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Engineering Context-Aware Systems and Applications: A survey

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Abstract

Context-awareness is an essential component of areas like Intelligent Environments, Pervasive & Ubiquitous Computing and Ambient Intelligence. In these emerging fields, there is a need for computerized systems to have a higher understanding of the situations in which to provide services or functionalities, to adapt accordingly. The difficulties that developing a context-aware system entails, drive researchers to modify already existing engineering methods or explore new ones in order to give a better response to the needs that they have. This reveals the need of a specialized development process for context-aware systems. We analyse the efforts of the community in order to encourage a Context-Aware Systems Engineering process, focusing on: (A) The state-of-the-art engineering techniques applied in the most common development stages; (B) Analysis of existing methodologies within these development stages; (C) The main challenges that are still open in the context-aware computing field.

Keywords: Context-Aware Systems Engineering, Context-Aware Computing, Context-awareness, Context-sensitive, Sentient Computing, Pervasive & Ubiquitous Computing, Intelligent Environments, Ambient Intelligence, Software Engineering, Systems Engineering.

1. Introduction

The miniaturization process of electronics has made a wide range of small devices available with sensing and computing capabilities, taking the computational paradigm out of the desktop. This has opened up new possibilities for interacting with technologies and bringing them closer to people's daily life experiences. The vision of Mark Weiser [1], predicted a trend where computers will disappear by becoming embedded in our daily lives. His view has influenced research in areas such as Pervasive & Ubiquitous Computing, Intelligent Environments or Ambient Intelligence. The common feature to these emerging fields is their need to know about the context in which they are functioning. Such feature, allows the system to understand the situations in which the user expects services delivered and in which way. Context-aware computing is a young field that aims at making computational devices capable to easily interpret both explicit and relevant implicit information during its execution. The primary aspiration is to serve users with minimal effort on their part, enhancing the usability of the systems and enabling a better human-computer interaction. Nevertheless, it is easy to have a gap between expectations on these systems and their real abilities [2]. The difficulties in its development make many of these systems remain as prototypes in

laboratories. There is a significant contrast between the development needs of systems with contextual awareness, compared to the traditional ones. In order to better fit these needs, the traditional development techniques and methods are constantly being modified in the literature, what reveals a need of a different engineering process. The appropriate development methods and tools can be the key to successfully achieving a way out from laboratories, reaching the general public. The aim of this survey is to provide a bit more understanding on the basis for engineering C-AS, reviewing the associated techniques and tools to support its development, analysing existing methods for engineering them and studying its open challenges. The intention of this work is not to provide a whole new engineering process, however, we hope the findings of this article may encourage and inform such future steps within our community. This work is based on a literature review and the results of a questionnaire carried out to a total of 750 researchers¹. The remainder of this paper is as follows: *Section 2* presents the main challenges in the development of C-AS, shedding light on the conceptualization and understanding of these systems. In *Section 3* the main engineering methods are analysed for each

¹From which almost the 5% answered during the period between 12th Sept. 2014 and 11th Oct. 2014. The participants were selected from seven conference proceedings between 2011 and 2014: CONTEXT 2011/2013, Aml 2011/2012/2013, IE 2011/2012/2013/2014, UbiComp 2011/2012/2013, Pervasive 2011/2012, IoT 2012, ICCASA 2012/2013. From these, 280 papers were selected as potentially containing researchers with some experience in context-aware computing. A list of 750 non-repeated emails was gathered from the papers and used for contacting the contestants.

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of the most common stages of a system development process. Then, several methodologies are reviewed in *Section 4*, comparing their methods and tools. We conclude in *Section 5*, suggesting new directions for context-aware computing.

2. Main challenges and concepts in Context-Aware Systems development

The aim of this section is to understand the main challenges that a developer has to face when creating a C-AS. First, we explain the conceptual challenges behind the development of these kind of systems. With these in mind, we try to shed a bit of light on their conceptualization. For this, we analyse the different ways of interacting with C-AS as well as the features of these systems. Second, we analyse the technological requirements of C-AS, to better understand the challenges of its development. For illustration purposes, two examples will be used through the explanations. For the first subsection, we will imagine a context-aware smart-phone that is able to detect when is intruding into social situations in order to avoid unnecessary interruptions [2]. For the second subsection, we will use the following example: *Jack has just arrived at a bus stop. At the moment, Jack's cellular phone rings alarm sound with displaying the following message: "Waiting time info: circulation shuttle bus arrives in 10 min. commuter bus arrives in 5 min"* [3].

2.1. Concepts and conceptual challenges

Many multi-disciplinary areas use context to enhance their possibilities. Each area understands the notion as a reflection of its own concerns, making it difficult to define and categorize [4] [5]. In the literature, several definitions can be found [6] [4] [7] [8] [9] [10] [5]. A detailed comparison between the differences and similarities of these is out the scope of this survey. Nevertheless, it has to be acknowledged that there is no consensus on the definition of context. Also, we highlight that Dey's [11] is the most acknowledged one, considering it as "*any information that can be used to characterize the situation of an entity*", where "*an entity can be a person, place, or object that is considered relevant to the interaction between a user and an application, including the user and applications themselves*". They also defined a system as context aware if "*it uses context to provide relevant information and/or services to the user, where relevancy depends on the user's task*". Independently from its definition, the adjective "context-aware" is generally used in the literature to describe any type of system that is able to use context. Nevertheless, the process of embedding contextual awareness can be dramatically different if it has to be done, for example: In a smart-phone application, a robot, a ubiquitous system or a web application [12], a context-aware animal species recognition [13], or an adaptive e-book [14], etc. What it has to be understood, is that context-awareness is a feature added on top of an existing system or functionality. By understanding this, the reader will also comprehend that the implementation of a contextual feature depends intrinsically on the system where it is going to be implemented. Let us take the

example of the context-aware smart-phone that is able to detect when is intruding into social situations in order to avoid unnecessary interruptions. In this case, the features will be developed on top of the phone, its operating system, and its application to make calls. This fact turns the system into a very ad-hoc solution. The main problem of being so specific, is that the amount of work employed to develop it will be difficult to reuse, even for developing the same context-aware smart-phone for a different operating system. So, there are two main issues conceptualizing context-awareness for development purposes: A) High contrast between systems considered as "*context-aware*" and the way they are developed; B) Since context-awareness definition depends on context, and since there is no agreement on what context is, it is difficult to define and conceptualize what a C-AS is.

2.1.1. Deeper Awareness: Human activity and behaviour

Although primitive C-AS can be relatively easy developed (e.g., weather display depending on user location), there is much more potential in applications involving deeper context consciousness. For this purpose, machines need to better understand context in human activity and behaviour. Nevertheless, the difficulty of developing C-AS grows exponentially with regards to the depth of the contextual awareness to be embedded. Generally, the attempts to create models of people in order to understand what the person is trying to do fail, due to the complexity of how human actions are determined by contextual factors [15]. Some theories try to explain the context in human activity and behaviour. Following, we briefly analyse some of them:

Situated Action: Suchman [16] acknowledged that computer artefacts are build relying on an underlying conception, based on the planning model of human action. She introduces the Situated Action, an alternative in which it is analysed how people find meaning in actions or how should they construct it. Instead of producing formal models of knowledge and action, she proposes exploring the relationship of knowledge and action to the particular circumstances in which they occur. The unit of analysis of Situated Action is not the individual, not the environment, but a relation between the two [17].

Activity Theory: Claims that context is defined by the activity itself. "*Activity comprises a subject (the person or group doing the activity), an object (the need or desire that motivates the activity), and operations (the way an activity is carried out)*". *Artefacts and environment are seen as entities that mediate activity*" [18]. The unit of analysis of this theory is an activity [17].

Distributed Cognition: Takes into account the representation of knowledge both inside the heads of individuals and in the world [19]. The system is not considered relative to an individual but to a distributed collection of interacting people and artefacts [17]. Hence, the unit of analysis in this theory is the whole system, centring in its functionality and understanding the coordination among individuals and artefacts [17].

The Locales Framework: Tries to understand the nature of social activity and work, and how *locale* can support these activities [18]. Locales are considered as a social worlds that apporportion and use particular locations and means for accomplish work. These, are abstract, and do not necessarily need to have a fixed meaning or be associated to a physical space.

Ethnomethodology: Focuses on the way people make sense to their everyday world, capturing a range of phenomena associated with the use of mundane knowledge and reasoning procedures.

Initially, the reader could think that embedding a deeper contextual awareness into systems is just a matter of understanding the context through one of these theories and then programming the resultant model. But the fact is that these theories work in a different manner. They all share an understanding of social facts as having no objective reality beyond the ability of individuals and groups to reorganise and orient towards them. Conversely, the developers of C-AS will naturally seek to reduce complex observable phenomena to essences or simplified models that capture underlying patterns, abstracted from the detail of particular occasions. These models, try to seek an objective reality in social facts, entering in conflict with the foundations of most theories in social analysis, which are incompatible with the idea of a stable external world which is unproblematically recognized by all. This issue, was recognised by Dourish [7]. He acknowledged that the problem comes from the overlapping of two philosophical traditions behind the understanding of context: Positivism and phenomenology. Context-aware computing stems from computer science, that derives from the rational, empirical and scientific tradition of positivism. On the other hand, phenomenology, is the background behind many of the theories to explain context in complex human behaviour and activity. The incompatibilities between these standpoints help to explain what are the limitations that exist when developing C-AS, as it is further described in the next subsection.

2.1.2. The limits of Context-Aware Systems

As mentioned before, there is no consensus on the definition of context. Once that the reader is aware that there are tensions between two incompatible philosophical backgrounds, s/he can start to understand why is so difficult to find an agreement on the definition of context. In what regards to its conceptualization, positivism looks at context as a representational problem, considering it as a “*form of information, delineable, stable and separable from activity*” [7]. The definitions made in the context-aware field, naturally adopt this point of view. For instance, Dey’s definition [11] allows designers to use the concept for determining why a situation occurs and use this to encode some action in the application [20], making the concept operational in terms of the actors and information sources [18]. Nevertheless, since the definition inherently has a positivist view, the potential of C-AS remains limited to the context that developers are able to encode and foresee. Let us retake the example of the context-aware phone that is able to silence itself at certain situations. For instance, let

us imagine that developers want to detect that the user is at the cinema. For this task, they can use the built-in sensors of the phone to detect luminosity, location, motionlessness and ambient sound. Then, they can program a rule to silence the phone whenever the sensors indicate certain values. In this way, the phone can detect when the user is at the cinema, but for detecting a completely different situation, the values of the sensors that will silence the phone (or even the sensors used) could be completely different. The problem of having to program computers, is that developers must know beforehand the context that they need to program. But they might not be able to foresee, or they just can not make the system infer some situations. The user might be at a job interview, s/he might be sleeping when some irrelevant notifications or calls arrive, the user could be in the middle of a wedding, a funeral, a trial, having a very important conversation, in the library, etc. The list of unforeseen or undetectable situations can be endless. Besides, some situations can be specific issues of one user, may not be useful enough to carry the effort of implementing them or may just happen once in the whole system life-cycle. Summarizing, if developers can not determine all that can be affected by an action, it will be very difficult to write a closed and comprehensive set of actions to take in those cases. There are three tasks that a developer may find difficult, or even impossible, when developing a C-AS under this perspective [18]: (A) Enumerate the set of contextual states that may exist; (B) Know what information could accurately determine a contextual state within that set; (C) State what appropriate action should be taken from a particular state.

On the other hand, phenomenology interprets context in a different way, recognizing it as an interactional problem and considering that: “(I) Context is particular to each occasion of activity or action; (II) The scope of contextual features is defined dynamically; (III) Context may or may be not relevant to some particular activity; (IV) Context arises from activity, being actively produced, maintained an enacted.” [7]. In this approach, the context can only be understood as the situation arises. Then, there is no need to unearth the underlying models that will describe the objective reality behind context, alleviating developers from the task of having to foresee it. For making this possible, there is a need to make machines exhibit human-like cognitive skills [21]. The idea is to extract the mathematical model of a brain, imitate it in a computer, and train it to satisfy the user needs. But is important to have a clear vision over what contemporaneous computerized systems can do. The contextual awareness of machines is from a radically different nature than the one of humans. Besides, computational systems are good at gathering and aggregating data, but in what regards to context-awareness, humans are still better at recognizing contexts and determining what action is appropriate in a certain situation [2]. It has to be mentioned that here has been a long debate about the feasibility of computational systems mimicking human-like intelligence since the early origins of artificial intelligence [22] [23] [24] [25] [26]. Although it is not the purpose of this survey to analyse in depth these theories and argue about

them, we would like to stress that they acknowledge some issues that artificial intelligence and context-aware computing have not been able to solve yet. For example, the limitation of computers to acquire expertise in the same degree and areas as humans, due to their different form of embodiment [23]. Also, the phenomenological perspective on context naturally gives rise to unpredictability. If the behaviour of the system can not be predicted, it can not be relied. So, a C-AS able to mimic human-like context consciousness, is intrinsically in conflict with the essence of computer science, that supports the creation of reliable systems, according to verifiable and well-defined specifications.

As explained, the development of C-AS is inherently in conflict with two opposite paradigms. Due to the limitations in both approaches, the near future of C-AS development can not be seen directly towards creating systems that exhibit human-like contextual awareness, nor to directly programming them on the basis of foreseen context. The creation of C-AS in the near future, comes through a combination of the current advances in both approaches, providing a higher cooperation between humans and computers and making the most of each others qualities. The demand of relating the needs and preferences of the users to the services of a system, becomes marked when it comes to set them up with contextual awareness. Contexts are closely related to the services that the system wants to provide, and these always involve people. In some cases it may involve robots or agents, but behind them there is always people as stakeholders of a system. Therefore, it will be more likely to create C-AS that meet the demands of users, if their opinion and preferences are taken into account, not only during the development, but during the whole life-cycle of the system.

2.1.3. Interacting with a Context-Aware System

The limitations explained in the previous subsection also influence the way in which systems interact with users. Inspired in the human-like contextual awareness, C-AS were originally intended to monitor the context and then act accordingly without any human mediation. The aim of being autonomous is to reduce the user intervention, easing the use of the system and decreasing user distraction [27]. As discussed in the previous section, humans are fitted with better contextual understanding capabilities. So, when a system takes away the control from the user due to a misinterpretation of the context, in situations where the user has a better understanding of what is happening, the user can reject the system and stop using it. In order to alleviate this problem, other viewpoints propose to change the autonomy of C-AS, enabling the users to have more control over the actions of the system. Let us retake the example of the smart-phone that is able to silence itself autonomously. Instead of letting the phone itself decide when to silence, a machine could answer when someone is calling [2]: “Lee has been motionless in a dim place with a high ambient of sound for the last 45 minutes. Continue with the call or leave a message?”. In this way, the higher understanding of context that humans naturally have, can be used to make the decisions about the actions of the system depending on the

situation. As the reader can observe, there are different ways to interact with C-AS. Barkhuus et al. [28] classified them into: A) Personalization, in which the users are able to set their preferences, likes and expectations to the system manually [5]; B) Passive context-awareness, where the system is constantly monitoring the environment and offers choices to the users in order to take actions; C) Active context-awareness, where the system is continuously monitoring the environment and acts autonomously.

We have classified the interaction with C-AS taking into two different dimensions: Execution and configuration. The first one, encompasses the involvement of the user in the system actions as the situation arises. The second one is related with the entanglement of the user for personalizing and adjusting the behaviour of the C-AS after the implementation of the system. Both dimensions can have different degrees of autonomy in between: I) Active, where the system changes its content autonomously; II) Passive, where the user has explicit involvement in the actions taken by the system. Following, we analyse them more in depth:

Active Execution: Systems that act autonomously, on the basis of pre-programmed rules, when a certain context is detected. For example, the screen of a smart-phone can switch from landscape to portrait automatically, depending on the values of the accelerometer. The heater in a smart-house can be autonomously switched on and off when the values of a thermometer sensor reach certain values. In this approach the vision of self-adaptive systems is paramount, which are able to adjust their behaviour in response to their perception of the environment and the system itself [29] [30]. Mizouni et al. [31] presented a framework for context-aware self-adaptive mobile applications using the advantages of the software product line feature modelling to manage variability. Projects such as MUSIC [32] [33] [34], also support the development of self-adaptive systems in ubiquitous environments.

Passive Execution: These, let the user specify how the application should change [35]. The user makes the decision as the situation arises by using the information provided by the system. For example, by displaying the current context, presenting the available services in a certain situation or asking for permission to take an action. Dey and Newberger [36] encourage the use of intelligibility features to let the user control the system. Those techniques can help expose the inner workings and inputs of context-aware applications that tend to be opaque to users due to their implicit sensing and actions [37]. It allows to understand how a context-aware application is working or behaving by showing it and can be used to allow a better user control. Lim and Dey [38], present the intelligibility toolkit to give support for context-aware applications. They facilitate developers to obtain eight types of explanations from the most popular decision models of context-aware applications.

Active Configuration: In this interaction mode, the system is able to learn from the user preferences in order to autonomously evolve his rules for future behaviour, after the system is implemented. Mori and Inverardi [39] [40] present a software life-cycle process for context-aware adaptive systems, where they characterize context by foreseen and unforeseen variations. In the first case the system evolves in order to keep satisfied a fixed set of requirements while in the second one the system evolves in order to respond to requirements variations that are unknown at design-time. In a further work [41], they focus on a decision support mechanism for simultaneous adaptation to system execution context and user preferences. Aztiria et al. [42] introduce a system which is able to discover patterns in the user actions to learn their frequent behaviour when interacting with Intelligent Environments. In a further work, the system has been aimed for the automated generation of context-aware reasoning rules [43].

Passive Configuration: In this approach, the user is involved in the manual personalization of his preferences, likes, and expectations of the system, after its implementation. The users, acting as non-professional developers, can create, modify, or extend existing context-aware artefacts [44]. Dey et al. [45] proposed *iCap*, a system that is the intermediate layer between low level tool-kits and users. They also present a specific solution [46] for user control, based on their Context Toolkit [47]. Guo et al. [48] present a meta-design approach to an Ubiquitous Computing management system that enables software co-design and knowledge sharing named *iPlumber*. Wojciechowski et al. [49] [50] also focus on the context modelling for End-User Development in Ambient Assisted Living (AAL). Lieberman et al. [44], originally introduced the End-User Development, classifying the type of activities involved in it as: A) *Parametrization or customizations*, considered as activities that allow users to choose among alternative behaviours already available in the application; B) *Program creation and modification*, in the form of activities that imply some alteration, aiming at creating from scratch or modifying existing software artefacts. Further information about the different ways of customization can be found in his work.

As stated before, systems do not necessarily have to be completely autonomously or dependent on the user, they can have hybrid approaches with different degrees of active and passiveness. For example, the autonomy level can be adjustable, enabling human users to collaborate with computational systems managing the system behaviour as a team. Ball et al. [51] consider enabling human-agent teamwork in Intelligent Environments by employing concepts of adjustable-autonomy and mixed-initiative interaction. Such approaches reduce the chance of guesswork needing to be done. If the user or agent can not manage the system in the usual way, they can seek help from each other, inheriting the benefits from autonomy level that is implemented. On the other hand, it also inherits the drawbacks from the opposite autonomy level. The advantages

and disadvantages of the different interaction approaches are presented in Table 1.

2.1.4. Features of a Context-Aware System

Schilit et al. [56] first identified different classes of context-aware applications. Pascoe et al. [57], later aimed at identifying the core features of context-awareness. Dey and Abowd [6] presented a categorization for features of context-aware applications, based on the classification of Schilit and Pascoe, namely:

1. *Presentation of information and services to the user.*
2. *Automatic execution of a service.*
3. *Tagging of context to information for a latter retrieval.*

The first feature decides which information and services are presented to the user, based on context. Nearby located objects might be emphasized, or for instance, a printer command might print to the nearest printer. The second feature is the automatic execution of a service. For example, let us consider a smart home environment. “When a user starts driving home from their office, a context-aware application employed in the house should switch on the air condition system the coffee machine to be ready to use by the time the user steps into their house” [5]. Finally, they present “contextual augmentation”, which extends the capabilities of sensing, reacting and interacting with the environment by using additional information. This is achieved by associating digital data with a particular context. For example, a tour guide can augment reality by presenting information about the attractions that they are surrounded by or are approaching [57]. In the previous subsections, we discuss the need to: A) Take into account the current limitations of C-AS; B) Include the different interaction levels; C) Have a more user-centred perspective. In order to accommodate these demands, we propose to extend Dey and Abowd’s features of C-AS into:

1. *Presentation of information to the stakeholders*
2. *Automatically triggered, approved or chosen execution of a service*
3. *Personalization of a service*
4. *Tagging context to information*

The first one is very similar to Dey and Abowd’s. It keeps the essence of Pascoe’s “presenting context”, but Schilit’s “proximate selection” and “contextual commands” are merged with our second feature. We have introduced the notion of collaboration between different stakeholders rather than just the users. The contextual information might arrive to some secondary or tertiary users that make the choices over the actions of the system, based on the users needs. Such as what happens in projects like POSEIDON² [58], where there is a need of secondary users to take care of the primary ones. Our second feature includes all the different involvement degrees of the user in the system actions, as the situation arises when it is executing. A service can be automatically triggered, being the system autonomous in

²POSEIDON stands for PersOnalized Smart Environments to increase Inclusion of people with Down’s syndrome

| Name | Pros | Cons | Name | Pros | Cons |
|------------------------------------------------------|----------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|---------------------------------------------------------|-----------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|-----------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|
| <i>Active Execution</i> (Self-adaptivity) | <ul style="list-style-type: none"> • Little or no effort required by users [52] • No special user knowledge is needed [52] | <ul style="list-style-type: none"> • Difficult to ensure that the system will take an appropriate action (Difficult to validate and verify the system) • Loss of control over what the system is executing and why [52] • There are still some open issues [29] [53] • Developers have all the burden • Users can be uncomfortable not understanding what happens with the information that the machine gathers from them | <i>Passive Execution</i> (Intelligibility & Control) | <ul style="list-style-type: none"> • Augments the trust of users [54] since they understand better how the system works • Easier to evaluate the system behaviour • The system will take the actions that the user wants | <ul style="list-style-type: none"> • Requires developers to understand how to generate explanations [38] • The users might not have enough expertise to take decisions on their own • Applications need to convey more information to explain actions to users [54] • May compromise the privacy of users if they are used on social interactions • Users can use their higher context understanding to better control the system [54] [2] |
| <i>Active Configuration</i> (Learning & Adapting) | <ul style="list-style-type: none"> • Little or no effort required by users • No special user knowledge is needed • Can unearth needs, preferences or habits difficult to see in other ways [42] | <ul style="list-style-type: none"> • Difficult to determine when rules should be created or deleted • The rules are based on sensors values (inaccuracy and uncertainty) • Loss of control over what the system is executing and why [52] | <i>Passive Configuration</i> (End-user programming) | <ul style="list-style-type: none"> • Offers greater motivation, control, ownership, creativity and quality to end-users [55] • Users are in control; users know their tasks best [52] • Releases developers burden | <ul style="list-style-type: none"> • Users might be forced to contribute and cooperate in context for which they could lack experience [55] • Meta-design is more complex and abstract than design • Complexity is increased (users need to learn adaptation components); Systems may become incompatible [52] |

Table 1: Comparative analysis on the interactivity levels that context-aware systems can have.

its decision. But it also can ask the approval of the user, or display a certain list of possible choices, as in Schilit’s “proximate selection”, to enable further collaboration between the system and the users. The third feature is related with being more useful to the stakeholders, relating its services to their preferences and needs, which can evolve in time. C-AS can adapt to these through the active or passive configuration of the system, as explained in the previous subsection. Finally, the last feature is the same as Dey and Abowd’s.

2.2. Technological Challenges

Once the concepts of C-AS development are clearer, the reader has to understand the technological challenges and demands that creating these systems entails. The following subsection highlights them, focusing more in the context information handling, as it is the major and more complex need, to finally analyse other important technological demands.

2.2.1. Context information handling

In order to enable context-awareness, there is always a need of capturing context information and making it available to applications and systems [59]. C-AS require separating how context is acquired from how it is used, so that applications are able to use contextual information without knowing the details of a sensor and how can it be implemented [47] [60]. The techniques for context information management have been widely researched and are well understood [5]. Despite the advances, the challenge for an engineering process is to facilitate the development and reuse of structures that enable context information management and support the adaptation to the specific needs of the applications/systems. Following, the life-cycle [5] of context information is used as a reference to better clarify the issues that this information management may entail:

Acquisition: First, the context information needs to be gathered. Generally, this happens from multiple and distributed resources, which makes the quality and authenticity of information difficult to achieve. Let us take the example of the smartphone able to inform about buses depending on the context. For developing such a system, Jack’s position can be obtained via the GPS of his phone. The information about the buses can come from an external server and the bus that Jack takes regularly can be manually provided by him. As it can be observed, for a reasonably simple system, the ways of sensing the different contexts are disparate. On the other hand, sensors in general, are likely to provide inaccurate, overlapping, contradictory or missing data (*e.g.*, providing the same information at different timings or with a jitter) [61]. It also has to be mentioned, that the addition and removal of context resources can give rise to scalability issues. For instance, in a future, the system of our example may not be prepared for obtaining the position from Jack’s PDA instead of his phone. Finally, it has to be taken into account that it will be difficult to obtain contextual information if many users share the same physical sensors and service resources [62].

Modelling: After the information is sensed, it needs to be translated into usable values. In this process, real world concepts are translated into modelling constructs. The raw value of Jack’s position may be in the form of: “42.85, -2.683333”. This information must be translated into more understandable information such as the name of a city, street, etc. These models require [63] [60]: 1) To represent any kind of context information, reflecting the entities of the real world and their relations; 2) Uniquely identify the contextual information, context and entities; 3) To be simple, reusable, expandable and able to use the information at runtime; 4) Validate pieces of data and encode its

uncertainty.

Reasoning: Based on the modelled data, different kinds of conclusions can be inferred, where this data can be seen as evidence to support the conclusion [15]. In this way, new knowledge and understanding is obtained, based on the available context [64]. In our example, what the system needs at this point, is to relate Jack's position to check whether if he is at a bus stop, so that it can find the time remaining for the next approaching bus and send a message to him. This process has typically three different phases [5]: (1) Context pre-processing, where data is cleaned to get rid of invalid, inaccurate and non desirable values; (2) Sensor data fusion, in which sensor data is combined to produce more accurate and dependable information; (3) Context inference, from low-level information to high-level one. In what regards to reasoning, representation expressiveness is in mutual conflict with soundness, completeness and efficiency [65].

Dissemination: Finally, both low-level and high-level context need to be distributed to the consumer. The context information must have high availability, ideally to be provided it in real-time. Another desirable feature is to discover new services that could provide new context information [15].

It also has to be mentioned that context information will inherently contain important data related to the users, what raises some privacy issues. Privacy concerns may differ from user to user, and may also be dynamically changing over time. The balance between privacy and the potential of the system is delicate, where the developer may fall into ethical issues. A detailed examination of these issues is not the focus of this survey, but the reader can have more information about ethical concerns that can influence the area at engineering level in [66]. Besides, it is difficult to obtain, ensure and evaluate the good Quality of Context (QoC) information, which depends on its [67]: Precision, probability of correctness, trustworthiness, resolution and contemporaneity.

2.2.2. Technological demands

The technological challenges are not only focused on the information management. We have classified the remaining most relevant needs of C-AS systems into:

- *Flexibility versus change:* Once the context information is provided, the rest of the system configuration can happen in many forms, that depend on the specific implementation of the system itself. Although the particular implementations can vary, a need that seems invariant is supporting a high amount of changes.
- *Cost:* C-AS are expensive to develop, deploy, execute and maintain. The amount of information that they need to manage makes them resource hungry [68] and dependable on a very expensive structure.
- *Reliability:* C-AS must be reliable, especially if they are going to be used in tasks where an error can put a human

life at risk. Even if they are not able to offer a continuous delivery of some services properly, they at least should be capable to perform its required basic functions tolerating errors, faults and failures. Fault tolerance in pervasive systems can be increased by [69]: (1) Efficiently detecting faults; (2) Isolating faults, to prevent its propagation to other parts of the system; (3) Providing a transparent fault tolerance; and (4) Good fault reporting mechanisms. Besides, it is difficult to evaluate the correctness of C-AS due to their increasing size and device diversity.

- *Infrastructure:* The expensiveness and complexity of C-AS development makes highly desirable for developers to have tools that support and ease their effort during the development of their systems. An infrastructure [70], is software that supports construction or operation of other software, comprising systems that range from tool-kits to network services or other sorts of platforms. So, it enables applications that could not otherwise be built or would be prohibitively difficult, slow or expensive. These kind of infrastructures are typical in C-AS development. Nevertheless, a certain infrastructure affords only certain styles of application and interface. This creates a tension between easing the development and the flexibility of the infrastructure, and it is a challenge itself.

Although the field has matured in the latest years, developers have still many issues to overcome when developing C-AS. The next step is to fathom the techniques proposed to develop these kind of systems.

3. State-of-the-art in the development of Context-Aware Systems

The previous section gives the reader a better understanding of the complications that C-AS developers may face. These, drive researchers to modify already existing engineering methods or to explore new ones in order to give a better response to the needs of context-aware computing. This section studies these specialized development methods and techniques in the literature for creating C-AS throughout the most common stages of a development process: (1) Requirements Elicitation; (2) Analysis & Design; (3) Implementation; and (4) Deployment and Maintenance.

3.1. Requirements elicitation

The requirements elicitation process helps developers to reach a better understanding of the user needs and demands by finding a systematic approach for eliciting, analysing, documenting, validating and managing software requirements from individual stakeholders [71] [72] [73]. If the right requirements are not well defined prior to the development of the system, it will be more likely to fail meeting the user and other stakeholder's expectations. Some of the traditional techniques for eliciting requirements can be classified into [74]: Interviews, questionnaires, task analysis, domain analysis, introspection,

repertory grids, card sorting, laddering, group work, brainstorming, joint application development, requirements workshops, ethnography based, observation, protocol analysis, apprenticeship, prototyping, goal based, scenario-based and viewpoints. The aim of this subsection is not to deeply review them, but to focus in requirement elicitation techniques that have been tailored for meeting the needs of C-AS development.

We have classified the different requirements elicitation techniques specialized for C-AS development into: (1) Requirements through visualization; (2) Based on previous context classifications; (3) Social sciences based; (4) User-centred; (5) Model-driven; and (6) Adaptive and goal oriented. We compare their advantages and disadvantages in Table 2. Finally, we analyse previous works for identifying common features of requirements elicitation techniques for C-AS, to which we add our conclusions.

3.1.1. Requirements through visualization

Some of the approaches are concerned with the visualization of requirements in order to improve the communication between stakeholders. Jorgensen and Bossen [75] presented Executable Use Cases (EUC) for gathering requirements in a pervasive health care system. EUCs are designed to (A) Narrow the gap between informal ideas about requirements and their formalization during system implementation and (B) Spur communication between users and developers. EUCs are based on UML-style use cases and have three different tiers: (1) Prose, where descriptions in prose of work processes and their proposed computer support (*e.g.*, in the form of typical-language use cases). (2) Formal, that provides a formal, executable model of the work processes and their proposed computer support, where several modelling languages can be used; (3) Animation, where the second tier will be graphically represented and animated with concepts that users are familiar with and understand. Perez and Valderas [76], present a tool-supported requirements elicitation technique that involves the end-user in the task of describing the main characteristics of pervasive systems and their requirements. Instead of interviews, their technique allows the natural visualization of the requirements which helps the end users interact with requirements engineers. The process has four phases: (A) *Context scope*, where the requirements engineer defines the role³ of end users and the domain of the system to be developed; (B) *System specification*, in which end-users describe the main characteristics and select requirements from a predefined catalogue and closed option interfaces; (C) During the *Advanced system* phase, the end users and the engineers refine the predefined requirements with new ones not available in the catalogue; (D) In *Validation*, the requirements engineers validate with the end-users the captured requirements. They remove any ambiguities or mistakes, creating a formal specification of them.

³The roles could be: *End-User*, with limited skills; *Advanced End-User*, familiar with computer applications; and *Requirements Engineers* who are professional computer experts.

3.1.2. Based on previous classifications of context

Some of the requirements engineering techniques are based on context-classifications. Krogstie [77] studies the challenges that specify the requirements to applications running on mobile technology. He presents six context categories (*i.e.*, spatio-temporal, environment, personal, task-oriented, social and information contexts) to guide the design of customised stakeholder interviews. Hong et al. [78] discuss that the context in which an application is being used becomes an integral part of the activity carried out with the application. Starting with the context categorization proposed by Dey et al. [6] (*i.e.*, location, identity, activity and time), the solution they propose addresses two goals of Interaction Design: (A) Usability and (B) User experience goals. For the requirements elicitation, they divide context into: (I) Computing, (II) User and (III) Physical. Kolos-Mazuryk et al. [79] acknowledge the difference between C-AS properties and those of traditional systems, classifying them into (A) Contextual and (B) Non-Contextual. They present a context-aware oriented requirements engineering method that is a hybrid between the general theory on design methodology and the inherent properties of pervasive services. Their method starts observing the stakeholders of the system to develop. Taking into account the different notions of context they use interviews, diaries, user testing and workshops to determine the needs of the stakeholders in what regards to the system. Using the information obtained, they build a model of the environment to refine the requirements. They use “games” to involve users in the requirements elicitation process.

3.1.3. Social sciences based

Some requirements gathering techniques used social sciences based approaches. Kjaer [80] proposes a requirement gathering process for the design of context-aware middleware. They video-recorded and documented the activities of people who worked at a farm while they were doing their daily work. They used an ethnographic study to classify the context. Their behavioural studies allowed them to determine a number of requirements for the middleware they were trying to develop. Fuentes et al. [81] presented an Activity Theory for Requirements Elicitation (ATRE). With their framework they try to address the lack of expertise in social analysis of developers by abstracting knowledge from Activity Theory [82] to gain new insights in the analysis of human context. Their method also improves the communication between stakeholders by introducing new perspectives in each social property. These are targeted for experts on social issues, requirements engineers, domain experts and customers. Finally, the properties are stored in a repository, where they can be organized in areas that are related to dimensions of concern in Activity Theory, indicating how customers and engineers must look for social properties according to the information they are interested in eliciting. In this way, the framework provides more complete requirements specifications regarding to the human context and its influence in the design of the system to be developed.

3.1.4. User-Centred

Sutcliffe et al. [83] introduce a Personal and Contextual Requirements Engineering framework (PC-RE). It captures and analyses requirements for helping developers to decide how personal requirements should be implemented. They include different layers for stakeholders, user characteristics and personal goals. In this way they encourage not only an analysis for evolving requirements, but also for contextual influences. The framework is designed to complement complement existing requirements engineering methodologies via scenario-based techniques. Their model aims to provide a framework of questions that drive the requirements investigation and interpret this as a check-list. An important feature of this work is the use of personalized user requirements. They argue that taxonomies for context-awareness have been personalized to groups rather than to individuals. They also remark that changes can happen in user characteristics over time, as well as social and cultural aspects. Evans et al. [84] present R4IE, a framework for a requirements engineering process for Intelligent Environments, in which context-awareness is a primary feature. Their work is similar to Sutcliffe's but they include stakeholder profiling with individual user customization. They also introduce a core ethical model, enhancing the addressing of the issues of social context and ethnicity and considering privacy. Zachhuber et al. [85] introduce a framework that is a combination of context simulation with the Wizard of Oz (WOz) technique, where a hidden human "wizard" simulates missing functionalities and system intelligence.

3.1.5. Model-Driven

Desmet et al. [86] present a Context-Oriented Domain Analysis (CODA) for identifying and modelling context-aware software requirements. It forces modellers to think by means of "context-unaware" behaviour, which can be further refined according to "context-aware dependant adaptations" at certain validation points. CODA can be represented: in a tree structure (graphically), using XML for writing its diagrams (textually) and mapping its semantics to elements in the decision tables (structurally). Choi et al. [87] propose a method for requirements gathering in C-AS based on variations of UML Use Case Diagrams. They introduce the following techniques: (1) Defining the scope of systems; (2) Service identification. In a further work [88], they introduce (3) Decision table or trees. They raise the context as a major issue in requirements analysis, encouraging analysts and stakeholders to pay attention to context related issues such as system platform, target users, intelligence, possible context-aware services and agreement with other stakeholders as well as understanding context with decision tables and trees. Ruiz et al. [89] describe a model-driven engineering approach targeting non-functional requirements, where they: (1) Derive a model-driven system design that meets specific requirements; (2) generate code that implements such design. Sitou and Spanfeller [90] present RE-CAWAR a requirements engineering process for context-aware and adaptive systems. It provides an integrated model for the usage context based on different models: (1) User Model, where the participants aspects are represented, characterizing the users and user groups;

(2) Task Model, to represent the activities aspects, identifying which task and interactions are needed to perform it; (3) Domain Model, that consists of any user visible, operable objects in the applications domain, representing the operational environment aspects; (4) Platform Model, that represents the physical infrastructure and the relationship between the involved devices; (5) Dialog model, where the interaction between the user and the system is depicted; (6) Presentation model, that shows visual haptic and audio elements needed for the interaction. Through an iterative process, stable needs are identified, as well as such that may change according to the context. The stable needs result in the functionality of the system, while the situational needs are further analysed to specify the adaptation logic.

3.1.6. Adaptive and Goal-Oriented

Finkelstein and Savigni [91] present a framework for requirements engineering in context-aware services, where they propose that requirements themselves can change during the system execution. They difference between: (1) Goals, as a fixed objective of the service; (2) Requirements, as a more volatile concept that can be influenced by the context. Oyama et al. [92] describe an approach of service requirements analysis using the feedback of contexts, to support the elicitation of user intentions and goals in a robust manner. They identify two approaches in the evolvability of C-AS: (1) Short-term evolution, to handle exceptions and to make correct reactions at runtime; (2) Long-term evolution, to monitor user behaviour and capture new system requirements based on human intentions. Baresi et al. [93] present FLAGS, a goal model that adds adaptive goals in order to embed adaptation countermeasures, fostering self-adaptation by considering requirements as live, runtime entities. They distinguish between: (1) Crisp goals, whose satisfaction is Boolean, and (2) Fuzzy goals, whose satisfaction is represented through fuzzy constraints. Adaptation countermeasures are triggered by violated goals and the goal model is modified accordingly to maintain a coherent view of the system and enforce adaptation directives on the running system. Siadat and Song [94] discuss the state-of-the-art requirements for adaptive systems, under the notion that requirements that are engineered at design time may require further reasoning or refinement at runtime in order to adapt to dynamic context-driven changes.

3.1.7. Conclusions

Other surveys have also studied the requirements elicitation techniques specialized for C-AS development. Following, we analyse their view on the most common characteristics in requirements elicitation for C-AS. Preuveneers and Novais [95] present a survey of the best software engineering practices in Ambient Intelligence. In all the approaches they surveyed for requirements elicitation, they highlight: (1) The importance to actively involve the end-user and to develop an elicitation process that is customized to the competences of the end user; (2) The need for an explicit representation of the context and goals of the user, and how the context impacts the interaction with the user; (3) An explicit formalization of which requirements are relevant for a given context and how these can evolve

| Name | Pros | Cons |
|-------------------------------------|--------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|-----------------------------------------------------------------------------------------------------------------------------------------------------------------|
| <i>Visualization</i> | <ul style="list-style-type: none"> • End-users are actively involved in the requirements elicitation • Users and developers can better communicate and understand | <ul style="list-style-type: none"> • Difficult to translate into formal requirements |
| <i>Pre-categorized</i> | <ul style="list-style-type: none"> • Can complement other requirements elicitation techniques | <ul style="list-style-type: none"> • Categories might be too broad or too narrow |
| <i>Social Science Based</i> | <ul style="list-style-type: none"> • Complement the SW engineering knowledge with the one of social experts • More complete requirements | <ul style="list-style-type: none"> • Complexity of including social experts as new stakeholders • Cost |
| <i>User Centred</i> | <ul style="list-style-type: none"> • Focuses on the needs of the stakeholders • Improves the usability | <ul style="list-style-type: none"> • Requires user involvement |
| <i>Model Driven</i> | <ul style="list-style-type: none"> • Forces developers to have different views • Help to decide the boundaries between elicitation and design • Enables better traceability | <ul style="list-style-type: none"> • Different readers can make different interpretations • Hard to capture non-functional requirements |
| <i>Adaptive & Goal Oriented</i> | <ul style="list-style-type: none"> • Provides means to capture and analyse variability • Opens the way to requirements evolution | <ul style="list-style-type: none"> • Difficult to determine when the behaviour of the system meets the requirements |

Table 2: Comparative analysis on the advantages and disadvantages of the different requirements elicitation techniques that are specialized for context-aware systems development.

when the context change. Alshaikh and Boughton [10] analyse how context works in requirements elicitation. In early stages, context is associated with the task of setting system boundaries, while in later stages, context is used implicitly within the scenario-based requirements (common-sense approach). Finally, they distinguish between context and requirements. *Context* is defined through the user’s situation and *Requirements* are described focusing on the user’s interaction with the system. Evans et al. [84] classify the prominent themes in requirements elicitation focused on context-awareness for Intelligent Environments: (1) The consideration, adoption and possible enhancement of a context taxonomy; (2) A general assumption that systems need to be adaptable to be context-aware; (3) Elicitation techniques used to capture end-user cognitive tasks require enhancement to account for context-awareness; (4) Identification of target user groups and acknowledgement that contextual requirements for either profile may evolve over time; (5) Requirements themselves might be context-driven; (6) The consideration of cultural context; (7) The adoption of goal-oriented requirements engineering where higher-order goals are apparent in the domain. They also acknowledge that there is lack of standards in what regards to requirements engineering for C-AS. From the literature review, we insight that:

1. A contextual adaptation stems from a functionality of the system. Typically, the functionality is first identified and then its possible contextual adaptations.
2. The different contextual adaptations are affected by the

needs of specific users or user groups.

3. Social sciences and social experts help to understand better the notion of context in requirements elicitation.
4. The notion of context in requirements elicitation is still not clear.

3.2. Analysis and Design

When the system requirements are well specified, an analysis can ease the development plan through a better understanding of the system implementation. The design brings developers closer to a feasible implementation plan. It has to be acknowledged that there is no set of universally accepted basic design and development principles, or standards, which lead to a uniform approach to the efficient C-AS development. The aim of this subsection is to study the different approaches for analysing and designing C-AS. We first focus on the design process itself, to examine more in depth: (1) The different architectures of C-AS and architecture patterns used for design; (2) Middleware; (3) Design-Patterns and (4) Verification.

3.2.1. Design process

Bauer et al. [96] identified the most common practices used by developers when designing a C-AS, dividing the process into: A) *Framing*: Designers will articulate and explore a concept of context, which imposes a set of limitations on what exist inside and outside the design space their work inhabits [96]. B) *Encoding*: In this stage designers will discuss the behaviour of the system and instantiate a vocabulary or codes to express its behaviour. C) *Unifying*: As the designers explore the design space, certain possible design solutions are brought to the foreground, which impose additional constraints over other concerns the designers address. D) *Evaluating*: As the process continues, the designer will focus on a solution that satisfies the constraints according to their encoded formulation of context. This allow them to determine when they have arrived at a satisfactory solution.

3.2.2. Architectures

An architecture is an abstraction, that generalizes the systems, without showing detailed implementation such as code or circuits. This subsection studies the architectures used for C-AS development. Due to their diversity, C-AS have adopted disparate ranges of architectures. Table 3 shows the different classifications of architectures according to existing literature surveys. Following, we analyse the works that classify generic architectures and we study the different architectural patterns that can be used for creating C-AS.

3.2.2.1. Generic architectures. Other works also study the common parts that different architectures have, providing a generic architecture for C-AS. Baldauf et al. [99] present a survey on C-AS, in which they introduce an abstract layer architecture for C-AS that is divided in: (1) Sensors; (2) Raw data retrieval; (3) Pre-processing; (4) Storage/Management and (5) Application. Hong et al. [62] introduce a literature review of

| Author(s) | Winograd | Chen et al. | Perera et al. |
|--------------------|-----------------------------------------------------------------------------------------------------------------------|--------------------------------------------------------------------------------------------------------------------------------|-------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|
| Reference | [97] | [98] | [5] |
| Year | 2001 | 2004 | 2014 |
| Architecture Types | <ul style="list-style-type: none"> • Widgets • Networked Services • Blackboard Model | <ul style="list-style-type: none"> • Direct Sensor Access • Middleware Based • Context Server | <ul style="list-style-type: none"> • Component Based • Distributed • Service Based • Node Based • Centralized • Client-Server |

Table 3: Different architecture classifications for context-aware systems.

C-AS, in which they classify architectural layers of this systems into: (1) Concept and Research; (2) Network infrastructure layer; (3) Middleware layer; (4) Application layer and (5) Infrastructure layer.

3.2.2.2. Architectural patterns. An *architectural pattern* is a set of architectural design decisions that are applicable to a recurring design problem, and parametrized to account for different software development contexts in which that problem appears [100]. We have gathered from the literature, the following patterns:

- *Event-Control-Action [101]*: A high level structure for systems that proactively react upon context changes. It provides a structural scheme to enable the coordination, configuration and cooperation of distributed functionality within services platforms. Divides the information management related tasks from the ones that trigger actions, under the control of an application behaviour description. It improves the extensibility and flexibility of the platform, since context processors and action components can be developed and deployed on demand. Besides, enables the dynamic deployment of context-aware applications and allows the configuration of the platform at runtime. It is divided into: (1) Event, where context concerns are placed in, that depend on the definition modelling of context information; (2) Control, that is provided with application behaviour descriptions, and connects the context events with the actions to take; (3) Action, that triggers the behaviour, which can be a service invocation on (external or internal) service providers or a network.
- *Context Sources & Managers Hierarchy [101]*: Aims at providing a structural schema to enable the distribution and composition of context information processing components (Context Sources and Context Managers). The structural schema consists of hierarchical chains of them, in which the outcome of a context information processing unit may become input for the higher level unit in the hierarchy. A context Manager inherits the features of context sources and implements additional functions to handle gathering context information from various context sources and managers. It enables encapsulation and a more effective, flexible and decoupled distribution of context processing activities (sensing, aggregating, inferring and predicting). It also improves collaboration among context

information owners allowing new parties to join the collaborative network in order to provide richer context information.

- *Actions Pattern [101]*: An action might be performed independently or in parallel, while some actions depend on or trigger others. In order to provide mechanisms to manage coordination of actions, this pattern provides a structure of components to support designing and implementing action concerns within context-aware services platforms. An action purpose defines an abstract action intention, while its implementation represents the realization of it, using specific implementation technologies. By defining a structure of Action Resolvers, Providers and Implementors, enables the coordination of compound actions and the separation of abstract action purpose from its implementations.
- *Sense-Compute-Control [100]*: It is a common pattern for structuring embedded control applications and pervasive environments that interact with the physical surroundings. This pattern consists of context operators fuelled by sensing entities whose operators refine (aggregate and interpret) the information given by the sensors. These refined data are then passed to controller operators that trigger actions on entities. The structure is based on a computing element that (1) reads all the sensor values; (2) computes control outputs and (3) sends the controls to all actuators.
- *Blackboards [97]*: Adopts a data-centric point of view. Rather than sending requests to distributed components and getting call-backs from them, a process post messages to a common message board, to which others can subscribe to receive messages matching a specified pattern that have been posted. All communications go through a centralized server.

3.2.3. Middleware

Middleware is the most used structure to collect context information, support the deployment of sensors and hide heterogeneity. By separating how context is used from how it is acquired, it eases the development of a generic set of applications by reusing and customizing the necessary structure for context manipulation. Although many middleware approaches have been presented, it is difficult to achieve a universal middleware tool, applicable to any area, and capable of solving all the challenges involved in the context provision to applications, despite the many standpoints in the literature [5]. In this direction, approaches like UniversAAL⁴, aim at creating an open platform and reference specification that makes technically feasible and economically viable to develop Ambient Assisted Living solutions. In order to better reuse their middleware, they provide a market in which developers will upload their applications to make them available to users. Besides, the ReAAL⁵ initiative has rolled-out active and independent living applications on top of UniversAAL, and has tested them with users in

⁴<http://www.universaal.org/>

⁵<http://www.cip-reaal.eu/>

| Pattern | Applicability | Benefits |
|-------------------------------------------------|-------------------------------------------------------------------------------------------------------------------------------------------------------------|---------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|
| <i>Event-Control-Action</i> | <ul style="list-style-type: none"> Gathering context info Full time connectivity Real time | <ul style="list-style-type: none"> Extensible and flexible applications Dynamic deployment of applications Separation of concerns (Control and Context Information) |
| <i>Context Sources & Managers Hierarchy</i> | <ul style="list-style-type: none"> Context information processing | <ul style="list-style-type: none"> Encapsulation, effective, flexible and decoupled distribution of context information management activities Filtering unnecessary information |
| <i>Actions Pattern</i> | <ul style="list-style-type: none"> Actions performed in parallel Dependency between actions | <ul style="list-style-type: none"> Avoids permanent binding between action and purpose Enables different implementations at platform run-time Actions may be changed or extended independently |
| <i>Sense-Compute-Control</i> | <ul style="list-style-type: none"> Large number of heterogeneous devices Embedded control applications Static environments | <ul style="list-style-type: none"> Allows the control of various devices Enables adaptation Reuse of existing components Diminution of complexity |
| <i>Blackboards</i> | <ul style="list-style-type: none"> Distributed applications Complex problem solving | <ul style="list-style-type: none"> Knowledge is reusable Knowledge sources can work concurrently Easy to add/remove knowledge |

Table 4: Benefits and applicability of architectural patterns for context-aware systems.

real life. Middleware has been deeply analysed in the literature. For this reason, it is out of the scope of this survey to deeply analyse them. The reader can find broader comparisons and studies related to middleware in Perera et al. [5], Preuveneers and Novais [95], Kjaer [102], Baldauf et al. [99] or Henriksen et al. [103], among others.

3.2.4. Design patterns

A design pattern is a semi-structured description of an expert's method for solving a recurrent problem, which includes a description of the problem itself and the context in which the method is applicable, but does not include directives which bind the solution to unique circumstances [104]. As in other domains, design patterns have also been suggested for context-aware computing. They can help designers to focus on what they want to implement without having to resolve recurrent issues. Usually, problems have a strong relationship with the platform where they are going to be executed, which makes their identification ad-hoc and difficult to reuse. We have classified the different patterns that can be obtained from the literature, according to the problem they intend to solve:

- *UbiComp features*: Enable ubiquitous and pervasive computing features.
- *Fluid interactions*: Solve common problems that arise from providing a better interaction with the users.
- *Privacy*: Address issues related with the confidentiality of the user data.

- *Physical-virtual spaces*: Looks at how physical objects and spaces can be merged with the virtual.
- *Monitoring*: Enable to systematically observe the system itself and environmental conditions.
- *Adaptations*: To dynamically perform structural and behavioural changes in an adaptive system without leaving it in an erroneous or inconsistent state.
- *Decision making*: Mechanisms to solve problems related with taking decisions.

It is difficult to determine design patterns that can be universally reused. Instead, they help to solve some specific problems that might not be necessarily applicable to any C-AS. Besides, it must also be acknowledged that there is no widely recognized technique for finding appropriate design patterns from existing C-AS. Due to space restrictions, a further analysis of these patterns is not provided, but each of the patterns is related to its corresponding paper in table 5. More information about design patterns can be also found in [95] [105] [106].

| UbiComp features & Decision making | Fluid Interactions | Privacy |
|-----------------------------------------|--------------------------------------------------------|------------------------------------------------------|
| UbiComp features | | |
| [107] Upfront Value Proposition | [108] [107] Follow-me displays | [107] Fair information practices |
| [107] Personal UbiComp | [108] [107] Context-sensitive I/O | [107] Respecting social organizations |
| [107] UbiComp for groups | [109] Typified context element | [107] Building trust and credibility |
| [107] UbiComp for places | [107] Scale of interaction | [107] Reasonable level of control |
| [107] Exploration and navigation guides | [107] Sense-making of services and devices | [107] Appropriate privacy feedback |
| [107] Enhanced emergency response | [107] Streamlining repetitive tasks | [107] Privacy sensitive architectures |
| [107] Personal memory aids | [107] Keeping users in control | [107] Partial identification |
| [107] Smart homes | [107] Serendipity in exploration | [107] Physical privacy zones |
| [107] Augmented reality games | [107] Active teaching | [107] Blurred personal data |
| [107] Streamlining business operations | [107] Resolving ambiguity | [107] Limited access to personal data |
| [108] Global data proxies | [107] Ambient displays | [107] Invisible mode |
| Decision making | [107] Pick and drop | [107] Limited data retention |
| [106] Adaptation detector | [108] Appropriate levels of attention and anticipation | [107] Notification on access of personal information |
| [106] Case-based reasoning | | [107] Privacy mirrors |
| [106] Divide & conquer | | [107] Keep personal data on personal devices |
| [106] Architecture-based | | |
| [106] Trade-off based | | |
| Monitoring | Physical-Virtual Spaces | Adaptations |
| [110] Flyweight | [108] [107] Physical-virtual associations | [110] Strategy |
| [110] Hybrid mediator-observer | [109] Active context element | [109] Rule-based adaptation |
| [110] Enactor | [107] Active Map | [109] Context wrapper |
| [110] Flexible context processing | [107] Tropical information | [106] Component insertion |
| [106] Sensor factory | [107] Successful experience capture | [106] Component removal |
| [106] Reflective monitoring | [107] User-created content | [106] Server reconfiguration |
| [106] Context-based routing | [107] Find a place | [106] Decentralized reconfiguration |
| | [107] Find a friend | |
| | [107] Notifier | |

Table 5: Classification of design patterns used for context-aware systems development based on their applicability.

3.2.5. Verification

The system complexity and hence the likely number of design errors, grows exponentially with the number of interacting system components. Although program testing can be a very

effective way to show the presence of bugs, it is inadequate for showing their absence [111]. In these cases, verification techniques are used to explore some general properties about the behaviour of a program. Most of the verification done in C-AS is in the form of model checking, an approach to formal verification that proves whether if a model meets a given specification. Other simulation and use-case based techniques are also employed. The rest of the section discusses some representative samples of the state-of-the-art.

3.2.5.1. Formal Verification. Formal verification techniques provide a safer development of systems in intelligent environments, what leads to increase their reliability [112]. Augusto et al. [113] show techniques as well as tools that can be used to model processes and interactions, detecting problems through simulation and verification in early stages of the development. They acknowledge SPIN [114], a generic and open verification system that supports the design and verification of asynchronous process systems, as a good tool for this task. SPIN accepts design specifications written in the verification language PROMELA [115], and it accepts correctness claims specified in the syntax of standard Linear Temporal Logic [116]. These tools have also been proved as supporters in the development of more correct and reliable Multi-Agent Systems [117]. On a further work, Augusto and Hornos [118], present a methodological guide which provides strategies and suggestions on how to model, simulate and verify these types of systems, divided in four stages: (1) *Informal modelling*, where informal descriptions of both the application domain and the correctness properties to be checked using natural language; (2) *Structural modelling*, in which entities to be considered are identified; (3) *Behavioural modelling*, where the contents of each process created in the previous phase is defined or refined by modelling the dynamic behaviour of the corresponding entities involved; (4) *Simulation and verification*, in which both techniques are used to increase the reliability of the models created. This phase also will require moving back to the previous phases and redefine models. Preuveneers and Berbers [119] also support a model checking approach in order to being able to verify the many possible configurations and contextual situation that a C-AS can be in. They discuss the major benefits and weaknesses of the SPIN tool. On one hand they acknowledge SPIN to be helpful identifying different contexts that give rise to conflicting actions, to be supportive finding non-deterministic system behaviours and to be capable of producing counter examples for unverifiable situations. On the other hand, they highlight that the explicit notion of time is counter-intuitive, that is difficult to model external influences making the outcome of the simulation subject of interpretation and that is very easy to overlook dependencies among context variables. Also there are no systematic extraction techniques and that in complex situations with multiple context variables, rules and assertions is likely that the exponential state space explosion becomes a critical concern for verifying the rule.

D'Errico and Loreti [120] present a set of formal tools that

allows specifying systems along with a model-checking algorithm to verify whether considered specification satisfy the expected properties. They introduce μ KLAIM, based on a simplified version of a Kernel language for agent interaction and mobility [121], which is based on an assume-guarantee approach: A system is not considered as isolated, but in conjunction with assumptions on the behaviour of the environment where is executed. The system can be specified in: (1) Process, accurately defined; (2) Environment, more abstract and formalized by logical formulae. To specify properties of μ KLAIM systems they use modal logic (MoMo) that allows describing interactions that the enclosing environments can have.

Liu et al. [122] present AFChecker, a public available tool to improve user's fault detection and inspection experiences. It has three major components: (I) *Model checker* based on a technique for fault patterns and their automated identification [123]. Which derives a state transition model from a set of user-configured adaptation rules and verifies the model to detect five⁶ common types of adaptation faults; (II) *Constraint inference engine*, that infers both deterministic and probabilistic constraints based on CHOCO⁷ by analysing the propositional atoms in the user-configured adaptation rules; (III) *Fault Report Processor*, that processes the fault reports generated by its underlying model checker. The ranking of fault reports for user's inspection can be dynamic or static, depending on the interaction mode.

3.2.5.2. Simulation and test-case generation. Park et al. [125] present CASS, a simulation tool for smart-homes that is able to generate virtual people in order to perceive its movements and actions through sensors. The tool is programmed in Java, and it allows to modify and delete sensor and devices according to the preferences of the developers. After, it can perceive simulated movements of virtual people, generating proper values for each sensor type. They also describe the system architecture and hierarchical rule structure model for smart-homes. Wang et al. [126], provide an approach for automating the generation of tests for context-aware pervasive applications. They provide an integrated solution to identify when context changes may be relevant, and a control mechanism to guide the execution of tests into potentially interesting contextual scenarios as defined by a coverage criterion that is context-cognizant. Their solution can be used to enhance other test suites of context-aware applications. Bertran et al. [127] introduced DiaSuite, a tool suite for the development of sense-compute-control applications. Within their suite of tools, they present DiaSim [128], a parametrized simulator to ease the acquisition, testing and interfacing of a variety of software and hardware components. The simulator is parametrized to a high-level description of the target environment, written in their own specification

⁶Non-deterministic adaptations, dead rule predicates, dead states (meaning that no rules can be satisfied in these states), adaptation traces and unreachable states.

⁷Open source Java library. <http://choco-solver.org/>

| Approach | Applicability | Pros | Cons |
|------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|-----------------------------------------------------------------------|---------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|-------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|
| <ul style="list-style-type: none"> • Tool: SPIN [114] • Language: PROMELA [115] • Methodology: MIRIE [118] | Intelligent Environments [112], Multi-agent systems [117] | <ul style="list-style-type: none"> • Identify contexts that can give rise to conflicting actions • Supportive finding non-deterministic system behaviours • Provide counter-examples for unverifiable situations | <ul style="list-style-type: none"> • The explicit notion of time is counter-intuitive • Difficult to model external influences • Easy to overlook dependencies among context variables • No systematic extraction techniques • In complex situations, many state spaces become a concern in verification |
| <ul style="list-style-type: none"> • Tool: μKLAIM [120] • Language: KLAIM [121] MoMo [124] • Methodology: μKLAIM [120] | Code on Demand, Remote Evaluation, Mobile Agents, Distributed Systems | <ul style="list-style-type: none"> • Allows specifying systems by means of mixed specifications • Associativity and commutativity of parallel and non-deterministic operators | <ul style="list-style-type: none"> • Descriptions of the whole system are required to establish system properties |
| <ul style="list-style-type: none"> • Tool: AFChecker [122] • Language: CHOCO⁷ • Methodology: X | User-configured rule-based adaptations | <ul style="list-style-type: none"> • Alleviates the false positive problem • Users can validate their own rules | <ul style="list-style-type: none"> • Only considers constraints on a binary basis • Might be too resource consuming for executing in a mobile device |

Table 6: Comparative analysis on the advantages and disadvantages of the different approaches for validating context-aware systems through model checking.

language (DiaSpec). This description is used to generate both a programming framework to develop the simulation logic and an emulation layer to execute applications. Furthermore, the simulation can be rendered, allowing to visually monitor and debug the system. Their tool can be found as an Eclipse⁸ plugin. Yu et al. [129] apply a bi-graphical reaction system to model the environment that interacts with the middleware and domain services in the development of C-AS. To model the data entities in the environment, they extend the bi-graphical sorting predicate logic and build a meta-model. Then, they create a model of the middleware using a extended finite state machine. By synchronizing the bi-graphical reaction system with the state machine, they can generate test cases to verify the interactions between the environment and the middleware. Finally, they show the reductions of the number of test cases by using a bi-graphical pattern-flow based testing on an airport example. Their tool is also in the form of an Eclipse⁸ plugin.

Generally, authors recognize three main issues when simulating C-AS[127][129]: Modelling, source simulation and performance. First, it is difficult to determine what to model and in what granularity. Likewise, the model needs to be accurate enough to match such granularity. Second, some issues about the correctness of the stimulus producers may arise when either the logged data are replayed from actual sensors or a domain-specific modelling function is introduced. Emulated sensors

⁸ Eclipse is an integrated development environment (IDE) from the open source community of tools, projects and collaborative working groups Eclipse. <https://eclipse.org/>

must be programmed in such way, that for a given input, they produce the same output as its equivalent real sensor. Besides, merging the different intensities of simulated sensors requires domain-specific knowledge. Finally, physical spaces may involve lots of services, accurate simulation models and rich simulation logics which can be resource consuming.

| Approach | Features | Limitations | Tool Support |
|-------------------------------------|---------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|-------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|--------------|
| CASS [125] | <ul style="list-style-type: none"> • Simulate virtual people perceiving simulated movements in sensors • Able to detect rule conflicts | <ul style="list-style-type: none"> • Very ad-hoc • Only applicable to smart home development | ✓ |
| Automated generation of tests [126] | <ul style="list-style-type: none"> • Enhance existing test-suites • Identify when context changes might be relevant | <ul style="list-style-type: none"> • Static analysis tools are conservative • Infeasible drivers | × |
| DiaSim [128] | <ul style="list-style-type: none"> • Automatically generates an emulation layer to run the application code unchanged • Generation of a simulation framework to allow the development of the simulation logic | <ul style="list-style-type: none"> • The simulation logic has to be done by developers | ✓ |
| Bi-graphs & EFSM [129] | <ul style="list-style-type: none"> • Test cases are generated tracing the interactions between the bi-graphical model and the middleware • The number of test cases is reduced by using a bi-graphical pattern flow | <ul style="list-style-type: none"> • Assumes that middleware invokes only atomic services • Reaction rules are triggered in matches with agents and/or a middleware analysis result | ✓ |

Table 7: Comparative analysis on the features and limitations of the different approaches for validating context-aware systems through simulations.

3.3. Implementation

After a good design and verified plan, there is a need to realize the implementation of the ideas into a tangible system. In this subsection we analyse the most common techniques for context information management and the most acknowledged programming paradigms that have been used for C-AS development.

3.3.1. Context information management techniques

There has been several research in what regards to context information management techniques [130] [131] [60] [132] [99]. Perera et al. [5], presented what we consider the most complete survey on it. They classified the context information life-cycle into: 1) Acquisition; 2) Modelling; 3) Reasoning and 4) Dissemination. They analysed each of the techniques and compared their advantages and disadvantages. Following, a brief summary of the main techniques for this purpose.

3.3.1.1. Acquisition. For acquiring context, they discuss five factors that need to be considered when developing context-aware middleware solutions:

- *Responsibility*: (1) *Pull*, the data is obtained from the sensors with a request; (2) *Push*, the sensor gives the data (periodically or instantly) to the software component that is responsible of obtaining it.
- *Frequency*: (1) *Instant*, when events occur instantly (e.g., Switching on a light or opening a door); (2) *Interval*, when events span a certain period of time.
- *Source*: (1) Directly from sensor hardware; (2) Acquire through a middleware infrastructure or solution; (3) Acquire from context servers (e.g., databases or web services).
- *Sensor types* [132]: (1) *Physical*, that generate sensor data by themselves; (2) *Virtual*, that do not necessary create sensor data by themselves and can retrieve data from many sources publishing it as sensor data; (3) *Logical*, that combine physical and virtual sensors to produce more meaningful information.
- *Acquisition process*: (1) *Sense*, in which the data is sensed through sensors, including the data stored in databases; (2) *Derive*, in which the information is generated by performing computational operations on sensor data; (3) *Manually provided*, in which users provide context information manually via preferred setting options such as preferences.

3.3.1.2. Modelling and Representation Techniques. In order to implement models related to context, there is a need of platforms and techniques with the power to support the expression and handling needs of context information. Below, a brief introduction to the most commonly used techniques for context modelling [130]:

- *Key-Value*: The simplest form of context models, involving a name and context value pairs. Used to model limited amount of data such as user preferences and application configurations. Contain mostly independent and non-related pieces of information, which are suitable for limited data transferring and any other less complex temporary modelling requirements.
- *Markup Scheme*: Hierarchical data structures are formed using these models, consisting of mark-up tags, attributes and content. It can be the intermediate data organisation format as well as mode of data transfer over network. It can be used to decouple data structures used by two components in a system.
- *Graphical*: Modelling of context using graphical notation as UML, Object-Role Modelling, and other DSLs. Ideal for long term and large volume of permanent data archival. Historic context can be stored in databases.
- *Object Oriented*: Take advantage of object-oriented concepts and techniques as encapsulation and inheritance. To represent context in programming code level. It allows context runtime manipulation. They work on a very short term, temporary and mostly stored in computer memory. Also support data transfer over network.
- *Logic Based*: Use facts, expressions and rules to define formal models. Different facts can be inferred separately and then used in existing rules to derive higher context

knowledge. It is used for generating high-level context using low-level one, generating new knowledge. It is also used for modelling events and actions as well as for defining constraints and restrictions.

- *Ontology Based*: Can be used to describe taxonomies of concepts, including relationships. Besides, they allow different context reasoning techniques and inference rules. Rather than storing data on ontologies, data can be stored in appropriate data sources, while structure is provided by ontologies.

All techniques have their strong points and drawbacks, although ontologies are the most widely adopted approaches, still have some deficiencies that could be mitigated in hybrid approaches [60]. Although the representation and information retrieval in ontologies can be complex, they support semantic reasoning, expressive representations of context, have strong validation, are application independent, allow sharing, have strong support by standardizations and have fairly sophisticated tools available.

3.3.1.3. Reasoning. Once the context is modelled, there is a need of creating new knowledge and have a better understanding based on the currently sensed context. Techniques for this purpose can be divided into [5]:

- *Supervised Learning*: Training examples are collected to label them according to the expected results. Finally, a function can generate the expected results using the training data. Techniques such as decision trees, Bayesian Networks, Artificial Neural Networks and Support Vector Machines are considered in this group.
- *Unsupervised Learning*: Techniques that can find hidden structures in unlabelled data. Such as K-nearest neighbour, Kohonen Self Organizing Map (KSOM), Noise and outlier detection and Support Vector Machines.
- *Rules*: One of the simplest, straightforward and popular reasoning methods. They usually have an IF-THEN-ELSE structure, but they can be based on simple mapping associations of IDs to entities (RFID) [38].
- *Fuzzy Logic*: Allows approximate reasoning instead of fixed one, extending the Boolean values from 0 or 1 to expressions that simulate closeness to a natural language. The confidence values represent degrees of membership rather than probability.
- *Ontological*: Based on description logic, ontological reasoning is supported by OWL and RDF, rules as SWRL, are increasingly popular.
- *Probabilistic*: It allows decisions to be made based on probabilities attached to the facts related to the problem. These include techniques such as Dempster-Shafer, Hidden Markov Models and Naive Bayes.

3.3.1.4. Dissemination. Once the context information is ready, it has to be distributed to the consumers, and it is closely related to context acquisition. The distribution techniques are:

- *Query*: The context consumer makes a request in a specific manner so that they can obtain some specific results.

- Subscription: The context consumer subscribes with the context management system. Then, this system will return the results periodically.

3.3.2. Programming paradigms

A programming paradigm is the structuring of thought that determines the foundation of a programming activity, influencing the structure and elements of programs. In this subsection, the mostly used programming paradigms for the C-AS development are briefly analysed. The intention is not to have a thorough research on them, but to highlight the most used ones. Due to space constraints, many papers have been omitted from each approach.

3.3.2.1. Agent-Oriented. An Agent is an autonomous entity which observes through sensors and acts upon an environment. Agent-Oriented paradigm is a branch of Artificial Intelligence (AI) that attempts to combine distributed systems, AI and software engineering in a single discipline [133]. The approach has been used in C-AS development, and it has been acknowledged as a promising approach by some authors [62] [134]. As an example, Murukannaiah and Singh [135] present Xipho, an agent oriented methodology that assists the developer in systematically modelling a context-aware personal agent (CPA) via cognitive constructs.

3.3.2.2. Aspect-Oriented. Aspect-oriented programming language extensions provide constructs for modularizing crosscutting concerns [136]. A crosscutting concern is one that does not align well with the structure established by object-oriented or functional decomposition [136]. Is a technique that allows the modification of applications with modular units of functionality which are used across the application's code, called aspects. Tanter et al. [137] present an open framework for context-aware aspects to both restrict the scope of aspects according to the context and allow aspect definitions to access information associated to the context. Dantas et al. [138] show a comparative study on aspect-oriented programming for C-AS, identifying CSAspectAJ as the most complete between the evaluated approaches, in what regards to synchronization issues, transparency, joint-point models, exception handling and implementation availability. Fuentes et al. [139] [140] presented an approach to design and implement aspect-oriented context-aware applications, run and test the design models, and show how these models map into an implementation.

3.3.2.3. Context Oriented. Context Oriented Programming (COP) [141] is a technique to enable context-dependent computation. Is concerned with programming language constructs to represent and manipulate behavioural variations. COP tries to isolate the definitions from the business logic of application, conceptually separating context provisioning from the execution of the adaptable software. Salvaneschi et al. [105] give an overview of the COP techniques from the perspective of software engineering, recognising it as an apparently natural approach for these kind of systems. They acknowledge that supporting dynamic adaptation through proper language-level

abstractions allows addressing the issues of adaptive software and avoid the decision logic for adaptive applications behaviour to be scattered. Appeltauer et al. [142] present a comparison of presented context-oriented programming languages and acknowledge that they still have some performance penalties.

3.3.2.4. Object-Oriented. This paradigm is based on the concept of *Objects*. An object is a structure that contains data in two forms: (1) Attributes, which are certain variables accessible within the object and (2) Methods, functions that contain code. Fortier et al. [143] introduce a programming and execution model supporting the development and execution of location-aware applications in mobile distributed systems. They inject dependencies between functionalities provided by physical devices and the application as consumers. In this way the developer can request technical equipment by using property constraints. Graff et al. [144] present an architecture for developing context-aware applications. They use and extend the dependency mechanism to connect different layers to avoid cluttering the application with rules or customization code.

3.3.2.5. Holoparadigm. Victoria-Barbosa et al. [145] present holoparadigm, which integrates different programming paradigms in order to develop distributed/embedded systems. The paradigm is based on an abstraction called *Being*, which can be elementary or composed of other beings. An elementary being is an atomic being without composition levels. Is divided into: (1) Interface, describing the possible interactions among beings, (2) Behaviour, that contains actions composed, which implement the beings functionality and (3) history, a synchronized shared storage space in a being, which supports the communication and synchronization among the behaviour actions. On the other hand, a composed being may be formed from other beings that can be executed concurrently and shares the history with its component beings. In order to coordinate the actions a model is used based on blackboard architecture. In further works [146] [147] they propose to apply a programming model specifically designed for the specification of context-aware applications, based on holoparadigm. It is intended to simplify the mobility management and the implementation of C-AS.

3.3.2.6. Model-Driven. As compilers let programmers specify what the machine should do instead of how it should do it, Model-Driven Development (MDD) [148] aims to specify the system via high-level abstraction models that will be transformed into code. Models aim to reduce risk, helping to understand both a complex problem and its potential solutions before undertaking the expense and effort of a full implementation [149]. Sheng and Benatallah [150] presented ContextUML, a modelling language based on the Unified Modelling Language (UML) [151] for the model-driven development of context-aware web services. Serral et al. [152] [153] introduce a model-driven development method for context-aware pervasive systems. It applies the Model-Driven Architecture (MDA) [148] and Software Factories (SF), along with the PerVML modelling language and the SOUPA ontology. Tesoriero

et al. [154] presented CAUCE, a methodology based on MDA [148], to provide a model-driven development of applications for Ubiquitous Computing environments. It is also worthy to be mentioned that there are some Domain Specific Languages (DSL) for the development of context-aware software systems [155] [156].

3.3.2.7. Feature-Oriented and SPL. Feature-Oriented Software Development (FOSD) is a paradigm for the construction, customization, and synthesis of large-scale software systems [157]. A *feature* is a unit of functionality of a software system that satisfies a requirement, represents a design decision, and provides a potential configuration option [157]. Ubayashi et al. [158] try to reduce the complexity of context-aware design by separating concerns. Inside the feature-oriented approach the Software Product Line (SPL) has also been used for the C-AS feature development. SPL is a set of software-intensive systems that share a common, managed set of features satisfying the specific needs of a particular market segment or mission and that are developed from a common set of core assets in a prescribed way⁹. Fernandes et al. [159] [160] propose UbiFEX, an approach that supports feature analysis process for context-aware SPL and feature notation that provides context information representation as well as context rules specification. Parra et al. [161] create a composition of assets binding context adaptation to features for a context-aware Dynamic Software Product Line (DSPL), named CAPucine. In mobile computing, Marinho et al. [162] show a SPL for mobile and context-aware applications, along with the approach used to build it and a verification mechanism [163]. Kramer et al. [164] present an approach to support static and dynamic variability of a single code base of GUI documents within features, providing tool support. They also present a generic context acquisition engine for mobile devices [165]. This engine is used as a single customizable acquisition mechanism which can monitor, manage and disseminate context information to applications that are running on the same device. It also supports the composition of captured context events.

3.3.2.8. Service Oriented. Service engineering can be defined as the specialization of software engineering that targets the development of applications for consumption by end-users [166]. Kapitsaki et al. [166] survey methodologies and solutions for context-aware service engineering. They also acknowledge that the service engineering community lacks of a universally accepted basic design and development principles that can lead to an uniform approach to context-aware service development. Abeywickrama [167] claims for the need of solid software engineering methodologies needed for context ware development and execution. They present a software-engineering-based approach, using a model-driven architecture, aspect-oriented modelling and formal model checking.

3.4. Deployment and Maintenance

Once the system is implemented, a typical life-cycle does not end. It is followed by evaluation and maintenance phases.

Also, techniques such as documentation, training and support are highly recommended, as they help future maintenance and enhancement, as well as user acceptance. This subsection analyses the evaluation and maintenance techniques for a C-AS specialized development. Maintenance is the modification of a software product after its delivery in order to correct faults, improve performance or other attributes¹⁰. C-AS require to handle change faster and cheaper than traditional approaches. An initial design tends to become outdated or insufficient fairly quickly because of changing requirements [44]. Despite the evolutionary nature of C-AS, it is difficult to find in the literature approaches exclusively focused on improving the maintenance of C-AS. In the classical software engineering paradigm, there are four core maintenance activities [168]: (1) Adaptive; (2) Perfective; (3) Corrective; and (4) Preventive.

3.4.0.9. Corrective. It is involved with fixing errors, faults or bugs in the system to restore. A bug is a defect that causes the system not to behave in the expected way. Debugging is the methodical process of finding and reducing the number of software and hardware defects in order to make the system behave in the expected way. It gets difficult to find bugs when it comes to classical programming, so in C-AS, where information is more complex to handle, it gets even more complicated. It has to be acknowledged that there is still very little research in specialized debugging methods for C-AS. Moos et al. [169] propose the use of intelligibility to help users debugging why the system is not working. In their approach, debugging for C-AS is introduced as a mean to assist the users in discovering the cause of the failure. In order to achieve this, they propose to include an information exchange approach from “explanatory debugging”.

3.4.0.10. Preventive. It tries to prevent problems with the system before they occur, anticipating adaptive maintenance needs before users experience problems. Failure handling issues are the most concerned theme of research for C-AS within maintenance. Chetan et al. [69] classify the possible failures into: (1) Device failures, due to the different kind of devices that conform a pervasive system; (2) Application failures, that include application crashes due to bugs, operating system errors, un-handled exceptions, and faulty usage; (3) Network failures, due to the different connection channels that devices can have; (4) Service failures, as service crashes due to bugs and operating system errors, faulty operation of services, wrong inferring and lossy delivery of events. Kulkarni and Tripathi [170] present a framework for programming robust context applications. They use a recovery model that consists of mechanisms for asynchronous event handling and synchronous exception handling. It integrates event handling at the object level with exception handling at the role level to build robust role-based context-aware applications. The exception interface for roles provides the ability for users to handle exceptions. In order to complement their application-level recovery mechanisms, authors suggest to use techniques such as replicating the trusted

⁹Definition from Carnegie Mellon Software Engineering Institute

¹⁰ISO/IEC 14764:2006

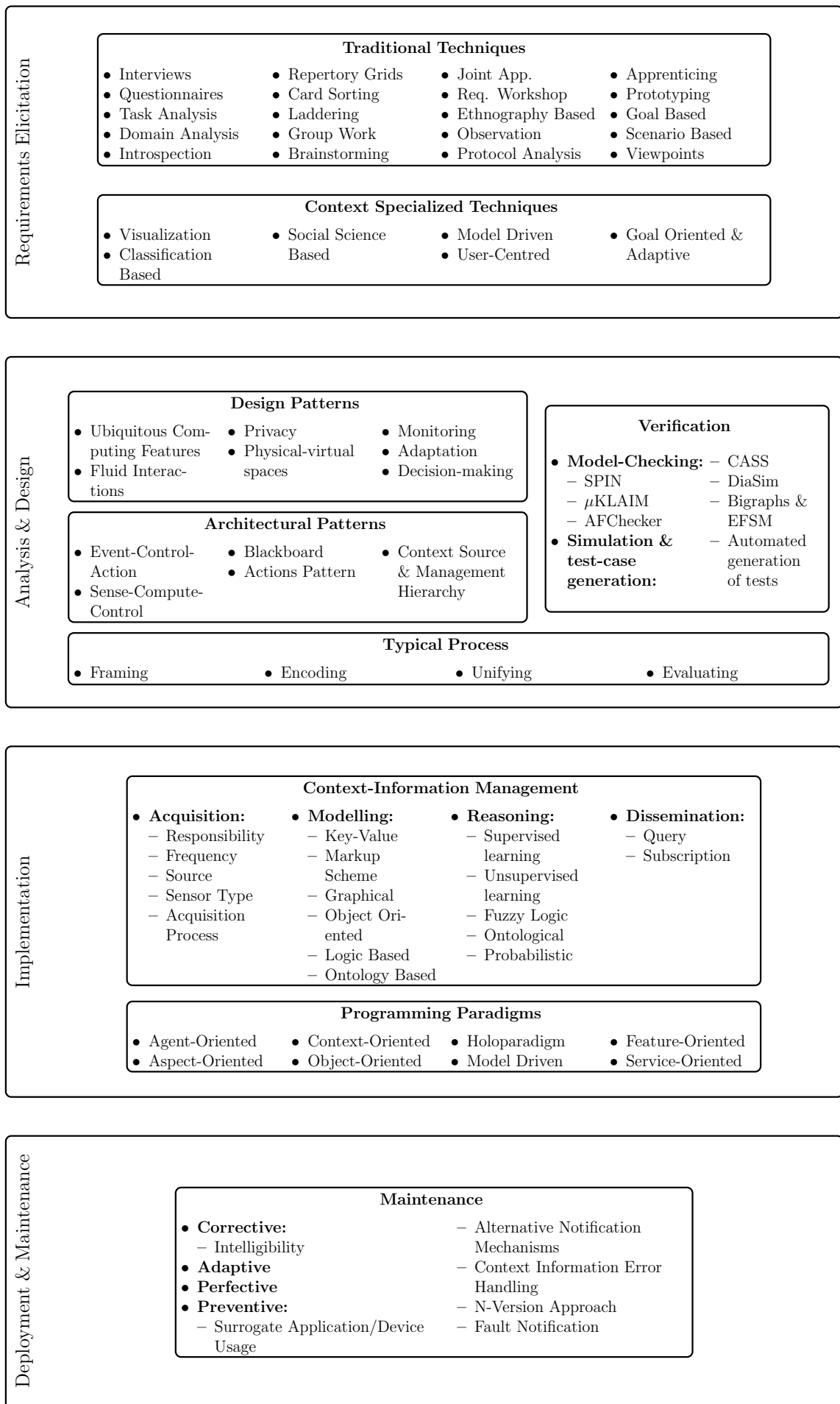


Figure 1: Summary of the techniques/approaches used for Context-Aware Systems Engineering.

servers and running the various managers in a primary backup. The techniques for failure detection can be classified into [69]:

- *Surrogate Application/Device Usage*: Upon failure, the process is restarted and restored from a stable storage device.
- *Alternate Notification mechanisms*: The system notifies the personnel through different devices. If the system discovers that a notification device has failed, it should reroute the message through a different notification channel.
- *Handling errors in sensing and inferring context*: Detecting errors happened during the sensing and inferring phases of context information. This could be done by employing redundancy (multiple sensors that sense the same), so that the results can be compared. Another technique could be to let users identify any errors that might experience.
- *N-Version approach*: Executing in N different implementations the same task and giving the correct answer to an arbitrator.
- *Fault notification mechanisms*: Notify the errors in the devices that the user is using. This creates a dependency graph that could span a large number of applications, services and devices.

3.4.0.11. Adaptive & Perfective. Adaptive maintenance is involved with adapting the system to the ever changing hardware and software developments. The adaptiveness concern present in C-AS literature is more related with the behavioural changes that the context triggers, more than the platforms in which the system will be executing. On the other hand, perfective maintenance is concerned with the improvement of the system features. To the extent of our knowledge, there is very little adaptive or perfective maintenance techniques for the development of C-AS.

4. Methodologies and Tools

The previous section analyses the techniques to implement C-AS. In this one, the focus is on the analysis of existing methodologies, biasing the ones able to offer open source tool support. The aim is to evaluate to what extent there is coverage of tool supported context specialized techniques during the engineering process. First, we assess the needs of a methodology for C-AS development through a questionnaire carried out to 750 researchers that made some work related to the development of these systems. We try to include the vision of experts in order to clarify why there is no commonly accepted methodology for this purpose and to identify which features would a methodology require to have better acceptance in the community. Second, we analyse existing methodologies for this purpose, to finally compare their approaches with the state-of-the-art techniques and the desirable features they should have.

4.1. Assessing the needs of a methodology

In an open question of our questionnaire, contestants were asked about the main reasons for not having a commonly ac-

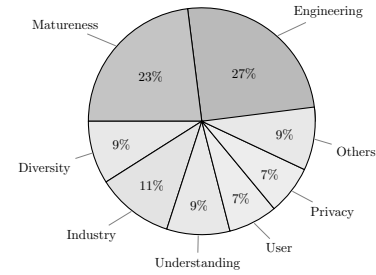


Figure 2: Pie Chart showing the response rate in each of the categories.

cepted methodology or tool for developing marketable C-AS. The responses were classified in eight different categories: Engineering, Maturity, Diversity, Industry, Understanding, User, Privacy and Others. The pie chart from Figure 2, shows the response rate obtained in each of the categories.

- Engineering**: There are lack of standards for representing information, models and general-purpose support. Better managerial support should be provided once C-AS are rolled out along with proper documentation. These systems must integrate other sub-systems (that sometimes use emergent ever-changing technologies). Interoperability issues were recognized as well as the absence of common middleware solutions to ease its development. Besides, the diversity of hardware-software requirements, that trade-off with each other and the absence of common vocabulary/concepts when developing C-AS has been acknowledged. The difficulty to adequate a prototype to a real system has not been evaluated. The research field has a bigger focus in the deliverables more than in the engineering process. Finally, software development companies believe that the application of formal methods in the early stages of a project delays them.
- Maturity**: The immaturity of the field was acknowledged, due to the technology: Expensive, invasive-size, not too powerful/useful or that depends on other technologies that are still evolving. Also, the infrastructure is either still very expensive or it has not been developed for the general public yet.
- Diversity**: Survey respondents also stated that there are many alternatives (SW Architectures, algorithms, methods, techniques, etc.), that can be required in a multiple type of developments (from operating systems to home automation), apart from the diversity of possible scenarios. One of the participants believes that context should be approached in different ways and another that the problem is that “different developers/researchers focus on different aspects”.
- Industry**: There is a need for the industry to invest behind the development of these systems. Some even acknowledge that the reasons why companies do not invest money in C-AS are that: “There is no clear business for “context-something” applications, users don’t care, they have it already” or that “Daily life environments not being equipped with appropriate seamlessly integrated devices for deliv-

ering contextualized application's functions".

- e) *Understanding*: There is no shared understanding of context and systems get the term wrong. One of the participants highlighted that there is no common vocabulary and concepts for C-AS.
- f) *User*: The user is a factor that influences the lack of acceptance. Participants report that the user opinions are not taken into account neither during the development nor while the system is executing. They also believe that users are not confident with C-AS.
- g) *Privacy*: Is one of the reasons behind the absence of acquisition of tools/methodologies. Mainly because the user does not feel comfortable with "a machine knowing too much about humans". They also recognise the lack of full control about the collected data. One of the contributors to the poll, states that user privacy should be taken into account from the first stages of the design.
- h) *Others*: A couple of experts referred to intelligibility and the control about the information of the user and the activities carried out in the environment. Others proposed that there was no union of communities that study the field and there is no reuse of knowledge between researchers/companies. Finally one of the survey respondents believes that presented C-AS do not work in perfect (or nearly perfect) real-time environments.

4.2. Desirable features for a methodology

Participants were also asked to evaluate how important they considered some features in the development of C-AS. From 0 to 5, where 0 is the lowest in importance and 5 the highest. The participants were also asked to suggest features they would include in a methodology that were not considered in the previous questionnaire. The answers were similar to the proposed features. Results can be graphically observed in Figure 3. The choices given where:

- 1.A *Help Defining Context*: The support to understand the context notion within the boundaries of the system to be developed. For example, coining vocabulary to define the system features.
- 1.B *Situations Representation*: The ability to represent situations in which the system is intended to act in a certain way in order to better understand them.
- 1.C *User Interaction Representation*: To be able to represent and model the interactions between the system and the users.
- 2.A *Device Relations Representation*: To represent and model the relations between devices.
- 2.B *Human Relations Representation*: To allow the representation and modelling of human relations and interactions.
- 2.C *Cooperative Environment*: To allow the combination of different environments in order to represent the details that would enable them to work together.
- 3.A *Context Modelling*: The ability to model the context information, for example using ontologies.
- 3.B *Context Reasoning*: To model the reasoning of the context information in order to choose the information that should

infer or the actions that it should take.

- 3.C *Privacy*: Enable the secure use of the information relative to users, so that is not interfered by other people or organizations.
- 4.A *Context Source Management*: It explicitly specifies how the context data will be obtained.
- 4.B *Knowledge Sharing*: It allows to define how will the system distribute the knowledge within its own boundaries and outside them.
- 4.C *Scalability*: Supports the system to handle a growing amount of work effectively, or enables the system expansion/reduction to accommodate that growth/decrease.
- 5.A *Testing*: Ensures that the system meets its requirements.
- 5.B *Quality of Context*: It provides a good quality of precision, probability of correctness, trustworthiness, resolution and contemporaneity of context information [67].
- 5.C *Traceability*: Allows to track a given set or type of information to a given degree.
- 5.D *Conflict Resolution*: Enable the conflict resolution of the C-AS, considering it as the process that enables a system

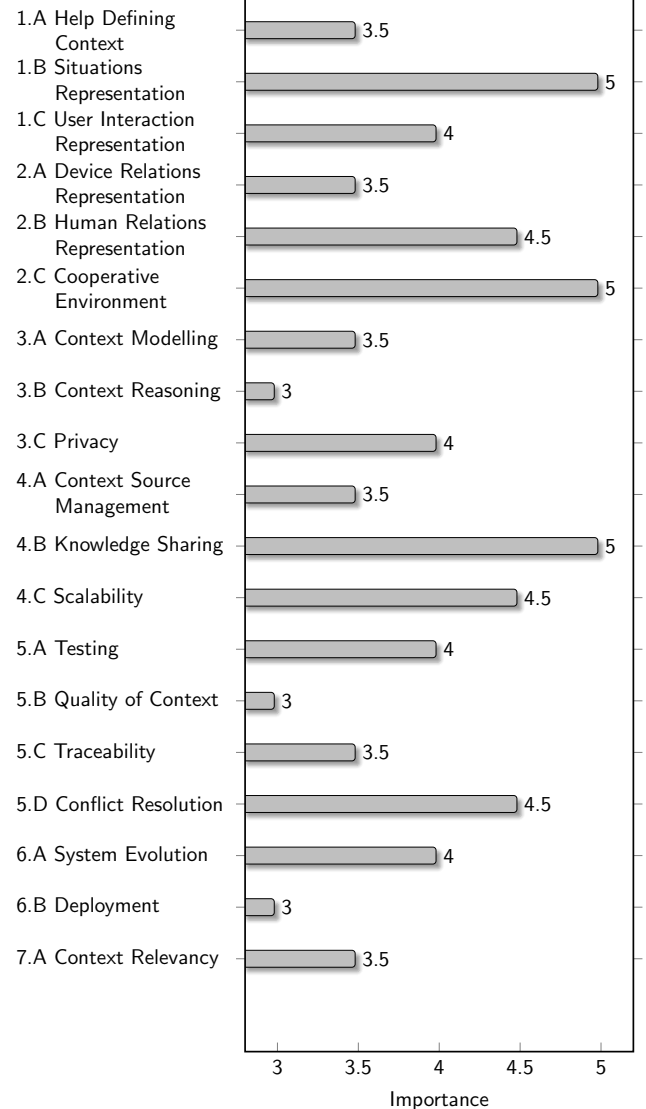


Figure 3: Bar graph showing the importance that contestants would give to including certain features in a context-aware development process.

to provide its safety-critical functionalities by recovering from errors and faults and preventing the system failure.

6.A *System Evolution*: Supports evolution and maintenance of the system.

6.B *Deployment*: Eases the system deployment.

7.A *Context Relevancy*: It allows to define which contexts are relevant depending on the situation.

4.3. Existing methodologies and tools

Following, a brief description of the main existing methodologies is provided. It has to be mentioned that the ones published in conferences are often only theoretical and do not present tool support. For this reason, and due to space restrictions, the methodologies, frameworks and tools here presented are only the ones published on journals.

Context Toolkit [47]: Was one of the first efforts to facilitate the development and deployment of context-aware applications by providing a framework to support it. It provides abstractions to separate the details of how things are done from actually doing them: (1) Context Widget, to separate the details of sensing context from actually using it; (2) Context Interpreter, to reason sensor data using different reasoning techniques; (3) Context aggregator (Server), to collect multiple pieces of context information that are related into a common repository; (4) Enactors, that serve as application units that acquire and take actions based upon context. Widgets, servers, interpreters and enactors are allowed to run on different computers, communicating over a network. This toolkit has been further extended by other authors [38] [45].

ISAMadapt [171]: Provides an integrated environment aimed at building general-purpose pervasive applications. It works on the basis of four main abstractions: Context, adapter adaptation commands, and adaptive behaviour management policies. They focus on supporting the follow-me semantics for building generic applications for building pervasive applications, investigating how context-awareness can be expressed at the programming language level. They offer an integrated software infrastructure both to design pervasive applications and to manage a pervasive environment at global scale.

Context Modelling Language (CML) [172]: Was created as a tool to assist designers exploring and specifying the context requirements of context-aware applications. They propose a set of conceptual models to support the software engineering process, including context modelling techniques, a preference model for requirements representation and two programming models. Along with it, they present an engineering process supported by a software infrastructure. The infrastructure is divided in seven phases: (1) Context Gathering, that allows the use of context interpreters and aggregators; (2) Context reception layer; (4) Context management layer; (5) Query layer; (6) Adaptation layer and (7) Application layer. Their work introduced improved opportunities for tool support into the software engineering process.

*The MUSIC*¹¹ *Project*: Methodology to facilitate the development of adaptive applications in open, heterogeneous Ubiquitous Computing environments. The methodology includes tool support and an adaptation middleware and is based on the separation of concerns between the business logic, context-awareness and adaptation. Design and implementation of context-aware adaptive applications is done via model-driven development. They provide a software development framework for the automation of the adaptation of the software at run-time, including: (I) A modelling language; (II) Generic and reusable middleware components that automate text monitoring & management and adaptation; (III) Tools to support the development: such as design models, transformation, deployment, testing and validation ones.

OPEN: OPEN [174] is an ontology-based cooperative programming framework for the rapid prototyping, sharing, and personalization of context-aware applications for users with diverse technical skills. To meet diverse developer requirements in the development and customization of context-aware applications, it implements three programming modes with diverse complexity: (1) Incremental mode, for high-level users, which supports the creation of new context-aware applications; (2) Composition mode, a programming mode for middle-level users; and (3) Parametrization mode, for low-level users, to enable them customize existing applications.

CA-PSCF [175]: is a model-driven approach to facilitate the creation of a context modelling framework that aims to simplify the design and implementation of pervasive services. It uses model-driven development to provide a systematic methodology that facilitates the generation of modelling frameworks and supports the overall service creation process. The process is as follows: (1) The oAW editor is used to define a code template, which conforms to a context meta-model; (2) With the context editor a context model is defined and validated; (3) With the context model and the code template, the workflow execution engine generates service code. Optionally, models can be transformed; (4) Source domain models are transformed to target domain models in a different domain language.

Human-Centred Computing Methodology for Cooperative Ambient Intelligence: Gross [176] introduces a cooperative Ambient Intelligence methodology, elaborated on existing approaches for organising software engineering and user-centred design processes. It suggests a new human-centred computing methodology for this aim. He acknowledges that many research issues remain for each phase in terms of: (1) Methods to be applied; (2) The adaptation of the method concerning the characteristics of the targeted technological innovation; and (3) The properties of the results of each phase. The life-cycle is divided into:

¹¹MUSIC [32] [173]: Self-Adapting Applications for mobile users in Ubiquitous Computing environments, supported by the European Union under research grant IST-035166 lasting from October 2006 to March 2010.

(A) Identifying the need for cooperative Ambient Intelligence; (B) Understand the situation of use; (C) Specify the user, ambient and cooperation requirements; (D) Produce software and hardware design solutions; (E) Produce embedded interaction and adaptation design solutions; (F) Perform software and hardware evaluation; (G) Perform overall evaluation in living laboratory; (H) Reach specified user, ambient and cooperation satisfaction.

MIRIE [118]: Methodology for Improving the Reliability of Intelligent Environments, is a generic methodology aimed to guide and inform the development of more reliable Intelligent Environments. They propose a strategy which consists in modelling the system to be developed using a simple and very abstract first model, and then refining it through successive steps by constructing models of increasing complexity. They demonstrate that it can be used along with the SPIN tool, which brings modelling capabilities through a language called PROMELA, as well as simulation and verification through the SPIN model checker which can process requirements written in Linear Temporal Logic.

PerDe [177]: Is a development environment that orients the designs of Pervasive Computing applications towards the user's needs. It provides a domain-specific design language and a set of graphical toolkits covering some of the development life-cycle stages for these kind of applications. It provides means to structure the application and allows the developer to build an application: (1) Focusing on the human situations evolved to the physical surrounding; (2) Characterizing the application along with attributes of a new application model by representing the intentions as the task requirements, service specification and instantiation of services in devices abstractly; (3) Specifying a programming structure that trades-off between the function requirement and the device capability; (4) Rapid prototyping.

DiaSuite [127]: Is a tool-based development methodology that uses a software design approach to drive the development process in the domain of Sense/Compute/Control (SCC) applications. It provides a design language called DiaSpec, dedicated to the SCC paradigm, based on two layers: *Taxonomy* and *application design*. The application specification can be represented by its data flow using an oriented graph. In addition, DiaSuite has a compiler that produces a dedicated Java programming framework, guiding the programmer to implement the various parts of the software system (Entities, context operators and control operators). The suite also includes a 2D-graphical renderer, for simulation proposes. The deployment can be done either in distributed execution platform or local.

4.4. Coverage of desirable features

The coverage of the most desirable features of our questionnaire compared to the existing methodologies can be observed in Table 8. We have considered to leave a deeper comparison

| No. | Name | Year | Paper | Requirements Elicitation Technique | Middleware | Verification Technique | Maintenance Technique | Requirements Elicitation Tool | Analysis and Design Tool | Development Tool | Evaluation Tool | Maintenance Tool | Situations Representation | Cooperative Environments | Knowledge Sharing | Human Relations Representation | Scalability | Conflict Resolution |
|-----|-----------------|------|-------|------------------------------------|------------|------------------------|-----------------------|-------------------------------|--------------------------|------------------|-----------------|------------------|---------------------------|--------------------------|-------------------|--------------------------------|-------------|---------------------|
| (1) | (1) | (2) | (3) | (4) | (5) | (6) | (7) | (8) | (9) | (10) | (11) | (12) | (13) | (14) | (15) | (16) | (17) | (18) |
| (a) | Context Toolkit | 2001 | [47] | - | ✓ | - | - | - | ✓ | ✓ | - | - | ✓ | * | ✓ | * | ✓ | × |
| (b) | ISAMadapt | 2002 | [171] | - | ✓ | - | - | - | ✓ | ✓ | - | - | ✓ | * | × | * | ✓ | × |
| (c) | CML | 2006 | [172] | * | ✓ | WB, BB | - | - | ✓ | ✓ | ✓ | - | ✓ | * | ✓ | * | * | × |
| (d) | CAMUS | 2007 | [178] | - | - | - | - | - | ✓ | ✓ | - | - | ✓ | * | * | * | * | × |
| (e) | MUSIC | 2012 | [32] | * | ✓ | Sim. | * | - | ✓ | ✓ | ✓ | - | ✓ | * | * | * | ✓ | × |
| (f) | OPEN | 2011 | [174] | - | - | - | * | - | ✓ | ✓ | - | - | ✓ | * | * | * | ✓ | × |
| (g) | CA-PSCF | 2010 | [175] | - | ✓ | MD | * | - | ✓ | ✓ | - | - | * | * | * | * | ✓ | × |
| (h) | - | 2010 | [176] | So | ✓ | - | - | - | ✓ | ✓ | - | - | * | * | * | ✓ | ✓ | × |
| (i) | MIRIE | 2013 | [118] | - | - | Frm. | * | - | ✓ | - | ✓ | - | ✓ | * | × | * | ✓ | × |
| (j) | PerDe | 2014 | [177] | - | ✓ | Sim. | * | - | ✓ | ✓ | - | - | ✓ | * | × | ✓ | ✓ | × |
| (k) | DiaSuite | 2014 | [127] | - | ✓ | Sim. | Perf. * | - | ✓ | ✓ | ✓ | ✓ | ✓ | * | × | * | ✓ | ✓ |

Table 8: Comparison of existing methodologies to develop C-AS.
 (1) Name: Name of the methodology; (2) Year: Year in which it was published; (3) Paper: paper reference; (4) Requirements Elicitation Technique: "-" = It does not mention any, "*" = Mentions a technique but does not go into details of how it should be, "So" = Social sciences based techniques; (5) Middleware: "✓" = It has a middleware platform, "-" = It has not; (6) Verification Technique: "WB" = White box verification, "BP" = Black box verification, "Sim" = Simulation based, "MD" = Model driven, "Frm" = Formal; (7) Maintenance Technique: "-" = Does not mention any technique, "*" = Mentions a technique but does not go into details of how it should be, "Perf" = Perfective technique; (8) Requirements Elicitation Tool, (9) Analysis and Design Tool, (10) Development Tool, (11) Evaluation Tool and (12) Maintenance Tool: "✓" = Supports the corresponding process with a tool, "-" = Does not offer tool support; (13) Situations Representation, (14) Cooperative Environments, (15) Knowledge Sharing, (16) Human Relations Representation, (17) Scalability and (18) Conflict Resolution: "✓" = Enables the feature, "X" = Does not enable it, "*" = It is not possible to evaluate if the system can have the feature or not.

out of this survey, as it is not possible to measure them in a useful way, due to their disparate aims and themes. Instead, we analyse the state-of-art techniques that could be used for creating the most desirable features of a methodology according to our questionnaire.

Situations Representation: During the requirements elicitation stage, techniques such as Executable Use Cases [75] or the tool presented by Perez and Valderas [76] can be used in order to represent situations that will help to gather context-related requirements. There is no much presence of situations representation during the rest of the most common stages of development. Although specific middleware infrastructures might have features for representing situations during this phase. All context information modelling and reasoning techniques need to enable the situation representation, but there is no support for understanding the situations and the contexts that they are going to be represented, stemming from the requirements.

Cooperative Environments: The cooperation between environments is a technique that stems from Ubiquitous Computing. The support in what regards to techniques for the cooperation between environments in context-awareness is very little, there is more support for this in other fields like Systems Engineering or Distributed Systems, which are out of the scope of this survey.

Knowledge Sharing: Is not taken into account during the early stages of the development. The techniques used for these are Queries and Subscribers as explained in Section 3.3.1.4. Although the deep analysis of programming paradigms is out of the scope of this survey it has to be mentioned that Holoparadigm, enables the knowledge sharing at programming level.

Human Relations Representation: As discussed in section 2.1, the human relationships and interactions are explained using social sciences, which stem from a phenomenological philosophical tradition. Bauer et al. acknowledge that during the C-AS system development, in its life-cycle, starts from a more highlighted phenomenological perspective and proceeds slowly transforming into a more positivist one. We can observe that human relations representation have more presence in early stages of the development, and lose support as the development process continues. Using behavioural studies are helpful to capture more completely human relationships and interactions into requirements of the system as shown by Kjaer [80] and Fuentes et al. [81]. Ethnography based and observation techniques can also be used for this purpose.

Scalability: The majority of the architecture patterns that are specific for C-AS development enable the scalability of the system. From these the highlighted ones are Event-Condition-Action, Context Source and Managers Hierarchy, Sense-Compute-Control and Blackboards. Nevertheless, it has to be mentioned that each of them enable different types of scalability and that a further analysis is out of the boundaries of this survey. Although the intention

is not to have a thoughtful comparison of programming paradigms, Feature Oriented one is prominent. Especially when it tends to Software Product Lines. Finally, the classical adaptive maintenance techniques will enable also the scalability. It is very difficult to measure scalability in Design Patterns, Middleware and Verification.

Conflict Resolution: There is very little support during the whole life-cycle of context-aware development for conflict resolution. Preventive maintenance can help enabling this feature. Also, the framework presented by Kulkarni and Tripathi [170], as well as other techniques like Surrogate Application/Device Usage, Alternate notification mechanisms, Handling errors in sensing and inferring context, N-Version Approach and Fault Toleration Mechanisms.

The results of the comparison show quite weak support in the state-of-the-art techniques for the most desirable features of a methodology, as it can be observed in Table 9.

4.5. Coverage of development stages

Generally, the engineering techniques are more concerned with the design and information management of C-AS, there is less attention focused on other stages the development process. The following subsection analyses the techniques and tool support of the methodologies through these stages.

4.5.1. Techniques

In general, there are no techniques for the early and latest stages of the development process. The human-centred computing methodology [176] mentions that ethnomethodologically informed ethnography can be applied for understanding the situation of use, but they do not deeply explain how the technique should be applied. Also MUSIC [32] and CML [172] mention requirements, but do not explain into detail the techniques. DiaSuite [127] offers perfective maintenance for the system, but does not supporting adaptive, preventive or corrective ones. The most used verification technique is simulation, but generally the verification support is not very strong. Finally, it has to be mentioned that most of the methodologies offer middleware support.

4.5.2. Tool support

There is strong tool support for the design and development of C-AS. Nevertheless, they do not offer support for other stages. No methodology enables the requirements elicitation with a tool, and only DiaSuite [127] allows the maintenance with one. MIRIE [118] offers a strong formal verification support, while MUSIC [32], PerDe [177] and DiaSuite [127] offer verification based on simulation. It has to be acknowledged that DiaSuite [127] is one of the most complete methodologies, regarding to this factors and within the scope of this survey.

5. Conclusion

C-AS have been a pressing issue for the last decades. As the field consolidates, more research related to the development

| | R.E. Context-Aware Specialised Techniques | R.E. Traditional Techniques | Architecture Patterns | Design Patterns | Middle- ware | Verifi- cation | Programming Paradigms | Context Information Management | Deployment & Maintenance Techniques |
|---------------------------------------|-------------------------------------------------|--------------------------------|------------------------------|--------------------|-----------------|-------------------|--------------------------|--------------------------------------|-------------------------------------------|
| Situations Representation | Visualization | Scenario Based | - | - | * | * | * | Modelling, Reasoning | - |
| Cooperative Environments | - | - | - | * | * | * | * | - | - |
| Knowledge Sharing | - | - | - | * | * | * | Holoparadigm | Dissemination, Acquisition | - |
| Human Relations Representation | Social Science Based | Ethnography Based, Observation | - | - | * | * | - | - | - |
| Scalability | - | - | ECA, CS&MH, SCC, Blackboards | * | * | * | FeO&SPL | * | Adaptive |
| Conflict Resolution | - | - | * | * | * | * | * | * | Preventive |

Name: Name of the methodology; Year: Year in which it was published; Paper: paper reference; ECA = Event-Control-Action, CS&MH = Context Source and Managers Hierarchy, SCC = Sense-Compute-Control; FeO&SPL = Feature Oriented and Software Product Lines; “-” = There is no technique; “*” = Not comparable within the scope of this survey.

Table 9: Comparison of the features that a methodology for C-AS development should support related to the state-of-the-art techniques.

of C-AS appears. There are two main paradigms in context that overlap, making difficult its conceptualization and development. Contemporaneous computers exhibit a different contextual awareness than humans, where these last are still better talented for understanding context. Besides, having to program computers forces developers to foresee all the possible contexts, which can be an impossible task. The gap between the limitations of creating human-like contextual awareness and the programming of unforeseeable contexts make the near future of C-AS development should take an intermediate direction. We have analysed the particular ways of interacting with context-aware systems and defined its features, considering these issues. Nevertheless, there are other reasons to have a different development approach, such as the flexibility, reliability, and dependency on a infrastructure to handle context information. The contextual information management has its own particularities, where the data requires challenging treatments for its acquisition, modelling, reasoning and distribution to applications, making the C-AS to be expensive.

As it can be observed, there is a significant difference between the traditional development techniques and methods and the ones specialised in the creation of C-AS. The literature review shows the great amount of different techniques and methods that have been modified from the traditional development to better fit the needs of C-AS creation. We have analysed them through the most common development stages of a system, as it can be observed in Figure 1. The new techniques and methods only focus on certain aspects of the engineering process, sometimes only solving specific problems of a system. The effort in research that developers and researchers carry out, is generally dedicated to what they want to implement. The ad-hoc nature of C-AS makes these research achievements difficult to be reused and compared.

Further, we have assessed through a questionnaire, the basis for a new methodology for C-AS development. In a questionnaire to some experts in the field, we have identified that the main reasons for not adopting these kind of methodologies

were related to the engineering of C-AS, where the diversity of systems and the lack of understanding on the notion of context also influenced. Besides the users are not taken into account and they might face some privacy issues. Also the lack of investment from companies was acknowledged. Besides, we have identified some of the most desirable features for a new methodology. After, we analyse the most acknowledgeable methodologies for the development of C-AS, showing its lack of coverage through all the most common stages of a system development.

The use of contextual awareness in computerized systems, has also opened new possibilities. We have deliberately not included in this survey new emerging areas closely related to context-aware computing that deserve further work such as self-adaptive systems [53], collective context-awareness, self-awareness [179], awareness systems [180], cognitive computing [21] or embodied interaction [181]. The evidence presented in this work supports the need of a more holistic approach in the development of C-AS, in which is taken into account: A) The conceptual limitations on C-AS development; B) The demand of a more user-centred perspective; C) The whole life-cycle of the systems. Current research in C-AS development generally focuses more on addressing particular problems, taking less into account the missing pieces of the bigger picture. We acknowledge that it is ambitious to unify these engineering techniques due to the still maturing state of the field and the ad-hoc nature of C-AS. Nevertheless, it has to be considered that the creation of systems that are able to go out from the laboratories to the market can potentially happen through applying well established engineering techniques. We believe that this survey can encourage the first steps towards achieving a solid *Context-Aware Systems Engineering* (C-ASE) process, that is tailored to the particular demands of these systems.

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