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Survey on context-awareness in ubiquitous media

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Abstract Context-awareness assists ubiquitous media applications in discovering the changeable contextual information and adapting their behaviors accordingly. A wide spectrum of context-aware schemes have been proposed over the last decade. However, most of them provide partial functionalities of context-awareness

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in ubiquitous media applications. They are specified to a certain task and lack of systematic research on context-awareness. To this end, this survey aims at answering how close we are to developing context-aware applications in ubiquitous media in a systematic manner. This survey proposes a reference framework to identify key functionalities of context-awareness. Then, it investigates the state-of-the-art advances in every functionality of context-awareness. Finally, it points out potential directions in context-awareness research and tools for building and measuring context-aware ubiquitous media systems.

Keywords Ubiquitous media · Context-awareness · Survey

1 Introduction

Ubiquitous computing is a computing paradigm shift where technologies become virtually invisible in our lives [110]. It creates many new opportunities for mobile TV, video conferences and multimedia visualization. For example, in [23, 28], a wireless multimedia system was built by employing sensors with both mobility and multimedia capabilities. The system enabled interactive multimedia services and made adaptive routings according to the contexts, e.g., user geographical location, bandwidth constraint and energy limitation. The goal of ubiquitous media is to build an intelligent media environment embedding computation and communication such that users share media services without awareness of underlying technologies. This intelligence in ubiquitous media is mainly achieved by context-awareness, an enabling technology that assists ubiquitous applications in timely sensing contextual information and adapting to the changeable contexts [99]. Contexts refer to the pieces of interesting environmental information, e.g., user id and location [87, 117].

Research on context-awareness in multimedia has grown dramatically since ubiquitous computing came into being in 1999. From the start, context-aware research was driven by integrated sensing, hardware miniaturization and object localization in smart spaces (e.g., meeting rooms, cars, campus and houses). Figure 1 illustrates a context-aware media infrastructure at the Museum of Nature and Human Activities in Hyogo [93], where four spots are specified for the animal specimen exhibition shown in Fig. 2. Each visitor has an pendant containing an active RFID tag. When a visitor stands in front of a LCD screen, the navigational system will detect the context of the visitor and illustrates course annotations together video introduction.

However, context-awareness requires more—the field requires an interdisciplinary approach, cutting across programming paradigms, operating systems, embedded systems, networking and many application areas. The challenges imposed by the breadth of the field have been enormous. These arise a sharp gap between the high-level requirements from ubiquitous media applications and the operation complexity in handling contexts from the environment. The application requirements cover various aspects, such as high adaptability, flexibility and intelligence. Owing to constrained resources, heterogeneous devices, and user frequent movement, handling contexts would be extremely tedious and error-prone. Along with the rapid evolution in ubiquitous computing, the gap becomes increasingly obvious.

A variety of projects in real-world applications have shed light on bridging the gap and removing the development impediments in designing ubiquitous media

Fig. 1 Context-aware active media at the Museum of nature and human activities in Hyogo, where the museum can intelligently navigate visitors

applications. These projects include smart tabs, pads and boards [111], Oxygen [35], active badge [109], Aura [45], Gaia [76], One.World [47], Pico [65], Easyliving [15], CoolTown [6], DataTiles [88] and ambient intelligence project [40]. However, they fail to explicate logically organizing context-awareness and rapidly building context-aware applications with appropriate designing and developing techniques in the following aspects. First, they provide transparent abstraction by hiding contextual information, but ubiquitous media applications require handling contexts as much explicitly as possible [95, 119]. Second, they partially support context-awareness. They are mainly concerned with how to continuously satisfy the preferences of individuals in the presence of mobility and heterogeneity. In contrast, ubiquitous media applications intend to cover the requirements of scenarios and applications. Thus, mobility and heterogeneity should be handled in a different manner. For

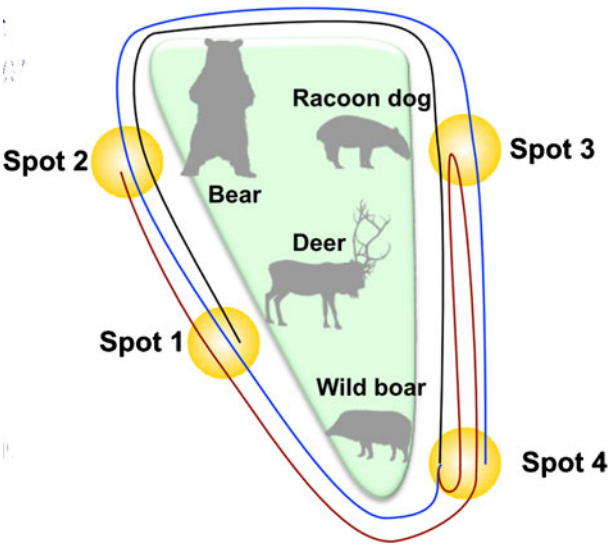

Fig. 2 Four spots in the exhibition room of animal specimens. The media infrastructure dynamically navigates their visitors among spots

instance, ubiquitous media applications will be fault-tolerant and flexible no matter how often users switch on/off a specific scenario. Third, ubiquitous media applications arise several challenging points, e.g., media studies concerns, tangible media design concerns and human-computer interaction [44, 60]. This definitely increases the complexity of implementing context-awareness in ubiquitous media applications.

To this end, this survey studies context-awareness in a systematic study. It explores the connotations and the way to achieve context-awareness. The distinct contributions of this paper are three-fold.

- It proposes a reference framework by which context-awareness in ubiquitous media is decomposed, analyzed and compared from programming abstraction, service and runtime support. This framework facilitates insights into the strengths and weaknesses of different systems and comparisons with a unified model.
- It classifies the context-aware efforts according to the functionalities and services contained in the proposed model. It also discusses the characteristics of these efforts by the classification.
- On the basis of widely investigating existing efforts, this paper identifies the open problems in context-awareness, and points out the future research directions.

The remaining of this survey is organized as follows. Section 2 introduces preliminary knowledge about contexts and context-awareness in ubiquitous media applications. Section 3 introduces a reference framework to analyze functionalities and identifies critical services to be provided by context-awareness. Section 4 overviews the state-of-the-art schemes and techniques corresponding to every functionality and service of context-awareness. Section 5 looks into the advances of runtime support in context-aware projects. Section 6 discusses challenging issues and points out future research directions. Finally, Section 7 concludes this survey.

2 Preliminary

This section firstly introduces what contexts are and then overviews how context-awareness is achieved in most existing ubiquitous projects.

2.1 Contexts

Generally, contexts vary with environment and users such that it is challenging to define them. We introduce contexts according to the context evolution.

- Contexts initially perceived are related to location. Contexts are mainly exploited to develop various location-based tourist services and systems [1, 37, 39, 83, 98].
- Contexts are enriched to incorporate other user information [21, 36, 79, 91]. User emotional state, attention focus and identities of nearby people are such contexts.
- Contexts are further widened to involve environment information [12, 50, 100, 104]. This is because the advent of going into the ubiquitous computing has stimulated broad and contrasting interpretations on contexts.

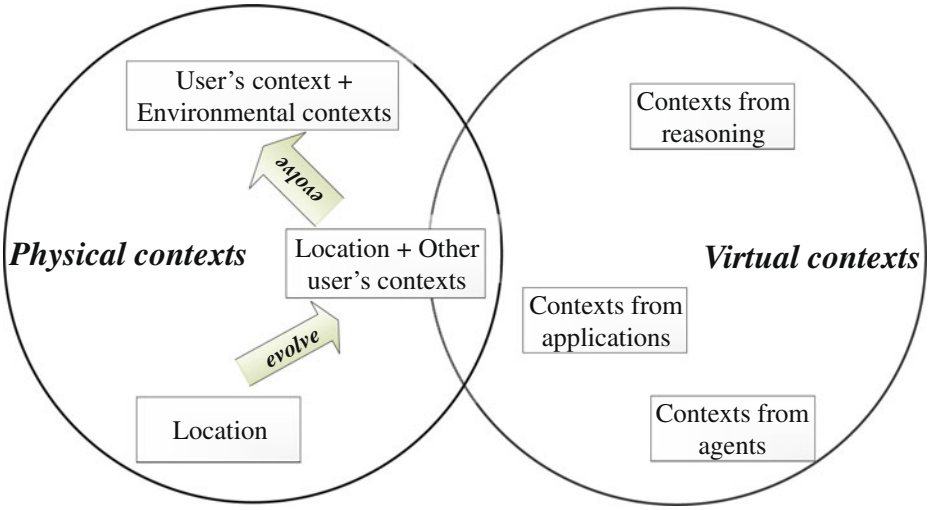

Fig. 3 Context classification, which illustrates our view on contexts into two categories

In this survey, we share the same view with [20, 56] that contexts refer to pieces of information that capture the characteristics of ubiquitous computing. We classify contexts into physical and virtual contexts based on context sources. Figure 3 illustrates our view on contexts, indicating the evolution process of physical contexts and the contents of virtual contexts.

- Physical contexts refer to contexts that can be aggregated by sensing devices. This kind of contexts involves accelerated speed, air pressure, light, location, movement, sound, touch and temperature. They can be easily gathered by sensing devices, and are widely used in various context-aware applications.
- Virtual contexts are contexts that are specified by users or captured from user interactions, including user preferences, business processes, goals and tasks. They enable ubiquitous media applications to be much more adaptive by further understand objects' contexts [16, 43].

2.2 Context-awareness in ubiquitous media

Context-awareness is a mechanism that assists ubiquitous media applications in adapting their behaviors to the evolving contexts [22, 67]. Suppose a call comes when Alice is watching Kongfu Panda in her smart bedding room. According to the call urgency and the caller's relationship with Alice, this smart space adapts its behavior correspondingly, i.e., reject or accept the call. We investigate this scenario and find that most ubiquitous media applications share a similar way to achieving context-awareness. First, they acquire physical and virtual contexts about Alice, including her identification, location, phone, and social network. Then, they exploits these contexts to determine what strategy should be taken when contexts keep evolving.

We abstract this scenario and get findings that context-awareness consists of three layers—sensor, context-aware and application layers, which is shown in Fig. 4.

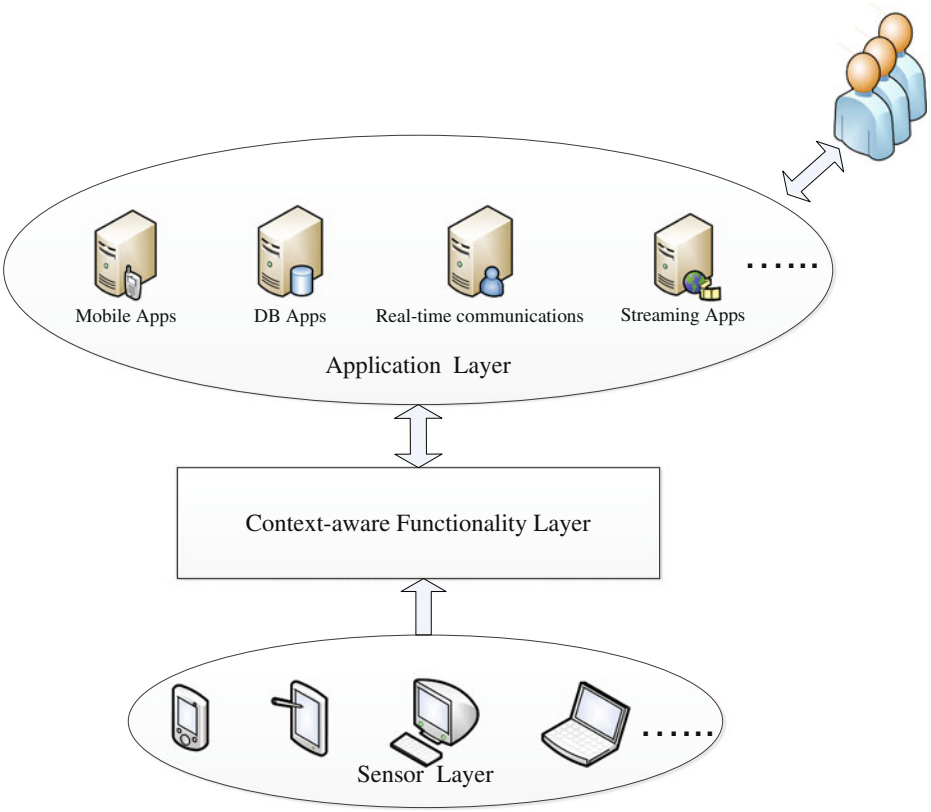

Fig. 4 The way of achieving context-awareness in most ubiquitous computing projects, consisting of three layers—sensor, context-aware and application layers. Sensor layer acquires contexts from context sources, context-aware layer encapsulates context-aware functionalities and leverages raw contexts to implement these functionalities as context services, and applications access the provided services to achieve their respective functionalities

Ubiquitous media is saturated with computing and communication capabilities so that ubiquitous media applications exploits these capacities to capture contexts. Then, applications deal with raw contexts in context-awareness modules, e.g., context preprocessing and reasoning. Finally, applications customize their behaviors according to the changeable contexts.

Note that most projects are bound up with specific tasks, and aim at hiding environment complexity by isolating applications from explicit schedule and management of devices, memory, protocols and heterogeneous problems related to architectures, operating systems, network technologies and programming languages. They satisfy not all users but the individuals, indicating that they may not achieve global optimization in the presence of mobility and heterogeneity. Meanwhile, they lack systematic research upon context-awareness such that they provide neither a series of rules and guidance to facilitate the development of general context-aware functionalities, nor reusable modules and libraries.

3 Reference framework

To identify the crucial functionalities in context-awareness, we propose a context-aware reference framework in this section. We firstly overview this framework in a systematic manner, and then introduce its every component. Throughout this survey, we interchangeably use 'node' and 'user' in the contexts without ambiguity.

3.1 Model overview

We classify context-aware in ubiquitous computing into three dimensions—programming abstraction, services and runtime support. To simplify context operations and facilitate the composition and migration of context-aware services, programming abstraction encapsulates and decouples contexts. It also defines service interfaces for application developers. Services provide implementation to achieve the abstraction. Whereas runtime support serves embedded operating systems as an extension with dynamically supporting the self-adaptation of services. Note that the reference framework assumes that QoS is encapsulated in every functionality of these dimensions.

By investigating the requirements and characteristics of context-awareness, we propose a reference framework shown in Fig. 5. This framework explicates the structure and the relationships of programming abstraction, services and runtime support. The goal of the framework is not only introducing key technologies, but identifying a set of functionalities and services that simplify the construction of new context-aware applications. These three dimensions provide elementary viewpoints

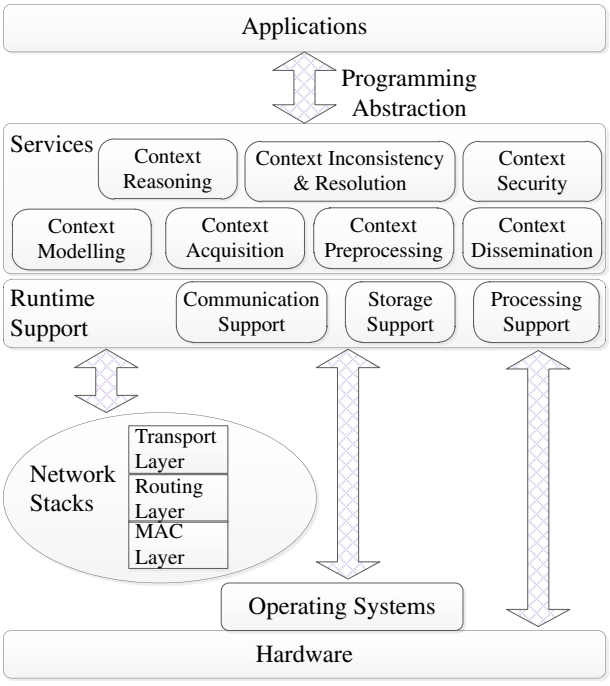

Fig. 5 The context-aware reference framework in ubiquitous computing, which is built on top of hardware, operating systems and networks

to envision context-aware applications, and thus encompass various functionalities. All functionalities may not be implemented in a context-aware module. They may be achieved in various manners or even being embedded. They are usually deployed to sensor nodes, sink nodes, and hand-held devices that may locate in widely different areas. Thus, nodes are capable of cooperating each other to achieve context-awareness.

3.2 Programming abstraction

Programming is an essential part in context-awareness, which forms the basis of implementing context-aware services. It separates the design and development of context-awareness from operations in the underlying ubiquitous infrastructures. It encapsulates the description, design and access of services into three components—abstraction level, programming paradigm and interfaces.

3.2.1 Abstraction level

It denotes that how application developers view the context-aware systems, consisting of two levels: node-level and system-level abstractions. The former abstracts a ubiquitous system as a distributed system including a range of cameras, sensors, hand-held devices, projectors and embedded devices. This level abstraction assists developers in programming individual devices belonging to the sensor layer for their action and cooperation [68, 70, 71]. The latter abstracts all context-aware functionalities as a single virtual module and provides a small set of programming primitives. It enables program developers to develop a single centralized program (global behavior) into subprograms that can be executed on local nodes (nodal behavior). Thus, it makes developers keep away from low-level operations, such as remote code data access, cache management, and node communication and cooperation.

In general, the former abstraction exploits the characteristics of nodes and hence is energy-efficient and saves many communication and cooperation overheads. Meanwhile, this level abstraction requires that developers be with adequate knowledge of nodes regarding hardware and software. Whereas the latter abstraction makes developers deal with actual applications rather than solving multifarious and error-prone issues in nodes. It allows developers to timely capture context changes and to handle them in a much more straightforward way than before. It also enhances code reuse to solve commonly encountered problems [49, 112].

3.2.2 Programming paradigm

It refers to a style of programming regarding how solutions to problems are to be formulated in a programming language, reflecting the view that programmers have of the execution of programs. Programming paradigm is dependent on applications. Given that contexts frequently evolve with individuals and situations in sensor-driven pervasive computing environment [66], we assort contexts into static and dynamic features. Context static features are captured by context acquisition through continuous, event-driven or query-based paradigms, while context dynamic features are gathered by diverse programming paradigms according to concrete requirements of applications. Common programming paradigms include Pub/Sub, message-passing

and concurrent paradigms. As a matter of fact, there are a huge number of programming languages, but fewer paradigms. Each programming language may realize at least one paradigm. Each paradigm is composed of a set of programming concepts, organized into a core as paradigm kernel language.

3.2.3 Interfaces

An interface is an abstraction that an entity provides itself to the outsider, while its type is a tagged constraint on programming interfaces. An example is that object-oriented languages standardize interfaces and their types between providers and requesters. Thus, requesters can handle messages by requiring providers to conform to this standard. This also enables requesters to select providers from a number of candidates, and providers to be extended by being able to accommodate future suppliers that comply with the standard.

There are two types of interfaces—declarative and imperative interfaces. The former assists declarative languages in query operation and file configuration with much resource consumption. It is known as SQL and XML in query operations. The latter helps imperative languages interact with networks and operating systems. It's representatives are C and Fortran based interfaces.

3.3 Services

Services are supposed to meet a significant requirement that context-aware applications should be rapidly built. These applications continuously adapt to highly complex and dynamic environment and functions in the presence of user movement and heterogeneous devices with limited communication and computation capabilities. However, most existing schemes are not qualified for constructing such services because they work in the form of objects and hide the operations on contexts [47, 95, 119]. Thus, users are often forced to adapt, which is antithetical to the vision of ubiquitous computing.

In order to satisfy this requirement, the reference framework proposes a set of context-aware functionalities that are abstracted in context modeling, acquisition, preprocessing, inconsistency detection and resolution, and reasoning. Thus, context-aware applications derive services from these abstractions. These abstractions are summarized in Table 1, embodying the core services that context-aware applications should possess.

Table 1 Functionalities of context-awareness in ubiquitous computing

Functionality	Definition
Modeling	A pattern designed to represent the object "context"
Acquisition	Gathering contexts from context sources
Preprocessing	Manipulating raw contextual information into a format that will be easily and effectively handled by applications, users or processing procedure
Inconsistency detection and resolution	Checking and resolving context inconsistency
Reasoning	Inferring implicit contexts from existing contexts

3.4 Runtime support

Runtime support aims at building execution environment where ubiquitous applications run smoothly with heterogeneous devices, networks, topologies and frequent movement of nodes. It extends embedded systems in terms of task scheduling, process communication, management of memory, power and resources. It is indispensable to ubiquitous applications, which involves many devices and nodes with limited capabilities, power and resources.

Runtime support can be achieved in several ways. It may be implemented as a virtual machine over a specific operating system in the sensor layer [108]. In Mate [68], it is built on top of open-source operating system TinyOS [69].

Thus far we have discussed all functionalities as well as services of the reference model. In the remaining of this survey, we focus on investigating how existing projects implement the functionalities involved in the proposed model, and then identifying challenging problems in context-awareness research community as well as future directions.

4 Context-awareness evolution in ubiquitous computing

This section discusses the existing context-aware techniques in ubiquitous applications. It gives a detailed coverage for most of the recently presented techniques focusing primarily on the functionalities involved in the reference framework. Section 4.1 introduces current context modeling techniques. Section 4.2 describes the existing efforts on context acquisition. Section 4.3 investigates the context processing techniques. Section 4.4 overviews the work on context inconsistency detection and resolution. Section 4.5 describes the latest context reasoning research.

4.1 Context modeling

Context model is a pattern to represent the object "context". Many context models have been developed over the last decade ranging from early simple to sophisticated complex models. We summarize context models based on the data structure used for expression and exchanging.

4.1.1 Key-value context model

Key-value model employs key-value pairs to enumerate attributes and their values describing contextual information, which is recognized as the simplest context model. It has achieved widespread success in early distributed frameworks to represent location information or service functionalities e.g., [99] and [92, 106]. Then, context discovery is applied by checking the matches of key-value pairs.

Key-value pairs are unable to represent complex contexts, although it is easy to manage. Consequently, it gets increasingly less used in the late context-aware research.

4.1.2 Markup context model

Markup model represents contexts by a set of symbols and annotations inserted in a text document to control its structure, formatting or relationships among its parts. These symbols and annotations may spring from the makeup languages with built-in semantics mechanisms (e.g., HTML), or the makeup languages without semantics (e.g., XML). They can be interpreted by devices to control how contexts should be organized and exchanged.

Two of the most popular markup context models are User Agent Profile (UAProf) standard [113] that captures capabilities and preferences for wireless devices, and Composite Capabilities/Preferences Profile (CCPP) that describes device capabilities and user preferences and instructs the adaptation of content presented to devices [114]. UAProf and CCPP as well as their derivatives are seriously limited by the pre-defined hierarchical structure and restricted overriding mechanisms. Besides CCPP and UAProf, there are several other markup context models proposed, such as Context Extension [58], Comprehensive Structured Context Profiles (CSCP) [53], ConteXtML [90], Centaurs Capability Markup Language [62], and the note-tags of the stick-e notes [14]. Nevertheless, these markup context models suffer from several problems in capturing context relationships, dependencies, timeliness, inconsistency checking, reasoning, and uncertainty removing from contexts [8, 99].

4.1.3 Graphical context model

Graphical model mainly encompasses the models based on the Unified Modeling Language (UML), Entity-Relationship Model (ERM) and Object-Role Model (ORM) [51]. UML is a standardized general-purpose modeling language and is suitable to model contexts. ERM and ORM are powerful methods for designing and querying databases at the conceptual level. They are adopted in [54].

Some variants of ERM and ORM have been devised subsequently in representing contexts. For instance, Context Modeling Language (CML) springing from ORM was developed and enriched for conceptual modeling of databases [52, 53]. It extends ORM in capturing different classes and sources of contexts, and introducing quality metadata to express imperfect contexts.

In summary, graphical context model is capable of expressing contextual information by graphical diagrams. It also facilitates the analysis, design and discovering relationship of contexts at the concept level. However, they are ineffective in the practical interchange, which is attributable to a fact that they are lack of sufficient detail to facilitate reliable interchange of their notations between modeling tools and applications.

4.1.4 Object-oriented context model

This kind of context models, e.g., Cue [96] and Active Object [30] incorporates encapsulation, inheritance and reusability of object-oriented into context representation. In most cases, this model technique encapsulates the processing of contexts at the object level, and allows instances to access contexts by inheritance mechanism.

However, object-oriented context models make high demands of developers that they must systematically analyze and design the entire context taxonomy. In addition, object-oriented models are complex and may not be supported in hand-held device with limited computation capabilities.

4.1.5 Logic-based context model

Logic is the study of reasoning that aims at analyzing and representing facts from a set of other facts. It has attracted unceasingly attention from academia and industry in ubiquitous computing that is characterized by complex, dynamic and incomplete contexts. A variety of logic-based context models have been proposed. Pioneering efforts [46, 78] have applied logic to represent contexts.

A typical logic-based context model is introduced in Cabot project [20, 115, 116], which is designed for checking and resolving context inconsistency. Contexts are modeled by first-order logic as a five-tuple, i.e., $context = (category, fact, restriction, timestamp)$.

4.1.6 Ontology-based context models

Resource Description Framework (RDF) and Ontologies incorporate semantics into XML-based representation. They are supported by many powerful software tools such as Stanford Protégé [102] and IBM Integrated Ontology Development Toolkit [57]. Many RDF-based and ontology-based context models have been proposed [55, 107].

Ontologies and RDF are promising techniques to model contexts because of their formal expressiveness and the ability of inferring contexts. However, it is hard to construct complete ontologies and differ ambiguity of ontologies [89]. Moreover, they are also seriously limited by inexact reasoning.

4.1.7 Multidisciplinary context model

This model is proposed in [12] and refined in [13]. It is a hybrid model, capturing context relationship and interpretations from psychology, computer science, and linguistics. It encompasses the information concerning applications, users, and environment.

This model is a conceptual model that does not exactly specify how to represent contexts. Moreover, it is confronted with the inter-operability problem.

4.1.8 Domain-focused context model

This kind of context models is tailored to application domains, and thus considerably improves the functionalities of context-aware applications. This model represents contexts as a four-tuple (who, $what$, $where$, $when$), and supports query and deletion operations [18]. Thus, such representation is suitable for very expressive, and flexible data usages.

Modeling contexts by a universal context model still remains open due to the complex, dynamic and incomplete characteristics of contexts. Thus far, this survey has investigated how contexts are modeled in existing context modeling techniques. In the next section will investigate the advances in context acquisition. Note that we overview existing ubiquitous projects in terms of these functionalities of the proposed reference model shown in Fig. 5.

4.2 Context acquisition

Context acquisition refers to gathering contexts from context sources, which is a prerequisite for context-aware applications. Contexts can be captured from sensing devices and virtual sources. The way to implementing context acquisition functionality relies on the application requirements and models. It may be either colligated in the sensor layer where sensed data and its interpretation form the contextual information or be implemented as an independent model [27].

In recent years, owing to its low cost, wide availability and location sensing functionality, RFID has attracted increasing attention in ubiquitous agents [24], internet of things [124], ubiquitous e-healthcare [25]. It consists of three key elements—readers that are silicon-based radio transceivers, which interrogate and interact with tags by electromagnetic waves, tags that are tiny radio clients, which store unique identification, and systems that provide a way to user RFID data [25, 125]. Table 3 shows the component of RFID systems. RFID devices acquire node real-time location, thus being widely used in applications.

4.2.1 Context acquisition paradigms

In the sensor layer, there are two primary paradigms to gather contexts: event-driven and query-based. Event-driven paradigm defines a model that a sensor node will immediately send its readings to the sink node when it detects an event. By allowing asynchronous communication, it satisfies the requirement held in ubiquitous computing in which most devices are resource-constrained. It is applied in Impala and TinyDB.

The representative case of event-driven model is the Pub/Sub paradigm, which exploits the power of the event-driven model that subscribers subscribe sophisticated subscriptions without worrying about how their subscriptions are delivered. In general, subscribers know neither where publishers are nor what they provide. But they can notify their interests to publishers mainly by web services or brokers or overlay network protocols, and merely receive messages that of their interests. Publishers or a pub service maintain a list of subscription so that they are able to deliver right message to right subscribers when an event is triggered (e.g., newly released message from publishers).

In contrast, the other paradigm for gathering contexts is query-based paradigm, which allows database-style query operations to be executed among sensing nodes and sink nodes through a declarative, SQL-like but a distributed interface [72]. When an application requires a certain kinds of context, it raise a query to sink nodes which turn to aggregating and searching sensor readings reported by nearby sensors. Given that sensors keep capturing information and only few readings are useful, query-based acquisition paradigm is appropriate in most cases. Therefore, it is supported by many projects, TinyDB [74], SensorWare [11] and CACQ [73].

Furthermore, query-based context acquisition paradigm can be easily customized to meet the challenges in ubiquitous computing. Consider that devices are seriously limited by power, Cougar improves the query-based model by distributing the query among the nodes to collect the raw contexts and do calculations with minimum energy consumption [10].

Table 2 Some sensing devices and their capturing contexts

Name	Captured contexts*
Audio sensors	Noise, music, decibel levels
Video cameras	Emotions, presence, behavior
Motion detectors	Presence, single or multiple users
Pressure sensors	Pressed, occupied, hand gestures
Light sensors	Ambient light, indoor brightness
Accelerometers	Motion, vibration, physical state
Bluetooth	Location
Infrared	Location
RFID	Location, activity, situation
GPS	Location
Environmental sensors	Weather, temperature, humidity
Event monitors	Events, schedules, notification, errors, updates
Action listeners	
Data loggers	
Agent process	

*This table lists some common contexts captured by sensing devices

4.2.2 What kinds of contexts are acquired

Ubiquitous media applications usually involve contextual information about physical environment and users. This contextual information chiefly includes light and vision, audio, movement and acceleration, location and position, magnetic field and orientation, proximity, touch and user interaction, temperature, humidity and air pressure, weight and power, emotion. In order to capture contexts, various enabling techniques have been employed, such as GPS and Motes [25, 26, 29], shown in Table 2.

Note that enabling techniques, e.g., image recognition, machine learning and data mining, can capture virtual contexts that may not be aggregated by physical sensors . They may collect data loggers or images and then analyze user preferences, emotions and satisfactions [32, 80].

On the other side, we look into existing research on context acquisition, and get findings that most context acquisition efforts emphasize on acquiring location that is the most important contextual information. An example is load sensing [97], which is a mature and robust technology. Applications equip all objects' surfaces in a specific scenario with sensing capabilities, and thus they can accurately and reliably identify objects' positions (Table 3).

Table 3 Some sensing devices and their capturing contexts

Elements	Criteria	Category	Description
Tags	Power source	Active	Sensitive
		Passive	Noisy
	In-board memory	Read only	Unchangeable, ex., ID
		Write	Writable, ex., states
Readers	Mobility	Stationary	Fixed location
		Mobile	Connected to wireless network
		mRFID	Connected to GSM, GPRS type
Systems	Service	Data aggregation	Data processing

4.2.3 How contexts are acquired

Data acquired by sensors is raw data and evolves into contexts when it is associated with interpretation or physical significance. For example, environmental contexts are connected with air and sound data, including air temperature, humidity, pressure, ambient noise and talking voice. Only all data is captured and interpreted, environmental contexts are aggregated.

Users or applications need to specify the relationships between sensor readings and contexts expected to be acquired. However, the types of contexts vary with applications, indicating that an application may require contexts that may be totally different from other applications. As a result, applications need to explicitly associate sensor readings and contexts, regardlessly of manually or automatically.

Figure 6 shows an example of the process of acquiring contexts on Muffin [118], which aims at detecting user behavior—walking or running or not. It firstly employs skin resistance sensors, accelerometer sensors, and ultra-range finder sensors to collect raw data. Then, it checks the attributes and values of these data to get low-level contexts, e.g., checking whether the value of the ultra-range finder sensor falls into the range of 0 and 100 to obtain the current location of the user. Finally, by incorporating other checking results and comprehensive analysis, it is able to aggregate the information about user current behavior.

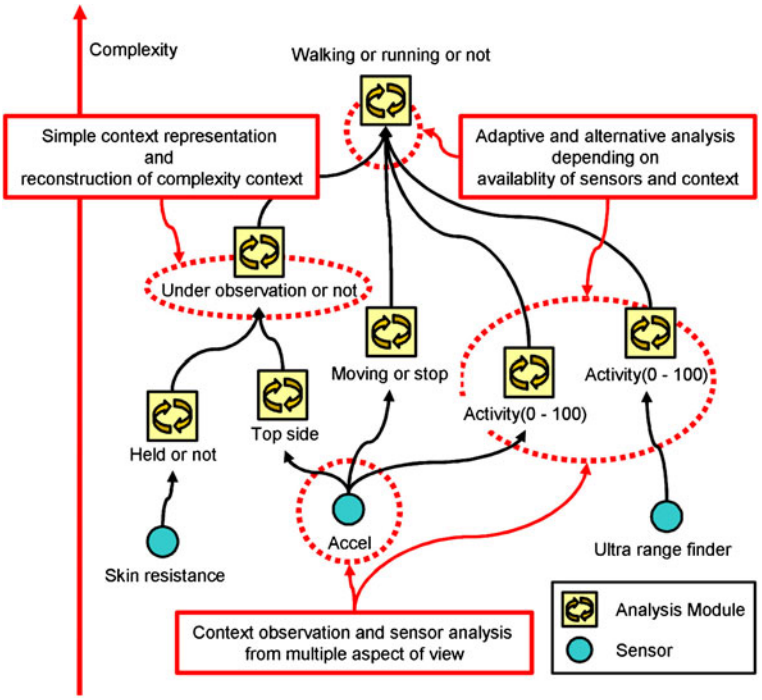

Fig. 6 An example of the process of context acquisition on Muffin [118], which detects user behavior by capturing sensor readings and corresponding interpretation

In summary, existing projects have conducted much research on acquiring contexts, and accumulated various experience in context acquisition. This experience indicates that contexts are mainly acquired from the sensor layer, and the most important context is location context. The proliferation of wireless communication, image recognition, machine learning, networks and software engineering has increasingly enabled existing techniques to capture more types of contexts. Projects ongoing and to be taken are supposed to leverage on more contextual information, and conduct comprehensive analysis of contexts to make ubiquitous media applications be further context-aware. Once contexts acquisition is finished, context-aware applications enter into the preprocessing step.

4.3 Context preprocessing

Contexts are often noisy and incomplete in ubiquitous media [61]. RFID readers capture 60–70% of the tags in their vicinity [24, 125]. Sensors deployed at the Intel Research Lab in Berkeley, on average delivered 42% of the data it was asked to report [59]. This is because sensed data and their interpretation as contexts are prone to errors. The sources of errors consist of, but are not limited to internal components, inaccurate measurement, and noise from external environment.

Context preprocessing is a context-aware functionality that is in charge of handling raw contextual information. This functionality significantly improves the context quality, particularly when contextual information is coarse-grained. We classify context processing techniques into two types: handling contextual information in the sensor layer or in the context layer. We omit the discussion of the first type that is not the focus of this paper.

4.3.1 Context preprocessing paradigms

Generally, there are three context preprocessing designs for contexts sensed by sensing devices—centralized, distributed and hybrid designs. In centralized designs, a central node or a centralized module is required to preprocess contexts captured and delivered by sensing contexts. In contrast, distributed paradigm allows sensors to filter and preprocess contextual information by aggregation nodes. The hybrid design aims at combining the strengths of the former two paradigms, in which several nodes are selected to aggregate their nearby contexts and then combine their results as final results and report them to requesters.

Context preprocessing can be achieved by event-driven, message-passing or query-based communication paradigms. In real-time applications, aggregation nodes are supposed to timely preprocess raw contextual information from sensors. Thus, real-time applications usually adopt the event-driven paradigm. While in applications that are not urgent, e.g., the temperature checking, most sensor readings are redundant. These sensors may filter redundant readings and just notify aggregation nodes about significant contexts. These applications do not require sensors to keep delivering their readings as the real-time applications do. In this case, message-passing is suitable. Meanwhile, applications and users may raise some questions about certain contexts. Then, the aggregation nodes had better communicate with sensors by the query-based paradigm. On the other side, virtual contexts are similar in context preprocessing with concrete contexts that are collected by

sensing devices. They can be handled in the same way as concrete contexts from devices.

4.3.2 Existing context preprocessing efforts

In the sensor layer, a variety of schemes have been proposed to preprocess raw contexts [41, 120]. They mainly employ statistical and probabilistic techniques such as Bayesian network, Kalman filter and linear regression to clean contexts. They enable programmers to specify cleaning stages using high-level declarative queries, and transparently translate these queries into the low-level operations necessary to produce results.

On the contrary, preprocessing contexts in the context level is rarely discussed [42]. Most context-aware work implicitly assumes that raw data is accurately interpreted as contexts. However, this assumption does not always hold. Context Query Language (CQL) was proposed for contexts aggregation and ontology integration.

To summarize, context preprocessing is mainly limited to processing raw data. Note that context inconsistency detection and resolution is exclude, which is discussed in the next section.

4.4 Context inconsistency detection and resolution

Contexts are often noisy, which necessitates context inconsistency detection and resolution in pervasive computing that compasses various resource-limited devices. To remove and solve context inconsistency, various schemes have been studied in recent years. Figure 7 gives two example of context consistency conflicts. One is that two locations for a user at the same time is unreasonable, the other is that the speed change scope (less than 150%) is out of the scope that the system allows, where L_k is abnormal.

In this section, we firstly investigate context inconsistency detection schemes and then introduce corresponding inconsistency resolution schemes.

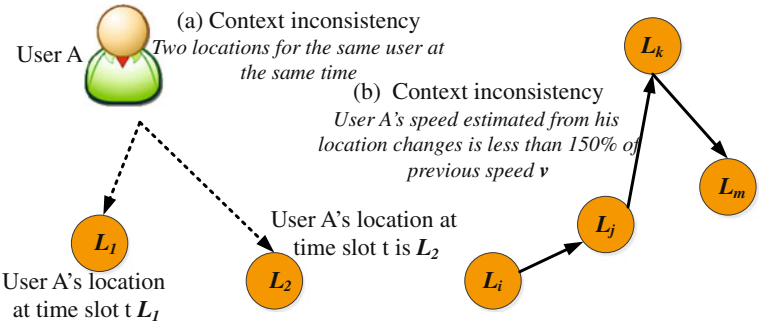

Fig. 7 Two examples of context inconsistency

4.4.1 Context inconsistency detection

The majority of existing context-aware efforts are concerned with frameworks that support context abstraction, reasoning and querying. Actually, they provide partial support for checking context consistency, and fall into logic-based, ontology-based and tuple-based inconsistency checking schemes.

- Logic-based context inconsistency checking schemes. Aura [45], CARISMA [17], CASF [94] and Context Toolkit [38] have conducted initial research on checking context Inconsistency by using logic rules. These projects mainly demonstrate that centralized architectures leverage the development of the functionality of context-aware applications. They also demonstrate that message-passing and event-driven paradigms are two appropriate paradigms in implementing context-awareness. Thus, they fall short of efficiently checking context inconsistency.
- Ontology-based context inconsistency checking schemes, which check context inconsistency by attributes, axioms and assertions [107]. However, ontology-based schemes have limited capability of removing noise in contexts and dynamically reasoning out contexts. Moreover, they impose a prerequisite that all domain ontologies must be defined beforehand. This usually incurs extra consultant cost.
- Tuple-based context inconsistency checking schemes, which check context inconsistency by tuple constraints. In [115], a context-aware middleware modeled context constraints by tuples shown in Section 4.1.5, and checked context consistency by semantic matching and inconsistency triggers among elements in tuples. This work is extended in [116], which can incrementally check inconsistency. However, these schemes implicitly assume that the contexts being checked belong to the same snapshots of time. This assumption is eliminated in [56] that checks context inconsistency by *happen-before* relationship among contexts in asynchronous environment.

4.4.2 Context inconsistency resolution

Regarding context inconsistency resolution, few schemes have been proposed. According to the manner that solves context conflicts, we classify them into user interference [86] and QoC-based (quality of context) categories [20, 77]

- User interference schemes, which resort to users to manually solve context inconsistency. Users cannot make sure that they are able to find and resolve all context inconsistency. Thus this kinds of schemes is neither scalable nor reliable.
- QoC-based schemes, which resolve context inconsistency by context quality. They introduce up-to-datedness, trust-worthiness, and other context quality policies according to the context QoC measurement e.g., source location and source state. Thus, these policies can resolve conflicts in rapidly evolving contexts. However, contexts are noisy and keeping evolving, which inevitably makes the inconsistency resolution harder.

Context inconsistency checking and resolution is one of the latest hot topics in context-awareness research community. What follows in the context-aware reference model is context reasoning that is to be investigated in the next section.

4.5 Context reasoning

Context reasoning infers implicit contexts from existing contexts. Many context reasoning schemes have been proposed to achieve context reasoning in a centralized manner or distributed manner. In a centralized manner, a node makes use of captured contexts to infer implicit contexts by various reasoning techniques. While in a distributed manner, nodes cooperate and make reasoning, e.g., context reasoning based on peer-to-peer ubiquitous networks [48]. We summarize a taxonomy of context reasoning in Fig. 8.

4.5.1 Exact context reasoning

It consists of Bayesian network [75], case-based [63], logic-based [85], ontology-based [107], and rule-based [9] reasoning techniques. We investigate exact context reasoning by following the taxonomy.

- Bayesian network can be regarded as a canonical context reasoning technique, which represents contexts by graph and probability.
  However, it is seriously limited by two assumptions. One is that it requires exhaustive and exclusive hypotheses, and the other is its exponential computation overhead.
- Case-based reasoning infers contexts based on the past cases. However, it falls short of accurately measuring the similarity among cases and automatically generating and analyzing cases.
- Logic-based context reasoning is designed for exact reasoning. It is inefficient when it is confronted with incomplete and imprecise contexts in ubiquitous media. It is also criticized for its poor performance in fuzzy reasoning. In addition, it lacks of semantics into their representation.
- Rule-based reasoning shares the similar idea with logic-based schemes that it infers contexts by pre-defined rules. It remains an open issue for rule-based schemes that how to dynamically generates rules according to the varying contexts.
- Ontology-based reasoning schemes incorporate semantics into context representation and reasoning. They implicitly suppose that all ontologies related to a specific domain are pre-defined. However, this supposition is not always true in

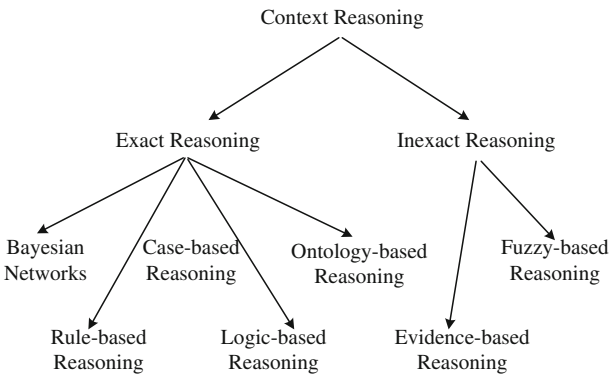

Fig. 8 The taxonomy of context reasoning

ubiquitous media. Moreover, most users resort to domain experts for ontology knowledge, which incurs extra human costs and hence restricts the application of ontology.

4.5.2 Inexact context reasoning

Fuzzy reasoning includes evidence-based [123] and fuzzy-based reasoning techniques [2, 33].

- Evidence theory, also known as Dempster-Shafer theory [34, 101], relaxes two assumptions held by Bayesian network and allows probability assignments to sets or intervals. It is capable of constructing the ground truth from pieces of information. Although [123] has extended the evidence theory in its two detrimental problems: heavy computation overhead and Zadeh paradox.
- To deal with imprecise and incomplete contexts, fuzzy context reasoning employs the fuzzy set theory, which depends on subjectivity in perceiving and representing concepts with member functions, rather than randomness in probability theory and statistics [122]. This reasoning technique provides a manner of combining captured data with expert knowledge.

In summary, inexact reasoning schemes cannot get the accurate implicit contexts and thus they may be unsuitable in ubiquitous media applications that require accurate contexts. They are seriously doubted about their effectiveness by probability community who prefer statistics, conventional probability and two-valued logic. In fact, inexact reasoning can be used as a way to inferring possible contexts in most applications.

4.6 Investigation of existing context-aware multimedia systems

Thus far, we have discussed most functionalities of context-aware services in the reference framework shown in Fig. 5. We aim to investigate how existing efforts achieve what degree of context-awareness. We selected Snap2Play [121], ConPhone [84], CAMP [3], CACH [82] and CMMM [31] as baselines.

Table 4 reports the comparison of selected context-aware media infrastructure. This implies that location is the most favorable context, and key-value context model is simple but yet powerful. This also shows that context reasoning and inconsistency functionalities are not available in most multimedia systems.

Table 4 Some sensing devices and their capturing contexts

Systems	Aggregation	Model	Preprocessing	Reasoning	Inconsistency
Snap2Play	Location	Key-value	Pilot test	X	X
ConPhone	Location	Key-value	X	Rule-based	X
CAMP	Scene	CDI/SMIL	Optimizer	X	X
CACH	Hospital environment ex. location, role	XML	X	Rule-based	X
CMMM	Location User preference	Key-value XML	MySQL	Rule-based	Yes

Table 5 Some sensing devices and their capturing contexts

Devices	Aggregation	Preprocessing	Communication
SmartTVs	ccd camera,microphone	Hand-gesture recognition	TV
	TV wireless network	Voice recognition	Wifi
sPhones	gps,microphone	Speech recognition	Wifi, 3G
	Camera	Hand-writing recognition	
Kinect	ccd camera, laser camera	Body-gesture recognition	Computer
	Microphone	Speech recognition	
Xtion	ccd camera, laser camera	Body-gesture recognition	
	Microphone	Speech recognition	
iPad2	Touch pad, camera, microphone bluetooth, Wifi	Proprietary software	Wifi, Internet
MyFi	Voice recognition	XM satellite radio station	
	Spatial information parser	Wireless FM transmitter	

Note that there are a number of context-aware multimedia systems that are customized for hand-held devices. We also investigated the pros. and cons. of context-awareness (particularly context aggregation, preprocessing and communication) in these types of applications. We extracted SmartTVs (http://www.gesturetek.com/newscenter/media.php?media=46), sPhones (http://www.apple.com/iphone/features/), Kinect (http://www.xbox.com/en-US/kinect), Xtion (http://us.estore.asus.com/), iPad2 (http://www.apple.com/ipad/), MyFi Radio (http://shopdelphi.com/consumers/support/faqs/myfi/).

The comparison result is given in Table 5, where context-awareness is supported in a lightweight manner. Owing to the limitation of communication and computation capabilities, the majority of hand-held devices do not provide the functionalities of context modeling, preprocessing, reasoning, and inconsistency processing.

5 Runtime support

Runtime support aims at building an execution environment for ubiquitous media applications by extending functions from underlying platforms in term of processing, communication and storage. It is indispensable to most ubiquitous devices and applications that are characterized by constrained resource, limited computation and communication capabilities.

Runtime support can be achieved in the sensor layer or the context layer. It is often implemented as a service or a virtual machine that embeds its functionalities into a middlewares-like module over a specific operating system.

- In the sensor layer, runtime support provides ubiquitous media applications with code interpretation, energy control, memory management, process handling, task scheduling, and thread concurrence and synchronization. Magnet [5] and LIME [81] are initial research on runtime support in the sensor layer.
- In contrast, runtime support for context-awareness is not yet fully discussed. Runtime support mainly involves some functionalities of handling and managing contexts in terms of device configuration, context storage, and assisting applications in adaption. Existing efforts have addressed many issues in context-awareness, but they do not provide adequate runtime support in the context

layer. For example, CARMEN [7] was an adaptive context discovery middleware that provided runtime support in discovering and acquiring contexts when contexts change. However, it is incapable of automatically configuring services in response to context changes without any intervention.

6 Challenging issues

Due to the complexity and high-level abstraction of context-awareness, many issues are still open and deserve further research, especially in the following aspects.

6.1 Programming abstraction

Programming abstraction substantially affects the development and application of context-awareness. It simplifies the programming effort and improves development efficiency, and provides a universal interface to interact with heterogeneous environment. It is dependent on a specific toolkit and a middleware.

- **Designing a programming abstraction for context-aware applications requires systematic design, rather than piece design**. As discussed in Section 3.2, programming abstraction consists of abstraction levels, interfaces and programming paradigms. Meanwhile, it is highly associated with context modeling, storage and underlying systems. We observe repeated activities from nearly sixty context-aware projects in almost all steps of developing context-aware media applications, i.e., from the context representation, acquisition to context exploitation. To our knowledge, only few ontologies and common libraries may be reused. Finally, media stream cannot be suddenly operated (e.g., back 5 min) [19]. This requires a new programming methodology to deal with.
- **Developing context-aware media applications need a bottom-up, decentralized approach**. Most existing context-aware systems are based on a top-down, centralized model where a central controlling entity facilitates and coordinates the functional operations of component devices. As technology advances, devices will be equipped with strong computation and communication capabilities. Therefore, the increasing capability of the component devices can be used to alleviate the role and load of the central controlling entity for achieving context-awareness.
- **Creating an infrastructure for rapidly building context-aware media applications necessitates a new manner to handling contexts.** Ubiquitous computing is characterized by transparent operation and reusability, which requires that applications should deal with contexts explicitly. Nevertheless, conventional schemes often hide context processing and thus cannot satisfy the requirement. Moreover, programming abstraction for context-aware applications is supposed to concentrate much on handling device heterogeneity, user mobility and asynchronous communication. To be specific, we enumerate some examples to reflect what should be paid great attention to: “what kind of abstraction is the best for context exchange among multi-organizational processes”, “how existing programming languages incorporate more aspects of contexts (e.g., annotation and metadata)”, “is it possible to set up a global share space for media service provisioning in

the cloud", and "when the message-passing programming paradigm rather than remote procedure call is used".

6.2 Context modeling

It is challenging to develop applicable and flexible ubiquitous media applications that covers various contexts in ubiquitous computing environment. Moreover, how to evaluate context models as good remains open. Ontologies have been recommended as the most expressive model based on six requirements in [64, 103]. However, these requirements are hard to evaluate, e.g., expressiveness and general rules. We share and extend the idea with [4] regarding context modeling.

- **Context model should at least contain context type and value information**. Meanwhile, it incorporates timestamp, source and confidence information of contexts as much as possible.
- **Context model may involve significant and compulsory parts**. These two parts play a significant role in reducing the complexity of removing context inconsistency, inference and resolution.

6.3 Context acquisition

The investigation in Section 4.2 shows that location is the most common context that are acquired by existing context-aware efforts. We consider two directions in context acquisition.

- **Acquiring news types of contexts that may enable applications to be more adaptive to changeable contexts**. Actually, there are a wide range of other types of contexts. Furthermore, exploiting new techniques that can capture more types of contexts to acquire contexts is a direction. These techniques keep evolving with the advance of communication, sensing and computation.
- **Gathering user's contexts from user behavior and communities is on the way.** This direction is not unique to context-awareness, and has been extensively researched in related disciplines (e.g., artificial intelligence, machine learning and software engineering). Given that sensors are easily error-prone, employing multiple sensors to monitor a specific object is attractive that may remarkably improve the accuracy of captured contexts. This also initiates non-trivial efforts on dynamically selecting sensors and intelligently fusing their readings.

6.4 Context reasoning

What will follow in context reasoning may fall into the change of manners in which it works, and the combination of exact and inexact reasoning techniques.

- **Large-scale context-aware applications (e.g., mobile transportation systems) require inferring contexts in a distributed manner**. Most context reasoning schemes rely on a central structure, which does not always hold in ubiquitous computing environment that is characterized by user movement and heterogeneous devices. Meanwhile, they are conducted on the limited scale of scenarios (e.g., smart rooms and labs).

- **Adaptive applications may benefit from the synthesis of exact and inexact reasoning**. Context-awareness includes exact, inexact or mixture requirements of context reasoning. To achieve adaptation, applications use or combine exact and inexact reasoning techniques correspondingly.

6.5 Context inconsistency detection and resolution

Owing to the noisy contexts, detecting and resolving context inconsistency is fundamental. It has drawn increasing attention in research community regarding two aspects.

- **Schemes for context inconsistency detection and resolution in a distributed manner are desirable for scenarios with user frequent movement and heterogeneous devices.** Most existing efforts work under an assumption that middleware or a central structure is available. As discussed in [20, 56], this assumption can not be always held, particularly in the peer-peer or urgent scenarios.
- **Incorporating semantics for checking context inconsistency and resolution may become a hot area**. The semantics of contexts refers to the information about specified objects. It helps ubiquitous media applications exactly understanding contexts and then make adaptation accordingly. Processing context semantics without ambiguity is challenging, but it is still a direction deserving to explore.

6.6 Runtime support

Section 5 shows that runtime support has been well-studied in the sensor layer and rarely discussed in the context layer. Given that many ubiquitous devices have limited communication and computation capabilities, runtime support should support context storage, task scheduling and process handling and concurrency.

Ubiquitous computing involves many nodes, which necessitates the efficient context exchange. Meanwhile, contexts keep evolving so that runtime should take context storage into consideration for rapidly context filtering and retrieving. Another possible direction is encapsulating runtime support into the cloud and hence users interact with systems with less involvement (e.g., no need to install and configure runtime support services). Note that we do not discuss the context security and privacy that is also a part of runtime support owing to its complexity and dynamics. For example, most security protocols fail in RFID devices because tags are seriously limited by communication and computation capabilities, and memory constraints. One way is to attaching access control to RFID-based systems [105].

7 Conclusion

Context-awareness in ubiquitous computing is an active research area, strongly driven by internal characteristics of ubiquitous computing. It makes ubiquitous media applications adaptive to the evolving contexts and to be intelligently tailored to user preferences.

In this paper, we have systematically investigated context-awareness in ubiquitous media. To identify key functionalities and services of context-awareness, we have proposed a reference framework from the systematic viewpoint—programming

abstraction, services and runtime support. We have further classified these into several sub-viewpoints. We extract functionalities from services as context modeling, preprocessing, reasoning, inconsistency and detection and resolution. Then, we have presented an overview of the state-of-the-art of existing context-awareness efforts by following the proposed reference model. Finally, we have identified possible challenging problems, and given detailed discussions on future research directions.

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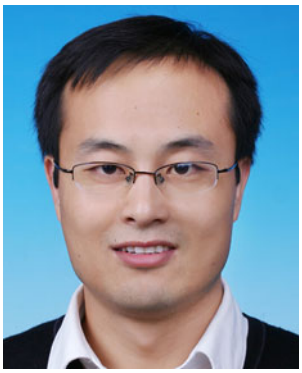

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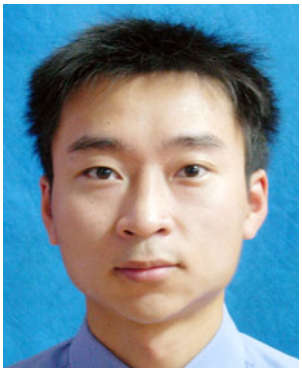

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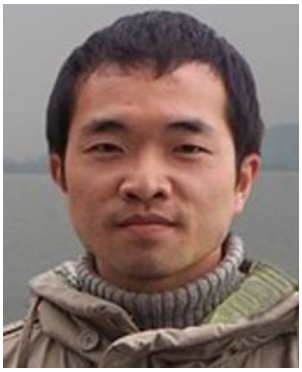

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