Applied Ergonomics 56 (2016) 11–18

Contents lists available at ScienceDirect

Applied Ergonomics

journal homepage: www.elsevier.com/locate/apergo

Suitability of virtual prototypes to support human factors/ergonomics evaluation during the design

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ARTICLE INFO

Article history:
Received 30 June 2015
Received in revised form
23 February 2016
Accepted 27 February 2016

Keywords:
Virtual prototyping
Human factors/ergonomics
Virtual environment

ABSTRACT

In recent years, the use of virtual prototyping has increased in product development processes, especially in the assessment of complex systems targeted at end-users. The purpose of this study was to evaluate the suitability of virtual prototyping to support human factors/ergonomics evaluation (HFE) during the design phase. Two different virtual prototypes were used: augmented reality (AR) and virtual environment (VE) prototypes of a maintenance platform of a rock crushing machine. Nineteen designers and other stakeholders were asked to assess the suitability of the prototype for HFE evaluation. Results indicate that the system model characteristics and user interface affect the experienced suitability. The VE system was valued as being more suitable to support the assessment of visibility, reach, and the use of tools than the AR system. The findings of this study can be used as a guidance for the implementing virtual prototypes in the product development process.

1. Introduction

A virtual prototype is a computer simulation of a physical product that can be presented, analysed and tested from various aspects. The process of constructing and testing a virtual prototype is called virtual prototyping (VP) (Wang, 2002). In recent years, the use of VP has increased in the product development process due to the improved availability and lowered prices of VP technologies (Choi et al., 2015). However, companies do not necessary know how to use VP technologies effectively, and for that reason they do not gain the full potential from it.

Virtual prototyping supports the evaluation of human factors/ergonomics (HFE) already in the early design phase. According to the principles of human-centred design (HCD) ISO 9241-210 (2010) and participatory design (Muller and Kuhn, 1993) of interactive systems, it is crucial to involve end-users and other stakeholders in the design and evaluation of technological products. International Ergonomics Association (IEA, 2000) defines HFE as “the scientific discipline concerned with the understanding of interactions among humans and other elements of a system, and the profession that applies theory, principles, data and methods to design in order to optimize human well-being and overall system performance”. Similarly, “Practitioners of ergonomics and ergonomists contribute to the design and evaluation of tasks, jobs, products, environments and systems in order to make them compatible with the needs, abilities and limitations of people” (IEA, 2000). According to Dul et al. (2012), HFE seeks to improve performance and well-being through systems design.

Virtual prototypes can be different in their level of virtuality and fidelity. Milgram et al. (1995) have developed a reality–virtuality continuum which is a continuous scale ranging between the completely virtual, virtuality, and the completely real, reality. Using the definition by Kalawsky (1993), virtual environment (VE) uses virtual reality (VR) technologies in order to provide human beings with the means of manipulation and sensory modalities. In practice, it means that humans are able to navigate in the VE (e.g. move from one place to another), manipulate objects (e.g. turn a steering wheel) and get sensory feedback (e.g. visual or auditory). The term mixed reality describes environments between virtual and real. An example of mixed reality is augmented reality (AR), which means that the user is able to see the real world, with virtual objects superimposed upon or composited with the real world (Azuma, 1997).

Several studies (e.g. Bordegoni et al., 2009; Bullinger and Dangelmaier, 2003; Cecil and Kanchanapiboon, 2007; Karkee

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http://dx.doi.org/10.1016/j.apergo.2016.02.015

et al., 2011; Kremer, 1998; Kim et al., 2011; Kulkarni et al., 2011; Lawson et al., 2016; Park et al., 2009; Seth et al., 2011) state that VP has been considered as a powerful prototyping solution to overcome the shortcomings of conventional prototyping methods. They conclude that the production of a physical prototype is costly and time-consuming and, therefore, the reduction of the number of physical prototypes would shorten the time to market. Mujber et al. (2004) summarise the benefits of virtual reality in manufacturing applications in three categories: design, operations management and manufacturing processes. The benefits at technological, design and business levels are described by Aromaa et al. (2012). In addition, Leino (2015) models the business and organisational value of VP.

In the prototype fidelity domain, there are related studies that do not apply virtual reality techniques but compare, for example, computer and paper prototypes (Boothe et al., 2013; Lim et al., 2006; Sauer and Sonderegger, 2009; Sauer et al., 2010). These studies show that the main usability issues can be identified with prototypes of different fidelity levels. Some usability issues, however, cannot be evaluated using these prototypes, and therefore, Lim et al. (2006) state that it is important to determine what aspects need to be evaluated before building low-fidelity prototypes.

Perez and Neumann (2015) requested consideration of VP tools in supporting the integration of HFE issues in the design of new workplaces. They identified the importance of the utility of the VP tools from the ergonomists' and engineers' points of view, also listing categories to be considered, such as time, cost, training, difficulty to use, trustworthiness, graphics, flexibility, usefulness, and report presentation. Other approaches to support the development and usability of VP systems have been suggested by Stanney et al. (2003); Sutcliffe and Gault (2004); Eastgate et al. (2014). In addition, Jia et al. (2012) proposed a method for the design of more usable and efficient virtual training systems. Canuto da Silva and Kaminski (2015) proposed a procedure for the selection of virtual and physical prototypes in the product development process.

According to Ma et al (Ma et al., 2011), the collaborative VE is a useful tool for supporting complex product design. Therefore, VP can be used to support communication and interaction between different stakeholders during design reviews (Aromaa et al., 2012; Bordegoni et al., 2009; Bordegoni and Caruso, 2012; Kremer, 1998; Leino, 2015; Shen et al., 2010). Huet et al. (2007)claim that design reviews are efficient tools for sharing information about the product and for managing knowledge exchange. In addition, the use of VP during the HCD is a complex task and therefore approaches to support the use of virtual prototypes in HCD have been developed (Barbieri et al., 2013; Bordegoni et al., 2009, 2014; Broberg et al., 2011; Ferrise et al., 2013; Hall-Andersen and Broberg, 2014; Mahdjoub et al., 2013).

The use of VP in HFE evaluation has been studied in several research projects such as those by Wilson and D'Cruz, 2006; Bullinger and Dangelmaier, 2003; Park et al., 2009; Bordegoni et al., 2009; Karkee et al., 2011. It seems that the fidelity of the prototype does not affect the subjective evaluation of the usability of the product, but it affects the task performance and therefore the HFE evaluations. Bruno and Muzzupappa (2010) discovered that VR techniques are valid alternatives to traditional methods for the usability evaluation of product interfaces, and that the interaction with the VE does not invalidate the usability evaluation itself. However, in VEs users may become fatigued more quickly, require more time and greater effort and experience more discomfort and more task difficulty than in a real environment (Hu et al., 2011). Therefore, Wu et al. (2012) discovered that the results from the 1991 revised NIOSH Lifting Equation RWL tool were significantly larger in a virtual prototype than in physical prototype. Pontonnier et al. (2013) compared assembly tasks in a real environment and in VEs with and without haptics. They discovered that the mechanical limitations of the haptic device lowered the sensation of presence and resulted in an increase in the difficulty compared to real environment and VEs without haptics. Lawson et al. (2015) compared virtual and physical prototypes and discovered that virtual prototypes had lower validity and reliability than physical ones for identifying entry and exit issues in passenger vehicles. Gavish et al. (2013) studied the use of VR and AR training for industrial maintenance and assembly tasks. They found that the AR system was suitable for training but the VR system's suitability needed to be evaluated further. Nee et al. (2012) review the use of AR applications in design and manufacturing.

Digital human models (DHMs) can be used for proactive analysis of HFE in design (Chaffin, 2005; Demirel and Duffy, 2007). Lämkull et al. (2009) found that DHMs have been proven to correctly predict HFE issues for standing and unconstrained working postures. In addition, DHMs can provide information to designers, for example, about workers' reach, clearance, vision, posture and strength capabilities (Feyen et al., 2000; Sanjog et al., 2015). Nevertheless, the functionality of DHMs still needs improvement (Chaffin, 2007; Lämkull et al., 2009). In this paper, however, we discuss only real users using virtual prototypes (see a mixed prototyping framework in Bordegoni et al., 2009).

Despite the research carried out in the area of VP, there is not enough knowledge of the efficient use of VP in HCD. In particular, the question regarding which type of virtual prototypes should be used in HFE evaluation remains open. Therefore, companies who use VP in design are unable to gain full potential from it. The purpose of this study was to evaluate the suitability of VP to support HFE evaluation during the design phase. Two virtual prototypes, augmented reality and virtual environment, were selected to be tested in this study. They were chosen because both technologies can be used to visualise new design solutions such as a maintenance platform for machines. The goal was to find out differences between different fidelity level prototypes in the reality–virtuality continuum. The findings of this study can provide guidance for the preparation and use of virtual prototypes in HFE evaluation. The paper is organized as follows. Section 1 presents related work. Section 2 describes the design of the study. Section 3 provides results from the tests. Section 4 discusses collected results and Section 5 draws conclusions.

2. The study design

2.1. Experiment design

The goal of the study was to evaluate the suitability of VP to support HFE evaluation. A semi controlled between-group experiment was employed in the study. Nineteen participants from a company that offers minerals processing solutions and services took part in the experiment. They were designers or other stakeholders from a product lifecycle of the maintenance platform of a rock crushing machine. They all deal with HFE issues such as performance and well-being during the design process. The independent variable was the type of a virtual prototype: AR prototype and VE prototype. The two experiments will be called AR test/AR system and VE test/VE system for the remainder of this paper. Dependent variables measured in this experiment were the suitability of the virtual prototype for the HFE evaluation, and the overall assessment of the design object. In addition, subjective workload was evaluated.