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Uncertain context data management in dynamic mobile environments

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HIGHLIGHTS

- We propose platform for acquisition and processing of contextual big data.
- Platform minimises the power consumption and conserves storage on mobile device.
- We use context data to build rule models that can express user preferences.
- We handle the missing or ambiguous data with uncertainty management techniques.
- Reasoning with rule models is provided by our rule engine for mobile platforms.

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ABSTRACT

Building systems that acquire, process and reason with context data is a major challenge. Model updates and modifications are required for the mobile context-aware systems. Additionally, the nature of the sensor-based systems implies that the data required for the reasoning is not always available nor it is certain. Finally, the amount of context data can be significant and can grow fast, constantly being processed and interpreted under soft real-time constraints. Such characteristics make it a case for a challenging big data application. In this paper we argue, that mobile context-aware systems require specific methods to process big data related to context, at the same time being able to handle uncertainty and dynamics of this data. We identify and define main requirements and challenges for developing such systems. Then we discuss how these challenges were effectively addressed in the KnowMe project. In our solution, the acquisition of context data is made with the use of the AWARE platform. We extended it with techniques that can minimise the power consumption as well as conserve storage on a mobile device. The data can then be used to build rule models that can express user preferences and habits. We handle the missing or ambiguous data with number of uncertainty management techniques. Reasoning with rule models is provided by a rule engine developed for mobile platforms. Finally, we demonstrate how our tools can be used to visualise the stored data and simulate the operation of the system in a testing environment.

1. Introduction and motivation

The notion of context has been important in conceptualisation of computer systems for many years. However, providing its constructive and precise definition proves to be a non-trivial task. In this work mostly the Dey's definition will be used, that describes context as "any information that can be used to characterise the situation of an entity" [1]. For the sake of clarity in this paper the entity is understood as a mobile user or device, while information that characterise its situation is any information that can be directly obtained from the mobile device sensors (so called low-level context), or that can be inferred based on this data (high-level context).

Research in the area of pervasive computing and ambient intelligence aims to make use of context information to allow devices or applications behave in a context-aware, thus "intelligent" way. Context-aware systems have been studied in several fields and developed for over 30 years. However, they are still identified by Gartner, alongside cloud computing, business impact of social computing and pattern based strategy, as *being one of the broad trends that will change IT and the economy in the next* 10 *years.*[1] In

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[1] See: http://www.gartner.com/newsroom/id/3114217.

this work, the primary emphasis is put on, what is called by Gartner, the *Smart Advisors*, narrowed to the concept of *mobile context-aware personal assistants*. Such systems are in the very early phase of commercial development, requiring lot of additional research and prototype implementations, but the interests and hopes associated with this technology are very high.

Building systems that acquire, process and reason with context data is a major challenge, especially on mobile platforms. Mobile environments in which such systems are immersed are characterised by high dynamics. The environment changes very fast due to user mobility, but also the objectives of the system itself evolves, as the user changes his or her needs and preferences. Therefore, constant updates of knowledge models are one of the primary requirement for the mobile context-aware systems. Additionally, the nature of the sensor-based systems implies that the data required for the reasoning is not always available nor certain at the time when is needed. Finally, the amount of context data can be significant and can grow fast, constantly being processed and interpreted under the soft real-time constraints. In fact, such a characteristic makes it a case for a challenging big data application. Furthermore, mobile platforms can impose additional constraints, e.g. related to the privacy of data, but also resource limitations, etc.

In this paper we argue, that mobile context aware systems require intelligent methods to process big data related to context. We identify main challenges and requirement for developing such systems. Then we discuss how they were effectively addressed in the KnowMe project.[2] We distinguish three phases that every context-aware system should pass during the development and later while operating on the mobile device. These phases are *acquisition phase*, *modelling phase*, and *processing phase*. Furthermore, we argue, that in mobile context-aware systems, the additional *feedback loop phase* should be provided to allow for constant adaptability of the system.

In our solution, the acquisition of context data is made with the use of the AWARE platform.[3] We extended this platform with techniques that can minimise the power consumption as well as conserve storage on a mobile device. The data can then be used to incrementally build rule models that can express user preferences and habits. A major challenge is the missing, or ambiguous data. We handle this with number of uncertainty management techniques. Reasoning with rule models is provided by a rule engine developed for mobile platforms. We also demonstrate how tools we developed can be used to visualise the stored data as well as simulate the operation of the system in a testing environment. This work is the continuation of our previous research discussed in [2–5]. The paper presents recent original results discussed in the Ph.D. Thesis [6].

The rest of the paper is organised as follows. In Section 2 we discuss challenges that need to be addressed to deliver context-aware systems on mobile platforms. We identify the important requirements, which are met by the solutions proposed by us. The architecture of these solutions is introduced in Section 3. Its main aspect is the management of context data, discussed in Section 4. In our opinion the techniques we offer are a good example of intelligent handling of big data on mobile devices. We provide an evaluation and applications of this approach, which include adaptable mobile systems able to provide intelligent context-driven recommendations in Section 5. In Section 6 we discuss related works to demonstrate how and why our approach can be considered a step forward compared to the current solutions. The paper ends with concluding remarks in Section 7.

[2] See http://geist.re/pub:projects:knowme.

[3] AWARE is an open source Android instrumentation framework for logging, sharing and reusing mobile context. It was released in 2013 for the research purposes by the University of Oulu. For more details see http://www.awareframework.com.

2. Challenges for context-aware systems on mobile platforms

The notion of context has been important in conceptualisation of computer systems for many years. However, providing its constructive and precise definition proves to be a non-trivial task. A general observation is that *context is about evolving, structured, and shared information spaces, and that such spaces are designed to serve a particular purpose* [7]. Schilit et al. [8] narrow this definition to be *where you are, who you are with, and what resources are nearby*. The common sense definition of context was also given by Bolchini et al. [9], who describe it as a *set of variables that may be of interest for an agent and that influence its actions*. In this work mostly the mentioned Dey's [1] definition will be used, narrowed to the case of mobile environments. In particular this definition includes the low-level contextual information provided by the AWARE framework, and high-level context, derived from low-level information.

Obtaining the low-level contextual information is performed in the first phase of building context-aware systems, which is defined as *acquisition phase*. It is responsible for delivering contextual information to the system both for the purpose of building a model and as an input for the processing phase.

The successive phases of system development are respectively: *Modelling phase*, during which a model of a system behaviour is created, and *Processing phase*, during which the previously created model is executed by the inference mechanism [10]. Classic approach for building context-aware systems assumes that the context is obtained in the acquisition phase, modelled (automatically or by knowledge engineer) in the modelling phase, and finally executed in the processing phase. Such a *three-phased approach*, when applied to mobile context-aware systems, exposes serious drawbacks connected with the nature of environment and the system dynamics. In fact, this approach needs to be redefined to meet the requirements of mobile context-aware systems.

The deep analysis of literature allowed us [2,6] to formulate four main requirements (**4R**) that should be met by every mobile context-aware system in order to assure its high quality and to cope with such drawbacks [11]. These four requirements are:

1. Intelligibility—should allow the user to understand and modify its operation.
2. Robustness—should be adaptable to changing user habits or environment conditions, and should be able to handle uncertain and incomplete data.
3. Privacy—should assure the user that his or her sensitive data are secured and not accessible by third party.
4. Efficiency—should be efficient both in terms of resource efficiency and high responsiveness.

Although the requirements are rather general, it can be shown that not all the phases of building classic context-aware system equally refer to them.

Fig. 1 shows the trade-off between the different modelling approaches and context acquisition layer architectures with respect to the (**4R**) requirements. The upper left triangle concerns the modelling approaches, the lower right triangle concerns context acquisition and processing architectures. Dotted areas reflect gaps which can be filled in order to meet more requirements. The processing phase is characterised by the superposition of these two. For example the context processing phase that will use rules (upper left corner) and direct sensor access architecture (lower right corner) will be characterised by the high intelligibility and privacy, but rather low efficiency and robustness. The combination of the approaches that will allow to meet all the four requirements is non trivial task, and requires a lot of modifications in existing methods for modelling and acquiring context.

The nature of mobile environment in which such systems are immersed, implies important assumptions regarding process of