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Hybrid reality-based user experience and evaluation of a context-aware smart home

Dong Woo Seo [a], Hyun Kim [b], Jae Sung Kim [a], Jae Yeol Lee [c,*]

[a] KISTI, Daejeon, South Korea
[b] ETRI, Daejeon, South Korea
[c] Chonnam National University, Gwangju, South Korea

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ABSTRACT

A smart home is considered as a new environment that can apply the use of Internet-of-Things (IoT). For that reason, the realization of the smart home requires the seamless integration among humans, physical objects, and user interactions. However, this accomplishment is currently unrealistic and expensive, considering the need to construct different types of physical smart homes and the need to evaluate them through the various aspects of user experiences. Thus, virtual reality is widely used for the preliminary test and pre-evaluation. However, there is little work to systematically evaluate the user experiences such as usability, natural and intuitive interaction between human and physical objects, and usefulness. This paper proposes a hybrid reality-based user experience and evaluation of a context-aware smart home. The user experience is provided by the integration of egocentric virtual reality and exocentric augmented reality. Furthermore, to make a smart home environment more natural and realistic, a world-in-miniature (WIM) of the smart home has been constructed where various kinds of tangible and physical smart home activities are allowed for prototyping a number of appliances, sensors, and human-physical object interactions. To evaluate the proposed approach, both qualitative and quantitative experiments are performed and analyzed. The proposed approach aims to provide developers and end users or consumers a useful tool for understanding and experiencing the smart home environment. Prior to the development of a physical smart home environment, it is essential for developers and designers to validate smart home services regarding context and visual awareness. Furthermore, it must be used for consumers or future residents to evaluate the smart home such that developers provide more customer-oriented environment and capture related problems before constructing the home.

1. Introduction

The Internet of Things (IoT) based on communication and information technology (ICT) will significantly change the way we live, shifting interactions between people at a virtual level in several contexts from the professional life to social relationships. Thus, the concept of IoT can be applied to various domains such as smart environment, transportation and logistics, healthcare and personal and social domains. A smart home, in particular, is considered to provide people a new type of smart space and lifestyle, significantly improving our quality of life [1–6].

However, the smart home usually requires the integration of many heterogeneous sensors and service applications in deployment and realization. Thus it is difficult to implement and test it in physical home environments since it takes a long time from building the scratch [3,4]. In addition, the physical smart home environment is inflexible because of its predefined spatial structure. Furthermore, adding or extending the sensors and devices is difficult and often associated with high financial costs [7]. This makes it impossible to have a scalable testbed. For this reason, it is required to develop a scalable and cost-effective way not only to demonstrate and deploy extensible smart home technologies but also to evaluate user experiences.

Although many previous research works have developed prototype systems to demonstrate the benefits of their smart home services, these works have typically focused on basic system integration such as interconnecting actuators, sensors, computers, and other devices in the environment. Integrating numerous heterogeneous elements is mostly a manual and ad hoc process. Unfortunately, many of these systems lack the ability to evolve as new technologies emerge or as an application domain matures [4].

* Corresponding author at: Department of Industrial Engineering, Chonnam National University, 77 Yongbong-ro, Buk-gu, Gwangju 500-757, South Korea.
E-mail address: jaeyeol@jnu.ac.kr (J.Y. Lee).

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Thus, a simulation-based evaluation and experiencing was suggested to solve this problem by testing various kinds of devices (e.g., virtual devices or real devices) and applications, validating interfaces and functions, and displaying scenarios [8]. In particular, the simulation-based testing and experiencing system should aim to provide architects, developers, and designers a useful tool for understanding and visualizing the interaction between environment and people [9]. Prior to the development of a physical smart home environment, it is essential to validate smart home services with respect to context and visual awareness for different users. Furthermore, it must be used for customers to evaluate the smart home system.

Many previous works have suggested different approaches to realize the smart home through simulation such as context-awareness and interactive visualization. Context awareness is considered one of the important issues in the smart home for testing various situations. Interactive visualization is also considered the other important issue for providing realistic interaction and immersive simulation of the smart home and thus verifying its feasibility and adaptability. Regarding context awareness and interactive visualization, the simulation-based approach must provide a new way of testing and validation of the smart home by providing a rich set of user experience before installing it in a real environment [7,9]. Furthermore, it is necessary to demonstrate the possibility of obtaining valid context information from virtual sensors as well as physical sensors, which can provide an additional solution to more easily and efficiently promote experiencing and testing [10,11].

Although some research works have suggested many context aware smart home systems and others suggested interactive visualization systems, we realized that more sophisticated research on the user experience of the smart home is still needed since most of the previous researches focused on the virtual or context-aware aspect of the smart home and excluded the physical aspect or vice versa. In addition, they have not considered both context awareness and user experience to evaluate and validate the smart home. We found that one solution is to combine virtual and augmented reality (VR/AR) with physical reality in which dynamically changing physical objects are virtually modeled and then embedded into the physical smart home environment. Furthermore, interactive visualization should be synchronized to virtual and physical objects through context awareness.

VR completely immerse a user inside a virtual and synthetic environment. While immersed, the user cannot see the real world. On the other hand, AR allows the user to see the real world, with virtual objects superimposed upon or composited with the real world. Therefore AR supplements reality, rather than completely replacing it [12]. In particular, immersive virtual reality (VR) technology has been popular thanks to a new generation of Head-Mounted Displays (HMD) providing stereoscopic views with high fidelity and low cost [13,14]. Augmented reality (AR) technology has also become popular because of advances in vision-based tracking techniques and to the adaptability to mobile devices. For these reasons, VR and AR have been used to provide user experiences in various applications [7,15,16]. Note that the performance and the usability of 3D user interfaces also play a critical role in the overall immersive experience for the user. However, VR with HMD has a drawback in providing natural interactions with virtual objects although various input devices and interaction techniques have been proposed for the basic 3D User Interfaces (3DUI) tasks of navigation, selection, manipulation, system control, and symbolic input [13]. AR cannot provide immersive experience compared with VR although it can be combined with real physical environments. Both VR and AR have similarities and differences, but they can complement each other in terms of the spectrum of virtual and physical integration. Ideally, it would appear to the user that the virtual and real objects coexisted in the same space. Therefore, it would be more attractive and reasonable to provide both experiences to users. Furthermore, interaction with virtual objects through context awareness in VR/AR environments should occur in real-time, providing convincing feedback to the user and giving the impression of natural interaction and immersion.

This paper proposes a new approach to the user experience and evaluation of a context-aware smart home through hybrid reality-based interactive visualization. The experience through interactive visualization is provided by the integration of egocentric virtual reality-based immersion and exocentric augmented reality-based intuitiveness. A more cost-effective user experience of the smart home can be provided in the hybrid reality environment through a world-in-miniature (WIM). The WIM of the smart home is constructed where tangible and physical smart home activities are allowed for prototyping a number of appliances, sensors, and human-physical object interactions. Another important characteristic of the proposed approach in the hybrid reality environment is its ability to dynamically superimpose virtual objects into the WIM-based smart home environment and to test bi-directional interactions among virtual-physical objects through context awareness and multi-modal interactions, thus rendering it easy to experience the feasibility and adaptability of the smart home. Since most previous works mainly studied one aspect of developers not the aspect of customers or both, our approach can provide a new way of evaluating the smart home with respect to the different aspects of users (in particular, end user or consumer aspect), which is essential to apply pre-evaluated smart home environment to real smart home environments. We will show the effectiveness and advantage of the proposed approach by several implementation results and the evaluation through user study. Section 2 reviews related work. Section 3 overviews the proposed approach. Section 4 demonstrates how to provide an immersive and interactive user experience of the context-aware smart home services in the hybrid reality environment. Section 5 systematically evaluates the proposed approach by a user study. Section 6 discusses the evaluation of Section 5. Finally, Section 7 concludes with a number of remarks.

2. Literature review

Many researchers have suggested different simulation-based approaches to realize the smart home through context awareness and interactive visualization.

Context awareness can play an important role in realizing smart home since the IoT environment is characterized by many smart sensors that can detect a variety of different contexts. The collecting, modeling, reasoning, and distribution of the context in relation to sensor data play a critical role in smart home environment [17]. Context-aware systems try to collect contextual information from sensors, analyze it, and deliver it to the application services. As one of the earlier efforts to provide framework support for context-aware application development, the aim of Context Toolkit is to facilitate the development and deployment of context-aware applications [18]. This is one of the earlier efforts of providing framework support for context-aware application development. Aura is a task-oriented system based on a distributed architecture and focuses on different computational devices used by human users every day [19]. Gaia is a distributed middleware infrastructure that coordinates software entities and heterogeneous networked devices contained in a physical space. Gaia is designed to support the development and execution of portable applications for active spaces – programmable ubiquitous computing environments in which users interact with several devices and services simultaneously [20]. CAMUS is a context-aware