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User-Centered Context-Aware Mobile Applications—The Next Generation of Personal Mobile Computing

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Abstract:

Context-aware mobile applications are systems that can sense clues about the situational environment and enable appropriate mechanisms of interaction between end users and systems, making mobile devices more intelligent, adaptive, and personalized. In order to better understand such systems and the potentials and barriers of their development and practical use, this paper provides a state-of-the-art overview of this emerging field. Unlike previous literature reviews that mainly focus on technological aspects of such systems, we examine this field mainly from application and research methodology perspectives. We will present major types of current context-aware mobile applications, and discuss research methodologies used in existing studies and their limitations, and highlight potential future research.

Keyword: context, mobile devices, context-aware mobile applications, usability

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I. INTRODUCTION

Today, computing is shifting toward pervasive, ubiquitous environments. Users can not only access the Internet, but also play games, send/receive e-mails, listen to music, and even watch video (e.g., Verizon Wireless VCast Mobile TV) on their mobile handheld devices, such as cell phones, palm pilots, and PDAs. Proliferation of mobile devices in our daily life and significant advances of wireless technology become an ever-increasing driving force of a variety of emerging mobile applications. Here we refer to mobile applications as software programs that are developed for and run on mobile handheld devices. For example, Google Inc., Yahoo!, and America Online (AOL) either have released or are currently developing mobile search solutions including local search services and SMS-based search services; businesses start applying wireless technologies to sales force automation, product tracking, and mobile advertising [Aalto et al. 2004; Scornavacca et al. 2006]. According to Gartner's 2006 Emerging Technologies report, amid this evolving trend, context-aware mobile applications—mobile computational systems that can sense clues about the situational environment and enable appropriate mechanisms of interaction between end users and systems—have gained increasing recognition as one of the emerging technologies in this field.

The major objective of context-aware mobile applications is to make mobile devices smarter, giving them an ability to recognize and interpret their usage environment in order to react proactively and intelligently. A typical example of context-aware mobile applications is location-aware tour guide systems that provide attraction guidance in real time based on the current location of users. Context-aware applications can also be used to facilitate social interaction, such as “Nokia Sensor,” a mobile application that allows users of mobile devices to create and exchange personal identities based on Bluetooth technology [Persson and Jung 2005]. Context-aware mobile applications are enabling our life to become, as Weiser envisioned in his 1991 seminal paper, “… a world full of invisible gadgets” [Weiser 1991 p. 74].

Although research and practice on context-aware mobile computing and applications have achieved remarkable success in the past decade, they are still in the early stage. This paper provides a state-of-the-art overview of this emerging field. There are two major contributions of this paper. First, the majority of previous literature reviews on context-aware mobile computing mainly focused on technological aspects of such systems, which targeted at computer scientists. This paper attempts to examine this field from an information system perspective, particularly focusing on real-world applications and research methodologies, aiming to help readers better understand context-awareness mobile applications and the potentials and barriers of their design, evaluation, and practical use. Second, although user-device interaction is essential to context-aware mobile computing and human-computer interaction is one of the key IS research areas, research on issues related to context-aware mobile computing is still scarce in the IS field. On the one hand, such a phenomenon could be caused by the immature technology, the lack of commercial-ready practical applications, as well as various challenges in conducting user studies using mobile devices. On the other hand, it provides IS researchers a great opportunity to make unique contributions to this emerging field. Based on the discussion of problems and limitations of existing research, this paper presents various potential research issues and knowledge gaps in the field of context-aware mobile computing for IS researchers, aiming to provide a roadmap for potential future research. To our best knowledge, there is no existing work with the same focus and objectives in the IS literature.

The rest of the paper will be organized as follows. In Section II, we will introduce major concepts in this field, including context, context awareness, and context management. Then, we will present major context-aware mobile applications in Section III. Next, we discuss current research status, research methodologies used in evaluating those applications, and limitations of existing studies in Section IV. Finally, we propose a number of potential future research issues and questions for IS researchers and conclude the paper in Section V.

II. CONTEXT: CONCEPTS AND TAXONOMIES

What Is Context?

According to Webster’s New Twentieth Century Dictionary, the term *context* is the whole situation, background, or environment relevant to some happening or personality. Researchers have tried to create rigid taxonomies and general “all-embracing” definitions of *context*. Its notion was first coined by Schilit and Theimer [1994] as location information that enables a computing system to adapt to its continuously changing location along with its nearby people and objects. By extending this notion, Dey and Abowd [2000b] refer to context as any information that can characterize the situation of an entity that is considered relevant to the interaction between a user and an application. Because we are examining context in a unique wireless environment characterized by the mobility, flexibility, and personalization, we define context as *any real-time information or entity that influences the interaction between mobile device users and mobile applications, as well as potentially changes the preferred behavior of those applications*. Here an entity can be a user, place, time, activity, or an object.

Context has been categorized in a variety of ways. Schilit et al. [1994] categorize context based on the source of context information, such as user context, physical or environment context, and computing context; Abowd et al. [1999] classify context into primary context (e.g., location, time, identity, and activity) and secondary context attributes of the primary context; Chen and Kotz [2000] extend that primary-secondary two-tier classification from an operational perspective by dividing context into two categories: active context that directly influences the behavior of a context-aware system, and passive context that is not considerably critical to the system; Barkhuus [2003] categorizes context information into three broad types, namely environmental context information, application utilization, and sensor based context. Individual pieces of context information will be aggregated to form a comprehensive understanding of the surrounding context for a mobile application.

We categorize context in a mobile environment into five groups based on its nature and source, namely user context (e.g., user preferences, information needs, and personal time schedule), device context (e.g., operating system, screen size, and embedded network protocol), activity context (e.g., task type and time to perform a task or an activity), network context (e.g., network bandwidth and connectivity), and external physical environment context (e.g., noise level in the environment, lighting, temperature, and the appearance of certain users nearby). We want to point out that not every piece of context information is necessarily useful for a specific mobile application. Under any given circumstance, normally only a few contextual factors are most relevant and can influence the behavior of an application. An aspect of the environment or situation becomes relevant context when it defines certain contextual states that can help predict or determine how information and services should be provided.

Context awareness can be defined as *the ability of an application to detect and understand its situational context and to adapt its behavior in a user preferred manner accordingly.* Context-awareness provides a backbone to enable non-intrusive access to personalized services and information in ubiquitous environments [Preuveneers and Berbers 2007]. Darwin stated that “It is not the most intelligent of the species that survive the longest. It is the most adaptable.” Such an argument is true in pervasive computing applications as well. Context-aware systems are aimed to adapt to the changing context dynamically and intelligently in order to meet users’ needs.

Context Management

Handling context information in a mobile environment is very challenging because context is dynamic; is normally acquired from multiple and heterogeneous sources; and needs to be disambiguated and integrated into sensible information. In knowledge management systems, knowledge has to be created either from data and information or by domain experts (i.e., knowledge acquisition), to be represented and disambiguated in a certain way that allows automated reasoning and inference, to be maintained and updated in order to reflect the current knowledge, and to be shared by others. Similarly, it needs context management in context-aware mobile systems, which includes a variety of issues related to acquisition, abstraction, interpretation (i.e., representation), aggregation, inference, or even sharing of context.

Context Acquisition

There are generally three methods for collecting context information, including sensing through various sensors, using software agents, and user profiling (e.g., [Krause et al. 2006]). A large variety of context information in a mobile environment is obtained via sensors with minimal user interaction. The sensing sources can be generally categorized as physical sensors, virtual sensors, and logical sensors:

1. *Physical sensors* (e.g., position sensors like GPS) usually consist of two components—devices and infrastructure. There is also an associated communication medium by which the devices and infrastructure communicate.
2. *Virtual sensors* usually represent an abstraction of context information (e.g., user’s schedule and activities) extracted from operating systems of mobile devices, wireless networks, or software embedded in mobile devices, such as calendars and appointment books.
3. *Logical sensors* often infer context information from a hybrid of both physical and virtual information to provide a higher level of information abstraction, such as logical deduction of whether a person can make an event scheduled in his appointment calendar on time based on his current location, the distance from an event location, and the estimated time it takes from the current location to the event location (e.g., based on speed limit of roads).

Separate handling of heterogeneous and distributed sensor-based infrastructures for context-aware applications can lead to low-quality or even erroneous outcomes or context ambiguity due to the mismatch between user anticipation and interpretation by applications. Another major challenge in sensor-based context-aware mobile systems is the noise and ambiguity of sensor data. One approach is to provide an interface that allows a user to manually disambiguate it, which is often troublesome and tedious. Another approach is to integrate data collected from multiple sensors, if available. The combination of diverse sensor data may produce a comprehensive picture that better characterizes a situation than any single sensor does. For example, the Mediacup [Gellersen et al. 1999] is a coffee mug augmented by hardware and software that deal with sensing, processing, and sharing context. It has several sensors embedded, including a digital temperature sensor, three ball switches to detect movement, and a switch that turns off when the cup is placed on a surface. The tracked temperature information in conjunction with some motion information are used to compute related context: *filled up*, *cooled off*, and *current temperature.*

Software agents can also be used to collect context information at real time. For example, a software agent can keep monitoring the wireless network traffic and help users determine the resolution of a video file being transferred; or keep track of highway traffic information publicly available so as to generate an effective route for a user when he drives.

User profiling has been extensively used in information retrieval and personalized information systems, such as information filtering and recommender systems. The basic idea is to collect preferences and/or needs of individual users either directly through user solicitation, or indirectly through explicit or implicit user feedback. Then, such user context is stored in a file called user profile, which will be used to adapt a system's behavior.

Context Abstraction

Context must be abstracted to make sense for an application [Han et al. 2008]. For example, GPS receivers provide geographical coordinates of an object. But context-aware tour guide mobile applications can make better use of detailed location information such as street or building names. There are two aspects of context abstraction. One is that the raw, noisy data collected should be cleaned or calculated, and the other is the fusion of different context features in order to find correlations between them.

Context Interpretation

Context interpretation is a process of transforming one or more context sources into a new, understandable piece of context information. It analyzes context information and makes a prediction. Context interpretation can be considered as high-level abstraction with a purpose of obtaining the semantics behind correlative context features.

In a context-aware system, context must be properly represented in a structured, uniform, and interchangeable format [Held et al. 2002]. Such standardized and structured context representation allows complex rules to be written and easy integration of context, and enables inductive and deductive reasoning on contextual information. Existing context modeling approaches can be classified into categories based on the scheme of data structures used for exchanging contextual information, as shown in Table 1 [Chen and Kotz 2000; Strang and Linnhoff-Popien 2004].

Each context modeling scheme has its pros and cons. So far, there is no standard model for context representation. Strang and Linnhoff-Popien [2004] argue that among existing developed context representation models, ontology-based model is the most promising one because it meets the requirements of context models for ubiquitous computing environments (e.g., handling distributed composition, partial validation, and incompleteness and ambiguity) the best. However, it does not mean that other approaches are totally unsuitable for ubiquitous computing environments.

Context Aggregation

Context aggregation is a process of logically selecting and integrating the only context information that is relevant to an application. Extracting relevant context information by fusing data from different sensors proves challenging because noise, faulty connections, drift, miscalibration, wear and tear, humidity, and other factors degrade data. Extracted context may overlap, change over time, and yield only partially reliable approximations [Korpipää et al. 2003].

Context Inference

Context inference is perceived as system adaptation based on real-time sensing of a user's context, aiming to augment mobile devices' cognition capabilities and interaction with users. One of the key challenges in context inference lies in the "interface" problem between mobile systems and the dynamic and unconstrained environment. According to users' interaction with a context-aware system, context inference can be conducted either *explicitly* through users' direct input and setting (e.g., users define their tasks or usage situation and the corresponding system reaction), or *implicitly* in which systems provide users with the inferred awareness based on users' ongoing interaction with the system.

In addition, context has to be disambiguated as much as possible through inference based on domain knowledge and local and global evidence. Most research on context ambiguity has mainly focused on how to make unambiguous synthesis of high-level information from low-level data, such as Korpipää et al.'s ontology structure approach [Korpipaa et al. 2004] and Dey and Mankof's mediation techniques that provide explicit dialogue between end users and context-aware systems [Dey and Mankoff 2005].

Table 1. Context Representation Methods

Method	Description	Pros	Cons
Key-value model	Using a list of attributes in a key-value for modeling contextual information [e.g., Schilit et al. 1993]	Very simple and easy to manage	May have a lot of blank slots (missing values); lack capabilities for sophisticated structuring for enabling efficient context retrieval algorithms
Markup scheme model	Using a hierarchical data structure that consists of markup tags with attributes and content to model context [e.g., Brown et al. 1997]	Able to cover the higher dynamics of contextual information	May be difficult and non-intuitive to capture complex contextual relationships and constraints
Object-oriented model	The detail of context processing is encapsulated at an object level. Access to contextual information is provided through specified interfaces only [e.g., Cheverst et al. 1998]	Employing encapsulation and reusability to cover parts of the problems arising from the dynamics of context	Not responsive to changes in context space; require low-level implementation agreement between applications to ensure interoperability
Logic-based model	Defining context as facts, expressions, and rules by using logic representation (e.g., predicate logic proposed by Ranganathan and Campbell [2003])	High degree of formality	They use crisp rules, which may not be suitable for dealing with context featured by uncertainty and ambiguity
Ontology-based model	Specifying different types of context and their relationships in a uniform way [de Almeida et al. 2006; Korpipää et al. 2003; Weißenberg et al. 2004].	Enabling contextual knowledge sharing and reuse in a ubiquitous computing system	Can only be used when context ontology can enumerate all possible context events that can trigger actions, which is often difficult; in most cases, ontologies are not publicly available

III. CONTEXT-AWARE MOBILE APPLICATIONS

Identifying and developing important practical applications are often considered critical for the adoption and advance of any technology innovation. Context-aware mobile applications have so far been explored mainly from a technological point of view—examining context-recognition and sensor technologies, inferring logic, and system architectures or infrastructures.

Those applications can be classified based on different criteria, such as the context used by applications, the purpose of applications, and active/passive reaction of applications. For example, an active application automatically adapts to context measurements by changing its behavior, whereas a passive application only presents new or updated context information to a user and let him take actions [Barkhuus 2003; Chen and Kotz 2000]. Most applications take into consideration a limited set of sensed context (with an average of 2.35) [Dey and Mankoff 2005], with location being the most popular context used.

In the rest of this section, we will introduce different types of context-aware mobile applications based on their purpose rather than context types, because some applications utilize several types of context. As a result, we can divide context-aware mobile applications into two broad categories (Figure 1). One group of applications is mainly for personal daily use, such as context-aware smart phones, mobile group socializing and collaboration applications, context-aware personal information management (PIM) tools, content adaptation, and mobile learning (M-learning). Another group of applications is public service-driven. They are developed as institutional services that are often available and used in a certain area (e.g., a hospital, a museum, a shopping center, and an office building).

Examples of this type of applications include context-aware mobile hospitals and patient care, location-aware tour-guide and road services, context-aware mobile advertising/marketing, and office assistant.

It is worth noting that given the current research status, we are far from being in the position to conclude that one application is more important than another. The purpose of introducing those applications is to motivate improvement of current applications and/or further exploration of other interesting and innovative applications that can significantly benefit both individual users and service providers.

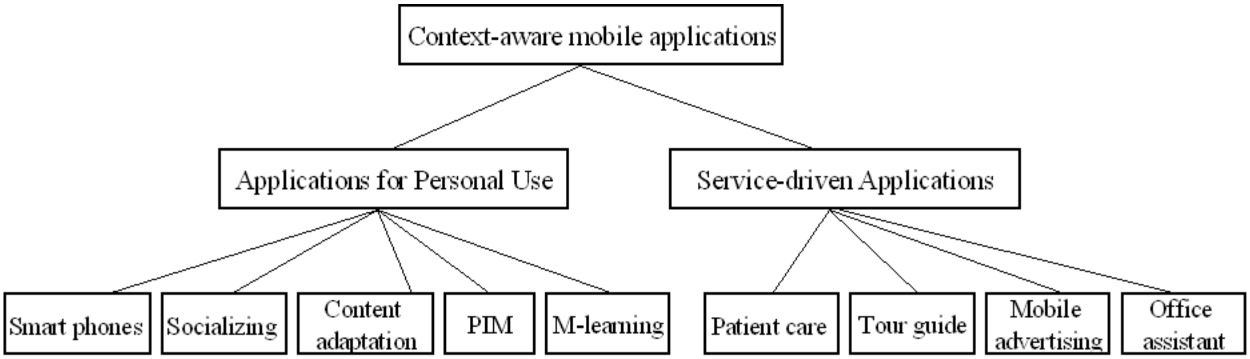

Figure 1. Different Types of Context-Aware Mobile Applications

Context-Aware Mobile Applications for Personal Use

Context-Aware Smart Phones

Sometimes the benefits (e.g., flexibility and accessibility) of cell phones could be overshadowed by the problems they create, as when a person's phone disrupts during an ongoing group activity such as a meeting and a class. Therefore, it is beneficial for both the caller and the callee to know the context of the other party. So a fundamental question is: how to make cell phones smarter by automatically changing their configurations according to the user context or context of the surrounding environment?

Some tools and techniques have been developed to minimize undesirable interruption by enabling a cell phone to be aware of its user's current context and behave accordingly. Exchanging/Sharing context information after a phone call is made is obviously too late; changing the cell phone setting every time when a user is in a new context is both inconvenient and inadequate; other people just keep their cell phone in the silent mode, which results in missing important calls. One context-aware approach is to enable the caller to know the appropriateness of the call before making it by getting information about the receiver's context. This approach, however, raises privacy concerns that may prevent receivers from publishing information about their context. Schmidt et al. [2000] propose a solution from a conceptual perspective. They suggest that a user can specify his/her context by choosing from a menu (e.g., at home, in the meeting, and busy). Such context data can be stored on a server so that a caller can query this server and know his current context. However, there are limitations of that approach as well. First, it causes an extra step (context checking with server) to make a phone call. Second, it will cause a lot of burden on users to keep updating their context. Another approach is to enhance the capability and awareness of cell phones. For example, if the cell phone of a callee detects that he cannot answer a call at this moment (e.g., based on his calendar or appointment book stored in the phone), a short text message will be automatically sent to the caller indicating when the callee can return the call.

Mobile Applications in Support of Social Awareness (Mobile Group Socializing) and Collaboration

One's behavior is always directly or indirectly linked to other people [Tamminen et al. 2004]. Sharing information about the current work context with one another is a core mechanism for collaboration between partners. This *social awareness* helps people judge how to engage in a cooperative effort and minimize interruptions when engaging in cooperative work, a phenomenon that Schmidt calls "appropriate obtrusiveness" [Schmidt 2002].

Physical proximity increases the likelihood of impromptu social conversations. Context-aware technology can be designed to consider not only the owner of mobile devices, but also the doings of other similar people, especially those nearby [Bardram and Hansen 2004; Cheverst et al. 2000b; Persson and Jung 2005]. Context-aware mobile systems in support of group socialization aim to either directly support socializing or indirectly take advantage of social information or social networks. By combining context-mediated social awareness with different mechanisms for initiating cooperation or social sessions, a person can choose between different strategies for communication and cooperation.

Nokia Sensor application [Kortuem and Segall 2003] allows mobile phone users to create digital identity expressions, which can be seen by other users within the Bluetooth range. This type of technology creates a digital "sphere" or "aura" surrounding each user, leading to interesting possibilities for social interaction. The overall research question in this area, called *Social Proximity Applications (SPA),* can be formulated as follows: in an encounter between spatially proximate people, how can information in digital realm support and augment existing social behavior, practice, and experiences taking place in real space? Another key issue is to determine what personal data people are willing to share. There are several types of SPA. The first type is concerned with providing awareness of who is nearby. The second type allows users to create a more or less sophisticated identity expression, and disseminates it to proximate users to facilitate social interaction and ad hoc collaboration, such as Newspilot [Dahlberg et al. 1999] and DigiDress [Persson et al. 2005]. The third type has some sort of intelligence embedded for data exchange between collocated users, with the purpose of giving recommendations or supporting collaboration. For example, by comparing two users' personal data, interesting social connections and commonalities can be discovered and the interaction between two acquainted or newly acquainted users can be formed or enhanced.

Mobile computing devices are increasingly used in support of collaboration because of the necessity for mobility in collaboration, such as health consultations, construction sites, and public transportation. One example is *Meme Tags* [Borovoy et al. 1998], which let users in a conference share "memes," namely short ideas or opinions, when they are close to one another (e.g., within an infrared communication range).

Context-Aware Adaptation of Content Presentation on Mobile Handheld Devices

Unique constraints of wireless networks (e.g., low bandwidth and unreliability) and mobile devices, as well as the mobility of users, present challenges for taking advantage of the convenience of mobile devices for Web information access. Currently, most existing Web pages are designed and optimized for desktop and broadband clients only. They are poorly suited for mobile devices. Therefore, how to adapt Web content to meet the needs of users, fit the characteristics of individual devices, and adjust to dynamic external context becomes important.

Merely squeezing original Web content into small screens of mobile handheld devices seems not working. Creating trimmed versions of content could get around this constraint, but differences in display capabilities of various devices would easily make a device-specific authoring approach too costly to be practical [Brewster 2002]. There have been some automatic re-authoring and client-side navigation approaches developed to adapt the content presentation for mobile devices through a series of transformations, including layout change and content format reconfigurations [Zhang 2007].

User and device profiles, as well as physical context, can be used to support such adaptation. User profiles can include user preferences about presentation layout and requirements for the quality of service (QoS), while device profiles specify the MIME media types and physical characteristics of a device, including screen size, memory size, operating system, as well as supported markup language. In addition, the physical context, such as lighting, can also be used. For example, a mobile system can automatically enlarge font size when it detects that the environment is dark. The major cost of multimedia access through a wireless network is the long transmission latency. From a QoS perspective, sometimes users do not need the best-quality rendition, but rather a good-enough quality to convey the needed information. A set of quality multimedia attributes (e.g., color, resolution, frame rate, scaling, and modality) can be specified for different types of multimedia content and used to define the QoS for content adaptation. For example, an adaptive system may regenerate multimedia content with fewer colors and lower resolution in order to reduce transmission latency based on real-time network traffic.

Context-Aware Personal Information Management (PIM)

Most PIM tools in mobile devices, such as calendar, reminder, and to-do list programs, can only provide a signal based on the current time, making them no more intelligent than a simple alarm clock. They do not make use of rich contextual information to proactively trigger reminders at appropriate time and location [Dey and Abowd 2000a]. For example, a reminder to bring relevant documents to a meeting should be automatically presented when a user is leaving his office and heading toward the meeting.

Memory Glasses [DeVaul et al. 2000] is a wearable context-aware reminder system that delivers reminders based on time, location, and user activity. It focuses on personal context and uses body-worn sensors (a camera and a microphone) to determine in which activity the wearer is engaged. Then, reminders associated with that activity are presented to the user via audio output. As a result, Memory Glasses can determine when it is appropriate to interrupt the wearer with a reminder. However, they are still limited due to the restricted use of context. CyberMinder

[Dey and Abowd 2000a] is a context-aware reminder tool, in which users can select a situation tab and establish an arbitrary rich situation associated with the reminder being created. Each sub-situation consists of a number of context types and values. If the recipient's current context and reminder information (sender identity and/or priority) match any situation defined in his configuration file, the pre-specified delivery mechanism will be used.

Context-Aware Ubiquitous e-Learning (M-Learning)

M-Learning refers to learning by using electronic content delivered to and presented on mobile devices. It can be used to implement the idea of real-time, on-demand learning. Context-aware M-Learning has become increasingly important because of the dynamically and continually changed learning settings in the learners' environment. Context is a key to the design of more adaptive mobile learning systems.

Malek et al. [2006] propose a new definition and classification of context for mobile learning. They classify context into individual context and shared context. The former gathers information relevant to the interaction between a learner and the M-Learning system. The latter gathers information relevant to collaborative group work or common interests shared by learners. In general, M-Learning systems rely more on learner context than other types of context. Yau and Joy [2007] adopt a proactive approach to learning content retrieval because of its increased context-aware capability. They introduce a Context-aware and Adaptive Learning Schedule (CALS) framework, consisting of a learning scheduling module for supporting learners' daily routines, a learning style adaptation module for adapting learning activities, and a context adaptation module to identify the learning context in which a learner is currently situated, and then to recommend appropriate learning activities based on the learning context. The proposed system retrieves the contextual information from the scheduled events database and two sensors, namely a GPS for location detection and a microphone for noise detection.

Service-Driven Context-Aware Mobile Applications

Context-Aware Mobile Hospitals and Patient Care

Hospitals are complex, information-rich environments that need coordination and collaboration among specialists with different expertise. It involves intensive information exchange and management. For example, nurses and physicians need to keep track of medical equipment and beds, which are constantly moved within a hospital. This makes hospitals an ideal application environment for pervasive and context-aware computing technology [Favela et al. 2004]. Some research attempts, such as [Skov and Høegh 2006; Wintterle 2008], have investigated health status monitoring, alert, and reminders based on scheduled activities, patient behavior, and daily activity modeling. Context-aware mobile healthcare systems can collect data from sensors in operating rooms; analyze data to construct the context of a surgery; identify medically significant events; and use RFID to track staff, tools and medicine. For example, a context-awareness infrastructure in the hospital described in [Bardram and Hansen 2004] is aware of the location of nurses, patients, the trolley, and the bed; a bed is equipped with various RFID sensors that can identify a patient lying in the bed and be aware of patient's conditions and treatment. Another example of such systems is the CHIS [Muñoz et al. 2003], which provides access to medical information based on the user's context and allows users to send messages that will be delivered based on the location and role of recipients, or the status of artifacts such as results of analysis.

A context-aware healthcare monitoring system involves the use of a pervasive device (such as a cellular phone) that aggregates data from multiple body-worn medical sensors and transmits the data to the backend. The volume of data generated by those sophisticated sensors, however, may overwhelm the resources on a mobile device. Mohomed et al. [2008] propose to imbue mobile devices with various context-driven rules to perform context-aware filtering of sensor data streams in order to reduce data transmission. Context-aware mobile computing is also used to support caregivers in home-based continuous care of chronic patients. The main services proposed by ERMHAN system [Paganelli et al. 2007] for continuous care, for example, include communication facilities; multi-channel shared access to patient related data; decision-support services and automated workflow for critical situation handling and alarm management; and mutual "social awareness" about network members' roles and actions.

Location-Aware Tour-Guide and Road Services

The most common context-aware mobile applications developed so far are location-based applications [e.g., Satoh 2007], which provide information and/or services based on users' current location. GPS is a common location-sensing technology used for outdoors, but it does not have coverage of indoors. Bluetooth and WLAN hotspots are frequently used for both outdoors and indoors [e.g., Aalto et al. 2004; Burrell and Gay 2002]. Other methods used for indoor location detection include ultrasonic and infrared based technology [e.g., Borriello et al. 2005].

One typical example is the mobile tour guide [e.g., Abowd et al. 1997; Cheverst et al. 1998; Fithian et al. 2003], which typically runs on a handheld device and guides a visitor to tour a particular indoor or outdoor space. As the visitor moves throughout the space, the application shows him/her current location on a map and provides information about the interesting attractions nearby. The *GUIDE* system [Cheverst et al. 2000a] integrates the use of personal computing technology, wireless communication, context-awareness, and adaptive hypermedia to support the information and navigation needs of visitors to the city of Lancaster. The context such as the visitor's interests, current location, and any refreshment preferences dynamically affects the interface of the system; Egraffiti [Burrell and Gay 2002] introduces an on-campus location-aware messaging application, in which users can create and access location-associated notes and the system employs wireless network-based location detection; *Mobile Location-Aware Handheld Event* [Fithian et al. 2003] is an event planner that provides a tourist guide service using GPS. It allows a user to set up event reminders. Moreover, the system takes the privacy issue into account. A user could set the visibility for individuals or groups to control who can see him/her. There has also been discussion about embedding chips in roads to detect traffic flow and provide this information (i.e., context) to drivers in real-time, so that in case there is heavy traffic on a road, the system can recommend drivers to take alternative routes in advance [IBM 2006].

Context-Aware Mobile Advertising/Marketing

Mobile advertising, an area of mobile commerce, is a form of advertising that targets users of mobile devices. Selective advertisements can be automatically delivered to mobile device users according to their interest and other context (e.g., location). In comparison with traditional advertising, mobile advertising offers such advantages as providing personal touch and customization to suit individual needs, and reaching target customers at anywhere, anytime.

Aalto et al. [2004] introduce a location-aware mobile advertising system based on Bluetooth positioning and WAP (Wireless Application Protocol) Push. Location itself may not be sufficient to trigger sending advertisements. It has to be complemented by personalization because different users likely have interest in different products. A Bluetooth Sensor sends unique Bluetooth device addresses of detected phones to the advertisement Server over a WAP connection, which scans a database to search for the Bluetooth device address in the request and maps it to a user account. Then it checks if there are any undelivered advertisements associated with the user account and the location identifier passed in the request. If there are, the short textual description of those advertisements is passed to the Push Sender, which transmits content and delivery instructions to a Push Proxy Gateway using the Push Access Protocol. The gateway encodes the pushed messages and delivers them to the user. Mahmoud [2006] develops a context-aware mobile advertising prototype system using information retrieval and filtering capabilities of mobile agents. The system is based on a Service-Oriented Architecture (SOA). It utilizes user's location, time, user preferences, and device capabilities as contextual cues. Advertisements can either be pushed to a user along with the results of a product search, or be treated as value-added services to which mobile users can subscribe.

Intelligent Office/Conference Assistant

The possibility of enabling context-awareness in an office environment has been explored. The *PARCTAB* System [Want et al. 1995] integrates a palm-size mobile computer into an office environment. The context used in the system is location, the presence of other mobile devices, the inferred presence of people, time, and the state of the network file system. The communicator, calendar manager, and locator system work together to provide convenient information access. The Active Badge system [Want et al. 1992] was developed at Olivetti Research Lab in early 90's. The office personnel wore badges that transmitted infrared signals. Sensors around the building would pick up those signals and report them to a central server. An application could query the central server to obtain the location of any person.

A context-aware conference assistant allows users to create notes and attach them to a certain slide or Web page. After the conference, users can use an application to retrieve the notes or other information about a particular presentation and share it among colleagues. For example, *Conference Assistant* [Dey and Abowd 2001] assists conference attendees by automatically displaying the conference schedule and showing multiple conference tracks, which can help attendees find some tracks of their interest. The system directs attendees to the appropriate room in which the track of interest is being held. When a user enters the room, the system not only shows the title of the presentation, but also offers help with recording the presentation.

The previous list of context-aware mobile applications is not exhaustive. There are other applications and studies that focus on building infrastructure or middleware for such applications, such as [Bellavista et al. 2007]. There are also potential context-aware mobile applications that could be explored on a large scale. For example, in the future, there might be sensors that can automatically detect the problem with the growth of agricultural plants and send farmers an alert or information related to how to resolve the problem (e.g., recommending to use a new pesticide). When a context-aware mobile application is deployed at a large scale, a potential problem is information overload. Of course, there are also cost issues associated with mobile services, which could be a hurdle to the individual adoption of such applications in some developing countries.

In summary, location-aware mobile applications are the most well-studied context-aware applications so far, from early location-based tour guide systems to the recent healthcare monitoring systems. Although user activities are a centerpiece in context-aware applications, how to model them remains a key challenge. An activity is a fundamental, meaningful unit of analysis to understand relationships among human minds, artifacts, and the environment. An activity event includes not only external resources (e.g., people, mobile devices, environment), but also internal mental processes (e.g., task goals and beliefs). Currently, almost all of the existing studies focused on routine, well defined activities (with a very small number of contexts considered), where contextual states and adaptation strategies are predicted or determined at the system design time. They tend to treat contextual factors as isolated, independent variables. There are some preliminary works attempting to tackle this issue, but the proposed models are at a fairly high and abstract level, and their effectiveness, modifiability, and generalizability need empirical validation.

Recently, context-aware mobile applications in healthcare are receiving increasing attention from researchers and practitioners. Last year, Microsoft Research called for and awarded a number of research proposals on using cell phones as a platform for healthcare, aiming to advance healthcare services and solutions by taking advantage of the latest wireless technology and context-aware mobile applications (http://research.microsoft.com/ur/us/fundingopps/rfps/CellPhoneAsPlatformForHealthcare_Awards.aspx). In addition, context-aware mobile applications for social interactions and mobile commerce are also emerging in the past few years, particularly in Europe. Some of them have been put in practical use.

From an application perspective, one of the major challenges that researchers are facing is to explore novel, non-typical context-aware mobile applications that provide significant benefits to users, along with flexible adjustment of user control and autonomy. Although the great potential of context-aware mobile applications is well perceived, it has not been fully realized in practice due to a variety of technical and usability challenges that need to be investigated and addressed through research. Particularly, most existing context-aware mobile application prototypes are lack of formal evaluation, which makes their practical feasibility and user acceptance uncertain. In the next section, we will discuss the state-of-the-art research on context-aware mobile applications.

IV. RESEARCH ON CONTEXT-AWARE MOBILE APPLICATIONS: CURRENT STATUS AND RESEARCH ISSUES

Categories of Research on Context-Aware Mobile Applications

The fundamental research question in context-aware mobile application research is: to what extent can context-awareness increase the usability of mobile applications? In our literature review, we mainly focused on the following specific questions: what were research methods used? Was there any empirical evaluation or validation of the proposed concepts/solutions of context-aware mobile applications? Based on those two questions, we categorize existing studies on context-aware mobile systems into different groups, as shown in Table 2.

Overall, we find that the majority of existing context-aware mobile research belongs to conceptual research and remains at a “proof of concept” level. As a result, many context-aware mobile systems explored in those studies were not tried out by users. They have yet been publicly available for use and their functions were designed based on assumed rather than examined end-user needs [Häkkilä 2006]. Only did a very small portion of studies include formal evaluation of the proposed solution. The GUIDE tour guide mobile application [Cheverst et al. 2000a] was one of the rare ones that demonstrated the long-term public usage. In that study, researchers attempted to validate and refine an initial set of requirements against a group of users, and to confirm whether or not people were prepared to accept the use of a context-aware tourist guide. The evaluation of the GUIDE system involved two phases: 1) an expert walk-through of the system that provided a crude first pass evaluation of the system's usability via a talk-aloud protocol, followed by an interview; and 2) a field trial. The limited number of practical prototype systems and even fewer empirical studies in the literature clearly indicate that the research and practice in this interesting field are still in an early stage.

Research Methodologies for Evaluation of Context-Aware Mobile Applications

To date, the majority of empirical research has been mainly concerned about users’ perception toward those applications and conducted in fixed indoor environments, primarily because such settings are relatively static and easy for context collection and interpretation. A variety of research methods have been used to evaluate context-aware mobile applications, as shown in Table 3.

Although it is highly desirable to conduct usability testing of a context-aware mobile application using real mobile devices in a real-world setting, researchers need to be aware of several unique challenges caused by the frequent and unpredictable context change, dynamic usage settings, immature sensing technologies, and unstable wireless

Table 2. Categories of Existing Research

Research Types		Detailed Description and Examples
Conceptual Research	Type I: no system, no user evaluation	Did not involve any user evaluation of the proposed concepts or frameworks [e.g., Barkhuus 2003; Dourish 2004; Kaasinen 2003]
	Type II: no system, but with user evaluation	Did not develop any prototype systems, but performed user studies by using either a survey or a desktop-based emulator to acquire users' perception or feedback toward their proposed solutions [e.g., Jones 2005; Sorvari et al. 2004])
Prototyping research	Type III: have a system, but without user evaluation	Developed a prototype context-aware mobile application, but did not perform any formal user evaluation of the system [e.g., Gellersen et al. 2002; Virgilio and Torlone 2005].
	Type IV: have a system, with user evaluation but using emulators	Some studies developed a prototype system and conducted user evaluation of the system on emulators, rather than on real mobile devices, such as [Khalil and Connelly 2005]. Using emulators on a desktop computer may not reflect the limitations of a specific context-aware mobile application running on real mobile devices, thus may introduce bias to user perception of applications.
	Type V: have a system, with user evaluation using real mobile devices	There were a very limited number of studies have both developed a prototype context-aware mobile system and performed some kind of user evaluation using real mobile devices [e.g., Aalto et al. 2004; Muñoz et al. 2003; Skov and Høegh 2006].

communication [Mathias 2001; Zhang and Adipat 2005]. First, many context-aware mobile applications require JavaScript and Java to function, therefore they cannot operate on some thin mobile clients that do not have the required engines. Second, there is a large volume and redundancy of context data. Many applications heavily depend on sensors. However, most sensors send redundant information. For example, a location sensor will constantly report the location of a device. What most context-aware applications really need is only the change of contexts. Third, user activities and environment are mobile and dynamic, and users' needs and preferences under certain context may frequently change. Fourth, mobile devices have limited memory, processing capability, and power. Applications have to minimize computation and consumption of storage and power on a mobile device. Fifth, wireless networks usually have limited bandwidth and are unreliable. Applications may lose wireless connection.

Table 3. Research Methodologies for Evaluation of Context-aware Mobile Applications

Methodology	Description	Limitations
Scenarios [Carroll 2000]	A set of components, including a setting that defines an environment, a plot that contains actions and events, and actors who perform those actions to accomplish certain goals or tasks in a given setting	The scenarios provided to participants may be unrealistic and miss important influential issues that exist in the real-world [Häkkilä 2006].
Interviews and surveys	Heavily used in the existing research for collecting users' perception and intention of adoption of such applications, as well as for eliciting users' thoughts or inputs on system design	Users' perception without real experience with a mobile application may not reflect the true intention.
Paper prototype [Häkkilä 2006]	Consisting of a simplified layout of a mobile device that shows key elements of a system	Due to its nature, paper prototyping can be an effective way to test user interface issues but is not appropriate for testing system functions and usefulness.
Controlled laboratory experiment	Users experience mobile devices and software applications in a well-controlled environment.	Restrictions on selected platform, devices, predetermined user activities and tasks, and relatively unstable wireless communication may make the findings less generalizable compared to field studies.
Field study	Users use real devices and test an application in a real-life environment featured with the possible occurrence of many expected and unexpected context changes and events.	Hard to control a variety of factors that may influence the user activities and findings
Hybrid method	Using combination of two or more methods, such as [Skov and Høegh 2006]	The complexity of design and implementation of a study increases.

Similarly, they might lose contact with sensors that detect contextual information. Therefore, applications should be able to fully deal with the possibility of disconnection from network resources or sensors. In addition, mobile middleware platforms that adapt middleware services, applications, or support self-adaptive applications must have processing and delivering mechanisms for either resource or context information [e.g., Capra et al. 2003]).

Many existing context-aware mobile applications utilize only one type of context information (e.g., location). However, in reality, they often need to combine multiple context information, such as aggregation of place, time, activity, and people's interest, coupled with relationships among those individual contextual factors that influence information needs and people's willingness to share information. This is a very complex and challenging process.
The lack of empirical evaluation of context-aware mobile systems is consistent with the findings of other studies. In an earlier survey of mobile business research [Scornavacca et al. 2006], the literature review method was used in 31.9 percent of all surveyed studies (the most), followed by case studies (23.8 percent), survey (17.0 percent), simulation (13.6 percent), and experiment (5.5 percent). We believe that major reasons of the above unusual distribution of research methodologies used are attributable to the immature technological solutions and challenges in conducting an empirical evaluation using real mobile devices in a dynamic and unreliable wireless environment, as indicated by the following examples:

1. Technical failure: For context-aware mobile systems, frequent technical failure and incorrectly executed device actions due to erroneous context acquisition or interpretation are common barriers. For example, in Aalto et al.'s location-aware mobile advertising study [Aalto et al. 2004], one Bluetooth sensor device crashed in the morning of the second testing day, and another crashed in the afternoon due to the Bluetooth sensor and SymbianOS WAP stack's internal state machines getting out of sync. Many users in that study walked past a Bluetooth sensor without an advertisement being triggered.

2. Controlling a variety of sensors and environmental factors that may influence subjects and/or mobile applications in a field setting is very challenging, because users are likely associated with many contexts over a period of time [Zhang and Adipat 2005]. In contrast, conducting a laboratory experiment to evaluate a context-aware mobile system is more feasible and reliable, which often endures various constraints. In the field study of GUIDE [Cheverst et al. 2000a], due to the concern that the study would be impinging on the leisure time of tourists, the visitors (i.e., participants of the study) were asked to use the GUIDE system as they wished and for as long as they felt happy, rather than performing some predefined tasks. Results showed that all participants expressed that the location-aware navigation and information retrieval mechanisms provided by GUIDE were useful and reassuring. However, visitors' level of trust on presented information varied.

   Another example is Barnard et al.'s study on comparison of use-in-motion evaluation scenarios for mobile devices [Barnard et al. 2007], which attempted to empirically validate the appropriateness of two evaluation methods that varied in representativeness of mobility: one that used a treadmill to simulate motion and another that used a controlled walking scenario. In user evaluation conducted in laboratory settings, treadmill walking is often used while investigating mobile devices and applications with user motion. In comparison with over-ground walking, treadmill walking is far more controllable and affords easier data collection. However, the use of a treadmill could be inadequate because it might be too unrealistic, due to the constant speed and inherent lack of navigation required by the participants. Barnard et al.'s study was conducted in a laboratory setting. Participants in the study were required to finish two tasks (i.e., reading comprehension and word search) on a PDA while either walking on a treadmill or navigating a path around a room. Although the experimental procedure was carefully determined, there are still various factors that may significantly affect the findings. For example, first, participants were asked to set up the speed of treadmill with their normal walking speed. However, the treadmill speed was constant once it was set. In reality, it is not uncommon that people slow down when they read. When participants walked around the room, their speed was not monitored. As a result, it is difficult for researchers to ensure if participants on treadmills had exactly the same speed as those walking on the ground. Second, there was no control over participants' past experience with treadmills. Some participants who often use treadmills could be more effective and comfortable with the experimental tasks than others who have used treadmills less frequently. Third, when participants walking in the room, they had to make turns at the corner, which did not exist in treadmill walking. Therefore, the former scenario could cause more distraction and cognitive workload than the latter. Such uncontrolled factors could severely influence the results that researchers derived.

3. The traditional task-centric evaluation is not appropriate for non-task centric interaction behaviors. It is still not clear how to apply traditional task-centric evaluation techniques to informal daily context-aware computing situations.

Despite the significant differences in interaction between mobile and desktop computing, many mobile devices and/or prototypes of context-aware mobile applications are investigated using traditional desktop-paradigm evaluation strategies. In particular, the evaluation of mobile devices in stationary, static desktop-like situations tends to be the norm. There is a clear need of evaluation methods for mobile applications that are specifically suited to mobile devices. In the absence of a perfectly controlled and natural experimental scenario, new experimental scenarios must be validated to ensure that they effectively balance control and realism. Researchers have to overcome those barriers and collect first-hand, empirical data that lend themselves to the development of theories and the design of effective context-aware mobile applications. Context-aware mobile applications are very user-centric, in which individual users may have different preferences and needs. Therefore, identifying users' needs and their expected system behavior under different context is critical to the success of context-aware mobile applications.

V. DISCUSSION: FUTURE RESEARCH

The drivers of various challenges in context-aware mobile applications are squared on the complication of establishing context-awareness infrastructures and the naturalistic dynamicity of mobile devices in varying situations, as well as the technical-social gap between heterogeneous, low-level sensors and users who are interested in higher-level abstraction of contextual information. Transition from static desktop computing to context-aware computing poses many unanswered challenges relating to contextual interaction and usability.

Today, from creating a widget to characterizing context into several classes, many studies have attempted to structure the complex nature of context sensing into models. Still, none of them is able to grasp and distinguish the actual human understanding of the diversity of context information from the technical understanding of sensor information. Most of existing research studies on context-aware mobile applications focus on technical issues, such as sensors, context management [e.g., Wyse 2007], and system architecture and design [e.g., Gui et al. 2006]. Overall, general and unifying theories or formalizations of context are still in their infancy and significantly lacking. Existing context frameworks, predominantly software oriented, are difficult to capture and manage human variability. Therefore, it is of great potential for IS researchers to develop new theories that can guide or facilitate the design and evaluation of more effective context-aware mobile applications.

Based on the literature, we have identified a number of important areas/issues that need to be systematically investigated in the future research. First, the design and implementation of a context-aware mobile application should be user-centered. Users sense the context around them, cognitively process it, form internal context, and generate a goal. So how does a context-aware mobile application detect internal context of users and provide appropriate assistance? Currently, the design of context-aware mobile applications seems to follow conventional software design process without taking the special characteristics of such systems into consideration [Häkkilä and Mäntyjärvi 2006]. The user-centered design emphasizes the importance of understanding users in their natural use of context, and involves activities such as monitoring users while carrying out their tasks in an authentic environment. For example, Oulasvirta et al. [2005] introduced bodystorming sessions. With that method, the design team can generate and assess design ideas when the scenarios are acted out in realistic circumstances in order to better understand the usage context. Because individual users may behave differently even under the same situation, attempting to define the context of use and associated system reactions in a way that is desired by all users is impossible and can result in risks and difficulty to users. Therefore, a context-aware mobile system should provide an easy-to-use interface for users so that they can configure or reconfigure context-triggered rules at any time.

Second, current context-aware mobile applications have typically been designed by academic researchers, where the main purpose is to have a proof-of-concept or a functional demonstrator. Context is an inherent part of usability. The human-computer interaction issue has not been devoted too much attention as it has not been the primary research area in context-aware mobile computing [Häkkilä 2006], although human and social aspects of context are crucial in making context-aware systems beneficial. Hence, there is a strong need for theoretical design guidelines that can bridge the gap between the currently far-apart user interface design and technical development of context-aware applications. Because context-awareness involves uncertainties, sensor fusion, and complex inferring, the reasoning about what circumstances have led to a certain device action or triggered a certain feature could be difficult from a user's point of view. The system design guidelines will not only advise the designer of a context-aware mobile application about how to design the system by following certain design process and specific UI (User Interface) style, but also help developers implement the system. Heuristics are another set of instructions often used by usability professionals, which typically intend to recognize the usability risks in an application.

From an HCI (Human-Computer Interaction) perspective, we need an empirical, user-centered approach to understanding contexts: how do they affect users, and how should they be used to make mobile devices smarter? According to an international standard, ISO 9241-11, *usability* is referred to as the "extent to which a product can be used by specified users to achieve specified goals with effectiveness, efficiency, and satisfaction in a specified context of use." Some usability risks related to context-aware mobile applications have been recognized but not systematically examined. Previous research mainly focuses on narrowly defined cases [Häkkilä and Mäntyjärvi 2006]. Bellotti et al. [2002] proposed motivating apprehension of five challenging questions inherent in sensing interaction mechanisms, in which traditional HCI fundamentals "do not fare well," urging for the need of real collaboration between social science, Human-Human-Interface (HHI), and HCI to provide a systematic framework for the design of sensing systems. Similar concerns are also raised in Dourish's "positivism vs. phenomenological" debate [Dourish 2004], calling for rethinking the conventional notion of context not as a "representational problem" that is mainly concerned about encoding and presenting the environmental "sensor-based" surroundings of a software system, but as an "interactional problem" in which environmental context and humans' ongoing activities, with which users interact directly. In addition, users desire natural interfaces that facilitate requirements elicitation and a richer variety of communication between human and mobile devices. Such interfaces require the development of both new software and hardware [Hong et al. 2005].

Recent research on human-computer interaction for mobile devices has demonstrated that the usability of mobile systems may benefit from utilizing context information to tailor the information and functionality presented to the user in a given situation [Kjeldskov and Paay 2006]. A promising and novel approach to interface design for context-aware mobile systems could be the concept of indexicality derived from the semiotics. Semiotics concerns the meaning and use of signs and symbols. A semiotic approach can contribute to a theoretical understanding of information representation and the design of context-aware user interfaces. The semiotics operates with three types of representations: symbolic (conventional); iconic (similarity); and indexical (material/causal). Symbols and icons are ways of representing information independent of context, such as text and graphical illustrations. Indexes, on the other hand, represent information with a strong relation to, for example, spatial and/or temporal context. The idea of applying indexicality to interface design for context-aware mobile applications is that if information and functionality in a mobile device can be indexed according to the user's situation, then information already provided by the context becomes implicit and does not need to be displayed. Hence, the user's environment becomes part of the interface. As a result, the limited screen size of mobile devices can be optimized to contain only the most vital content, and the required user interaction with mobile devices can be reduced.

Häkkilä and Mäntyjärvi [2006] proposed the first set of design guidelines for context-aware mobile applications. Those guidelines include consideration of the uncertainty in decision-making situations, prevention from interruptions, personalization, avoiding information overflow, securing the user's privacy, remembering mobility, securing the user control, access to context, visibility of system status, and usefulness. The design guidelines were evaluated with design assignments, a process to simulate a product creation process. Questions included whether people were able to use the guidelines in general, what were the relevancy, applicability, and impact factors of the guidelines, and whether people felt that their design could be improved by using guidelines (subjective perception). The results from the evaluation suggested that the proposed guidelines would be applicable to the design of context-aware mobile applications, and the designers felt that the resulting UI designs were improved because of the guidelines.

Third, privacy is another critical issue while designing and developing context-aware mobile applications. The appropriate protection of users' privacy is critical for user acceptance and use of context-aware mobile applications. For example, privacy handling in location-based mobile applications should be concerned with issues like ownership of location information and disclosure of one's location information to others. Skepticism arises as to where and how privacy handling should take place [Sidnal and Manvi 2006]. From a user's point of view, the privacy aspect is often central. The privacy concern will be even greater for future pervasive systems that gather sensitive context information from many sensors to infer a user's location. For example, users may not be willing to share their current location or to give information about themselves to others. Most people do not like the idea of being precisely located at anytime by anyone, especially when the location data are logged. Potential usability risks have also been identified with diminished user control [Barkhuus 2003]. Users of a context-aware mobile device should be able to configure the sensor environment so that it matches the user's privacy preferences. It means that users have to recognize which information is recorded and which information can be deduced from those data [Ortmann et al. 2007].

Several architectural concepts for privacy protection in mobile or ubiquitous environments have been proposed. However, only a few existing context-sensitive systems, such as E-Graffiti [Burrell and Gay 2002], GeoNotes [Persson et al. 2003], and InfoRadar [Rantanen et al. 2004], provide some kind of privacy solutions. Many systems ignore security and privacy concerns. A possible solution is that when any context is collected, an owner will be assigned who can define a set of rules indicating what context can be accessed by whom and under what situation. When an application wants to access context, it must first authenticate itself using standard public-private key encryption. Ortmann et al. [2007] presented an architecture of privacy management platform for pervasive mobile

Table 4. A List of Potential Future Research Questions	
Context management	How can we improve disambiguation and integration of noisy and heterogeneous sensor data in order to obtain a more precise interpretation of context?
	How can we represent context to improve context inference and interpretation?
	Some researchers [e.g., Chen and Kotz 2000] propose to store context, which can be retrieved later by the user, but a fundamental question remains unanswered: How will the stored context be reused later?
	How can we model "activity" context? Obviously, it would be difficult to exhaustively model all possible activities that a user may involve. In addition, those constituents of an activity may dynamically change, making the model update and maintenance more difficult.
User control	Given that people's sense of control decreases as a mobile device's autonomous capabilities increases, and given the personal connection people feel toward their devices, how much control are users willing to give up in exchange for the convenience offered by a context-aware application?
Context-aware functionality	What context-aware functionality is generic enough to be in the "awareness" infrastructure?
	What functionality is more specific and should be provided in the application layer?
	How can we decide what information and functionality should be presented to the user, and make use of information already implicitly presented in the user's surroundings [Kjeldskov and Paay 2006]?
	How can we alleviate the information overload problem in context-aware mobile applications?
	How can we avoid triggering a false alarm? False alarms must be minimized in some applications such as context-aware healthcare monitoring services. Imagine a situation where an aged widow lives alone in a house equipped with medical sensors to monitor her activities and alert her physician when an abnormal pattern is detected. Typically, she goes to a church every Sunday morning. But on one Sunday, she chose to stay at home to watch breaking CNN news on TV. In this case, a context-aware mobile system has to also utilize other context such as motion and physical characteristics (e.g., body temperature and blood pressure) to make a judgment about whether she is at home because of the sickness or not.
System development	What are the generic system design guidelines for building effective context-aware mobile applications?
	How can we develop and standardize user-centered design processes?
	What are killer applications of mobile context-awareness?
Security and privacy	How can we address security issues with respect to authentication and authorization to prevent malicious access to a context-aware mobile application?
	How can we protect the privacy of users of context-aware mobile applications?
Impact	What is the cultural effect on the deployment and adoption of context-aware mobile applications?
	What is the impact of context-aware applications on the diverse aspects of human-device interaction and user experience?
	What are the social and economic impacts of context-aware mobile applications?

systems. It includes a management layer, which is responsible for communication with other mobile devices and services and for distributing data and configuration requests; a middle layer, which is set up by virtual sensors that include a certain amount of management functionality; and the bottom layer represents a real sensor network, which is configured by virtual sensors. The privacy demand of users that describes all prohibited and allowed sensor readings is stored in user configuration.

Fourth, how much user interference is needed, or what level of automatic context-aware adaptation should be allowed in a context-aware mobile application? On the one hand, context-aware mobile applications are aimed to detect, understand, and react to various related contexts automatically and are intelligently based on known user preferences. So theoretically, the less user interference, the better and smarter a system is. On the other hand, users' preferences may vary frequently (e.g., a user may not want to continuously receive nearby restaurant information from a location-based mobile service after he just finishes his lunch). Too many automatic system adaptations, even if they are relevant, can frustrate users. As a result, users may have to frequently update their preferences. Besides, not all users may agree or feel comfortable with their mobile device deciding how and when context-awareness should be used [Karmouch et al. 2007]. So far, user preferences, typically specified in user profiles and stored in mobile devices, are usually entered by users themselves. In other words, it is users who determine how their mobile applications should behave when certain circumstance occurs, and they can turn those context adaptation features on and off at any time. Although theoretically this user-driven approach is desirable, we are still uncertain about its practical feasibility in real use, especially when frequent updates have to be made by users. Would users get upset when they have to keep modifying their preferences or system configurations and eventually abandon the system?

Fifth, a large amount of context data collected by many sensors may cause an information overloading problem. For instance, when a user equipped with a location-aware mobile system walks into a shopping mall, his/her mobile device may be flooded by numerous advertisements, information about business hours, discount information, forthcoming events, and new product introduction sent by stores that detect the presence of his/her device. As places, objects, activities, and mobile devices equipped with sensors keep growing, the intensity of interaction between a mobile device and surroundings may increase exponentially. Predefining all possible context-sensitive responses is not feasible. Machine learning methods can be used to allow individual independent learning of context-aware preferences [Krause et al. 2006].

Based on the previous discussion and challenges and limitations in research on context-aware mobile applications introduced earlier, we generated a list of potential research questions that merit further investigation (Table 4).

While the wide deployment of context-aware applications in mobile devices is still not ready, and context-awareness research is still far from distinguishing between technical understanding and the human perception of context information, we believe that the next generation of mobile handheld devices will be increasingly equipped with adaptive, personalized, and intelligent context-aware applications.

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