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Precision study on augmented reality-based visual guidance for facility management tasks

Fei Liu[a,b], Stefan Seipel[a,b,*]

[a] Department of Industrial Development, IT and Land Management, University of Gävle, Gävle, Sweden
[b] Centre for Image Analysis, Uppsala University, Uppsala, Sweden

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ABSTRACT

One unique capability of augmented reality (AR) is to visualize hidden objects as a virtual overlay on real occluding objects. This "X-ray vision" visualization metaphor has proved to be invaluable for operation and maintenance tasks such as locating utilities behind a wall. Locating virtual occluded objects requires users to estimate the closest projected positions of the virtual objects upon their real occluders, which is generally under the influence of a parallax effect. In this paper we studied the task of locating virtual pipes behind a real wall with "X-ray vision" and the goal is to establish relationships between task performance and spatial factors causing parallax through different forms of visual augmentation. We introduced and validated a laser-based target designation method which is generally useful for AR-based interaction with augmented objects beyond arm's reach. The main findings include that people can mentally compensate for the parallax error when extrapolating positions of virtual objects on the real surface given traditional 3D depth cues for spatial understanding. This capability is, however, unreliable especially in the presence of the increasing viewing offset between the users and the virtual objects as well as the increasing distance between the virtual objects and their occluders. Experiment results also show that positioning performance is greatly increased and unaffected by those factors if the AR support provides visual guides indicating the closest projected positions of virtual objects on the surfaces of their real occluders.

1. Introduction

Augmented reality (AR) supplements the real world with virtual information through computer displays in an interactive manner. With this technology, a user's sensory perceptions of the real world are enhanced, which allows him or her to understand the surroundings more thoroughly and therefore perform tasks in hand more efficiently. The potential capability of AR to fundamentally change the way people access useful information closely related to the world around them has attracted a vast amount of research and developments in the field during the past two decades, which leads to the incessant extension of the application areas. When Azuma published his influential survey paper on AR in 1997 [1], AR was mainly explored in medicine, manufacture of complex machinery and military. Thirteen years later, not only did the AR applications in those traditional areas become more sophisticated but it had also seeped into personal information systems, offices, entertainment and education, as summarized in the survey of Van Krevelen and Poelman [2].

1.1. AR and built environment

Among these rapidly growing application areas of AR, the Architecture, Engineering, Construction and Facility Management (AEC/FM) industry has attracted much attention lately. This can be seen from the overall increased trend of AR-related publications in AEC/FM reported by [3]. AEC/FM projects usually involve a lot of information. According to [4], a typical large-scale project (10 million US dollars or more) can generate 50 different types of documents with 56,000 pages in total, equivalent to 3000 MB of digital contents. In view of such a large amount of information as well as the intensive demand of accessing it, the AEC/FM community has been vigorously adopting information technology to digitally manage various phases of a construction project [5,6]. The recent development in this aspect is the Building Information Modeling (BIM) technology [4,7], which aims to overcome information fragmentations existing in both project phases and collaborations between different roles [8]. Although BIM and related technologies greatly bring down the costs and increase the efficiency of construction projects in the form of information integration, construction practitioners still need to mentally apply the digital

* Corresponding author.
E-mail addresses: liufei787@gmail.com (F. Liu), stefan.seipel@hig.se (S. Seipel).

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information to the physical world when they are performing such tasks as on-site planning, management and inspection [9]. BIM and related technologies provide little answer to the challenge of seeing and manipulating virtual data directly in the physical world where they are related [10]. AR, on the other hand, shows substantial promise in tackling such a challenge by presenting a natural user interface to the virtual information which overlays on the real world directly and thus minimizes possible mistakes caused by the disconnection between the virtual and the real world.

As vital parts of FM, Operations and Maintenance (O&M) can especially benefit from AR technologies [11]. This is owing to a unique capability of AR, which is often referred to as "X-ray vision" visualization [12]. Within the context of built environment, there are plenty of facilities and installations that are not readily visible for maintenance workers, for example, electricity wires inside a wall or a ceiling, pipelines buried underneath roads. The application of AR allows workers to see through solid objects and visualize maintenance targets *in situ*. Consequently, the usefulness of AR in terms of O&M is rather obvious.

On the other hand, in order for an AR application to be useful, the accuracy of registration between the real and the virtual world is of utter importance [1]. This is particularly true for O&M tasks dealing with hidden infrastructure in built environment. Generating virtual overlay of the infrastructure which accurately aligns with the occluding physical object is the prerequisite for further maintenance procedures, such as locating leaking pipes behind a wall or drawing up a plan for replacing current HVAC (Heating, Ventilating and Air Conditioning) utilities of a room. Furthermore, inaccurate registration for underground infrastructure can lead to mis-located excavation operations which waste time, money and even cause life danger [13,14]. Therefore, constant research efforts have been made to perfect the tracking and registration aspect of AR systems, with improved hardware and software technologies regularly reported. Some examples of the latest results can be found in [15–17].

However, no matter how accurate an AR system is, in the end it has to be put into the hands of users to realize its purpose. In other words, if we regard an AR system as a user interface into the virtual information, there is an interaction loop involving users perceiving its output, mental cognition processing the output and finally determining a motor action [18]. Therefore, the output received by users contains errors from both themselves and the system. In this study, we aim to explore factors that affect users' ability to correctly establish spatial relationships between virtual objects presented through AR "X-ray vision" and real objects in the O&M setting. To this end, we designed and conducted user experiments which looked into an intuitive application scenario of locating virtual pipes behind a real wall (for an illustration see Fig. 1a) via a hand-held video see-through AR system.

1.2. Research objectives

In order to locate any 3D building component represented as a visual overlay upon real solid surfaces (e.g. walls), users of an AR system need to mentally establish its true spatial position in terms of its actual 3D position behind the real solid surface or, equivalently, in terms of its closest projected position on this surface. In our case of virtual pipes, these positions are the black lines on the wall plane as illustrated in Fig. 1a, or as indicated by O in Fig. 1b. Due to a spatial distance between the pipe and the wall, a naive determination of the pipe's closest location on the wall would be exactly where the line of sight intersects with the wall, namely at point Q in Fig. 1b, which results in a horizontal parallax error E_p. According to Fig. 1b, the expected E_p can in this case be predicted as

$$E_p = \frac{d \cdot h}{d + w} \tag{1}$$

where h is the horizontal offset from the viewer in front of the wall with respect to the pipe, w is the distance between the viewer and the wall and d is the depth of the pipe behind the wall. In a real situation, however, users of AR "X-ray vision" are expected to minimize E_p based on the awareness of their spatial relation within the real environment and the understanding of the pipe's spatial relation with the wall. Hence, we hypothesize that given sufficient depth cues for spatial understanding in AR "X-ray vision" visualization, users are able to mentally compensate for E_p. In addition, according to Eq. (1), the horizontal offset of the viewer position and pipe depth are expected to affect user's performance in establishing the closest pipe location on the wall, which leads us to further hypothesize that lateral errors in designating pipe positions on the wall, if not fully compensated for by users, depend on h and d.

Our experiments, which are described in Section 5, attempt to test the aforementioned hypotheses and investigate in what way different kinds of visual guides will affect users' performance in determining the closest projected position of the pipe on the real wall through establishing the spatial relation between the pipe and the wall. Section 3 presents the technical details of our AR system developed to conduct the experiments.

2. Related work

AR has been reported to have positive impacts on tasks which demand high precision and/or accuracy from various application domains. Henderson and Feiner [19] found that subjects were significantly faster and more accurate with AR-based dynamic, prescriptive instructions than the ones presented through traditional 3D graphics and a stationary LCD monitor when it comes to psychomotor tasks, which are common in manufacturing and maintenance. AR has also been adopted to project visual cues on vehicle panels to improve precision and accuracy of manual welding in automotive manufacturing [20]. *Physio@Home* [21] is an AR prototype system for guiding proper physical therapy exercises. The authors reported that test participants performed most accurately with the visual guides

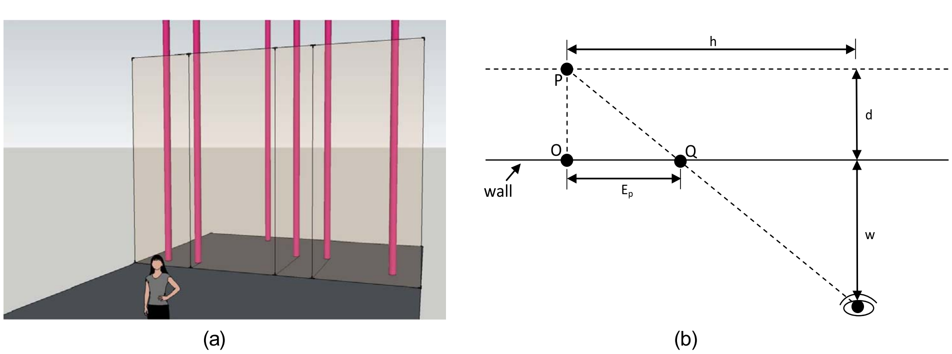

Fig. 1. (a) Closest projected positions of some pipes on the wall (indicated by black lines); (b) top view of the parallax error E_p for pipe position P.