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Prototyping and analysing ubiquitous computing environments using multiple layers ☆

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ABSTRACT

If ubiquitous computing (ubicomp) is to enhance physical environments then early and accurate assessment of alternative solutions will be necessary to avoid costly deployment of systems that fail to meet requirements. This paper presents APEX, a prototyping framework that combines a 3D Application Server with a behaviour modeling tool. The contribution of this framework is that it allows exhaustive analysis of the behaviour models that drive the prototype while at the same time enabling immersive exploration of a virtual environment simulating the proposed system. The development of prototypes is supported through three layers: a simulation layer (using OpenSimulator); a modelling layer (using CPN Tools) and a physical layer (using external devices and real users). APEX allows movement between these layers to analyse different features, from user experience to user behaviour. The multi layer approach makes it possible to express user behaviour in the modelling layer, provides a way to reduce the number of real users needed by adding simulated avatars, and supports user testing of hybrids of virtual and real components as well as exhaustive analysis. This paper demonstrates the approach by means of an example, placing particular emphasis on the simulation of virtual environments, low cost prototyping and the formal analysis capabilities.

1. Introduction

Deploying a system prematurely can be a costly process. For this reason many tools have been developed to specify and to prototype early versions of a design so that the implications of the design can be explored. The development of ubiquitous computing environments brings fresh challenges to prototyping. The impact of a potential design cannot be fully understood without understanding the context in which the design is developed. APEX is a framework that allows designers and developers to model, analyse and simulate ubicomp environments. It is designed to support the development of ubiquitous systems that enhance physical environments with sensors and situated elements. Examples of such elements and sensors are public displays, personal devices, wireless and RFID sensors. The purpose of these ubiquitous systems is to improve the experience of people within the environment. They provide services to occupiers of the space, as they change context, through explicit and implicit interactions.

User experience has been defined as “a person's perceptions and responses that result from the use and/or anticipated use of a product, system or service” (ISO DIS 9241-210, 2008). Issues such as physical texture of the environment may often have an important impact on the experience that occupants have of a space. Ubiquitous computing environments involve situated elements. For this reason changing the design can often involve costly physical reconfiguration. While realistic evaluation requires exploration in the proposed physical environment, some development and evaluation may be achieved using prototypes and simulation. APEX uses 3D virtual worlds to create an immersive experience of the space. Virtual immersive 3D environments can be used to simulate relevant (including textural) aspects of the target space. Such

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simulation enables production of early information about the use of the system. Target users can experiment with the system and provide early feedback. This paper extends previous work (Silva et al., 2012, 2010, 2009) by describing the whole simulation environment. It focuses on the low cost prototyping features of the tool. It illustrates the approach using an example environment within a smart home. The environment alerts carers when a child is likely to be affected by an asthma trigger.

Hands-on evaluation of a prototype is not sufficient in itself to fully recognise the implications of a design. APEX therefore offers a set of patterns, from which properties or heuristics can be developed. These patterns enable further analysis of the system under development. Empirical techniques for analysis are combined with formal analysis seamlessly. The analysis approach echoes the philosophy of Scholtz and Consolvo (2004) who use a set of sample measures to evaluate ubiquitous computing applications. These measures assess whether adequate design principles are satisfied and if the design produces the desired user experience. APEX allows exhaustive analysis of a developed prototype behaviour against a set of properties derived from patterns that are supported by the framework.

The APEX framework offers three complementary perspectives of a system under development.

1. A 3D simulation of the environment (created in a "virtual world" supported by the OpenSimulator[1] web based 3D application server) captures the texture and the spatial characteristics of the environment.
2. Rigorous behaviour models of system behaviour, that include sensors and dynamic objects, can be created, analysed and animated using CPN Tools (Jensen et al., 2007) embedded within the environment.
3. External (physical) devices can be connected to the virtual world using Bluetooth.

Each layer supports a specific type of evaluation. The virtual world simulates the smart environment, making it possible for potential users to explore scenarios within the world. Users can interact with the prototype by manipulating physical handheld devices, using designs proposed for the deployed system, or by controlling avatars located in the virtual world. Avatars can also simulate the behaviour of users autonomously. The modelling layer allows the developer or designer to analyse scenarios systematically, using properties offered by the patterns. Several modelling approaches which were considered as the basis for behaviour models include (Hybrid high-level Nets (HyNets) [26], Communicating Sequential Processes (CSP) (Hoare, 2004), Flownets (Massink et al., 1999), ASUR++ (Dubois et al., 2002), Interactive Cooperative Objects (ICO) (Navarre et al., 2005) and Coloured Petri nets (CPN) (Jensen et al., 2007). CPN was chosen because of the substantial set of tools available and its expressive power in the APEX context. The integration of physical components in the physical layer, for example smart phones, allows exploration of how the evolving design would work.

In summary APEX supports:

- the design of ubicomp environments and the exploration of design alternatives, with a particular emphasis on how users will experience these designs;
- analysis either by animation (similar to program execution) or by more formal analysis of behaviour;
- multi-layered development, in which analysis can be combined with evaluation of virtual simulations and actual implementations of components of the proposed design;
- the whole prototyping cycle (design, experience, test and analysis);
- multiple users with collaborative features (e.g. speaking and chatting) enabling interaction between users.

Section 2 discusses literature that is related to the framework. The example that is used to demonstrate the capabilities of APEX is introduced in Section 3. The APEX framework (Section 4) is then described. The method of developing a prototype of the example is described in Section 5. The analysis process is described in Section 6. Section 7 briefly outlines the results of a preliminary evaluation of the framework. Finally conclusions and future work (Section 8) are outlined.

2. Related work

The evaluation, simulation and analysis of ubiquitous systems is already a rich area of research. Relevant research can be categorised in terms of early evaluation of ubiquitous systems, the development of prototypes using virtual environments and analysis techniques.

2.1. Early evaluation of ubiquitous systems

Current prototyping tools (see IEEE Pervasive Computing, 2005 for an early overview of approaches) are mostly concerned with single devices, rather than systems of systems combining people and devices. Examples are UbiWise (Barton and Vijayaraghavan, 2003), UbiREAL (Tamai et al., 2006), d.tools (Hartmann et al., 2006), Topiary (Li et al., 2004) and Activity Studio (Li and Landay, 2008). It is recognised that prototypes should be explored within their envisaged setting (Abowd et al., 2005) and therefore tools produce prototypes either for the real world (for example, d.tools, Topiary and Activity Studio) or for a virtual world (Ubiwise and UbiREAL).

d.tools supports the prototyping of physical devices. It combines elements of a real and simulated world, from design to test and analysis. It allows the development of both physical components (e.g. sensors and actuators) and virtual components in a device editor. The behaviour of the device is modelled using statecharts. The statecharts can be animated for user testing and behaviour can also be analysed. Activity Studio, in contrast, is a tool for prototyping and *in-situ* testing of context aware software applications. It supports the testing of low-cost prototypes in experimentally relevant environments over extended periods. It is possible to explore prototypes over time involving several users, either using real sensors or gathering data from users. Topiary, on the other hand, allows users to explore context aware prototypes using a storyboarding approach. Several other tools use Wizard of Oz techniques to avoid the need for physical sensors and actual physical spaces.

These evaluation and prototyping techniques are valuable but they do not address the interplay between device and environment *in situ* (Abowd et al., 2005). This interplay is crucial to understanding how the system works as a whole. Displays, devices and sensors form an integrated whole that, together with the physical characteristics of the environment, contribute to the texture of the resulting system.

UbiWise and UbiREAL simulate ubiquitous systems using virtual environments. The simulation acts as a development test bed for the devices and software. The APEX framework, in contrast, supports the design of the environment itself, with a particular emphasis on how users will experience it.

[1] http://opensimulator.org/ (last accessed: 3 December 2012).