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A graph-based approach for interference free integration of commercial off-the-shelf elements in pervasive computing systems

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HIGHLIGHTS

- Reflective framework to manage behavior interferences between COTS Ubicomp systems.
- Meta-model for representing the behavior and interaction of COTS Ubicomp systems.
- OpenSim-based pre-deployment test of behavioral/functional interferences.
- Post-deployment introspection and adaption of behavioral/functional interferences.

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ABSTRACT

Commercial off-the-shelf devices and applications are expected to be pivotal in the coming massive deployment of pervasive computing technology in home settings. The integration of these devices and applications in the same household may result in unplanned interactions involving users and entertainment, communication, and health-related devices and applications. These unplanned interactions are a serious concern when, for example, communication or entertainment applications interfere with the behavior of health-related devices. This paper presents a novel graph-based approach for representing the expected behavior of commercial off-the-shelf devices and applications, their interactions, and for detecting interference in pervasive computing systems. A set of home care scenarios is used to assess the applicability of this approach. We then provide two setups where this approach can be applied: (i) in a pre-deployment setup, where simulation is used to detect possible instances of interference, and (ii) at run-time, collecting observations from devices and applications and detecting interference as it occurs. For pre-deployment and simulation we use Opensim to recreate a home household. For run-time, we use Simple Network Management Protocol for systems state introspection and a sliding window mechanism to process the collected data-stream.

1. Introduction

The widespread deployment of pervasive computing systems into households raises serious challenges in the areas of safety, management, economy and technical viability. We are particularly interested in the detection and resolution of functional interferences between commercial-off-the-shelf (COTS) systems/elements typically deployed in pervasive computing systems. Communication systems (e.g. a VOIP phone), home automation systems, and health-care systems are examples of these COTS systems. Functional interference is also known as feature interaction (FI) in other domains such as telecommunication and software engineering [1]. In this paper, we present an overview on FI that may lead to unplanned and unsafe behavior in pervasive computing systems scenarios. We use an abstraction model to represent the behavior and interactions among COTS pervasive systems and a framework to address FI. Our present work complements a previous intra-system FI detection approach [2] with mechanisms for identifying and possibly solving the causes of FI. More precisely, we extend our previous graph-based representation of the state of COTS systems with explicit information on inter-system interactions, allowing that the state of each COTS system can affect and be affected by the state of other COTS systems. We consider that these inter-system interactions occur through a set of environment-bound media. Room temperature, brightness, humidity, soundness and also user related information (e.g., user awareness and interaction) are examples of such media. We also represent the temporal and spatial dependencies on these interactions with the aim of improving FI detection and resolution.

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This paper is organized as follows. The remainder of the introduction presents an overview on FI in pervasive computing and highlights the problems addressed in this paper. Section 2 details the graph-based model and Section 3 presents the proposed approaches for FI detection and resolution. Section 4 describes the Safe Home Care (SHC) reflective architecture and components used to support the evaluation process of the model, FI detection, and resolution approaches. This tool can be used to look for FI before or after COTS systems deployment in the household. In order to look for FI before deployment, we can generate synthetic data *a priori* through an Opensim simulation (cf. pre-deployment). In already deployed scenarios, we collect and process system's state information at runtime via SNMP Introspection. Section 5 discusses use-case scenarios to evaluate the model and compares FI detection approaches with different levels of introspection. Section 6 presents our final remarks and discusses the future work.

1.1. Overview on interference or feature interactions in Ubicomp

Ubiquitous computing environments are becoming part of people's daily lives through the use of a wide set of COTS systems like smart televisions, drug dispensers, home automation and communication systems, and entertainment devices that support and help users at home. Typically COTS systems are developed independently and without the previous knowledge about which systems will be deployed in the same household. Hence, when such systems are purchased, they are not prepared to interwork in the same-space without the previous management information. When a system feature (or service, function) affects the behavior of another system through an interaction medium, a FI interference has occurred. Thus, it is crucial to create a model to represent, reason and *a priori* detect FI. Interactions between two (or more) systems can happen without malfunction (e.g., both COTS contribute to increase the temperature). However they can also be unsafe, when one system disturbs or interferes with the normal operation of another COTS (in this case, we say a FI or interference has occurred).

1.2. Representing the state of COTS systems

The presented approach deals with COTS systems integration in ubiquitous computing scenarios. A behavior model is proposed that comprises a set of expected states for each COTS system. A State corresponds to a COTS system condition at a moment in time (e.g., phone is ringing, user answers phone, drug dispenser notifies a missed intake, etc.). States provide high-level information about what is happening with each deployed COTS system. A given COTS system Behavior corresponds to a set of States that follow an expected sequence. For example, when the phone receives a call ($state_1$) it starts ringing ($state_2$); when the user decides to answer the call ($state_3$), the phone stops ringing ($state_4$); when the user hangs-off the phone the call ends ($state_5$). The following sequence of states $\langle state_1, state_2, state_3, state_4, state_5\rangle$ depicts a possible expected behavior of the *Phone* COTS system. This example depicts a possible interaction between two elements: (i) the Phone, and (ii) a User—particularly, when the user picks up the phone call. The presented model depicts this interaction, e.g., for $\langle state_4\rangle$, as it is affected by the medium "*user interaction*" and it affects "*environment sound*".

1.3. Representing interactions between COTS systems

The interaction happens when a COTS system is in use, and interacts with other systems through one or more media (e.g., concrete environmental variables such as temperature and sound, or more abstract variables such as user attention and awareness). There are two different types of interactions: (i) some COTS states affect media and (ii) other states will be affected by these media. For example, when the phone starts ringing it may affect the user attention (cf. *Awareness* medium) if no other system requests focus, only then the user may answer the call. We consider that the expected behavior of a COTS system is its natural behavior. The expected behavior of COTS system is defined as its behavior when it is deployed in a household without any other COTS system. In other words, it is the designed behavior planned by the manufacturer or learnt by a machine learning approach (e.g., observing COTS state/behavior). Thus, when combining several systems in the same place, the expected behavior of a COTS system may interfere with the natural behavior of other systems through a shared media, possibly causing unexpected behavior. There are two types of interactions: (i) safe, when two COTS systems affect the same media, resulting in a desirable behavior (e.g., two COTS systems attempt to increase the living room's temperature); or (ii) unsafe, when they produce undesirable behavior (e.g., two COTS systems interact constantly with the living room's lights, one switches it on and the other turns it off). Usually the occurrence of interferences between systems are considered or classified as undesirable by researchers. These problems are known as FI [3]. They were introduced in the telecommunications field and later extended to pervasive computing [4]. Calder and Magill consider FI as interferences between services or features (e.g., call forwarding in telecommunications) [1]. Morla and Davies propose a framework for describing and reasoning about the problem of interference in ubiquitous places [5]. We also consider that each COTS system provides a service for a smart space and that these services might interfere with each other.

1.4. Related work on FI detection and resolution

In [6], the authors propose a methodology to avoid interference in smart environments. They record "normal" user interaction patterns with the systems deployed in the smart space. Those patterns are then compared with the observed user behavior. The interference detection is based on a probability model that matches the expected and observed user activity. For example, if the user does not open the refrigerator throughout the day, as usual, this is considered as an abnormal behavior and should be reported. In [7], the authors present their view of Smart Homes where COTS systems deployed at home are connected with web services provided by manufactures, maintenance, banking and provisioning services (cf. Internet of Things—IoT). These systems should be configured to respect pre-defined Service Level Agreement (SLA) contracts that specify risk levels (cf. failure, security, resource usage and costs, etc.). The compliance with SLAs is then checked by analyzing information collected from COTS systems and uploaded into the cloud. They rely on the probabilistic or rule-based models that use data observations from several services and homes to determine different risk probabilities and trigger actions or notifications (e.g., predict failures, adjust operation to energy restrictions). These projects, however, focus on individual COTS systems management and contrary to our approach, do not provide a solution to address the unexpected behavior caused by interactions between deployed systems (cf. Feature Interaction or Interference).

In [4], Kolberg et al. propose a solution to ease the integration of independent systems in an intelligent space. They detect resources that can be shared between systems (e.g., environmental sensors or actuators). The smart space manages concurrent access to resources using system priorities and protocol interworking techniques to avoid interference. This approach focuses on interactions between different systems, but the user is not considered as a possible source or sink of interference. Similar to [4,6], we aim to capture the state of the ubiquitous deployed systems. However, unlike these approaches, we use a graph representation that implicitly