

# Context-based configuration management: state of the art and challenges

Ghislain Loaec \*

\* University of Burgundy

Submission Candidate

The fundamental objective of ubiquitous computing is to ease the human labor in computer use. This results in enhancing the resources available throughout the physical environment. In order to extract the maximum benefit of a digital environment, embedded systems and services must cooperate. Software failures due to configuration errors are commonplace as computer systems continue to grow larger and more complex. The primary challenge with context-handling interacting with humans, is that there is no standard, or reusable model that can be used to handle context.

Context-Aware | Configuration Management

Abbreviations: CAD, context-aware deployment; OMG, object management group; CCM, COBRA component model;

## 1 Introduction

Software configuration imposes a major cost on system administration. Configuration errors may result in security vulnerabilities, application crashes, severe disruptions in software functionality, unexpected changes in the UI, and incorrect program executions. Dealing with context seems to be a major challenge which the field of Artificial Intelligence (AI) will have to face in the next few years.

A context-aware system must be capable of mimicking a human's ability to recognise and exploit implicit information in the environment, in order to advance or correct the operations of its functionalities. This entails a dynamic configuration for every component of a context-aware system, in order to adjust its behavior depending on the situation. Although identifying and deducing a human activity is a challenge, it is critical that context-aware applications should operate by conveying the appropriate information to the right place at the right time through inferring the user's intention. Context-aware computing is a computing paradigm in which applications can discover and take advantage of contextual information such as location, time of day, people and devices, and user activity.

In this paper, we present common architecture principles of context-aware systems and derive a layered conceptual design framework to explain the different elements common to most context-aware architectures. Based on these design principles, we introduce various existing context-aware systems focusing on context-aware middleware and frameworks, which ease the configuration of context-based applications and services.

## 2 Background

Much debate has occurred and are still taking place about the meaning of both context and context aware computing. While most people tacitly understand what context is, they find it hard to elucidate.

... any information that can be used to characterize the situation of an entity. An entity is a person, place or object that is considered relevant to the interaction between a user and an application, including the user and the application themselves. [3]

This definition makes it easier for an application developer to enumerate the context for a given application scenario. If a piece of information can be used to characterize the situation of a participant in an interaction, then that information is context.

The Five Ws are questions whose answers are considered basic in information-gathering. They constitute a formula for getting the complete story on a subject. According to the principle of the Five Ws, a report can only be considered complete if it answers these questions starting with an interrogative word:

- **Who** is it about?
- **What** happened?
- **When** did it take place?
- **Where** did it take place?
- **Why** did it happen?

Each question should have a factual answer facts necessary to include for a report to be considered complete. Importantly, none of these questions can be answered with a simple "yes" or "no".

Context-aware computing : exploit the progress in sensing and mechanisms for observing the environment to systematically collect implicit context [2]

This context information can be formed into an abstract model of all actors in a system.

Context-aware computing was first defined by Schilit and Theimer as any system that "adapts according to its location of use, the collection of nearby people and objects, as well as changes over time" [30] Since then, there have been numerous attempts to define context-aware computing, most of which have been too specific

## 3 Context overview

Context is effective only when shared [37].

To ensure context is shared, context must first be gathered and managed by a context-aware system. This implies that the context-aware system must understand what context is before it can go on seeking and categorising this information.

**3.1 Classes of context.** Schilit et. al. propose the following classification of context information: [30]

- **Computing Context** - network connectivity, bandwidth, and nearby resources such as printers, displays, or workstations.
- **User Context** - the user's profile, location, nearby people, and current social situation.
- **Physical Context** - lighting, noise level, traffic conditions, temperature.

Each of these categories contains a wealth of information relevant to the context-aware system. They cannot however be used in isolation to full effect. The intention of the context-aware system is to gather and merge them together in order to achieve an overall picture of the situation. After the context is stored in a buffer or repository, the system will decide then what is relevant to the user at the present moment.

Context information may alternatively be subdivided into two categories: physical context and virtual context.

## Reserved for Publication Footnotes

### 3.1.1 Virtual context

The virtual context may include the version of the operating system, the interface capabilities, the wireless technology used to accomplish communication, email messages sent and received, and documents edited.

### 3.1.2 Physical context

The physical context on the other hand may be the presence of another entity, be it a user or device, the proximity to a particular printer, information indicating if the user is standing, walking or sitting or the current weather conditions. This entity can be summarized as any acquirable data by the use of a sensor : lighting, noise level, traffic conditions, temperature (cf. 3.6)

### 3.1.3 Historical context

The contexts stored across a time span. Considered to be useful but rarely used except for mobile applications. The system must decide what historical information is worthy of being kept. The evaluation the historical information is prohibitively costly and so requires very efficient algorithms

**3.2 Context information characteristics.** Researchers at the University of Queensland have classified four characteristics: [8]

#### 1. Context information exhibits a range of temporal characteristics

Context has already been subdivided into physical and virtual environment ; it can be furthermore categorized into :

- Static information : any information related to the user's environment that is invariant.
- Dynamic information : must be accumulated continuously, frequently and automatically.

Additionally, past context information may be needed to understand the full state of the environment

#### 2. Context information is imperfect

This considers the validity of context, in particular dynamic context information. The speed at which the context information changes raises reasons for the doubt over the soundness of the context. This "delay between the production and use of context information" [8] is a concern. Other sources of concern regarding the soundness of context information include the reliability of information from the context producers : sensor failure, broken path between producers or any source that would provide wrong or outdated information.

#### 3. Information has many alternative representations

The raw data gathered from both physical and virtual environment can take on many forms and must be processed when combined with other context informations. The probability of the context-aware system obtaining a 100% success rate in "capturing the relationships that exist between the alternative representations" [8] of the context information and the one apt to the current situation is extremely low.

#### 4. Context information is highly interrelated

Context information derived from a particular origin may have a very close link with its source, so much so that it is dependant on the origin. Context may not be reliable where the characteristics of the derived information are intimately linked to the properties of the information it is derived from [8].

**3.3 Context-aware system.** A system is context-aware if it uses context to provide relevant information and/or services to the user, where relevancy depends on the users task. Context-aware systems can be implemented in many ways, but in order to accomplish this objective, the context aware system generally must :

- Gather the information
- Serialize this information
- Merge the information to generate higher context
- Automatically take action based on the retrieved information

- Make the information available to the user, immediately, in the future, or when it is required to enhance and aid in the completion of the user's task.

The researchers of the Context Toolkit at the University of Berkeley propose that there are three features that a context-aware application must support: [13]

1. Presentation of information and services to a user
2. Automatic execution of a service for a user
3. Tagging of context to information to support later retrieval

The developers of Kimura System have designed distributed components of a pervasive context-aware system. These components fall into three classes [36], these are:

1. Context Acquisition - the system gathers context information and adds it to a repository.
2. Context Interpretation - the system converts the gathered context information into a working context.
3. User Interaction, the system displays the working context to the user

**3.4 Gathering context information.** Some context information is explicitly given to the system, such as user's name, age, email, environment variables or registry. Other primitive physical information such as light, heat, pressure readings can be acquired through the use of sensors

Location and identity are the most frequently sensed pieces of context.

Sensors are not always 100% accurate or reliable, particularly if they are disposable. The information gathering system must be tolerant of sensor failure, and any information gathered from sensors must be subjected to sanity checks to help verify its correctness. Sensor fusion is one method of avoiding this difficulty [31]

Let's take for instance a power plant, with several sensors which gives the context information of temperature. The system must take some decision whether to cool generously the reactor or not. The consequences of an underestimation of the temperature would be catastrophic. It might be prudent either to simply average the results and discard reported values that differ too greatly from what other sensors report. This method would avoid drastic measures being taken by the context system to correct what it considers to be temperature variations but are actually simply the result of sensor failure.

### 3.5 Retrieving context information.

- Push Model - The context source gathers the context information before it is needed. It gives better performances but requires large and frequent resource consumption for some information that may never be exploited.
- Pull Model - Collects only the context information that is required. It allows to get the information on demand but is exposed to network delays and services unavailability

The method of context-data acquisition is very important when designing context-aware systems because it predefines the architectural style of the system at least to some extent. Chen (2003) [9] presents three different approaches on how to acquire contextual information.

#### 3.5.1 Direct sensor access

This approach is often used in devices with sensors locally built in. The client software gathers the desired information directly from these sensors, i.e., there is no additional layer for gaining and processing sensor data. Drivers for the sensors are hardwired into the application, so this tightly coupled method is usable only in rare cases. Therefore, it is not suited for distributed systems.

### 3.5.2 Middleware infrastructure

The middleware based approach introduces a layered architecture to context-aware systems with the intention of hiding low-level sensing details. This approach is equivalent to client-server model, more flexible the widget since it promotes the independence of each components in the context-aware system. Every component must be able to perform the following functionalities : establishing connections, organising input and output messages and managing faults. This model is significantly more complex but the approach is pretty straightforward since it supports large range of device and application using standard coding and networking protocols.

### 3.5.3 Context server

This distributed approach extends the middleware based architecture by introducing an access managing remote component. Gathering sensor data is moved to this so-called context server to facilitate concurrent multiple access

**3.6 Architectures for Managing Context.** Winograd (2001) [37] describes three different context management models for coordinating multiple processes and components:

- **Widgets** The key objective of the widget is to separate the application from the context acquisition issues in order to abstract the complexity of collecting and managing the context information. The widget is used as a mediator to pass only the pertinent information to the application, A context widget functions independently of applications, which permits multiple applications to use it simultaneously. A context widget is also responsible for maintaining a complete history of the context acquired for the user's situation. It remains the most prevalent model.
- **Network services** This more flexible approach, argued for example in Hong and Landay (2001) [21], resembles the context server architecture. Instead of a global widget manager discovery techniques are used to find networked services. This service based approach is not as efficient as a widget architecture due to complex network based components but provides robustness.
- **Blackboard** In contrast to the process-centric view of the widget and the service-oriented model, the blackboard model represents a data-centric view The blackboard model adopts a data-centric point of view, matching a specified patterns in data. In this asymmetric approach processes post messages to a shared media, the so-called blackboard, and subscribe to it to be notified when some specified event occurs. Advantages of this model are the simplicity of adding new context sources and the easy configuration.

#### 3.6.1 Trade-off criteria

When deciding on the most suitable model for a context aware system, we want to consider the trade-off characteristics :

- **Efficiency** : accelerate the throughput of information considering the the bandwidth and latency caused by the explosion in the number of networked applications and devices.
- **Effort in configuring** : considering te various amount of components, perform a change in the configuration state, without the disruption or total failure of the system, it not a tedious task. This model must make sure the edit is safe.
- **Robustness** : the degree to which the system can cope with failure
- **Simplicity** :

a system that requires complex understanding by system builders in order to make use of its facilities will be used only by those who have the dedication and motivation to master it. [37]

- **Extensibility** :

services supporting a general notion of context must be easily extensible to accommodate new and unanticipated sources of context information. [18]

The trade-offs can be used to compare and contrast the different models for context management.

The widget model has tight coupling of system components, which may make it the most efficient model in some circumstances, however it suffers from complex configuration and issues with powerlessness in the cause of failure. The infrastructure model with its independent components may be extremely complex, which is a no factor for many developers, however its positive criteria of straightforward configuration and robustness may compensate for the negative implication of complexity. Finally the blackboard model with its very loosely coupled components may suffer from efficiency problems, but it is a simple, robust, easily configurable model. [37]

**3.7 Representing Context.** There are several ways to modelize context information :

- **Key-Value** : simplest data structure for context modelling. They are frequently used in various service frameworks, where the key-value pairs are used to describe the capabilities of a service
- **Markup scheme** : hierarchical data structure consisting of markup tags with attributes and content. Profiles represent typical markup-scheme models.
- **Graphical** : Unified Modelling Language (UML), extension to the Object-Role Modelling (ORM) by context
- **Object oriented** : use the full power of object orientation (e.g., encapsulation, reusability, inheritance). Existing approaches use various objects to represent different context types (such as temperature, location, etc.), and encapsulate the details of context processing and representation
- **Logic based** : high degree of formality. Typically, facts, expressions and rules are used to define a context model. A logic based system is then used to manage the aforementioned
- **Ontology based** : represent a description of the concepts and relationships. very promising instrument for modelling contextual information due to their high and formal expressiveness and the possibilities for applying ontology reasoning techniques

Conclusion of the evaluation presented in Strang and Linnhoff-Popien [34], based on six requirements, show that ontologies are the most expressive models and fulfil most of their requirements.

Korpić et al. [25] present some requirements and goals having designed a context ontology:

- **Simplicity**: the used expressions and relations should be as simple as possible to simplify the work of applications developers
- **Flexibility and extensibility**: the ontology should support the simple addition of new context elements and relations
- **Genericity**: the ontology should not be limited to special kind of context atoms but rather support different types of context
- **Expressiveness**: the ontology should allow to describe as much context states as possible in arbitrary detail.

A single context atom can be described with a couple of attributes. The two most obvious are:

- **Context type** : category of context such temperature, time, speed, etc. This type information may be used as a parameter for a context query or a subscription.
- **Context value** : raw data gathered by a sensor. The unit depends on the context type and the applied sensor, e.g., degree Celsius, miles per hour, MegaByte etc.

Context type and context value are not enough information to build a working context-aware system. Additional attributes that might be useful include:

- **Time stamp** : date/time-value describing when the context was sensed. It is needed e.g., to create a context history and deal with sensing conflicts.
- **Source** : how the information was gathered. In case of a hardware sensor it might hold the ID of the sensor and allow an application to prefer data from this sensor.
- **Confidence** : the uncertainty of this context type. Not every data source delivers accurate information, e.g., location data suffers inaccuracy depending on the used tracking tool

### 3.8 Interpreting the context.

Interpretation refers to the the process of raising the level of abstraction of a piece of context [14]

After sensing, acquiring and saving the context from various sources the next activity for the context-aware system is to produce a mechanism for achieving context interpretation, so that the gathered context information is utilised in a fitting manner. The interpretation may involve integrating numerous contexts into one to provide a higher-level context, thus the interpreter alters context information by raising its level of abstraction. One approach is to use context fusion to convert the lower level context into higher level usable by applications. [17]

### 3.9 Layered conceptual framework.

- Application
- Storage management
- Preprocessing :
  - Translation : not implemented in every context-aware system but may offer useful information if the raw data are too coarse grained. The preprocessing layer is responsible for reasoning and interpreting contextual information
  - Aggregation / Composition : consisting of several different context data sources, the single context atoms can be combined to high-level information in this layer
- Raw data retrieval : appropriate drivers for physical sensors and APIs for virtual and logical sensors. The query functionality is often implemented in reusable software components which make low-level details of hardware access transparent by providing more abstract methods such as `getPosition()`.
- Sensors :
  - Physical sensors : hardware sensor to capture physical data
    - \* Light
    - \* Visual context
    - \* Audio
    - \* Motion / acceleration
    - \* Location
    - \* Touch
    - \* Temperature
    - \* Physical Attributes
  - Virtual sensors : source context data from software applications or services tracking systems, electronic calendar, travel booking system, mouse movement, etc.
  - Logical sensors : physical + virtual + additional information from databases in order to solve higher tasks

### 3.10 Security and Privacy.

Privacy is intrinsically bound up with control [4]

As context may include sensitive information on people, e.g., their location and their activity, it is necessary to have the opportunity to protect privacy. Context-aware systems raise privacy challenges not previously considered by traditional systems. The control of the various sensors and services is not well specified in Dey et al. [14], although often applications such as Context Toolkit are implied to be under the control of a "user". Users are assigned to sensed context data as their respective owners. They are allowed to control the other users access.

However, the control over systems determining the presence of individuals in a room or other location, on the other hand, is not specified at all. This is a critical point.

In general, in a context aware environment with a suite of context aware applications, an individual operates within many social environments, and social environments may make a use of many individuals' data.

Often disregarded aspects, security and privacy belong to the most important components of a context-aware system as the protection of sensitive context data must be guaranteed.

## 4 Existent systems and frameworks

In Table 1 we have summarised the main aspects of the discussed approaches. The architectural style of a context-aware system is mainly driven by the context acquisition method. The main criteria for a reasonable architectural approach is the separation of concerns between the context acquisition and the user components as proposed by Dey (2000) [13]. All the frameworks presented in this paper support this separation of concerns.

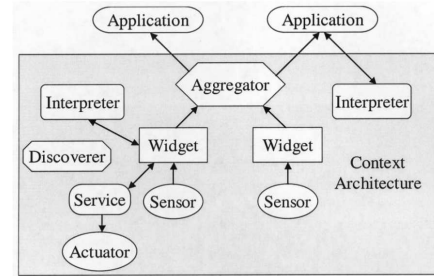


Fig. 1. Example configuration of context toolkit components

**4.1 Sensing technologies.** In every framework, the sensing technology is implemented differently. In order to support the aforementioned separation of concerns, it is important to encapsulate the concrete sensing mechanism in separate components. Furthermore, it allows to access the contextual data via defined interfaces. There is so far no standard description language or ontology to enable the reuse of contextual information across various middleware systems and frameworks. Therefore, proprietary solutions have emerged, as used by many frameworks. For sensing the context information SOCAM has the most sophisticated approach : web services provide apis (using SOAP) for external virtual sensors and internal providers for querying sensors are consumed by using context events. Those context events are modeled in OWL based on a predefined ontology.

**4.2 Context representations.** For providing intelligent and adaptable context-aware applications or services, the context model and the context processing logic supported by individual frameworks is a major criteria. Ontologies provide a rich formalism for representing context information. Based on a highly sophisticated ontological model, the reasoning engines can derive new concepts to adapt the service behaviour accordingly. The key-value context representation used in Context Toolkit is, therefore, a major drawback. The fact that such attributes do not hold any semantics restricts consequently the development of intelligent context processing and aggregation. In addition, non-ontology based model requires a consequent programming effort and tightly couples the context model to the rest of the system. Moreover, the reasoning and knowledge sharing across systems are impossible due to the lack of declarative semantics of programs. SOCAM, for instance, uses a general upper ontology to specify basic common contextual properties and to refine this general ontology. In order to provide very fine grained possibilities for specifying and formalising context, some domain-specific ontologies can be defined.

**4.3 Resource discovery.** Resource discovery mechanisms are rarely implemented despite the importance of such dynamic mechanisms, especially in a pervasive environment, where the context sources and available sensors change constantly. SOCAM is the only system based the service oriented architecture. It offers a service locating service, which dynamically binds to available context providers. This missing feature in most frameworks is indeed a consequent shortcoming since it implies that the used context sources are stable and permanently available, which is not always the case in real-world applications. If one or more context sources behave wrong, it may lead to a decreased availability of the context-aware service or application.

Architecture	Sensing	Context model	Context processing	Resource discovery	Historical Context data	Security and privacy	
CASS	Centralized Middleware	Sensor nodes	Relational data model	Inference engine and knowledge base	n.a.	Available	n.a.
Cobra	Agent based	Context acquisition module	Ontologies (OWL)	Inference engine and knowledge base	n.a.	Available	Rei policy language
Context Management Framework	Blackboard based	Resource servers	Ontologies (RDF)	Context recognition service	Resource servers + subscription mechanism Discoverer component	n.a	n.a.
Context toolkit	Widget based	Context widgets	Attribute-value tuples	Context interpretation and aggregation		Available	Context ownership
CORTEX	Sentient object model	Context component framework	Relational data model	Service discovery framework	Resource management component framework	Available	n.a.
Gaia	MVC (extended)	Context providers	4-ary predicates (DAML + OIL)	Context-service module (first-order logic)	Discovery service	Available	Supported (e.g., secure tracking, location privacy, access control)
Hydrogen	Three layered architecture	Adapters for various context types	Object-oriented	Interpretation and aggregation of raw data only	n.a.	n.a.	n.a.
SOCAM	Distributed with centralized server	Context providers	Ontologies (OWL)	Context reasoning engine	Service locating service	Available	n.a.

**4.4 Historical context management.** Although most frameworks keep a history of context data, none of them actually exploits it. Yet, It could allow to provide highly adaptable context-aware services if historical context was used to implement self-learning algorithms. Furthermore, contextual information can be predicted to proactively provide a certain set of services to the user.

**4.5 Security and privacy.** Another important aspect is security and privacy. Contextual information mostly considers user profile information and other sensitive information. Therefore, concepts are needed to express policies and to define ownership of context information. CoBrA includes an own flexible policy language to control context access, called Rei [23]. This policy language is modelled on deontic concepts of rights, prohibitions, obligations and dispensations and controls data access through dynamically modifiable domain dependent policy rules. Gaia uses several mechanisms to define privacy restrictions and secure communication for tracking locations of people. The Context Toolkit implements the concept of context ownership, which is used to allow access to the context to the owner only. Security concepts are not implemented in the other frameworks. Many systems totally lack security modules, others offer basic security mechanisms and only a few systems provide advanced and sufficient security options.

**4.6 Conclusion.** Every system and framework uses its own format to describe context and its own communications mechanisms which appears to be the main problem of today's context-aware systems.

## 5 Research directions and challenges

In this paper we described different design principles and context models for context-aware systems and presented various existent

middleware and server-based approaches to ease the configuration of context-aware application.

There are several research areas involved in the development of context-based configuration. Here are three of the most relevant :

**5.1 Middleware and implementation details.** The need for new middleware arises on the implementation side. Current middleware technologies are not adequate to handle the restrictions imposed by mobility and smart environmental systems : volatile connections, processing and memory restrictions on mobile devices, narrow communication channels, reduced screens, restricted input mechanisms, and the list goes on. There are a set of context-aware implementations in litterature with some working prototypes :

- **Hydrogen** [20]: a three layer architecture
- **Gaia** [10]: another middleware infrastructure, extends typical operating system concepts to include context-awareness.
- **CybreMinder** [2]: a context-aware system for sup- porting reminders
- **Context Toolkit** [14]: a widget based architecture

**5.2 Representation of context-information.** The representation of context-information is another concern. We presented in this paper a generic ontology approach. It is based on four main concepts: user, environment, platform and resources. Presently, ontologies are mainly employed to enable communication across the different devices in the same network. As proposed by ContextUML [33], the Unified Modeling Language (UML) can also be used to model context. The models could be used to separate the definition and information related to the context from the specific implementation. There are other characteristics that make context information difficult to model, as stated before, it is sometimes necessary to differentiate between static and dynamic information.

**5.3 Semantic rules.** Another area of research would be concerning use of rules to express behavior in terms of high-level elements. Rule languages are used in some cases to achieve context-awareness. CRIME [26] for example, is a prototypical implementation of the Fact Space Model, which is a coordination language that provides the applications a view of their environment. The rules in CRIME describe the behavior of the applications according to the context information. CRIME also deals with disconnection by invalidating the facts and the conclusions that are drawn from devices that are no longer available in the environment

## 6 Conclusion and discussion

Component technologies will play a fundamental role in the next generation computer systems as the complexity of software and the diversity and pervasiveness of computing devices increase. However, component technologies must offer mechanisms for automatic management of inter-component dependencies and component-to-resource dependencies. Otherwise, the development of component-based systems will continue to be difficult and frequently lead to unreliable and non-robust systems.

Future ubiquitous computing environments will be composed of thousands of devices running millions of software components. Current systems rely heavily on manual configuration but with a system composed of millions of components this will no longer be possible. There are only two ways out of this situation: static configuration or dynamic, automatic configuration

Since future environments tend to be more and more dynamic, automatic configuration seems to be the only viable solution.

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## Appendix: Glossary

- CAdComp : Context-aware deployment of component-based applications
- CaSS : Context-Awareness Sub-Structure
- CoBrA : Context Broker Architecture
- SOCAM : Service-Oriented Context-Aware Middleware

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