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Context-aware systems: A literature review and classification

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ABSTRACT

Nowadays, numerous journals and conferences have published articles related to context-aware systems, indicating many researchers' interest. Therefore, the goal of this paper is to review the works that were published in journals, suggest a new classification framework of context-aware systems, and explore each feature of classification framework. This paper is based on a literature review of context-aware systems from 2000 to 2007 using a keyword index and article title search. The classification framework is developed based on the architecture of context-aware systems, which consists of the following five layers: concept and research layer, network layer, middleware layer, application layer and user infrastructure layer. The articles are categorized based on the classification framework. This paper allows researchers to extract several lessons learned that are important for the implementation of context-aware systems.

1. Introduction

Emerging ubiquitous or pervasive computing technologies offer 'anytime, anywhere, anyone' computing by decoupling users from devices (Dey, 2001; Hill et al., 2004; Kwon, Choi, & Park, 2005; Kwon, Yoo, & Suh, 2005; Schilit, Adams, & Want, 1994). To provide adequate service for the users, applications and services should be aware of their contexts and automatically adapt to their changing contexts-known as context-awareness (Bolchini, Schreiber, & Tanca, 2007; Dey, 2001; Zhu, Mutka, & Ni, 2005). Context is very important, since it provides information about the present status of people, places, things and devices in the environment (Korpipää, Mäntyjärvi, Kela, Keränen, & Malm, 2003; Kwon, 2004). Context is any information that can be used to characterize the situation of an entity. An entity is a person, place, or object that is considered relevant to the interaction between a user and an application, including location, time, activities, and the preferences of each entity (Dey, 2001). Context-awareness means that one is able to use context information. A system is context-aware if it can extract, interpret and use context information and adapt its functionality to the current context of use (Byun & Cheverst, 2004). The term context-aware computing is commonly understood by those working in context-aware, where it is felt that context is a key in their efforts to disperse and transparently weave computer technology into our lives. One goal of context-aware systems is to acquire and utilize information on the context of a device in order to provide services that are appropriate to the particular people, place, time, event, etc. These systems aim to provide context-aware access to information, communication and computation.

In late 1980s, there was a period of beginning activity on context-aware computing. A few of context-aware computing has met the interest. However, the activity seems to be increasing dramatically. Nowadays, to overcome new challenges and requirements found in context-aware systems, many researchers have made efforts to design and implement network, user infrastructure and middleware which effectively provide users with context-aware services. Numerous articles of journals and conferences have published research related to context-aware systems. In other words, many people are interested in context-aware systems. Therefore, we feel that this is a good time for a review analysis, since it has been over a year since many papers were published. Currently, it is difficult to compare articles, because the available research is published in quite different journals. Accordingly, the main objectives of this review are:

- To classify and summarize research relevant for context-aware systems.
- To provide a conceptual framework for the integration and classification of articles.
- To derive suggestions for context-aware systems researchers based on the literature review.

Chen and Kotz (2000) surveyed the literature related with context-aware computing in mobile computing. They defined the terms context and context awareness, listed the context-aware applications that have been built, discussed approaches to sense and model the context, and looked into supporting infrastructures, security and privacy issues. However, in 2000, articles published in

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journal were not enough to analyze context-aware systems. Furthermore, a classification standard does not involve all fields of context-aware systems. Therefore, a new survey research on context-aware systems is needed. Baldauf, Dustdar, and Rosenberg (2007) suggested the abstract layer architecture for context-aware systems and introduced various existent middleware and server-based approaches to ease the development of context-aware applications, where each layer is explained based on various research. However, suggestions for further study, literature review related with each layer, introducing framework of many research and presenting current research issues are not broad.

The remainder of this paper is structured as follows. In Section 2, a methodology to extract the literature is illustrated. Section 3 presents general characteristics of the literature research. Section 4 illustrates the proposed classification framework. Section 5 describes each feature of classification framework (concept and research, network, user infrastructure, middleware, application and service). Section 6 contains discussions and suggestions. Finally, Section 7 concludes the paper with brief concluding remarks.

2. Procedures

A total of 237 articles from 2000 to 2007 were obtained and reviewed. Articles were found via computerized search of the topic areas. The search was narrowed using the terms context-aware. A detail illustration of methodology for extracting articles is followed.

2.1. The selection criteria

The selection criteria were used to select and accept the context-aware articles. If the papers did not meet the selection criteria, then they were excluded. The three criteria are described as follows:

- The literature was based on a search in the descriptor for 'context-aware'. Various online journal databases were selected to search context-aware literatures. Context-aware articles are found in comprehensive subjects such as computer science, engineering, etc. Subjects of online database which are summarized according to fields of context-aware systems are shown in Table 1.
- This paper surveys the articles published from 2000 to 2007. The reason for selecting this time period is that many journals and conferences have published researches related to context-aware computing since 2000.
- This paper covers only journal articles. Other publication forms (The conference proceedings, unpublished working papers, master's and doctoral dissertations, newspapers and books, etc.) were not included. Furthermore, LNCS (Lecture Notes of Computer Science) is excluded, because of numerous articles having contents of computer science. The reason for choosing the journal is that both practitioners and academicians use journals frequently to obtain knowledge and spread their study findings. Thus, journal articles indicate the highest level of research.

2.2. Data sources and procedures to extract articles

The papers were selected according to the procedures shown in Fig. 1. First of all, the articles were searched using six online databases. The total number of articles is 1419. The number of articles by each online database is as follows: Science Direct (288), IEEE Xplore (100), Springer Link Online Libraries (43), ACM Digital Library (200), Wiley InterScience (94), Ingenta Journals (421), and EBSCO (Electronic Journal Service) (273). Next, 996 articles were excluded because they did not have the word of context-aware systems in the titles and abstracts. Next, the articles were carefully reviewed to select those that considered context-aware as the core part. Two hundred and thirty seven articles remained because 186 articles did not meet the second selection criteria. Based on these procedures, a total of 237 articles met all the selection criteria.

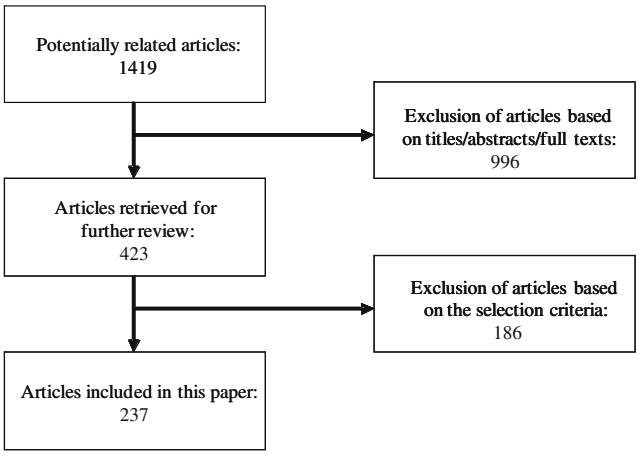

Fig. 1. The procedures to select the articles.

Table 1
The online databases and subjects.

Online database	Subjects	Online database	Subjects
IEEE Xplore	Biomedical communication and information communication	Science Direct	Business, management and accounting
	Networks/systems		Computer science
			Decision science
	Computational intelligence		Engineering
	Computer engineering		Psychology
	Computer graphics		Social science
	Control systems	EBSCO (Electronic Journal Service)	Computer science
	Distributed computing/real-time systems		Library science
	Socio-political aspects of technology		Mathematics
	Software design development	ACM Digital Library	Computer science
			Engineering
			Social sciences
		Ingenta Journals	Computer science
			Education
			Engineering
Wiley InterScience	Computer science engineering	Springer Link Online Libraries	Computer science
			Engineering

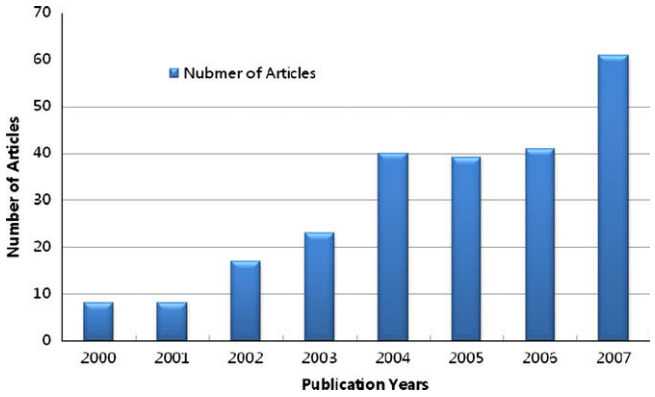

Fig. 2. Classification of articles by publication year.

3. The general characteristics of the articles

3.1. Classification of articles by publication year

The number of articles by publication year is depicted in Fig. 2. Numerous context-aware articles have grown considerably since 2000. The number of articles in 2007 have becomes 7 times more than the number of articles in 2000. The number of articles from 2001 to 2004 had been increased continuously, and the number of articles from 2004 to 2006 has been almost the same. It is absolute that the concern about context-aware systems was increased and will be continued.

3.2. Classification of articles by online database

The article by online database is categorized in Table 2. There are a total of 181 articles from online databases. We use 7 online databases to search the articles. In Table 2, IEEE Xplore is the highest percentage of articles (74 articles, 31%), because it offers articles of many journals (IEEE Pervasive Computing, IEEE Internet Computing, IEEE Wireless Communications and IEEE Transactions on Software Engineering) which have subject relevant to context-aware systems. Science Direct stores journal articles of various study fields, therefore this database is the second highest of articles (60 articles, 25.6%). Other online databases are Springer Link Online Libraries (57 articles, 23.9%), Ingenta Journals (18 articles, 8%), ACM Digital Library (16 articles, 7%), Wiley InterScience (9 articles, 4%) and EBSCO (Electronic Journal Service) (3 articles, 1%). When the same article is found repetitively among different online database, the article number of database having more number of articles is increased.

3.3. Classification of articles by journal

The articles by journal articles are categorized in Table 3. There were 65 journals that published context-aware articles. Most of them were related to the computer science, electronic engineering and information management. Table 3 specifies journals that published four or more context-aware articles and the others that published only one article or no more than 3 related with context-aware systems are omitted. Pervasive computing and ubiquitous computing is closely connected with context-aware computing. Therefore, journals which focus on pervasive computing or ubiquitous computing have published articles relevant to context-aware systems. As Table 3 shows, IEEE Pervasive Computing published the most articles on context-aware systems (23 articles, 10%). Expert Systems with Applications and Personal and Ubiquitous Computing published 10 articles (4%). Distribution of articles according to the journal shows that various journals have published articles relevant to context-aware systems.

Table 2
Classification of articles by publication year.

Online database	Number of articles
IEEE Xplore	74
Science Direct	60
Springer Link Online Libraries	57
Ingenta Journals	18
ACM Digital Library	16
Wiley InterScience	9
EBSCO (Electronic Journal Service)	3
Total	237

Table 3
Classification of articles based on the journal.

Journal articles	Number of articles
IEEE Pervasive Computing	23
Personal and Ubiquitous Computing	10
IEEE Internet Computing	6
Wireless Personal Communications	5
IEEE Intelligent Systems	5
Mobile Networks and Applications	5
IEEE Transactions on Software Engineering	4
The Others	139
Expert Systems with Applications	10
Computer Communications	6
Journal of Systems and Software	6
Pervasive and Mobile Computing	5
World Wide Web	5
IEEE Wireless Communications	5
Interacting with Computers	4
Total	237

4. Classification framework

4.1. Abstract architecture of context-aware systems

The abstract architecture of context-aware systems is drawn based on the literature that explores the context-aware prototype, systems, and application to offer classification criteria for dividing the literature appropriately. To make the abstract architecture, SOCAM, ACAI, NAMA, PeCAN, X-CAF, CyberDesk, WebPADS, CAPIAs, Hycon service framework, Culliver's Genie, Intelligent Agent framework, context-aware agent architecture, reference framework for multi-target user interfaces, etc. are reviewed in detail. As the results of literature review related with context-aware architecture, we present general abstract layer architecture of context-aware systems. As Fig. 3 shows, this architecture consists of four layers: (1) network layer involves a network supporting context-aware systems and sensor collecting low-level of context information; (2) middleware layer manages processes and stores context information; (3) based below layers, application layer provides users with appropriate service; and (4) to offer suitable inter-

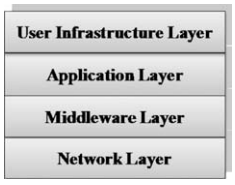

Fig. 3. Abstract layer architecture of context-aware systems.

face to users, interface of context-aware systems is managed in user infrastructure layer.

4.2. Classification framework of context-aware systems

The classification framework is developed for classifying the literatures related with context-aware systems, based on the abstract architecture of context-aware systems. The classification framework developed here consists of the following five layers: concept and research layer, network layer, middleware layer, application layer and user intrastate layer. Without the concept and research layer, layers of classification framework and layers of context-aware systems architecture are the same. As Fig. 4 shows, each layer has detailed categories for dividing the literatures in layers.

Fig. 4 depicts a graphical classification framework for context-aware systems. Context-aware applications and services require technology from the foundation of wireless network, user infrastructure, and middleware. Moreover, application and technology related with network, middleware and user infrastructure are based on concept and research activities. Concept and research layer involves overview, algorithm, development guideline, framework, context data management, evaluation and privacy and security categories. Network layer consists of protocol, sensing, network requirement and network implementation. Middleware layer is classified as agent-based middleware, metadata based middleware, tuple space based middleware, OSGI based middleware, reflective middleware and sensor selection middleware. User infrastructure layer is divided into interface and usability categories. Application and service layer consists of smart space, tour guide, information systems, communication systems, m-commerce and web service.

5. Result of article classification

The articles by subjects are categorized in Tables 4–9. Table 4 shows the number of articles, percentage of subject, and percentage of all subjects, while Tables 5–9 represent all references of the context-aware systems articles.

The context-aware concept and research has the highest percentage of context-aware articles (87 articles, 37%). In context-aware concept and research, the category can be divided into 7 subjects. Most of the articles are related to "development guideline", "context data management" (13 articles) and "algorithm" (28 articles). The "algorithm" is divided into 3 categories, namely "agent" (3 articles), "context reasoning" (14 articles) and "service recommendation" (10 articles). There are many articles related to guidelines, context data management and algorithm to develop the context-aware application and systems. Other topics are "overview" (8 articles), "framework" (10 articles), "privacy and security" (12 articles), and "evaluation" (3 articles). The second highest percentage of context-aware articles is related to context-aware application (63 articles, 26%), which has six categories. The majority of this section is related to the "m-commerce" (19 articles)". The "smart spaces" (11 articles) are the second portion of context-aware application and are composed of "home" (3 articles), "hospital" (7 articles) and "class room" (1 article). Other topics are "tour guide" (6 articles) and "communication systems" (10 articles), "information systems" (7 articles) and "Web Service" (9 articles). Network infrastructure has the third highest percentage of context-aware articles (41 articles, 17%). The articles are mostly related to the "internet protocol" (11 articles), "handoff management" (7 articles), "Sensing" (13 articles), "network requirement" (4 articles) and "network implementation" (5 arti-

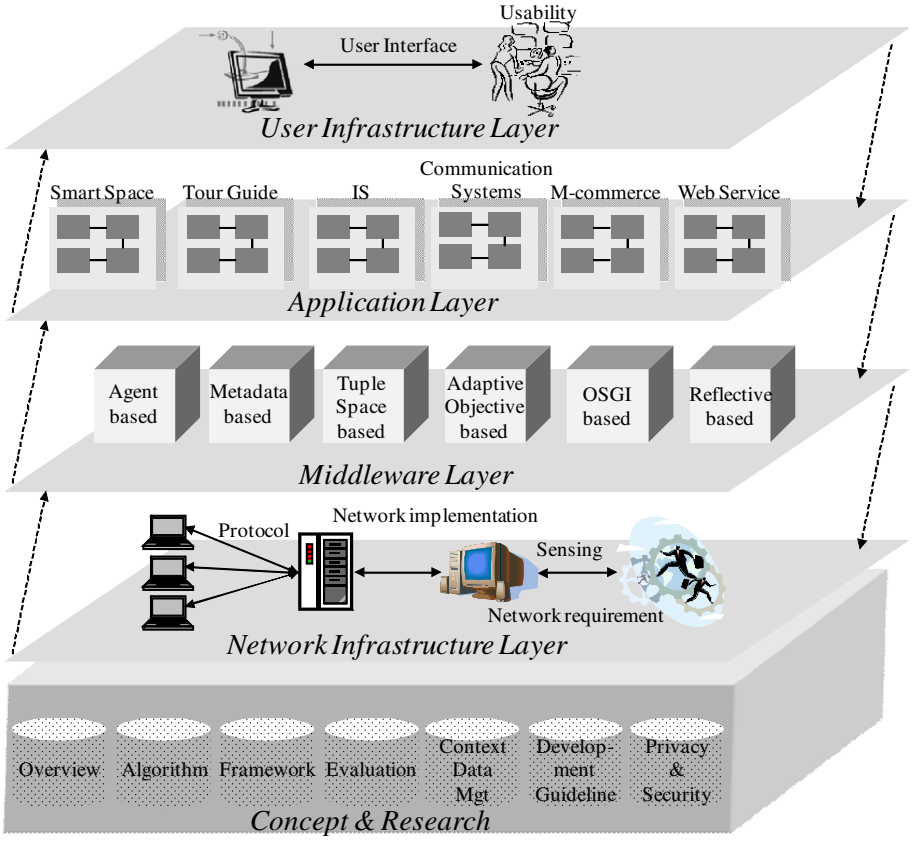

Fig. 4. Classification framework of context-aware systems.

Table 4
Classification of articles by subject.

Classification criteria	Number of articles	Percentage of subject (%)	Percentage of all subjects (%)
1. Concept and research	87	100	36.6
1.1. Algorithm	28	32.2	11.8
1.1.1. Agent	4	4.6	1.7
1.1.2. Context reasoning	14	16.1	5.9
1.1.3. Service recommendation	10	11.5	4.2
1.2. Development guideline	13	14.9	5.5
1.3. Framework	10	11.5	4.2
1.4. Context data management	13	14.5	5.5
1.5. Evaluation	3	3.4	1.3
1.6. Privacy and security	12	13.8	5.0
1.7. Overview	8	9.2	3.4
2. Network infrastructure	41	100	17.2
2.1. Protocol	11	26.8	6
2.2. Handoff management	7	17.1	2.9
2.3. Sensing	13	31.7	5.5
2.4. Network requirement	4	9.8	1.7
2.5. Network implementation	6	14.6	2.8
3. Middleware	31	100	13.0
3.1. Agent-based middleware	11	35.5	4.6
3.2. Reflective middleware	5	16.1	2.1
3.3. Metadata based middleware	2	6.5	0.8
3.4. Tuple space based Middleware	3	9.7	1.3
3.5. Adaptive and objective based middleware	6	19.4	2.5
3.6. OSGI based middleware	4	12.9	1.7
4. User infrastructure	16	100	6.7
4.1. Interface	13	81.3	5.5
4.2. Usability	3	18.8	1.3
5. Application	63	100	26.5
5.1. Smart space	11	17.5	4.6
5.1.1. Home	3	4.8	1.3
5.1.2. Hospital	7	11.1	2.9
5.1.3. Class room	1	1.6	0.4
5.2. Tour guide	6	9.5	2.5
5.3. Information systems	7	12.7	3.0
5.4. Communication systems	10	15.9	4.2
5.5. m-Commerce	19	30.2	8.0
5.6. Web service	9	14.3	3.8
Total	237		100

cles). The articles related to the middleware have 31 articles (13%). The category of this middleware part can be also divided into six subjects. The articles are related to "agent-based middleware" (11 articles), "reflective middleware" (5 articles), and "adaptive and objective based middleware" (6 articles). The fewest of context-aware articles is related to user infrastructure (16 articles, 7%). The user infrastructure can be divided into two parts, "interface" (13 articles) and "usability" (3 articles).

In result, the concept and research has the highest percentage of context-aware articles, in which the most explored subject is the algorithm. This represents that the context-aware studies are in developing stages and much research have been conducted in this area. The fewest of context-aware articles is related to user infrastructure.

Fig. 5 shows the number of distribution of articles by the year and classification framework. Articles of concept and research layer and application and service layer have been increased continuously by increasing the total number of articles from 2000 to 2007. Almost Articles which have issues of privacy and security are published in 2005 and 2007. It means that the concern about privacy and security has increased recently. Context-aware systems can provide users with better service based on analyzing physical context and personal context such as user schedule, user preferences and so on. However, grasping user context causes risk of security and privacy relevant to personal information. Articles which focus on context reasoning are distributed almost from 2002 to 2004, because many algorithms for finding user context such as Bayesian network algorithm, decision tree, case based reasoning and rule based reasoning has been already developed. Approximately 65% of articles involved in application layer were published from 2005 to 2007. In accordance with developing fields of the other layer, context-aware computing application and service have been implemented recently. However, articles in user infrastructure, network infrastructure and middleware layer are decreased after the peak publishing point of each layer. For example, articles in middleware layer were increased until 2004, and then decreased until. This phenomenon was caused by recent research that covers several category of framework from concept to application. In other words, the tendency of recent research focuses not only on basic concept but also implantation or case-study. Therefore, articles of application category in our classification framework have been increased continuously.

5.1. Concept and research layer

This represents the references according to the detailed categories in concept and research layer in Table 5. "Context-aware concept and research" involves theories and foundation to construct context-aware systems. Algorithm is an essential part in developing the context-aware systems and is divided into three sections such as agent, context reasoning, and service recommendation. The algorithm category has research related to an AI methodology that provides the foundation for a technology of intelligent systems. Here, it is applied as three indexes within the concept and research layer: (1) designing and modeling algorithm, message bus encoded by XML, role and communication methods of agents, (2) increasing accuracy and efficiency of algorithm for extracting high-level context from low-level context, and (3) developing algorithm or method to recommend appropriate service according to the context of user. Context data management represents the framework to manage the context and context information. Development guideline describes the guideline related to the development of many kinds of context-aware applications and services. The framework of context-aware systems illustrates acquiring, discovering, interpreting and accessing various contexts to build context-aware services. The framework of context-aware systems is similar to an architectural sketch of a house. It gives users a general idea of what the systems will look like and how it will implement systems. The framework shows the general capabilities of the systems, a user interfaces system functions, system (data) flow, system management, etc. The evaluation is focused on the evaluation method of the system that is developed in each paper. The overview deals with the general definition, characteristics and history of context-aware.

Ontology is generally defined as a 'representation of a shared conceptualization of a particular domain', and further defined by 'axioms that offer additional constraints and meaning as well as rules and heuristics that can derive additional useful information'. Ontology language has been developed in the Semantic Web and has converged to a new W3C standard called Web Ontology Language (OWL; Smith, Welty, & McGuinness, 2004). Semantic web metadata standards such as Resource Description Framework (RDF) and OWL provide standard representation for context data

Table 5
References of concept and research layer.

Classification criteria			References
Concept and research	Algorithm	Agent	Arcos and Plaza (2002), Hattori, Cho, Ohsuga, Isshiki, and Honiden (2004), Kao and Yuan (2005), Krause, Smailagic, and Siewiorek (2006)
		Context reasoning	Anagnostopoulos, Ntarladimas, and Hadjiefthymiades (2007), Brunato and Battiti (2005), Castro and Munz (2000), Chetan, Ranganathan, and Campbell (2005), Drakatos, Pissinou, Douligeris, and Makki (2007), Ladd, Bekris, Rudys, Kavraki, and Wallach (2005), Niemegeers and Heemstra De Groot (2005), Ranganathan, Al-Muhtadi, and Campbell (2004), Sajal, Nirmalya, and Abhishek (2006), Samaan and Karmouch (2005), Satoh (2003), Smailagic and Kogan (2002), Weber, Sorkine, Lipman, and Gotsman (2007), Xiong and Hassan (2006)
		Service recommendation	Byun and Cheverst (2004), Hatala, Wakkary, and Kalantari (2005), Kocaballı and KoçyiğitGranular (2007), Kouadri and Younas (2007), Kwon and Kim (2004), Meeuwissen, Reinold, and LiemInferring (2007), Pertselakis, Ferles, Tsiolis, and Stafylopatis (2005), Soldatos, Stamatis, Azodolmolky, Pandis, and Polymenakos (2007), Syukur and Loke (2007), Yuan and Peng (2004)
	Development guideline		Anhalt et al. (2001), Augustin et al. (2006), Avrahami, Gergle, Hudson, and Kiesler (2007), Bolchini et al. (2007), Casas, Cuartielles, Marco, Gracia, and Falco (2007), Henricksena and Indulska (2006), Hong and Landay (2001), Julien, Payton, and Roman (2004), Kwon (2004), Kwon, Choi, and Kim (2007), Qing, Károly, Christian, Paulo, and Bernhard (2006), Qiu, Chang, Lin, and Shi (2007), van Sinderen, van Halteren, Wegdam, Meeuwissen, and Eertink (2006)
	Framework		Dix et al. (2000), Doulkeridis, Loutas, and Vazirgiannis (2006), Johnson (2007), Jones, Grandhi, Terveen, and Whittaker (2004), Kao and Yuan (2004), Panagiotakis and Alonistioti (2006), Rogers and Muller (2006), Roussaki, Strimpakou, and Anagnostou (2007), van Kranenburg, Bargh, Iacob, and Peddemors (2006), Vuković, Kotsovinos, and Robinson (2007)
	Context data management		Abecker, Bernardi, Hinkelmann, Kühn, and Sintek (2000), Chaari, Ejigu, Laforest F., and Scuturici (2007), Demiris, Vlahakis, Makri, Papaioannou, and Ioannidis (2005), Korpipää et al. (2003), Liao, He, and Tang (2004), Reignier, Brdiczka, Vaufreydaz, Crowley, and Maisonnasse (2007), Roussaki, Strimpakou, and Pils (2007), Satoh (2007), Serrano and Serrat (2006), Simons and Wirtz (2007), Smith, Ma, and Ryan (2006), Qi and Venkatasubramanian (2007), Zimmermann, Specht, and Lorenz (2005)
	Evaluation		Griswold et al. (2004), Morla and Davies (2004), O'Grady et al. (2005)
	Privacy and security		Bhatti, Bertino, and Ghafoor (2005), Bhatti, Samuel, Eltabakh, Amjad, and Ghafoor (2007), Falkovych and Nack (2006), Hill et al. (2004), Jiang and Landay (2002), Jorns, Jung, and Quirchmayr (2007), Jutla, Bodorik, and Zhang (2006), Minami and Kotz (2005), Tentori, Favela, and Rodriguez (2006), Vassilis, Loukas, Dimitris, and Stavros (2006), Yee, Korba, Lin, and Shih (2006), Zhang, Qi, Zhao, and Hou (2007)
	Overview		Brown and Randel (2004), Chalmers (2004), Dey (2001), Intille (2004), Lieberman and Selker (2000), Liechti (2000), Loke (2006), Prekop and Burnett (2003)

Table 6
References of network layer.

Classification criteria		References
Network infrastructure	Internet protocol	Benedetto and Nardis (2006), Boukerche, Pazzi, and Araujo (2006), Chen and Mohapatra (2005), Friday et al. (2003), Giaffreda, de Carvalho, Melia, Giaffreda, and de Carvalho (2007), Kellerer, Wagner, Balke, and Schulzrinne (2004), Lin, Tsai, and Lai (2005), Singh and Acharya (2005), Tyan and Mahmoud (2005), Yau and Karim (2003), Zhu et al. (2005)
	Handoff management	Balasubramaniam and Indulska (2004), Bellavista, Corradi, and Foschini (2007), Marias, Prigouris, Papazafeiropoulos, Hadjiefthymiades, and Merakos (2004), Mcnair and Zhu (2004), Qing et al. (2006), Rocha and Endler (2006), Yang, Wu, Yang, and Liu (2007)
	Sensing	Brilingaitė and Jensen (2007), Gellersen, Schmidt, and Beigl (2002), Gellersen, Kortuem, Schmidt, and Beigl (2004), Goulev, Stead, Mamdani, and Evans (2004), Gross, Egla, and Marquardt (2006), Jonker, Persa, Caarls, de Jong, and Lagendijk (2003), Knight et al. (2007), Matsushita (2001), Michahelles and Samulowitz (2004), Pfeifer (2005), Schmidt and Laerhoven (2001), Xu, Fu, Lee, and Winter (2007), Zhong and Gilbert (2005)
	Network requirement	Dixit (2002), Harter, Hopper, Steggles, Ward, and Webster (2002), Kanter (2002), Yang et al. (2007)
	Network implementation	Aguiar, Sarma, Bijwaard, Marchetti, and Pacyna (2007), Beigl, Gellersen, and Schmidt (2001), Cano, Ferrandez-Bell, and Manzoni (2005), Gonzalez-Castano, Garcia-Reinoso, Gil-Castineira, Costa-Montenegro, and Pousada-Carballo (2005), Riva, Nadeem, Borcea, and Iftode (2007), Wang et al. (2004)

Table 7
References of middleware layer.

Classification criteria		References
Middleware	Agent-based middleware	Alahuhta, Löthman, Helaakoski, Koskela, and Röning (2007), Bellavista, Corradi, Montanari, and Stefanelli (2006), Bellavista, Corradi, and Stefanelli (2002), Chen et al. (2004), Julien and Roman (2006), Khedr and Karmouch (2005), Khedr and Karmouch (2004), Kumar et al. (2003), Riekki et al. (2003), Román et al. (2002), Soldatos, Dimakis, Stamatis, and Polymenakos (2007)
	Reflective middleware	Capra, Emmerich, and Mascolo C. (2003), Chan and Chuang (2003), Chan, Chuang, Cao, and Leong (2004), Qin, Shi, and Suo (2007), Sacramento et al. (2004)
	Metadata based middleware	Bellavista, Corradi, Montanari, and Stefanelli (2003a), Bellavista, Corradi, Montanari, and Stefanelli (2003b)
	Tuple space based middleware	Cabri, Leonardi, Mamei, and Zambonelli (2003), Curino et al. (2005), Murphy and Picco (2004)
	Adaptive and objective based middleware	Alex, Kumar, and Shirazi (2008), Trumler, Bagci, Petzold, and Ungerer (2005), Yau and Karim (2004a), Yau and Karim (2004b), Yau et al. (2006), Wu et al. (2007)
	OSGI based middleware	Choi, Shin, and Shin (2005), Gu, Pung, and Zhang (2005), Gu, Pung, and Zhang (2004), Yu, Zhou, Yu, Zhang, and Chin (2006)

in context-aware systems. In other words, ontology will play a crucial role in enabling the processing and sharing of information and knowledge on the middleware. The reasons are as follows:

- Providing a shared and common understanding of a domain that can be communicated across people and application systems (Chen & Finin, 2003).

Table 8
References of application and service layer.

Classification criteria			References
Applications and services	Smart space	Home	Baek, Lee, Lim, and Huh (2005), Intille (2002), Schulzrinne, Wu, Sidiroglou, and Berger (2003)
		Hospital	Agarwal, Joshi, Finin, Yesha, and Ganous (2007), Bottazzi, Corradi, and Montanari (2006), Favela, Rodríguez, Preciado, and González (2004), Favela et al. (2007), Kjeldskov and Skov (2007), Muñoz, Rodriguez, Favela, Martinez-Garcia, and González (2003), Rodríguez, Favela, Martínez, and Muñoz (2004)
		Class room	Sung et al. (2005)
	Tour guide		Bellotti, Berta, De Gloria, and Margarone (2005), Cano, Manzoni, and Toh (2006), Cheverst, Mitchell, Davies, and Smith (2000), Cheverst, Smith, Mitchell, Friday, and Davies (2001), O'Hare and O'Grady (2003), Pashtan, Heusser, and Scheuermann (2004)
	Information systems		Celentano and Gaggi (2006), Kwon (2006a), Kwon, Yoo, et al. (2005), Kwon, Yoo, and Suh (2006), Norrie et al. (2007), Signer, Grossniklaus, and Norrie (2007), Wilson, Doyle, Weakliam, Bertolotto, and Lynch (2007)
	Communication systems		Fogarty, Lai, and Christensen (2004), Goularte, Pimentel, and Moreira (2006), Raento, Oulasvirta, Petit, and Toivonen (2005), Ranganathan, Campbell, Ravi, and Mahajan (2002), Schmidt, Takaluoma, and Mantyjarvi (2000), Schilit, Hilbert, and Trevor (2002), Sumi and Mase (2000), Sumi and Nishida (2001), Udugama, Kuladinithi, Gorg, Pittmann, and Tionardi (2007), Yuan and Chen (2007)
	M-commerce		Anagnostopoulos, Tsounis, and Hadjiefthymiades (2007), Becerra-Fernandez, Cousins, and Weber (2007), Bouvin, Christensen, Frank, and Hansen (2003), Broens, Halteren, Sinderen, and Wac (2007), Chakraborty et al. (2007), Genco, Sorce, Reina, and Santoro (2006), Kwon (2003), Kwon and Sadeh (2004), Kwon, Shin, and Kim (2006), Maiden, Omo, Seyff, Grunbacher, and Mitteregger (2007), Mandato, Kovacs, Hohl, and Amir-Alikhani (2002), Riva and Toivonen (2007), Roussos, Marsh, and Maglavera (2005), Skov and Høegh (2006), Stylianos, Nikia, Kia, and Christos (2007), Syukur and Loke (2006),Wac, Halteren, Bults, and Broens (2007), Wohltorf, Cissée, and Rieger (2005), Yu et al. (2006)
	Web service		Blake, Kahan, and Nowlan (2007), Debaty, Goddi, and Vorbau (2005), Ceri, Daniel, Facca, and Matera (2007), Gandon and Sadeh (2004), Kanter (2003), Kwon (2006b), Kwon, Choi, et al. (2005), Kwon, Yoo, et al. (2005), Lee (2007), Pashtan, Kollipara, and Pearce (2003)

Table 9
References of user infrastructure layer.

Classification criteria		References
User infrastructure	Interface	Alexander and Matthias (2006), Bell, Feiner, and Höllerer (2002), Calvary et al. (2003), Hatala and Wakkary (2005), Hong, Dickson, Chiu, Shen, and Kafeza (2007), Korhonen et al. (2007), Kurvinen, Lähteenmäki, Salovaara, and Lopez (2007), Lieberman and Chu (2007), Lum and Lau (2002), Mäntyjärvi and Seppänen (2003), Rehman, Stajano, and Coulouris (2007), Selker (2004), Smailagic and Siewiorek (2002)
	Usability	Barnard, Yi, Jacko, and Sears (2005), Burrell and Gay (2002), Kaasinen (2003)

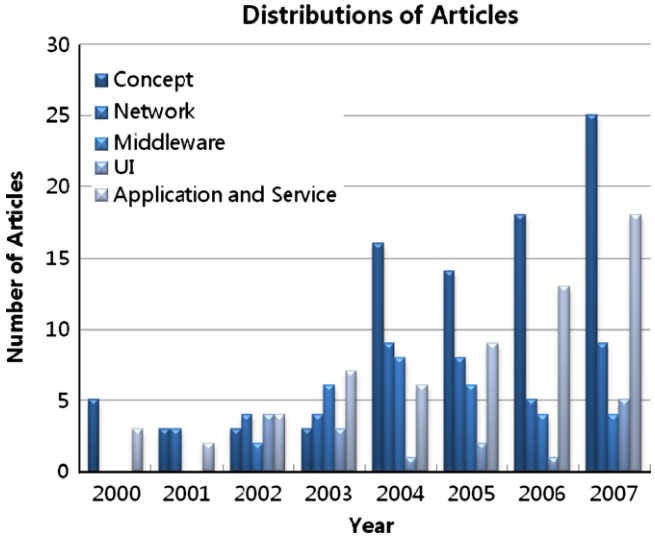

Fig. 5. Distribution of articles number by year and classification framework.

- Facilitating knowledge sharing and reuse in an open and dynamic distributed systems (Kwon, Choi, et al., 2005; Kwon, Yoo, et al., 2005; Gruber, 1993).
- Deriving fresh knowledge and facts based on reasoning contextual data and information by using inference engines.
- Allowing devices and agents not expressly designed to work together to interoperate, achieving "serendipitous interoperability" (Wang, Dong, Chin, Hettiarachchi, & Zhang, 2004).

Although some research only focuses on ontology, the number is very few. Ontology is generally used for reasoning and expressing context data. Therefore, they do not need to have a separate category for ontology.

5.2. Network layer

As shown in Table 6, we categorize the network infrastructure layer into internet protocol, handoff management, sensing, network requirements and network implementation. Context-aware computing needs to dynamically adapt to changes in this context and connect entities based on network. Therefore, many researches are conducted to offer appropriate network for providing context-aware computing. Internet protocol category involves presenting mechanisms and design of session initiation protocol (SIP), mobile IPv6, an integral part of constructing self-configuring mobile ad hoc networks and object discovery. Handoff management category has article about the process of transferring an ongoing call or data session from one channel connected to the core network to another. Article topic of handoff management category is treating heterogeneous network for seamless communication environments. The sensing category is responsible for capturing, abstracting and acquiring context information of the situations in the environment. When implementing context-aware systems, the basic idea is to use the sensor data and predict the current situation. Therefore, the sensing category consists of sensing algorithm, sensing technology and wearable sensing mechanism. Network requirements category means collecting requirements for the adaptation method which can support seamless computing infrastructures, framework for integration for user services out to the

mobile devices and heterogeneous network infrastructures. Network implementation category involves realizing the network which can provide context-aware computing environments. Although many researches related with context-aware computing illustrate network layer, the research which are specially focused on network are only involved in this category. A part of research related with constructing context-aware systems involves an illustration of sensing. However, these researches do not belong to the network category, because network sensing is not their core part.

5.3. Middleware layer

Table 7 indicates the references according to the detailed categories in middleware layer. The context-aware systems can be made up of several basic parts. Almost all the middleware parts gather context information, process it and derive meaningful actions from it. Context-aware systems must have middleware support for providing customized services. The middleware allows agents to acquire contextual information easily, reason about it using different logics and then adapt themselves to changing contexts. Therefore, the middleware facilitates the development of context-aware agents. There are many types of middleware. This paper divides the currently available middleware for context-aware systems into seven categories. The essential part of agent-based middleware is mobile agents. Mobile agents are regarded as a highly potential technology for many application areas. They emerge as a middleware technology suitable to develop context-aware services, and have been developed to implement the needed active infrastructure and the MA-based middleware design and implementation. Reflective middleware possesses the unique ability to model itself through self-representation, such that the manipulation of its behavior may be changed. A middleware systems with self-representation is causally connected if changes made to the self-representation directly affect the implementation of the middleware. The opposite is true if changes to the middleware implementation change the self-representation. Metadata provides information on users, devices resources, and the preferred binding strategies. Metadata based middleware facilities perform runtime binding management actions based on metadata and context and location visibility. Tuple spaces have been considered for use in sensor networks and as a blackboard with a mechanism that permits to retrieve partially known information. This is a shared repository of information, which can be accessed via well-defined primitives. Adaptive middleware is a middleware for context-aware applications in smart-home setups. In this scheme, the middleware matches the Quality of Context (QoC) requirements with the QoC available with the sensors. The application's QoC requirements are mapped to a utility function using the QoC attributes of the sensors available. OSGi-based middleware reliably manages context-aware services to support context acquisition, discovery, and reasoning.

The middleware using agents for managing complexity in the delivery of context-aware systems have recently emerged. Autonomous, proactive, rational and social agents are engaged in opportunistic collaboration in the solution of appropriate service, because context-aware systems are comprised of many dynamically interacting components. Numerous incarnations of agents are found from the reactive agent that responds in a stimulus response manner, the agent that minimizes the need for a complex representational context model, to the agent that support reasoning in a collaborative context.

5.4. Application and service layer

Table 8 indicates the references according to detailed categories in applications and services layer. There are many types of context-aware application, which provide the user with smart environment such as home, hospital, class room, etc. When a user wants to go to unfamiliar places such as museum, they play an important role as a tour guide. In addition, context-aware applications include information systems, especially decision support systems, communication systems as social community, m-commerce, and web service.

Based on the analysis of the literature review related with context-aware application and service, characteristics of context-aware computing application and service are extracted as follows:

- Compute device to operate independently of human control. To provide the user with services autonomously, context-aware applications are customizable by using user context and preference. Automatic execution of service is conducted when in a certain context.
- Context-aware applications act in anticipation of future goals or problems. Context-aware applications not only handle current task, situation and action but also, anticipate future behavior, moving point and problem of user.
- In context-aware application, various devices are interconnected among each other and they recognize each other on a certain distance, because proximal devices distance between user and device or between devices are important factors to offer appropriate service to user.
- Context-aware applications provide a rich set of capabilities and services to the nomad as she moves from places to place in a transparent and convenient form.

5.5. User infrastructure layer

Table 9 shows the references according to the detailed categories in user infrastructure layer. It is characteristic for handheld devices and their users that they are continuously moving in several simultaneous fuzzy contexts. The usefulness of a given context-aware systems is most likely to suffer from the small screen and a dynamic context of users. Mobility is at its core the very essence of context-awareness. The dynamic environment sets special requirements for usability and acceptance of context-aware systems. Therefore, research of user interface (UI) and usability of handheld device are carried out. In UI category, a content adaptation system for overcoming small interface such as PDA and cellular phone, user modeling and human–computer interaction for considering the emergence of ubiquitous and mobile computing environments are presented. In UI research, it is suggested that the contents were confusing when a screen changed due to a location change. Usability category involves investigating the user needs based on user interviews, field evaluations with users, and expert evaluations of context-aware services. Appearing context-aware devices and services introduces a new level of complexity when it comes to usability evaluation. Usability evaluation methods have been measured against desktop environments. Some researchers investigated general guidelines for evaluating context-aware systems, while others have evaluated novel interfaces and ways of interacting. They suggested a hybrid evaluation method comprised of cognitive walkthrough and heuristic evaluation for UI supporting mobility of context-aware systems.

6. Discussions and suggestions

Context-aware systems are still developing in order to improve. Many researchers have been concerned about context-aware systems and context-awareness, and as shown in Fig. 2, the concern has increased from 2000 to 2007. Moreover, reports or white paper of many project have been published increasingly. However, con-

text-aware systems are not fully implemented in real life. As shown in Table 4, much research has focused on the concept and research layer. The scope of applications or services in most articles is limited to small regions; laboratory, school, hospital, smart room and so on. In addition, strategic alternatives or business models for gaining the revenue by using context-aware systems are very few. Furthermore, technologies related to context-aware systems are merely standardized. The architecture, method of context modeling, inference algorithm, network implementation and devices of users in each project are different. Furthermore, middleware, applications and services make use of different level of contexts and adapt the way they behave according to the current context. Therefore, according to the level and type of contexts along with the goal of context-aware systems, the context modeling methodology, inference algorithm, agent structure, and interaction method of agent are changed. Although the interaction between agents in the same middleware and cooperation between components of the same architecture are investigated, a standard for interaction, cooperation and operation in the different context-aware application has not been studied. Finally, we found that context sensing, context managing and context-aware services and applications are included in ubiquitous computing environment. Context awareness is a key factor for new applications in the area of ubiquitous computing.

The immediate future of context-aware application and service may increasingly lie in its everyday life; as researchers are beginning to realize the impossibility of developing systems and application only in laboratory environments. Therefore, possible future research agenda may include answers to the following questions.

6.1. How to extract and use the cognitive context in context-aware application?

Most of the context-aware systems focus on the external context, called physical context. External context means context data collected by physical sensors. It involves context data of the physical environment, location data, distance, function on to other objects, temperature, sound, air pressure, time, lighting levels surrounding users, and so on. The external context is important, and very useful for context-aware systems, because context-aware systems provide recommended services for a person based on analyzing the external data. However, to provide personalized services according to user preferences, task and emotional state of user, the cognitive domains, such as information retrieval, decision making, situation monitoring, and so on, are needed. However, a few authors have addressed utilizing the cognitive elements of a user's context. Several researchers have proposed models to capture the internal elements of context. This model differs from many of the previous approaches, because it focuses on extracting a user's cognitive activities, rather then extracting the user's movement based on a physical environment. Cognitive context information is key information to satisfy user by providing personalized context-aware computing services. In the early stage of research, only the physical context information was collected to be aware of user's context. Recently, some of the literatures which focus on cognitive context have been introduced. However, it is insufficient to establish context-aware systems that reflect cognitive context. To provide suitable and personalized service for the user, more studies need to be conducted in this area.

6.2. What are design patterns of context-aware systems?

Design patterns are defined as recurring solutions to design problems you see over (Berczuk 1994). They focus on the reuse of recurring architectural design themes, and have a recurring design problem that is generated in a specific domain and suggest a solution (Buschmann, Meunier, Rohnert, Sommerlad, & Stal, 1996). Design patterns from another format sharing knowledge such as development guidelines are distinguished by the following reasons.

- To help designers address high-level problems as well as low-level ones by showing the hierarchical structure between design patterns.
- To capture the essence of recurring problems and their solutions in a compact form.
- To have many examples of actual designs, alternatives to apply the solution, and some of the tradeoffs in applying the solution.

Design patterns have been proposed in many domains as a format for capturing and sharing design knowledge between practitioners. They can also assist designers in developing context-aware systems. Design patterns of context-aware systems will provide an effective way for sharing solutions to design problems and reuse prior design knowledge. Also, the designer of the context-aware systems will avoid dangerous design problem and easily solve the difficult recurring problems. Some effort has aimed at unearthing common design patterns for context-aware systems. However, suggested design patterns are not specific, nevertheless, general and very few research has been conducted. Therefore, research on design pattern of context-aware systems should be conducted, because there are many potential benefits in developing a design pattern.

6.3. Which is the best inferring algorithm to extract user context and provide service to user?

Various algorithms used in context-aware systems are classified into two parts. First, algorithm is utilized to infer high-level context of user. According to levels of abstraction, context is divided into low-level context and high-level context. Low-level context is raw data collected directly from physical sensors, while high-level context is inferred from low-level context. This part involves the algorithm of context reasoner to extract high-level context and inferring algorithm to extract correct position of user, near object, and environments. Second, algorithm is recommending suitable service. According to the activity, location and preference of user, recommended services of context-aware systems are different. Although location is critical to determine service, user profile (such as sex, age, style, preference, and so on) also has influence on recommending service. Therefore, for increasing user satisfaction by recommending service that customer wants to receive, an inferring algorithm based on context and user profile is used. In the two parts, Bayesian networks for handling causal relationships between various events, probabilistic logic, fuzzy logic, decision tree, neural network and support vector machine (SVM) are applied. Moreover, many researches focus on improving accuracy and efficiency of these algorithms. However, the research for comparing these algorithms according to the context data type, amount of context data, research scenario and components of environments has not been carried out. Since finding the suitable service quickly and correctly from on low-level context is very important in limited computing environments, research related with the best inferring algorithm for extracting user context and providing the service with users should be conducted.

6.4. How to deal with concurrently enormous data, information and knowledge having different format to serve suitable service to users?

The raw data of low-level context are usually gathered from different physical sensors. Data type, formats and abstraction level

from different physical sensors are different. Devices and physical sensors of context-aware systems use various scale and unit, and low-level context has different elements. Context-aware systems store data, information and knowledge that have different relationship, format and abstraction level in the context base. Furthermore, context-aware systems collect context history storing sensor data over time to offer proactive service. Context history stores huge amount of data on location, temperature, lighting level, task, utilized devices, state of devices, selected services and so on. To quickly provide suitable service to users, context-aware systems should manage variety, diversity and numerous amount of context. However, previous research suggested only a concept to control this problem. Therefore, a methodology and real implication for treating variety, diversity and numerous mount of context are needed.

6.5. How to extract the best solution when the context of users is conflicted?

Conflicts occur on context-aware computing environments when many users use the several physical sensors and service sources. Thus, the conflicts of context-aware systems are classified into sensing conflict, service resource conflict and user preference conflict.

- *Sensing conflict*: Not matching results from several physical data sources. If the coordinates of GPS and spotting of a camera are different, then sensing conflict is generated.
- *Service resource conflict*: Selecting only several users among many users that want to be provided with the same service, due to limited service resource. If context-aware systems offer services without possessing all the necessary service resources, then service resource conflict occurs.
- *User preference conflict*: Providing only several users with personalized service, because the preference of users is not the same, although the same context of users is identified. If family members like different TV programs at the same time, then preference difference between family members leads to user preference conflict.

The problem of conflicts has been approached by using information fusion, time stamps and fuzzy algorithm. However, it is still not solved perfectly, because it is difficult to provide personalized services under the limited resource. Therefore, a study on methodology and actual guideline for harmonizing all conflicts are required.

6.6. How to reflect the preference of users for satisfying user needs?

The preference of each user is different according to user context and profile. Predicting the preferences of users and providing the personalized services based on users' preferences have carried out by various research. Especially, predicting the preferences of users in e-commerce users for providing the personalized services is one of the important issues. Recommendation systems providing personalized services have been carried out by many researchers. However, the research considering users' preferences on Context-aware computing is a relatively insufficient in the context-aware systems research field (Byun & Cheverst, 2004). There were some limitations in previous research for providing the personalized services on context-aware systems. First, the users have to input their preferences directly. Second, they did not provide automated services. Finally, it is difficult to provide new user with the personalized services. Thus, it is difficult to provide the users with the automatic personalized services due to these limitations. Hence, proposing the context-aware systems to provide the personalized services based on context history in context-aware computing is needed.

6.7. How to save users information in context-aware systems?

As Table 5 shows, the research has been conducted in the area of security and privacy. The context-aware systems that do not consider user privacy and security in systems that deal with personal data will not be publicly accepted. Therefore, general and several approaches to implement security and privacy in context-aware systems have been studied. Although privacy and security are an important aspect of context-aware systems, applicable context-aware systems utilizing these approaches have not been investigated yet, due to their complexity. In other words, most researches have only focused the concept for protecting privacy and security. The more research related with privacy and security is needed for context-aware systems to become a reality.

A user utilizing context-aware systems uses many available computers embedded in everyday artifacts, like PDA, navigation, and so on. Each user uses many personal computing devices, and at the same time, the same publicly available device is used by many users. Furthermore, context-aware systems store and handle sensitive and personal data. Common to context-aware systems is the lack of appropriate security and privacy mechanisms that can effectively ensure a secure user authentication. Therefore, the need for authentication arises as the information and data stored in context base is highly personal and should be protected. Hence, more research on context-aware systems that can be protected from unauthorized access is needed.

6.8. How to evaluate performance of context-aware systems?

It is essential to improve managing and planning context-aware systems based on performance evaluation, because "what you measure is what you get". Various models such as Balanced Score Card (BSC), IS Success Model, Control Objectives for Information and Related Technology (COBIT), Information Economics, and so on, have been applied to suggest measures that can evaluate the performance of information systems by considering diverse perspectives. Due to the unique characteristics of context-aware systems such as portability, mobility, proactiveness, nomadicity, and so on, the current technology for evaluating information systems (IS) does not provide techniques to formally define, verify, implement, and analyze them. Therefore, research on the model and performance measure reflecting the characteristics of context-aware systems should be conducted.

7. Conclusions

The review was organized according to the framework developed with the purpose of providing a comprehensive overview of research on context-aware systems. The review introduced the context-aware systems concept, network infrastructure, middleware, application, user infrastructure and presented an exhaustive list of each layer of context-aware systems. In this paper, we reviewed the literatures for the concept and applications, and examined them using dimensions related to ongoing and emerging issues in context-aware systems. This paper is based on a literature review of context-aware systems from 2000 to 2007 using a keyword index and article title search. Overall, we found that the activity related with context-aware computing seems to increase dramatically and can be classified into designing and implementing network, user infrastructure on handheld device, middleware which are enough to provides users with context-aware services, concept and research being the base of context-ware application,

and application and service. It provides sufficient literature for the researchers on the use of context-aware systems, and we hope that it will motivate the researchers and practitioners to examine context-aware systems issues and its applications. The framework of context-aware systems offers a general development guideline, fundamental component and relationships within component of context-aware systems. Furthermore, on the basis of this framework and the literature review, selected opportunities for future research were discussed.

It is concluded that different social science methodologies, such as psychology, cognitive science, and human behavior could implement context-aware computing. Integration of qualitative, quantitative and scientific methods and integration of context-aware theory and concept studies may broaden our horizon on this subject. Finally, the ability to continually change and obtain new understanding is the power of context-aware computing.

Although considerable attention was given to the framework design and classification of the literature review, some limitations still exist. First, some relevant articles might have been overlooked. Much the literature has been found by the title, keyword or abstract only. Although the title in most cases describes the content quite well this is not always so. In order to conduct a comprehensive literature review, the topical focus was kept relatively narrow on context-aware systems. Moreover, this paper makes a brief literature review of context-aware systems from 2000 to 2007 in order to explore how context-aware systems have developed in this period. White paper, practical reporter and many articles related with context-aware systems were not reviewed, because seven online databases were searched in this paper. Period and searching limitation may not satisfy the need of readers looking for a review on context-aware systems. Finally, the correlation between the framework and real projects of context-aware systems are not illustrated. The review did not involve the role and interaction methods of logical components in architectures of SOCAM, CASS, CoBrA, GUIDE, Hydrogen, Gaia, Context Toolkit, STU21 project and so on, since only articles of journals were extracted and analyzed.

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