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A survey on engineering approaches for self-adaptive systems

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ABSTRACT

The complexity of information systems is increasing in recent years, leading to increased effort for maintenance and configuration. Self-adaptive systems (SASs) address this issue. Due to new computing trends, such as pervasive computing, miniaturization of IT leads to mobile devices with the emerging need for context adaptation. Therefore, it is beneficial that devices are able to adapt context. Hence, we propose to extend the definition of SASs and include context adaptation. This paper presents a taxonomy of self-adaptation and a survey on engineering SASs. Based on the taxonomy and the survey, we motivate a new perspective on SAS including context adaptation.

1. Introduction

The complexity of modern pervasive information systems is increasing. Due to the growing number of powerful mobile and embedded devices as well as the omnipresence of relatively high speed wireless networking, users today expect systems to operate whenever and wherever they want, while traveling, at home, at work, or during vacation. Systems are highly distributed and must integrate all available, highly specialized and heterogeneous devices (ranging from embedded sensor nodes to Cloud servers) and data streams (including web data and real time sensor data) that operate in an ever-changing environment with fluctuating network resources and availability. In additions, systems are no longer restricted to small, tightly controllable areas with single administrative responsibility, like smart rooms or buildings but are interconnected, leading to truly pervasive, global systems like Smart Cities or the Internet of Things.

Developing, configuring, and maintaining such systems is a very difficult, error prone, and time consuming task. One promising way to reduce this effort is self-adaptation. A *self-adaptive system* (SAS) is able to automatically modify itself in response to changes in its operating environment [1,2]. The modification is done by adjusting attributes (parameters) or artifacts of the system in response to changes in the system itself or in its environment. In recent years, SASs have seen an increasing level of interest in different research areas like Pervasive Computing, Autonomic Computing [2], and Nature-Inspired (Organic) Computing [3].

SASs provide so called self-* or self-management properties like self-configuration, self-healing in the presence of failures, self-optimization, and self-protection against threats [2,4]. For achieving adaptive behavior, basic system properties are self-awareness and context-awareness [5]. Self-awareness describes the ability of a system, to be aware of itself, i.e., to

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be able to monitor its resources, state, and behavior [6]. Context-awareness means that the system is aware of its operational environment, the so called context [7]. According to Dey, context is "any information that can be used to [characterize] the situation of an entity. An entity is a person, place, or object that is considered relevant to the interaction between a user and an application, including the user and applications themselves" [8]. The system uses sensors to collect information about its context and reasons about the information.

In this paper, we provide a structured overview of self-adaptation and approaches for engineering SASs, analyze future research directions, and motivate the need for a new perspective on self-adaptation in pervasive computing systems. Our main contributions are as follows: First, we develop a taxonomy for self-adaptation that integrates existing views on self-adaptation and specifically context-adaptive systems, which are most relevant to pervasive computing. Second, we survey existing approaches for engineering SASs. Third, we discuss a new type of SASs.

These contributions are directly reflected in the structure of the remaining part of the paper. In the next section, our taxonomy for self-adaptation is presented. In Section 3, we present approaches for engineering SASs. Based on the taxonomy and the approaches, in Section 4 we describe a new perspective of a SAS. A conclusion closes the paper.

2. Self-adaptation

In this section, we summarize different aspects and perspectives on self-adaptation in SAS research and adaptation in general, e.g., in pervasive systems, and present them in a comprehensive taxonomy for self-adaptation. Our taxonomy incorporates the results of an extensive literature review and integrates different existing taxonomies and works on (self-)adaptation. Fig. 1 shows an overview of our taxonomy. In the remaining part of this section we discuss the different dimensions of our taxonomy.

Our taxonomy presents important characteristics of self-adaptation. These issues must be addressed by the implementation of the adaptation logic of such adaptive systems. They influence the reasoning about adaptation as well as monitoring. The presentation of techniques for the implementation of the adaptation logic follows in Section 3.2.

Before going into detail about our taxonomy, we first provide an overview of the main sources and influences for it. Different taxonomies for self-adaptation or adaptation have been developed over the years. As one of the first ones, Rohr et al. describe a classification scheme for self-adaptation research in 2006 [9]. In their work, they classify self-adaptation among the dimensions *origin*, *activation*, *system layer*, *controller distribution*, and *operation*. In 2009, Salehie and Tahvildari present an overview over the landscape of self-adaptive software and related research challenges, including their own taxonomy for self-adaptation [5]. A current overview of adaptation can be found in [10], in which Handte et al. classify the adaptation support for pervasive applications into the dimensions of *time*, *level*, *control*, and *technique*. Macías-Escrivá et al. describe in a recent survey current approaches, research challenges, and applications for SASs [11]. All these surveys provide important insights into the field of SAS. However, none of them gives an integrated view, incorporating all different existing views and aspects. In contrast, the goal of our work is to present such a uniform taxonomy for self-adaptation.

Additionally, several works discuss aspects of self-adaptation. McKinley et al. highlight the difference regarding *parameter* vs. *compositional* adaptation [12]. In [1], the authors discuss the spectrum of adaptation from static activities to dynamic ones. In 2008 and 2010, two Dagstuhl seminars focused on research issues regarding the engineering of SASs [13,14]. Furthermore, there are two surveys that focus on Autonomic Computing. In [4], Huebscher and McCann present an overview of Autonomic Computing and its applications, whereas Dobson et al. highlight autonomic communications in [15].

In [5], Salehie and Tahvildari introduce the 5W + 1H questions for eliciting adaptation requirements:

- When to adapt?
- Why do we have to adapt?[1]
- Where do we have to implement change?
- What kind of change is needed?
- Who has to perform the adaptation?
- How is the adaptation performed?

Other authors formulate similar questions (e.g., [12,16–18]). According to Salehie and Tahvildari, the questions must be addressed during implementation of a SAS [5]. Therefore, it seems reasonable to answer these questions when speaking about adaptation. Our taxonomy shows, how we answer the six questions.

As mentioned above, the different aspects of the taxonomy answer the 5W + 1H questions. However, our taxonomy has a different view on the dimension known as type of control. Automatic control is distinguished from manual control [10]. As a SAS should adapt without user involvement, we do not include this aspect in our taxonomy. In other words, the question: "*Who has to perform the adaptation?*" is not answered with our taxonomy, because the nature of a SAS leads to an automatic type of adaptation. Table 1 shows how the taxonomy answers the questions for adaptation. In the rest of the section, we present our taxonomy in more detail.

[1] The why question was changed for this work. In [5], it was understood as motivation for building SASs.