the user, and N21 networks all devices, enabling H21 to contact surrounding or remote E21 at any time. Through these three elements, the Oxygen program establishes natural, close, and comprehensive connections between computer systems and users.

2.2.5 Aura Project—Invisible Computing

In 2000, Carnegie Mellon University launched the Aura project. This project adds a software layer (called Aura) between users and the computing environment, which acts as an agent to manage and maintain multiple loosely coupled computing devices in distributed computing environments that change frequently, to accomplish users' target tasks. Aura's philosophy is that "user attention" is the most precious resource and should be focused on tasks rather than managing and configuring hardware and software resources. To achieve "distraction-free" computing, Aura addresses these issues by reconsidering system design, aiming to provide each user with a location-independent, continuous, invisible computing and information service atmosphere. To achieve this goal requires effort at every layer, from hardware, network, operating system, middleware to user interface and applications, aiming to develop, implement, deploy, and evaluate a large-scale system comprising wearable, handheld, desktop, and computing facility computers that fully demonstrates ubiquitous computing concepts.

The Aura project encompasses numerous research areas including task-driven computing, energy-aware adaptation, intelligent networks, speech recognition, language translation, augmented reality, multimodal user interfaces, mobile data management, wearable computers, user interface adaptation, data and network adaptation, security and privacy, user/virtual space interaction, and evaluation criteria and methods. These elements are integrated into many independent research projects such as the Darwin intelligent network, the Coda distributed file management system, and Odyssey providing operating system support for resource adaptation. The Aura system represents a typical example of an agent system.

2.2.6 Active Space—UIUC's Gaia Project [3]

Gaia was the ancient Greek goddess of Earth. In the 1970s, some viewed the Earth's atmosphere, oceans, lithosphere, and biosphere as a single cybernetic, self-operating super-organism, naming this global entity Gaia. In 2000, the Gaia project at the University of Illinois at Urbana-Champaign's System Software Research Group applied this concept to computing, extending traditional computer systems to various devices and surrounding physical spaces. Gaia's goal is to design and implement a middleware operating system to manage resources in active spaces, enabling seamless interaction between virtual and real-world objects and transforming physical spaces into interactive spaces or active spaces for ubiquitous computing.

Gaia employs component-based service management. The Gaia component management core utilizes existing middleware platforms, providing three abstractions: Gaia components, Gaia nodes, and Gaia component containers. Nodes represent any device capable of executing Gaia components, grafting various services onto components such as presence service, event manager, location service, security service, environment service, etc. These are then provided to users through an application framework. Gaia's research primarily includes location awareness, active spaces, security and trust mechanisms, system software and infrastructure, sensors and networks, etc.

2.2.7 Fluid Software—Berkeley's Endeavour Project

Endeavour derives its name from a navigator's ship, symbolizing how the ocean connects many parts of the world. The project's philosophy is to establish ubiquitous information infrastructure where components flow within the facility, adjusting their form according to their usefulness and current tasks, like water in the ocean. In 1999, Berkeley launched the Endeavour project, whose goal is to provide entirely new, global-scale information infrastructure through information technology. This infrastructure dynamically and in real-time coordinates any available resources worldwide to meet users' computing needs, fundamentally facilitating information interaction between people and devices (including information sources) and among people themselves. The project attempts to develop universal information entities based on this new fluid system to implement novel problem-solving approaches and learning methods. Endeavour's first innovation is "fluid software," which can adaptively select where to execute and where to store, obtaining available resources through protocols and providing services to other entities. The second innovation involves automatically extracting information about interactions between people and other people or information sources under conditions where information entities have large-scale capabilities to capture and organize human activities, thereby maximizing the efficiency of human activities and the accumulation and acquisition of experience or intelligence.

The Endeavour project primarily comprises four research areas: information devices, information entities, applications, and design methodology. Information device research includes integrating sensors, actuators, cameras with positioning and communication functions, display devices, and handheld and mobile computing devices such as vehicles and mobile robots, ensuring these devices can be integrated into the system. Information entity research includes technologies necessary to support fluid software (component collaboration, device diversity support, always-available data management, etc.). Application research primarily supports high-level decision-making through collaborative environments and supports educational and learning spaces.

2.2.8 Portolano Project—Data-Centric Networks

In 1999, the University of Washington began the Portolano project. This project proposed “data-centric networks” to meet the requirement of making computing itself invisible. The program argued that current computer technology development remains technology-driven rather than user needs-driven. To change this situation, the project 致力于研究根据用户的位置变化而自适应地改变软件用户界面的机制、以数据为中心的网络以及新型的分布式服务模型。它强调不可见 (invisible) 和基于意图的计算 (intent-based computing), 根据用户在环境中与日常对象交互来推断用户的意图, 提出了一种建立在与应用和用户交互的移动智能体 (agent) 之上的基础设施。并试图建立这样的应用: 用户接口不是在计算机上, 而是这个计算机; 用户没有连接网络, 但是用户的数据可以在网络上传输; 用户没有显式地发出执行命令, 但是智能体可以根据用户的意图自发地操作。主要研究三个方面: 用户接口、网络基础设施、分布式服务。

2.2.9 Disappearing Computer

Starting in 1998 (though related engineering actually began in 2001), European universities and research institutions launched the Disappearing Computer research program. The program’s objectives were to study how information technology could be integrated into everyday objects and how this would generate new ways to support and improve people’s lives, and how collections of interactive information entities could support daily life. The main research content comprised three aspects: creating information entities based on new software and hardware architectures embedded in everyday objects; studying how these collections of intelligent information entities work together and the resulting new functions and applications; and researching the temporal and spatial consistency and continuity of human experience in these environments. Disappearing Computer encompasses several projects, including Ambiente described below.

2.2.10 Intelligent Environments—Germany’s AMBIENTE Project [6]

AMBIENTE—Smart Environments of the Future is part of the EU-funded Disappearing Computer project, undertaken by the German National Research Center for Information Technology.

AMBIENTE includes the following projects: 1. **AMIGO**—Ambient Intelligence for the Networked Home Environment (started 2004): Researches and develops open, standardized interoperable middleware and intelligent user services for networked home environments, providing seamless interoperability between services and applications. 2. **Hybrid Games**—Entertainment of the Future (started 2003): Designs a new type of computer game introducing new representation methods such as audio and video, and immersive game virtual worlds. 3. **Ambient Agoras**—Dynamic Information Clouds in a Hybrid World (2001-2003): Provides users with location services, location-related information, and orientation sense through display devices embedded in the environment and mobile devices that help users communicate, navigate, and work. 4. **InterSmArt**—User-oriented Design of New Interaction Forms for Smart Artefacts: Researches

new interaction methods between intelligent entities. 5. **RoomWare** (started 1997): Integrates objects in rooms such as doors, walls, and furniture with embedded devices to create computer-enhanced rooms supporting information and communication technology, such as dynamic walls, communication chairs, and interactive tables. 6. **InterSpace**—Novel Group Interaction in Ubiquitous Computing Environments: A Microsoft-sponsored collaborative work project researching new group interaction technologies for coordination among multiple heterogeneous devices, including: interaction among multiple heterogeneous devices, support for multi-user collaboration, coordination between personal and public devices, and integration of users, devices, and context. 7. **i-LAND**—An Interactive Landscape for Creativity and Innovation: An application instance of the building concept for collaborative work in future intelligent environments within AMBIENTE. It integrates physical and virtual spaces, utilizes components from RoomWare, and allows dynamic configuration and automatic distribution for project teams. 8. **BEACH**—the Basic Environment for Active Collaboration with Hypermedia: A software platform providing multi-user data sharing functionality and serving as a framework for collaborative software. Initially developed as a software component for the i-LAND project, it provides basic functions for project team collaboration and modules supporting creative sessions and slide presentations.

2.2.11 u-Korea—South Korea’ s UT Project

In 2003, South Korea’ s Ministry of Science and Technology officially launched ubiquitous computing R&D work (called the UT project), establishing a specialized management agency and listing it as one of the key frontier research projects for the 21st century in South Korea’ s scientific community. South Korea plans to achieve technological leadership by 2013 and build a truly ubiquitous computing environment. The UT project involves 5 research institutes, 14 companies, and 18 universities in South Korea, with an average annual budget of \$17 million and a 10-year development period. Three core technologies have been selected for development: autonomic computing architecture, smart sensors, and identification technology. The UT project targets the forefront of global information technology development, aiming to promote the industrialization of related application technologies and improve the living standards of South Korean citizens. To this end, the project has proposed the slogan “A world-class ubiquitous technology leader for the benefit of human society.” The UT project is divided into three key phases, with goals respectively targeting ubiquitous computing in home environments, towns, and the entire nation.

2.2.12 Visual Space—IBM’ s DreamSpace [7]

Humans communicate and discover the world through vision and conversation. Computers can be designed to allow natural human-machine interaction using modalities such as speaking, gesturing, eye movement, moving, and reaching. IBM Watson Research Center’ s DreamSpace project aims to allow users to col-

laborate in shared spaces. The system can “hear” voice commands and “see” gestures and body positions, enabling natural human-computer interaction similar to human-human interaction. Computers can understand users, allowing them to freely focus on understanding and thinking about actual objects and information with minimal limitation and distraction from the computer. Currently, this research uses wall-sized 3D images and sound for interaction, without keyboards, mice, wires, or remote controls. DreamSpace, also called “visual space,” is a networked workspace where computer systems automatically adapt to human needs to improve usability, enjoyment, and optimize information organization and understanding processes. This is ideal for many application scenarios such as education, entertainment, scientific visualization, and video conferencing.

Additionally, IBM has conducted the WebSphere Everyplace project, whose goal is to make enterprise applications easier to deploy on mobile devices. The technology’s core is a WebSphere-based extended service, a middleware that can be embedded in other application software, enabling software developers, device manufacturers, and enterprises to extend IBM’s WebSphere platform and Java-based applications in handheld devices. Using this technology, developers need not rewrite programs for mobile devices, nor use micro-browsers to access information; end users can download needed applications and data on demand.

2.2.13 Location Awareness—HP’s Cooltown

HP’s Cooltown combines Web infrastructure with ubiquitous computing concepts. HP Labs engineers installed devices in rooms that could broadcast URLs to handheld devices. Through wireless networks, people moving through the space could access information and services anytime and anywhere. This “location-aware” system, called “Cooltown” by HP, is part of the company’s nomadic computing research project, which 致力于将万维网资源与自然目标和地方结合起来。Users can connect various computing devices via the Internet.

Cooltown technology developed an infrastructure to support Web representations of people, places, and things, using Web mechanisms to locate and connect physical entities in the real world. It solved physical integration problems using embedded server technology, virtual representation of physical locations, embedding URLs in the real world, and new interaction technologies. In office environments created using Cooltown technology, every object has a URL. Users access and manipulate physical entities in space through Web-style URL access.

HP plans to apply Cooltown technology to home appliances such as printers and radios, enabling these devices to interoperate through wireless connections and specialized software, effectively greatly expanding Web infrastructure.

2.2.14 Easy Living—Microsoft’s EasyLiving [8]

Microsoft’s EasyLiving project for intelligent home and work spaces aims to build intelligent environments that facilitate interaction among people, comput-

ers, and devices, making computer use more convenient. The project 致力于智能环境的体系开发, 涉及中间件、几何世界建模、定位感知、服务描述等技术。Its key features are machine vision, automatic and semi-automatic calibration of multi-sensors, and device-independent communication. EasyLiving's goal is to make computers in future homes and offices (intelligent spaces) as natural as electric lights. Through computer vision, the intelligent space can perceive people within it, respond to voice and gesture commands, know its geometric space and capabilities, and easily extend them. Such systems have three characteristics:

1. **Self-Aware Spaces:** EasyLiving spaces should be able to perceive activities and content within them to appropriately respond to human movement and requests. Such a self-aware space knows its geometric location, the people within the space, their actions and preferences, and the resources available to meet their requirements.
2. **Casual Access to Computing:** Computers are accessible anywhere in the space without requiring people to go to a specific location to interact with them, nor requiring specialized equipment or badges for computers to know where users are. EasyLiving's "casual access" goal means computers are everywhere in EasyLiving spaces, and users can always send signals to computers via cameras and microphones. Since computers continuously track users and their contexts, they can always respond appropriately.
3. **Extensibility:** EasyLiving extends the "plug-and-play" concept. New devices should be intelligently and automatically integrated into the system. One aspect of extensibility is treating new devices as resources the system can use arbitrarily.

3 Research Content and Technical Challenges

Ubiquitous computing is an interdisciplinary, comprehensive research direction involving extensive content and technologies.

3.1 Main Research Content and Key Technologies

Ubiquitous computing research primarily includes ubiquitous devices, ubiquitous networks, system software, and human-machine interactive interfaces, while forming multiple research areas such as context computing, smart spaces, wearable computing, and security & privacy [9,10]. [Figure 1: see original paper] describes the main aspects of ubiquitous computing.

3.1.1 Ubiquitous Devices and Ubiquitous Networks The ubiquitous computing environment is a universally interconnected environment, with ubiquitous devices and ubiquitous networks as its important components. Based on functionality, ubiquitous devices can be categorized into information terminals, sensing devices, and smart objects.

Information terminals enable users to connect to networks via wired or wireless means to access various information and services anytime and anywhere. Typi-

cal information terminals include PDAs, smartphones, and network computers, with smartphones considered the preferred platform for ubiquitous computing [11]. Information access terminals in ubiquitous environments typically feature mobility and intelligence.

Sensing devices include equipment for identifying object identities (such as RFID tags) and devices for sensing physical objects and environmental states (such as sensors and smart dust).

Smart objects are formed by embedding computing and communication capabilities into everyday objects (such as furniture [12] and home appliances) to enable computers to perceive and control such devices, establishing a bridge between the physical and virtual worlds. Beyond interconnection among computers, various objects connect with other objects through different methods. The network environment in ubiquitous computing includes various wireless networks, the Internet, telecommunications networks, television networks, as well as RFID networks, wireless sensor networks, GPS networks, and other types of networks—these constitute the ubiquitous network. Ubiquitous networks support automatic interconnection in heterogeneous environments with heterogeneous devices, support adaptation to dynamic environmental changes, and provide ubiquitous communication services. Current ubiquitous network research focuses primarily on wireless and mobile networks, ad hoc networks, wireless sensor networks, and peer-to-peer (P2P) transmission.

3.1.2 Context Computing A crucial characteristic of ubiquitous computing is autonomous perception of object and environmental state information and its changes in ubiquitous computing environments. Through context computing, contextual information is utilized to provide users with efficient information interaction and personalized services. Common contextual information includes: time, location, and scene environmental information; screen size, storage capacity, and processing capability device information; and user information such as identity, operating habits, personal preferences, and emotional states. Context computing involves context awareness, context modeling, context reasoning, and applications [13].

Context information can be captured through sensors, extracted from existing information (such as calendars and weather forecasts), or directly set by users. Sensors include not only those for physical information like sound, light, and electricity but also RFID tags, cameras, GPS systems, and other sensing devices. They can even include monitoring whether users are using computer keyboards (used by programs like ICQ to sense user status) and network monitors that statistically analyze network traffic and characteristics. Many contexts require new sensing technologies and hybrid approaches.

Context computing is an important support for ubiquitous computing services. However, context information has characteristics of diversity, real-time nature, concealment, and timeliness, which affect the accuracy of context reasoning.

Current research includes context representation models and context reasoning models.

3.1.3 Smart Spaces and Wearable Computing A smart space is a workspace embedded with computers, information devices, and multimodal sensors. Its purpose is to enable users to conveniently access information and obtain computer services, thereby efficiently achieving personal goals and collaborating with others [14]. Smart spaces can be realized at different scales, based on discrete environments such as homes, offices, classrooms, supermarkets, or airports. Local smart spaces can be implemented first, then gradually interconnected and expanded globally [13,15].

Wearable computing is a typical representative of smart spaces [16], integrating ubiquitous devices into an intelligent agent. By wearing computing and interaction devices on the body, people can conveniently obtain computing and information services anytime and anywhere. Typical wearable computing devices include wearable battlefield computers, smart clothing, smart gloves, and smartwatches.

3.1.4 System Software Ubiquitous computing system software needs to manage the large number of networked information devices, smart objects, and computing entities in ubiquitous computing, providing system-level support for data exchange, message interaction, service discovery, and task coordination among them. Ubiquitous computing system software differs from traditional distributed system software, with two fundamental characteristics: physical integration and spontaneous interoperability. Due to the dynamic nature of tasks and heterogeneity of devices in ubiquitous computing environments, ubiquitous computing system software must address device and service discovery, adaptation, and other issues, achieve management of physical entities and coordination mechanisms between modules, while ensuring system robustness and security [17].

The Gaia system is a typical representative of ubiquitous computing system software, bringing operating system functionality into physical space and extending operating system functions to the environment and many functions for interactive spaces. The Gaia system is built on middleware, and its architecture [18,19] is shown in [Figure 2: see original paper].

3.1.5 Human-Computer Interface Technology Ubiquitous computing is “human-centered.” In ubiquitous computing environments, users should be able to use various devices (such as sensors, palmtops, laptops, and PCs), especially portable ubiquitous devices, to access needed services and collaborate on tasks through appropriate interaction methods. Since ubiquitous devices vary greatly in functionality and performance, ubiquitous computing systems must mask these differences and provide users with a natural interface to access the physical world, offering more harmonious and efficient interaction between humans and

ubiquitous computing environments, such as voice input, electronic paper, and eyeglass displays.

Current ubiquitous computing interface technology research focuses on: (1) Interface adaptability—systems can generate interfaces suitable for devices based on their types and capabilities; (2) Interface “invisibility” —beyond traditional graphical user interfaces and command lines, providing multiple natural human-computer interaction methods such as voice, gestures, and handwriting, which should become default or implicit interaction methods. Additionally, there are body behavior and emotion-based multimodal interaction interfaces; (3) Multimodal fusion interfaces—organically combining the above two aspects to adaptively select the most appropriate device interface for human-computer interaction based on people, devices, and their environments.

3.1.6 Adaptive Technology In ubiquitous computing environments, devices’ own resources—including computing power, storage capacity, battery capacity, and interaction methods—vary significantly. Additionally, due to changes in device location, time, and place, resources such as wireless network bandwidth during movement, network handover, and surrounding service devices also change continuously. This leads to a mismatch between user resource requests and system resources. Therefore, adaptation issues must be resolved—systems must adopt strategies to ensure applications execute automatically and smoothly based on their resource states.

Adaptive strategies employed in ubiquitous computing systems mainly include: 1. **User context adaptation:** Systems collect user context information, infer user intentions, and automatically change executing programs. This approach often leads to distortion issues. 2. **Device resource adaptation:** Determines device-running programs based on device capabilities and current resource status. 3. **System resource state adaptation:** Selects next activities conversationally based on system resource status. 4. **Reservation systems:** Systems reserve certain resources to meet some users’ minimum service requests.

3.1.7 Component and Middleware Technology Ubiquitous computing opens new application models. Two main factors drive its development: innovations in network environments and hardware device technologies adapted to ubiquitous computing environments, and innovations in system software technologies adapted to ubiquitous computing environments. The latter provides system support for ubiquitous computing applications based on component and middleware technologies, with the Gaia system being a typical representative.

Current middleware technology research for ubiquitous computing environments remains largely exploratory. The reasons are: first, ubiquitous computing environment construction itself is still in the research and exploration stage, with new technologies and devices continuously being applied; second, user demands for applications in ubiquitous computing environments are also evolving, with

significant differences in requirements across different users and application scenarios. Current development trends are to fully utilize existing widely-used component and middleware technologies, adopt publicly open technical specifications and standards, and unify network service environments with smart spaces.

3.1.8 Resource Discovery and Service Composition Technology Resource discovery technology refers to the ability of ubiquitous devices to automatically discover available services in the network and communicate with each other without user intervention in ubiquitous computing environments. This requires enhancing network packets' ability to execute code, enabling them to call discovery functions stored on master nodes or select optimal paths to obtain these services.

Ubiquitous computing systems have distributed characteristics, while distributed system services are vertically integrated rather than horizontally layered. Through vertical integration, systems can provide complete solutions to problems, but at great cost and with insufficient flexibility. Although system management and regulation are centralized in vertical systems, users often cannot accurately obtain the service subsets they require, and deploying new services or changing services in vertical systems is difficult. Ubiquitous computing environments are highly heterogeneous and dynamic systems. Services they provide are dispersed across different devices and systems, making vertical organization of system services clearly inappropriate; horizontal layering is more suitable for ubiquitous computing environments. Under horizontal layering, system service addition and modification can be seamlessly integrated into the original system without requiring user configuration, achieving service "invisibility" and transparency. The basis for optimizing services can be provided by Quality of Service (QoS) parameters.

3.2 Technical Challenges [20]

"The most profound technologies are those that disappear. They weave themselves into the fabric of everyday life until they are indistinguishable from it" [2]. The ubiquitous computing environment Mark Weiser envisioned is built upon such technology based on ubiquitous computing and communication capabilities. In such environments, computing and communication are both "ubiquitous" and "invisible." After more than 20 years of effort by ubiquitous computing researchers, many fantastical concepts have become reality, but many challenging problems remain to be explored and solved.

1. **Disappearing computing requires low-power and embedded technologies:** Miniaturization and embedding are the main implementation means for disappearing computing. However, miniature and embedded devices have limited energy reserves and are quite sensitive to power consumption issues. Beyond leveraging achievements in materials technology from physics, chemistry, and biology, how can we approach

device design and manufacturing from a systems perspective? Sleep and wake-up energy-saving technologies in computer technology represent one attempt, and better software-hardware co-design technologies can reduce energy consumption, but such reductions are always limited. Generally, the lifecycle of embedded devices far exceeds the support time of their energy reserves. Will there be technologies to “borrow energy” (including energy scavenging and energy conversion) from the embedded system, or hybrid methods combining energy saving and energy borrowing? These are questions requiring exploration.

2. **Context computing requires appropriate context models:** Providing personalized services based on context reasoning is one goal of ubiquitous computing. The accuracy and efficiency of reasoning are closely related to context characteristics: (1) **Real-time nature of context**—much context information changes continuously over time, such as hazardous environment information, critical patient vital signs, and various information in field control, requiring real-time collection and immediate reasoning. This necessitates real-time sensors and sensing technologies; (2) **Diversity of context**—diversity brings representation challenges, making unified expression difficult, and even individual signal quantities have dimensional differences, requiring research on how to establish representation models for context information; (3) **Concealment of context**—beyond context information obtained through sensors and user settings, large amounts of context are hidden in existing information systems and networks, requiring new mining technologies to accurately obtain this information; (4) **Timeliness of context**—obsolete context information makes reasoning results inaccurate or erroneous, requiring perception of more complex contexts—composite contexts; (5) **Pragmatics of context**—context reasoning is essentially understanding context, a process not based on axiomatic systems but similar to natural language understanding, strongly dependent on the usage environment (agent, recipient, occasion); (6) **Fuzziness of context**—for the digital world, context can be precise, but many contexts are difficult to characterize digitally or are inherently non-digital and fuzzy. Additionally, many other factors affect reasoning.

These numerous factors constrain context reasoning technology development. Decades of AI research have not satisfactorily solved reasoning problems (even logical reasoning). In ubiquitous computing environments, pursuing a unified format to represent context models may be unrealistic and unable to express diverse contexts. Could we establish a class of context models that are feasible and effective throughout the entire context computing process, including representation, storage, and computation?

3. **Autonomous collaborative computing requires entity description semantics:** In ubiquitous computing environments, entities such as people, ubiquitous devices, and software systems form a collaborative com-

munity requiring multi-level natural interaction and autonomous collaboration—including between ubiquitous devices, between software systems, between people and ubiquitous devices, and between people and software systems—to achieve the “disappearing computing” state. Interaction and collaboration are like “speaking” and “acting” among people. Natural interaction technology has been relatively well-researched with some achievements and products. However, autonomous collaborative computing places higher demands on various entities, requiring them both to “speak” and to “act.” Therefore, we need to understand what capabilities (functions) entities have, their magnitude and effectiveness, and establish appropriate semantic description methods for them and mechanisms to coordinate these capabilities.

4. **System robustness requires appropriate computing models:** The Church-Turing computing theoretical model has guided computer development, bringing brilliance and global technological progress to the field. For distributed and concurrent problem spaces, this model’s descriptive capability has obvious deficiencies. Distributed and concurrent problems are precisely important characteristics of ubiquitous computing systems. Seeking new computing models is the most challenging work in ubiquitous computing.

4 Summary and Outlook

Although the concept of ubiquitous computing has existed for only slightly more than two decades, it has had a significant impact on the development of computer and information science, guiding computer technology and information technology toward a “human-centered” direction. Currently, the various technologies required for ubiquitous computing have basically become reality, and various research institutions and companies have invested substantial human and material resources to research ubiquitous computing prototypes, achieving certain results. However, there remains some distance from truly meaningful ubiquitous computing. The key issue lies in how to seamlessly integrate existing technologies. This requires establishing certain industrial standards and strengthening research cooperation and exchange. Moreover, as ubiquitous computing research deepens, many previously unconsidered economic and social issues have become increasingly important.

The core content of ubiquitous computing is “human-centered,” pursuing “human care.” In the fusion space established by ubiquitous computing, people can transparently obtain computing services anytime and anywhere without sitting in front of a computer. In a sense, this makes computing disappear. This service access method can even be proactively provided by the system without user awareness— “transparent service” or “personalized service.” In ubiquitous computing environments, each device needs to respond to or anticipate users’ various needs, while each device and the entire environment must maintain a non-intrusive state for every user in the environment without requiring user

attention for intervention— “distraction-free computing.” Computing and information transmission will no longer be a job or skill but become a natural part of our lives, allowing computers to learn to understand human expressions and feelings, ultimately enabling people to use computing in the most natural way. This is the ideal state of “ubiquitous computing.”

References

- [1] 李幼平, 马卫东. 泛印技术. 中国计算机学会通讯, 2006.
- [2] Mark Weiser, The Computer for the twenty-first Century, Scientific American, 1991, 265(3).
<http://srg.cs.uiuc.edu/gaia/index.html/>
<http://portolano.cs.washington.edu/>
<http://www.disappearing-computer.net/>
http://www.ipsi.fraunhofer.de/ipsi_e/nav/ipsi_f_contact.html/
<http://www.research.ibm.com/thinkresearch/pervasive.shtml/>
<http://research.microsoft.com/easyliving/>
- [9] 李锦涛. 普适计算研究, 信息技术快报, 2005,3 (10).
- [10] 朱珍民, 史红周. 网络终端与普适计算的发展趋势 [J]. 信息技术快报,2004,2(4).
- [11] M. Satyanarayanan, Swiss Army Knife or Wallet, IEEE Pervasive Computing, 2005, 4(2).
- [12] Masaki Ito, Akiko Iwaya, Masato Saito, Kenichi Nakanishi, Kenta Matsumiya, Jin Nakazawa, Nobuhiko Nishio, Kazunori Takashio, Hideyuki Tokuda, Smart Furniture: Improvising Ubiquitous Hot-Spot Environment, ICDCSW' 03.
- [13] Andy Harter, Andy Hopper, et al., The Anatomy of a Context-Aware Application, Wireless Networks, 2001, Vol. 8.
- [14] N. Streitz, J. Geissler, and T. Holmer, Roomware for Cooperative Buildings: Integrated Design of Architectural Spaces and Information Spaces, CoBuild' 98.
- [15] B. Johanson, A. Fox, and T. Winograd, The Interactive Workspaces Project: Experiences with Ubiquitous Computing Rooms, IEEE Pervasive Computing, 2002, vol. 1.
- [16] Martin, T., Wearable and ubiquitous computing, IEEE Pervasive Computing, 2003, 2(3).
- [17] 徐光祐, 史元春, 谢伟凯. 普适计算, 计算机学报, 2003,26(9).
- [18] M. Roman, C. K. Hess, R. Cerqueira, R. H. Campbell, and K. Narhstedt, Gaia: A Middleware Infrastructure to Enable Active Spaces, IEEE Pervasive Computing, 2002, vol.1.
- [19] 史元春等. 普适计算: 营造以人为本的信息服务新环境, 中国计算机学会通讯, 2006.
- [20] M. Satyanarayanan, Pervasive Computing: Vision and Challenges IEEE Personal Communications, 2001, 8(4).
- [21] <http://www.informationweek.com>

Author Biography:

Zhu Zhenmin: Deputy Director and Professor, Ubiquitous Computing Research Center, Institute of Computing Technology, Chinese Academy of Sciences, zmzhu@ict.ac.cn

Note: Figure translations are in progress. See original paper for figures.

Source: ChinaXiv – Machine translation. Verify with original.