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Building's digital twin model shown as first-person and third-person views

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Abstract. Construction industry is currently facing challenges such as a high number of occupational injuries and a somewhat weak connection between design and construction phases. One way to amend the situation is to increase data availability to construction professionals. Information about the structure and features of the building to be built should be shared so that various professionals can use the so-called digital twin model of the building for his/her purposes. We have created a concept for delivering the building information model (BIM) that can be viewed in various ways from various devices. We tested the viewing and using of BIM in augmented reality (AR), with high-end eXtented Reality (XR) technology (Microsoft HoloLens 2) and a tablet. Briefly, according to our test results, AR seems to be good when user needs to be perceived him/herself as if inside the building model, and tablet suits for viewing the digital model from the outside of it. Novice users of the AR technology need much more support in using the technology than the experienced ones. All test participants found the concept good and the technology with which to use it as promising.

1. Introduction

Construction industry is important, impacting economic growth and long-term national development [1] and providing infrastructure for the society in the form or buildings. In construction industry, design phase is traditionally a separate activity and construction teams are usually formed for almost every new construction project [2]. The connection between the design and the construction work is consequently weaker than it could be, making construction work more error prone, a situation to be avoided by easily accessible design information. Also, the number of occupational injuries is highest among construction workers, compared with major industries [3]. These kinds of issues are important to handle. Being labour intensive, one approach is to affect workers at the construction site. Then, the remedy may be found in developing solutions, which affect and support the workers, or construction work management, or both.

Digitalisation can be regarded as an effective means to improve safety in the construction industry, by representing the actual situation at the site, providing text-free interfaces, and by engaging better the user [4], and to enhance production as a whole. An already existing example of digitalisation in construction industry is Building Information Modelling (BIM). BIM can be defined in various ways (see, e.g., [5]); for the purpose of this paper, it can be defined as datasets containing information about a building as well as the digital representation of the building.

This paper describes a study performed in the EU-funded project BIMprove (Improving Building Information Modelling by Realtime Tracing of Construction Processes; see [6]). It is established to provide means and ideas for construction site digitalisation as part of Industry 4.0. In the project, among other things, BIM model will be upgraded with as-built real-time data and provided to users with Augmented Reality (AR) technology. Augmented reality means that virtual objects are integrated in our real, three-dimensional environment, both perceived simultaneously and in real time [7]. This model will enable, for instance, the comparison between planned and real features of the building and making remarks in the critical locations of the digital building model about, e.g., safety risks.

We have conducted a user test, reported in this paper, of our AR solution for construction workers and other professionals needing BIM at construction site. Most building-trade users may not be familiar with AR technology so usability issues can prevent or at least considerably slow down the deployment of the solutions. Even managers may have difficulties in using software tools [8], not to mention workers. This means that usability issues, at least, should be corrected as well as possible.

Our tentative user interfaces for tablet and HoloLens 2 XR glasses are for viewing and editing building related information. First, in section 2, literature review is presented. In section 3, an overview of the general-level user interface concept for presenting BIM is provided. Then, in section 4, the research methods for our user test are described and justified, thereafter (section 5) the main results are focused on, followed first by discussion comparing our results to the related literature (section 6) and, finally, by conclusions (section 7).

2. Literature review

Building engineering sectors (architecture, engineering, construction, and operation) are striving for better performance, recently through automation and digitalisation [9]. Efforts related to the implementation of AR represent this endeavour. AR is one tool to support BIM adoption. Even if AR is fast becoming a well—known tool in construction industry [10], its implementation is far from its desired state [9]. Review in scientific publications about BIM-based AR systems [9] shows that the number of articles is limited, reflecting slow integration of AR with BIM.

AR has been shown to have the many potential benefits at construction phase: improved collaboration, reduced miscommunication, increased quality and detection of errors, enhanced decision-making, increased integration of safety considerations, increased input accuracy, better information access, improved information flow, and better documentation [11]. There are, however, also drawbacks. Limitations have been mostly found in data transfer due to connectivity limitations at the construction site [9].

The existence of usability problems in AR, irrespective of the domain in which it is tested, is twofold. Studies in which the virtual world is only or mostly just viewed, such as when using the AR for training or guiding the way, usability has been found good (e.g., [12-14]). In studies where the virtual world is manipulated, usability issues have been found, at least with HoloLens 1 (see, e.g., [15, 16]).

HoloLens 2 has not been studied extensively from the perspective of the usability of manipulating virtual objects. It is known that for children, tap interaction (touching an element in the augmented world), contrasted to air tap (gesture in which the palm is first open and then thumb and index finger touch each other) and voice command is the most effective in the selection of an AR object without training [17]. When an augmented aircraft was manipulated, usability was found good measured by SUS (System Usability Scale) as a whole but still, regarding gestures, especially grab gesture, were not properly recognised by the HoloLens 2, which was found frustrating [18].

3. Overview of the general user interface concept

One of the objectives of the BIMprove project is to demonstrate how digital twin concept can benefit the management of a building throughout its life cycle. A step to reach this objective is to create concepts and develop applications with which users can use the digital twin at the building construction phase. A user interface (UI) concept for construction professionals utilising AR has been created by Helin et al. [19] and the related user interface categorisation is described in Aust et al. [20]. In this paper, we present an AR application for those who need building information for hands-on work at the site, such as workers (BIM@Construction) (about the applications, see [19, 20]).

The application can be perceived from two different modes, Immersive Digital Twin mode and Mobile mode (see figure 1). Immersive Digital Twin mode is used with a Microsoft HoloLens 2, enabling a truly three-dimensional (3D), binocular experience of the building model with many functionalities. Mobile mode can be used in a mobile phone or tablet and in it, the two-dimensional building model can only be used for viewing and navigating in the building.

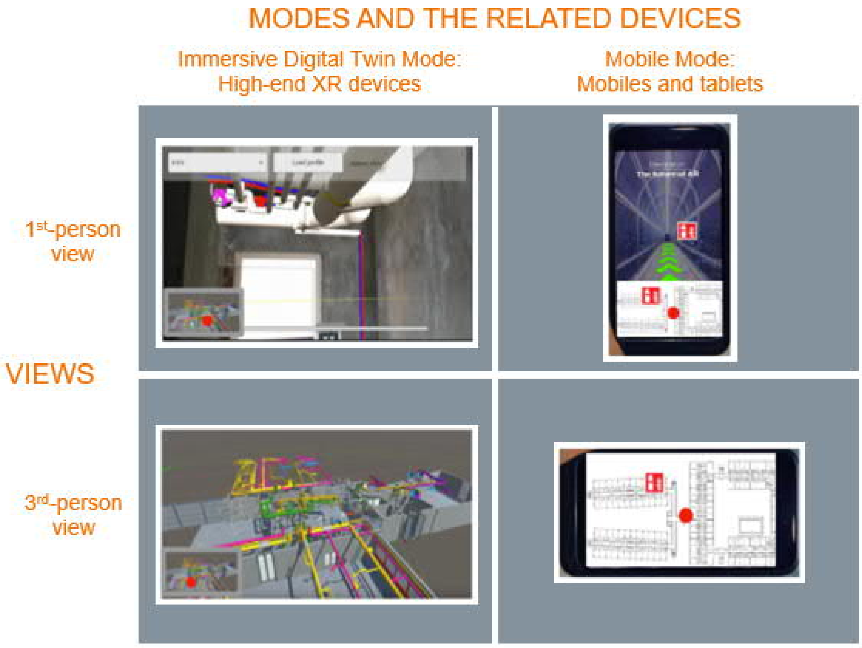

Figure 1. The general-level UI concept, grouped by mode and view.

User can have the 1st person or the 3rd person view in Immersive Digital Twin and Mobile Modes. In the 1st person view, user will see information from digital twin in real scale, e.g., can feel as if being located in a real room in Virtual Reality. In the Immersive Mode, the experience is truly three-dimensional whereas in Mobile Mode, three-dimensionality is only created by pictorial cues, without binocular disparity. In the 3rd person view, user can see information from digital twin in free distance and can zoom in and out in a map; in both cases, user is presented in the map with a red dot. In Immersive Mode, a three-dimensional layout of a floor is presented and in Mobile Mode, a two-dimensional map is provided.

BIM@Construction provides relevant information about the building at the construction site and offers a possibility to add more information to the digital twin of the real building. The possibilities of the solution are described in the task list of the user test (see section 4 in this paper). An extensive demonstration with HoloLens 2 and tablet can be found in YouTube [21].

4. Research Methodology

User test was performed to get feedback about the development needs of the solution. Test was organised as a lab test. The AR system tested, a building related application shown with a head-mounted display, presents a model of a building, with very little surfaces and with the main structure only, complemented with some details such as plumbing and stairs.

User test was built around the key concepts of usability and user experience. Usability, or ease-of-use, or user-friendliness, is a commonly known concept. It is not a property of a person or thing but an emergent property depending on the interactions among user, product, task, and environment [22].

User experience, in turn, encompasses perception, action, motivation, cognition and, especially, emotions [23] in the context of using some artefact.

The present test is the first user test for this solution, focusing on the user interface qualities. Usability and user experience are appropriate approaches in our user study because we wanted to collect test users' conceptions, experiences, and ideas as broadly as possible, to find out what to develop further.

4.1. Participants and technology

There were 4 test participants: one with prior but superficial knowledge of the application, one with prior knowledge of the technology (HoloLens 2) only, and two naïve users with no experience of HoloLens or the application itself. All users were researchers with experience of studies over many domains. Even if a small sample is not recommended as such, it has also been estimated that four subjects are able to identify 40% or more of usability problems [24] which is enough for the purpose of this test.

The choice of participants ensures that flaws, which are apparent to first-time users are identified but possibly neglected by experienced user (as an experienced user may have grown accustomed to some flaws), are identified. Similarly, an experienced user may identify such flaws, which are neglected by first-time users, as first-time users may be overwhelmed by the first impressions, neglecting some other flaws. By having participants with different levels of AR related expertise, a larger variety of usability issues can be identified.

Two tool versions to show the application were used: Microsoft HoloLens 2 as the head-mounted mixed-reality system and Android Tablet for the mobile augmented reality.

Microsoft HoloLens 2 models are already built for interaction with 3D models. Scale of those models is usually dictated by the Field of View of the headset. In order to overlay digital twin information on top of the real building, additional pivot objects should be created. Naturally, pivot object placement should match the placement of the fiducial markers in the real world. That way the digital twin and its real-world counterpart will be located in the same coordinate system.

The mobile mode version of the tested AR application uses computer vision for feature and plane detection in order to place AR-based object in the scene. It doesn't necessarily need fiducial markers but works well with them since they can be used for on-site tracking and contain additional image features (texture and contrast variation). In the same way as a HoloLens 2 application, the tablet version of the mobile mode provides both the 1st and the 3rd person views.

4.2. User interaction with test devices

In this study, two different devices in AR mode require different user interactions, even if they serve the same purpose. For the tablet, user interaction is limited to the touch screen controls. User can press buttons, check the toggle switches, and drag the sliders as it is usually done on the tablets and smartphones. Additionally, the tablet version includes rotation controls for the building model in 3rd person view - user can touch the ring on the base of the model and drag it to rotate the model.

Contemporary AR devices, including HoloLens 2, use hand tracking as input source for interaction with UI elements on the screen of the head-mounted display. In the HoloLens 2 version of the study, user can interact with the UI through near and far pointers. Near pointer use is similar to the direct interaction with tracked hands - user can press virtual buttons with index finger or use pinch gesture to move objects and manipulate transform handles such as sliders. Far pointers are used like a real-world laser pointer; first a ray from the hand is sent from the base of the palm towards the object and thereafter, a pinch gesture is the input source for clicking a button or dragging an object. Rotation of an object is done by using a pinch gesture and turning the wrist. Scaling the model is performed with two-handed pinch gesture, and the model can be rotated at the same time by moving the hands back and forth. Floor plan scrolling can be done with near interaction just by touching it, and two-handed touch interaction will scale the floor plan. Far pointers will do the same with the pinch gesture.

"Tools" menu in our application is designed to utilise standard HoloLens 2 object interactions (for exclamation and question mark tools), with the addition of new interaction possibilities. For example, application includes a post-it note in which user can write text with a virtual keyboard. It is also possible to use a virtual tape measure device - a combination of two standard objects, a tape measure enclosure and the tape tip. User can move those two parts separately to measure the distance.

4.3. Proceeding of the test session and data collection

Testing was conducted for one test participant at a time. Before the test, introductory videos were shown and a test instructor was available for supporting with problems in using the devices throughout the test. In the test, several tasks were used.

Tasks for third-person views are the following: initialise the tablet/HoloLens 2; modify the view (rotate and zoom the building model); view Menu panel (it has three further alternatives: Tools, Floor plan, and Options panels); choose Options panel and there, hide and show building layers, adjust the opacity of the building structure and floor in a continuous way by using sliders in the augmented reality; choose Floorplan panel and there, increase the size of the floorplan; and in the HoloLens version, additionally, make the floorplan to follow you when you move, by pushing a Follow Me button; choose Options panel and there, change to Immersive Mode.

Tablet task for the first-person view was only to check wires on the building structure. In HoloLens 2, user was to choose one of the additional tasks for the first-person mode; the restriction was due to time limitation: (a) use in Tools panel for measuring distance of a pipe from the wall; (b) use the Tools panel and create a post-it note, write there something and attach it on the building model; or (c) use the Tools panel and add a warning sign (i.e., an exclamation mark) somewhere on the building model.

First, tablet version was tested, in third-person and thereafter in first-person view. Then, HoloLens version was tested, with the same order of views.

Data collection methods were chosen to reveal design flaws and provide new ideas from the usage perspective. Participants were asked to think aloud [25] when performing the test tasks, i.e., to tell their thoughts, intentions, and feelings about the usage of the application at hand as they appeared in their mind, as faithfully as possible, and describing continuously what they were doing when performing the test. The method of thinking aloud is proved to be efficient in identifying usability flaws; for instance, it has been found that an evaluation based on an analysis of logs of user interactions requires more test participants than a thinking-aloud based study [24]. Thinking aloud provides detailed information about the experienced quality of the user interface.

Immediately after the test, users were asked to fill in a SUS (System Usability Scale) [26] questionnaire to provide an overview of the usability of the UIs in a systematic and uniform format. SUS is an often-used method to measure usability in AR related tests with adult participants ([15, 16, 18]). After filling in the questionnaire, an interview was conducted. The test situation was gone through with the participant in a chronological order, supported with still images about the test situations, taken before the actual testing. Questions were asked about the usability and user experience of the user interfaces. Participants were also asked about possible further ideas or comments about the applications they had tested.

4.4. Data analysis

Focus on data analysis was on user experience and usability of the HoloLens 2 application, so there were fewer questions for tablet than for HoloLens. This choice is reasonable as much less is known about usable solutions in the HoloLens-based 3D environment, and there are more unknown options to control Hololens-based view than in the already familiar tablet one.

Verbal expressions (thinking aloud) were collected to get feedback especially about such features, which require amendment, and the possible frequency of the comments was not counted – as there was a small number of test participants, all comments were treated as important. Verbal expressions were classified based on the interview questions as the questions were broad by nature. So, responses to the question “would you describe your overall experience of HoloLens”, can be found in the response category of ‘Overall experience with HoloLens 2”.

The SUS scores, ranging from 1 to 100, calculated from individual questionnaires, represent the usability of the application running in HoloLens 2. SUS yields a single number representing a composite measure of the overall usability of the system being studied. Scores for individual items are not meaningful on their own [27], especially with such a small number of participants, so only the final scores are used. According to validation studies ([28, 29]), the SUS score starting from 68-70 represents the level of acceptable system usability.

5. Results

Tests proceeded according to plans. The inexperienced participants needed support in many tasks whereas the experienced ones needed support very little if at all. For the experienced test participants, it took about one hour to perform all tasks, whereas the inexperienced ones needed about 1 hour 20 minutes.

5.1. Tablet related comments

Tablet was found good to get an overview of the building. It was found easy to use and interaction with it was effortless. Rotating and zooming the building worked well and pictures and resolution were found clearer and crisper than the ones in HoloLens. On the negative side, the screen of the tablet was found quite small for the purpose of scrutinising the building model and the buttons to push appeared rather small on the screen.

5.2. Overall experience with HoloLens 2

There was a variety of positive comments regarding HoloLens 2. Each of the following statements are comments from different test participants – no participant repeated something that another participant had said. HoloLens 2 was found useful; there were quite a lot of options to operate; colours were good (expect for white); the building model was accurate; and the user interface was found plain and simple. One participant told that (s)he is impressed. HoloLens was also found better than virtual reality (the reference was not specified); and all, except for a slider shown in the augmented reality, was commented to work well.

There were also negative descriptions. HoloLens was found too bright, hurting eyes; the view was found a bit unclear; resolution was too low; more feedback was needed; and one participant told that (s)he was conflicted and confused when using the HoloLens (but the same person was also impressed by HoloLens).

5.3. Controlling HoloLens 2

There were three virtual panels in HoloLens. It was commented positively that panel follows nicely quite nicely (the Follow-Me functionality) and can also be moved elsewhere if needed. In the positive vein, it was also noted that menus are self-explanatory; that it is good that panels are scalable; menus are easy to use, with the exception of closing them, which was found difficult. On the negative side, slider switches were found difficult to use; more feedback was wished for about the performed actions; dragging and resizing were found difficult; and the Follow-Me functionality of the panel went accidentally on.

5.4. HoloLens 3rd person view

The third-person view elicited both positive and negative comments. Third-person view was found to be visually good and also easy to use. One test participant considered it to provide a better overview of the building than the first-person view. On the negative side, it was also stated that the third-person view is better in tablet than in HoloLens. Zooming was found difficult for a first-time user; and the field of view was considered limited in the third-person view.

Regarding HoloLens floorplan, scalability was found to be a good feature. Some commented that it would have been good to be able to make the floorplan even smaller, to see more about it. Floorplan scaling was also found to be a difficult procedure and one comment was that the floorplan is a bit too far away, probably reflecting the difficulty of moving it. Moving floorplan was also considered a bit slow. Text was described as fuzzy so that it was hard to read it. One specified that the text was hard to read regarding the floorplan but that otherwise text was clear.

5.5. HoloLens 1st person view

Most general-level comments regarding the first-person view were positive: it was found interesting; the participant could imagine (s)he is really in the middle of the virtual floor; it was possible to see enough details; it is better than the 3rd-person view, but the field of view was found too small in the immersive mode.

There were a lot of detail-level comments about HoloLens Tools, developed for the application. Many aspects were found positive: buttons were easy to press; rotating and zooming the building model was easy, when being familiar with HoloLens; and one participant assumed correctly that the blue corners of the model are the points to grab when scaling the model. It was found good that the user is able to measure such distances in the model, which are beyond the reach of user’s hands in the virtual world. The functionality, which ensures that the menu is not far away from the user (the Follow-Me functionality) was reported to function nicely. Text writing was found easy and the font in the note was liked as it looked as if being handwritten.

Also development needs were identified. Buttons could perhaps be a bit larger. Pushing buttons, as well as zooming, were found difficult in HoloLens. Slider, used for tuning the level of opacity of the building elements, was also found hard to use. There was also some unclarity with the meaning of some commands in menu (“Structure floor” and “Adjust the note”). Dragging and resizing were found difficult for a participant not familiar with HoloLens before the test. It was also difficult to put the exclamation mark to the correct location in the post-it note; it was found tilted in a weird way and regarding writing as a whole, HoloLens keyboard was found easy to use but wasn’t evaluated to be very suitable for longer messages. Measuring functionality was commented to be rough, one user stated that it was hard to evaluate whether the distance is 30 cm or two meters; and the keyboard located in the virtual environment was not natural to use.

5.6. New ideas for HoloLens 2

Regarding the more technology related suggestions, HoloLens was wished to provide a larger field of view. Initialisation, a rather basic functionality, was hoped to be simplified. An option to choose between voice and gesture commands was wished for. It was also suggested that a first-time user could see more instructions. The font could be scaled smaller when the text becomes longer.

Also functionalities could be elaborated. It was stated that the present length measurement could be developed to handle even more complex measurements. Finally, an idea was provided about how to use present functionality: post-it notes could be used in also other contexts, such as in safety related comments.

5.7. SUS scores

Test participants filled in the SUS questionnaire only based on their use of HoloLens application. SUS scores range from 70 to 85 and the average score is 77. Based on the SUS scores, all the test participants evaluated the system usability as acceptable.

6. Discussion

User test was successful in the sense that features worth maintaining in the application as well as various development needs were identified. As a whole, application proved to be in an acceptable level from the usability point of view. Not all flaws the test participants reported are self-evident – some features, such as pushing buttons, were found easy to use or positive by some participants and difficult or otherwise negative by others. Such contrasting comments will be handled as features, which may need further development.

The focus in this study is on usability and the testing with construction professionals takes place later. Test provided ample feedback for further application development. Hence, it can be concluded that the number of 4 test participants, with researcher as background, was sufficient. The method of thinking aloud, supported with after-test interview, proved to be efficient in identifying usability flaws. Such flaws would have been missed if only a SUS questionnaire had been used.

Regarding the test results as a whole, all test participants found the concept good and the technology with which to use it as promising. Many solutions in the building's digital twin model and the related viewing and manipulating options are unique to the present study, but some results can be compared with other studies.

In accordance with other studies (see, e.g., [30]), the field of view of HoloLens 2 is rather restricted compared to user's wishes and natural vision. Also, the selecting of the virtual objects was found cumbersome in both our study (difficulty in, e.g., pushing buttons) and the ones of others (see, e.g., [31]). The SUS score for HoloLens 2 is in the same level with the SUS score obtained with a study comparing many devices; in the present study, the score was 77 and in the study of Balani and Tümler [31], it was 73.69, both representing "good" usability.

Our test participants complained about the view as it was perceived a bit unclear or grainy. This is contrasting to Hanna et al [32] as according to their experience, HoloLens has a sufficient visual resolution when used in the demanding context of anatomic pathology. They used, however, HoloLens, not HoloLens 2 as was done in present test, which raises even more questions as one can assume that a newer version of a device is better than a former one. Whether this is a question of differences between the specific devices, not device types, or something else, such as different application context or individual preferences, remains unanswered in this paper.

The difficulty to use HoloLens when being unexperienced was an issue identified in the present study and also by Balani and Tümler [31]. This raises the question of whether there is a need to have novice and expert versions of an AR application. Novice version could provide instructions whereas in expert version, instead of instructions, more complex functionalities could be provided. Another perspective is that pre-test training could have diminished or eliminated the need for personal guidance during the test.

7. Conclusions and Further Research

Our paper presents a user interface concept for the construction industry and shows, as an example, one user interface type and the related user test with the results. In the test, building model was handled in HoloLens 2 and tablet applications. Overall, test participants were satisfied or even impressed about the HoloLens solution. Those who were familiar with HoloLens 2 from other contexts had no difficulties in using the building model, whereas those who were not, had clearly more difficulties and needed support in using the system.

Irrespective of usage background, all test participants found HoloLens as usable and even useful in the building context. Tablet seems to serve its purpose by showing a clear overview of the building whereas head mounted display (HoloLens 2) has its strength in being used in an immersive way.

Many drawbacks identified in the test about HoloLens 2 application were the same as the ones found in other studies. They are related to HoloLens as a device, which is rather natural, as applications can be very different from each other but the qualities, which depend on the technical features of the system, remain the same.

The present results form only a basis for usability and user experience related results of digital twin viewed and used via HoloLens 2. More research is needed, involving professionals in construction industry and with a larger sample of participants, to obtain reliable and valid results, ensuring that the application is appropriate for construction work.

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