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A taxonomy of ubiquitous computing applications

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Abstract Ubiquitous computing is emerging as a new paradigm in next-generation information technology. This new paradigm has been embodied into tremendous business models and applications through lots of ubiquity-related technologies. In this study, a new taxonomy for these business applications and technologies is suggested. In order to prove the practical values, two case applications of the taxonomy are conducted. In the cases, 24 ubiquitous computing services and 19 ubiquitous computing projects are classified so that the status quo of ubiquitous computing is analyzed.

Keywords Ubiquitous computing · Taxonomy · Case applications

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1 Introduction

Many Information Technology (IT) applications enable individuals to enhance their quality of life and companies to execute business innovation and/or design new revenue models. The IT environment innovation has gone through four stages. The first one is 'main-frame computing innovation,' the second one, 'personal computing innovation' and the third stage innovation is 'distributed computing environment,' finally, the fourth stage innovation is presumed to be 'ubiquitous computing innovation' [16]. At this juncture, ubiquitous computing innovation, based on a network which links every object, is regarded as a fusion technology between physical and electronic space.

Mark Weiser defines main characteristics of ubiquitous computing as follows [15]. First, every computer can be linked with a network. Second, users do not have to be aware of the linking process. Third, through human-friendly interface, situation-appropriate services are provided on the network at the right time. On the ground of these characteristics, many countries such as US, Europe, Japan and Korea are trying to take initiative of ubiquitous computing-related standard and technology. The following table compares each country's ubiquitous-related definition [3] (Table 1).

US has been focused on real-time computing through smart object, Europe on monotonous collaborative infra and mobility-driven nano-smart-object. Japan is concentrating on anywhere-connection

Table 1 Comparison of ubiquitous computing terms and values (US, Europe, Japan, and Korea)

	US	Europe	Japan	Korea
Terms	Ubiquitous computing, pervasive computing	Disappearing computing, ambient computing	Ubiquitous network	Ubiquitous appliance
Concepts and values	Service by smart devices	Intelligent cooperation by information artifacts	Anywhere connection by small chip, smart card, context roaming	Single function appliance using short range wireless Interface
Research field	Computer devices	Every objects	Network	Appliances
Core technology	Short-distance radio communication, Sensor, MEMS, Small size object chip			

environment while Korea is trying to launch nationwide ubiquitous computing strategy through information super-highway. Each country, though differing in values sought shares three basic ideas on ubiquitous computing-intelligence, network and mobility.

In this study, previous researches of ubiquitous computing are suggested in the following chapter. In Chap. 3, a new taxonomy for applications in ubiquitous computing environment is developed. In Chap. 4, it is applied to current ubiquitous computing services and projects, and implications of the mapping results and future researches are suggested.

2 Previous research

2.1 Ubiquitous computing definitions

Concepts of ubiquitous computing vary by scholars and research institutes. Table 2 shows various notions and definitions of ubiquitous computing [6,7,13,15,22].

The definitions vary and are apt to be changed as technology evolves. Therefore, they need to be redefined as a general notion which carries basic ideas suggested by many definitions. In this paper, we define ubiquitous computing as 'technology environment in which computers are invisibly embedded in every object and linked with each other so that information sharing and communication are possible in anywhere, anytime and any place.'

2.2 Ubiquitous computing classification scheme

In order to understand ubiquitous computing environment, overall characteristics of ubiquitous computing should be considered first. Previous definitions of ubiquitous computing often failed to reflect these characteristics. While it is not an easy work to induce unique and/or essential characteristics of ubiquitous computing because technologies consist of various and cross-discipline technologies, there have been a number of researches on ubiquitous computing taxonomy and its characteristics.

First, the characteristics of ubiquitous computing are divided into context-adaptable network environment, convenience and variety-based terminal environment, easy access environment to services/applications and multi-user-based high bandwidth environment. Based on this categorization we have reviewed a previous research with five technology areas- ubiquitous system technology, advanced network technology, application enhancement technology, appliance technology, and platform technology [5].

Second, there is a research done which categorize ubiquitous technology in a location-based perspective [1]. Hightower and Borriello [1] suggest six criteria for ubiquitous computing technology and project taxonomy—physical location versus symbolic location, absolute location versus relative location, localized location computation, recognition in accuracy/precision, scale, cost and limitations.

Third, NRI suggested hierarchical classification for ubiquitous information service. The following table represents information service in ubiquitous computing environment based on level of intelligence [10] (Table 3).

Forth, Kwon et al. tried to categorize ongoing ubiquitous computing related research into four areas of focus: U-device, U-environment, U-media, and U-People, as listed in Table 4 [4].

Table 2 Comparison of ubiquitous computing definition

Scholar and Research Institute	Definition
Ken Sakamura [13]	Ubiquitous computing is being able to use computers anywhere at any time.
Mark Weiser [15]	Ubiquitous computing has as its goal the enhancing computer use by making many computers available throughout the physical environment, but making them effectively invisible to the user.
Friedermann Mattern [7]	Everyday objects will become smart and they will all be interconnected.
IBM(2005)	Pervasive computing delivers mobile access to business information without limits from any device, over any network, using any style of interaction. It gives people control over the time and the place, on demand.
Leem et al. [6]	Ubiquitous computing is a technology, in which invisible computers are embedded and connected with all things so that anyone can communicate, exchange and share information anywhere anytime.

Table 3 Taxonomy for ubiquitous computing service based on level of intelligence

Intelligence level	Classification	Description
High	u-intelligent service	Service that grasp situation and achieve necessary action naturally accordingly
	u-behavior proposal service	Service that inference user's request and propose action information that need in situation
	u-context notification service	Service that supply information that grasp and want situation according to that is indicated already by user
	u-information offering service	Service that search information that want by real time whenever there is user's request and chase and offer
Low	u-communication service	Service that anytime, anywhere, any-device transfer simple information through ubiquitous network

Table 4 Classification of ongoing research in ubiquitous computing

Classification	description
U-device	Device for identifying user's context
U-environment	Smart environments enabled by devices, network infrastructure, and operating systems
U-media	I/O medias for user's context-aware
U-people	Ubiquity-based services for minorities

2.3 Limitations of previous research

Current ubiquitous computing research is mainly focused on fundamental technologies which are required in establishing ubiquitous computing environment. If we are to come up with future development blueprints and rational technology application guidelines, technology taxonomy should be in order and much research, other than those mentioned above, should be done. However there are several limitations.

(1) Mainly concentrating on fundamental technology, technology-centered taxonomy fails to reflect real-world situation of ubiquitous computing environment.
(2) Technology-centered taxonomy does not consider end users, who eventually use the ubiquitous environment. After ubiquitous computing environment being established, the characteristics of users are hard to be identified.
(3) Ubiquitous information service hierarchical taxonomy is based on level of intelligence and anticipates future services to be categorized. Therefore, actual services/applications and their characteristics are hard to be extracted.

Consequently, in order to understand the characteristics of ubiquitous computing environment and future evolution and research direction, taxonomy for ubiquitous service and application, which are explicated through

ubiquitous computing technology, needs to be established.

3 A taxonomy for ubiquitous computing applications

In this chapter, application classification scheme is suggested based on ubiquitous computing environment. With the classification scheme, characteristics, trends of actual applications and services could be analyzed. After mapping current applications and services with the classification scheme, future evolution direction of ubiquitous computing application/service could be drawn out, making it possible to identify appropriate fundamental technology for the evolution process of ubiquitous computing.

Ubiquitous computing environment is marked by anywhere, anytime and anyone-based characteristics. It is thought that applications and services under ubiquitous computing environment are based on those characteristics. Therefore, the following criteria could be suggested.

(1) Subject: ubiquitous computing application should be easily used by anybody.

   (a) In order to separate this dimension, it is divided into anyone-oriented (anyone) and someone-oriented (someone)

(2) Time: ubiquitous computing application should be used anytime.

   (a) In order to find out ubiquitous computing characteristics according to time, it is divided into anytime-oriented (anytime) and sometime-oriented (sometime)

(3) Place: ubiquitous computing should be used anywhere

   (a) In order to find out ubiquitous computing characteristics according to place, it is divided into anywhere-oriented (anywhere) and somewhere-oriented (somewhere)

The following table describes taxonomy for ubiquitous computing application by subject, time and place (Table 5).

4 Applications of the taxonomy

For the case application of the taxonomy suggested in the previous chapter, 24 ubiquitous computing services and 15 ubiquitous computing projects are adopted. In Sect. 4.1, ubiquitous computing services were matched and its results were drawn. In Sect. 4.2, ubiquitous computing projects were applied and the mapping results are suggested. In Sect. 4.3, the results of two applications were summarized, implications and future direction is induced.

4.1 Ubiquitous computing services and its results

Unlike the services supplied under the traditional IT environment, ubiquitous computing service identifies individual preference and conducts intelligent information gathering and supply.

Therefore, ubiquitous computing service requires four functional characteristics,

(1) Identification: to supply individual preference to corresponding person.
(2) Notification : to suggest appropriate behavior to user(s)
(3) Monitoring : to check out user's situation by implanting invisible computers in surrounding objects
(4) Tracking : to track user's movement and behavior

These are ubiquitous computing-specific functions, different from existing computing technology.

In this study, 24 ubiquitous computing services reflecting above four functions are suggested through many articles, papers and reports. 24 services are quoted from NTT Data Ubiquitous Research Association, ETH m-lab and Nomura Research Institute. Services differ in characteristics by each institution as follows.

(1) NTT Data Ubiquitous Research Association – individual-level service perspective, making improvement in daily living space.
(2) ETH m-lab – enterprise-level service perspective, making improvement in business process.
(3) Nomura Research Institute – based on three business models such as Concierge, Knowledge asset management and Wide area measurement, it concentrates on efficiency improvement of individual, enterprise and public.

Table 5 Taxonomy for ubiquitous computing applications

Criteria	Characteristic	Description
Subject	Generality	Characteristic in which most society constituent uses ubiquitous computing through computing environment that have simple interface and autonomy
	Specialty	Characteristic in which specific individual or group uses ubiquitous computing to achieve specific purpose
Time	Always	Characteristic in which anytime network connectivity is guaranteed
	Temporary	Characteristic which is used at specific time by temporal request of user according to construction of ubiquitous computing
Place	Mobility	Characteristic in which anywhere connectivity of network is guaranteed to use user's ubiquitous computing
	Fixation	Characteristic in which ubiquitous computing environment can be used in specific place

Since the services suggested above involve individual, enterprise and public, the scope they cover is very comprehensive. Furthermore, four functions-Identification, Notification, Monitoring, and Tracking- are also reflected in those services. The following table summarizes the services suggested above [8,11,14] (Table 6).

The suggested ubiquitous computing services can be categorized by three dimensions shown in Chap. 3 – subject (generality-specialty), time (always-temporary), and place (mobility-fixation). The mapping results are shown in the following table.

From the results shown in Table 7, the following implications could be drawn.

(1) Generality-always-mobility is the main characteristic of ubiquitous computing.

   (a) Lots of services are molded into generality-always-mobility dimension. That implicates that current ubiquitous applications are mainly sought to be the fundamental characteristics of ubiquitous computing rather than to support multi-characteristic services.

(2) User recognition needed

   (a) Generality-mobility-temporary services are supplied by users' temporal request. That means users should be aware of the needs of accessing to network. This fact indicates current stage of ubiquitous computing- users' certain behavior and/or request is still needed for ubiquitous service to be supplied.

(3) Quality improvement of user's daily life environment

   (a) Generality-always-fixation services tend to concentrate on quality improvement of user's daily life environment. These services are likely to have some problems such as data converting between heterogeneous devices, mobility control and management.

On the other hand, a number of services in each dimension group may deliver meaningful implications. The following figure shows service distribution from the mapping results (Fig. 1).

General results of the service mapping table show that generality-dimension includes 19 services, specialty-dimension 5, always-dimension 20, temporary-dimension 4, mobility-dimension 19, and fixation-dimension 5. Therefore, we can conclude that ubiquitous computing services are generally based on generality, always and mobility characteristics.

4.2 Ubiquitous computing projects

There have been lots of ubiquitous computing-related projects driven by governments and research institutions. These projects can be mapped with the classification scheme suggested in this study in order to find out their current position and characteristics. However, it poses a serious analytical dilemma due to absence of official references or statistics on the global status of whole projects. Even when we find some source, the information acquired often turned out to be insufficient or doubtful [2,9,12]. Therefore, we make a guideline by literate review and take an exploratory survey of many professionals from both public and private sources to aggregate the public (government and universities) and private firm's data by ourselves. Our guideline which is used for identifying appropriate projects has requisites and essential features as below;

Table 6 Service of ubiquitous computing environment

Service	Description
Asset management	Financial management such as recognizing money stream of user(individual, corporation, etc.)
Augmented reality game	By using ubiquitous computing devices or network, existing virtual reality (CYBER) game can be fully realized
Automatic toll/fee collection	Automatically calculate road utilization fare, recognizing vehicles
Barrier free navigation	Service enabling the disabled to move freely
Benchmarking marketing	By comparing and analyzing information that users wished to acquire with the information that is acquired from surrounding ubiquitous computing appliance, valuable marketing information could be induced
Billing and payment	As payment ways are diversified, ubiquitous computing supports various settlement means (Smart card, portable phone, etc.)
Context aware marketing	Offering marketing information according to user's present situation, habit and behavior
Crime prevention	Prevention of crime by monitoring and censoring crime activities
Emergency care	When urgency (fire back etc.) occurs, the information is notified to user
Environment care	Space conditions such as humidity, temperature, time, light are controlled and managed according to users' preferences
Facility management	By embedding computers to facilities (building, machine, etc.), previously programmed management is done on specific occasions (breakdown, collapse, etc.)
Health care	After acquiring information on users' current health condition through sensors, information analysis is made and the result is offered
Market survey	Through computer chips planted in each goods, sales volume, movement, the place where the goods are used can be investigated
Object shopping	Acquiring information through network and communication between objects, purchasing things through computers planted in objects
Offering learning programs	Anytime and Anywhere offering of the programs necessary for learning
Part tracking	Acquiring Information about location, amount, status of part through planted computers in part
Pet tracking	Grasping location information of pet through planted computers on pet
Pollution monitoring	Grasping pollution status of air, water, soil, etc., and tracking pollution source
Security	Prevention of crimes activity, which is achieved through sensor that is planted in life space
Spatial and temporal information	Providing traffic information to road traffic manager such as road status, traffic accident, etc.
Support for learning and Qualifications training	In education spot (home, school, etc.), differentiated and personalized education is possible according to users' education level and learning capability
Vehicle information	By acquiring real-time information on users' vehicle, potential dangerous situation could be prevented
Vehicle navigation	Offering the optimal route to destination by analyzing traffic information
Vehicle tracking	Acquiring the information about location and path of various vehicles (freight car, the train, airplane, motorcycle, etc.)

(1) Anonymity : should keep user's privacy and share all services to everyone equally

   (a) For privacy and security reasons, all data must be processed at each user's node and be provided them equally in order to conceal user's identity.

(2) Practicality: should have a prototype or Commercial-Off-The-Shelf (COTS) product.

   (a) Projects must have a practical proof, such as a prototype or product. Implementation is one of the most critical factors to approve project's feasibility.

(3) Concept of space : should contain concept of space (i.e. location or position information)

   (a) It should comprise location information because it plays an important role in making variations and diversifying its application and data.
   (b) Location awareness, tagging position data, tacking object or any other fusion with location information.

Table 7 Taxonomy of ubiquitous computing service

Subject	Time	Place	Case
Generality	Always	Mobility	Asset management/automatic toll, fee collection/billing and payment/context aware marketing/crime prevention/facility management/offering learning/pet tracking/vehicle information programs/vehicle tracking
Generality	Always	Fixation	Emergency care/environment care/health care/security/support for learning and qualifications training
Generality	Temporary	Mobility	Augmented reality game/benchmark marketing/object shopping/vehicle navigation
Generality	Temporary	Fixation	No result
Specialty	Always	Mobility	Barrier free navigation/market survey/part tracking/pollution monitoring/spatial and temporal information
Specialty	Always	Fixation	No result
Specialty	Temporary	Mobility	No result
Specialty	Temporary	Fixation	No result

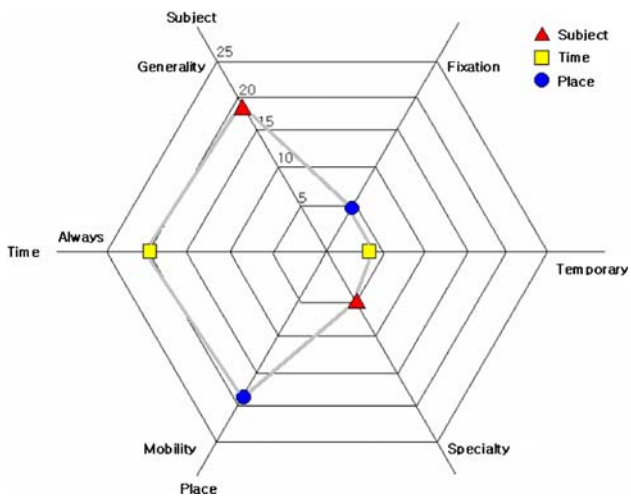

Fig. 1 Service distribution from mapping results

(4) Multiple sources: It should not excessively emphasis on a specific technology.

   (a) It should create newer and more valuable applications by the combination of existing technologies. Not just only inaugurating an innovation of technology.

(5) Continuance: should always connect up and interact with other engaged components

   (a) It should always work on and operate by any normal requests to keep availability of services.

Although many candidates were limited and speared globally, we exclude things out of guideline and choose appropriate projects relevant to our subject elaborately. Hence, they enable to embark in making our own taxonomy. The following table summarizes each project and its brief description [17–21,23–28] (Table 8).

The projects suggested above are aiming to establish future ubiquitous computing environments. By mapping them into the taxonomy framework, evolution direction and next-day ubiquitous computing environment/characteristics can be identified. The following table shows a brief result of the mapping (Table 9).

From the mapping results, some implications are drawn as follows.

(6) Generality-always-mobility services are the main stream of current research projects

   (a) A majority of projects is inclined to anyone, anytime and anywhere-based services(generality-always-mobility), which means future ubiquitous computing-related infrastructure

Table 8 Research project of ubiquitous computing

Project	Description and government/institute
Aura	Aura is to provide each user with an invisible halo of computing and information services that persists regardless of location (Carnegie Mellon University - http://www-2.cs.cmu.edu/~aura/)
Auto-ID	All physical objects will have embedded intelligence that will allow them to communicate with each other and with businesses and consumers (MIT Auto-ID Center - http://www.autoidcenter.org)
Cooltown	Communication of Nomadic users is possible environment realization using digital communication means to make web and interaction always (HP -http://www.hpl.hp.com/research/mmsl/projects/cooltown.html)
Easy Living	Develop a prototype architecture and necessary technologies for intelligent environment (Microsoft - http://research.microsoft.com/easyliving/)
e-HII	Home Information Infrastructure is enrichment of lifestyles in the era of digital networking by linking home information infrastructures to public services (Matsushita Electronic Industrial Corporation - http://matsushita.co.jp/mtj/v4801/pdf/p0101.pdf)
Grocer	The main aim of GROCER is to place new technologies (Bluetooth, WAP, RFID, etc.) at the level of the practical user by allowing users to use these technologies to perform everyday activities in the case of this project grocery shopping (Navarra University - http://www.disappearing-computer.net/projects/GROCER.html)
Oxygen	Oxygen will help us automate repetitive human tasks, control a wealth of physical devices in the environment, find the information we need, and enables us to work together with other people through space and time (MIT Computer Science Lab - http://www.oxygen.lcs.mit.edu)
Portolano	Deploy and Investigate invisible computing systems based on a active fabric overlaying the wireless/wired infrastructure (University of Washington : Department of Computer Science & Engineering –http://portolano.cs.washington.edu)
Smart Dust	Development of autonomous sensor node(mote) in 1 mm 3 (University of California - http://robotics.eecs.berkeley.edu/~pister/SmartDust/)
Smart-Its	Development of "Smart-Its" - small-scale embedded devices that can be attached to everyday objects to augment them with sensing, perception, computation, and communication (EU, ETH - http://www.smart-its.org/)
Smart Room	Provide an unencumbered user-interface to a virtual environment (MIT Media Lab - http://www-white.media.mit.edu/vismod/demos/smartroom/)
Think that Think	Provide sophisticated sensing and computational architectures, seamless interfaces and understanding of context and affect (MIT Media Lab – http://ttt.media.mit.edu)
TRON	Create standards for real-time operating systems used in embedded systems and for related specifications (Tokyo University – http://sakamura-lab.org/TRON)
U-IT839	Contains 8 major services, 3 infrastructures and 9 engines that make Korea's Ubiquitous environments and boost overall ubiquitous IT industries (Ministry of Information and Communication in Korea(MIC) - http://www.mic.go.kr/html/ebook/report_2006/it839/it839 /default1.html)
Smart Space	Provide Pervasive devices, sensors, and networks, provide infrastructure for context-aware smart meeting rooms that sense ongoing human activities and respond to them (NIST Smart Space Laboratory - http://www.nist.gov/smartspace/)
SPOT	Smart Personal Object Technology(SPOT) was formed in order to make everyday objects smarter through software and services (Microsoft – http://research.microsoft.com/spot)
Amble Time	Provide "travel-sensitive alarm clock" to explore ways that location-based information and ad-hoc networking could support participation in interactive stories (MIT Media Lab Europe – http://medialabeurope.org/research/group.php?id=4)
Urban Tapestries	HP lab's Urban Tapestries is an action research project combining social research interaction design and cultural production (Giles Lane at el., "Urban Tapestries: Wireless networking, public authoring and social knowledge," Personal and Ubiquitous computing of ACM, Vol. 7 pp 169–179, Springer-Verlag, 2003)
Grand Challenges-5	"GC-5: Architecture of Brain and Mind" concerned with a multidisciplinary attempt to understand and model natural intelligence at various levels of abstraction, demonstrating results of our improved understanding in a succession of increasingly sophisticated working robots. (EU IST WG - http://www.cs.bham.ac.uk/ research/projects/cogaff/gc/)

Table 9 Mapping results of ubiquitous computing project

Subject	Time	Place	Case
Generality	Always	Mobility	Aura/Auto-ID/Cooltown/Grocer/Oxygen/Portolano/Smart Dust/Smart-Its/TRON/Think that think/U-IT839/Smart Space/SPOT/Amble time/Urban Tapestries/
Generality	Always	Fixation	Easy Living/e-HII/Smart Room/Grand Challenges-5

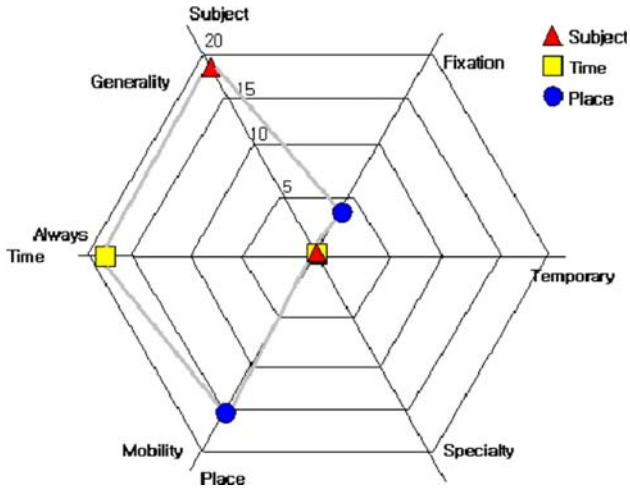

Fig. 2 Project distribution of mapping results

and environment will be established to support these services.

(7) Supporting daily life improvement

(a) Generality-always-fixation based on projects is mainly aimed to improve daily life and environment for users. With technical maturity of some ubiquity-related issues such as data converting and mobility control, services are expected to move to generality-always-mobility based ones.

From the mapping results, implications can be drawn based on the number of projects by each dimension. The following figure shows ubiquitous computing-related projects distribution (Fig 2).

General result of mapping number of projects for each dimension is that generality-dimension has 19 projects, specialty-dimension 0, always-dimension 19, temporary-dimension 0, mobility-dimension 15, and fixation-dimension 4. This result indicates that ubiquitous computing-related projects are inclined to generality-always-mobility characteristics.

4.3 Case study conclusions

Ubiquitous computing taxonomy and its case study suggested in this study can be concluded as follows

(1) Quest for generality-based service—For the time being, applications in ubiquitous computing environment are likely to be developed for the ones that anybody can use for their general purposes rather than for the specific group for its special purpose.
(2) Quest for anytime-based (always) services—Currently, sometime-based (temporary) services require users' awareness and appropriate behavior to access network when needed, which can be burden to users. Applications in ubiquitous computing environment will be developed for non-awareness and anytime-based services.
(3) Quest for anywhere (mobility)—applications in ubiquitous computing environment supporting daily-life will be developed for mobility-based services. However, a couple of technical improvements such as data converting between heterogeneous devices and mobility control/management should be achieved.

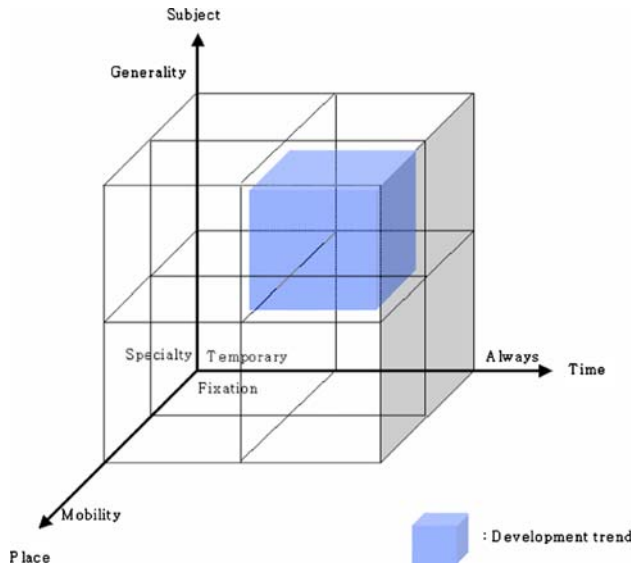

Fig. 3 Trend and future direction of ubiquitous computing application

The following figure represents these conclusions and trend Fig 3.

The emergence of ubiquitous computing will provide rich and exciting opportunities for future research. But previous Ubiquitous computing researches have been mainly focused on technologies which are required in establishing the ubiquitous computing environment.

In order to understand the characteristics of ubiquitous computing related to environment, future evolution and research direction, the definition of ubiquitous computing and its taxonomy are suggested. In addition, 24 services and 11 applications are mapped in order to analyze the current state and future direction of ubiquitous computing.

More researches are needed to analyze many various ubiquitous computing applications using this taxonomy. As a result of the future researches, Ubiquitous technology trend and strategic application could be drawn.

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