Virtual Construction: Interactive Tools for Collaboration in Virtual Reality

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Abstract. Virtual technologies and game engines provide new possibilities for collaborative virtual design within digital building models. The current paper describes an approach, in which computer-aided design (CAD) models of buildings are transferred into a game engine based environment, where they can be reviewed and further designed collaboratively. Following a user-centered design (UCD) process based on interviews and iterative interactions with designers and architects, the prototype of Virtual Construction ─ a game engine based platform for collaborative virtual design meetings ─ was designed and implemented using Unreal Engine 4. The interactive tools developed can be used both in full immersive virtual reality and using traditional devices (e.g. laptop or desktop computers). Based on identified user needs, interaction techniques were implemented for moving, rotating, and aligning objects, adding and resizing shapes and objects, as well as moving and measuring distances in the three-dimensional (3D) building model. In addition, the communication techniques implemented based on user needs included synchronous features such as voice communication, text chat, pointing, and drawing, and asynchronous features such as leaving messages and feedback augmented with screenshots to exact virtual locations. Other implemented scenarios included different lighting scenarios, an evacuation scenario and crowdsourced voting between different designs.

Keywords: Virtual construction, collaborative design, user needs, game engine.

1 Introduction

Historically, building designs were visualized by producing two-dimensional architectural and technical drawings. They were followed by CAD tools, which enabled the creation of interactive 3D visualizations of buildings. The currently prevailing trend, Building Information Modelling (BIM), extends 3D building models by adding dimensions such as time (schedules), quantities, costs, and sustainability and risk analyses. BIM allows following the principles of Virtual Design and Construction (VDC), which among other things emphasizes the importance of visualization and collaboration during the building design phase [1, 2].

According to existing research, presenting building 3D models visually is a crucial part of planning, construction and maintenance phases in terms of collaboration and understanding [3]. Especially in complex or largescale models, immersion is one of the major key factors for being able to intuitively perceive all aspects of the scene. Detailed walk-in virtual models can quite accurately simulate the user experience of real, completed buildings after they have been taken into use [4]. While the visualization features in CAD and BIM software have improved, they still have some drawbacks, when it comes to collaborative visual building design.

For example, Kosmadoudi et al. [5] reviewed existing literature on design in CAD environments and presented examples of limitations associated with using CAD software including limited efficiency, limited creativity, potential lack of motivation, and limited possibilities for interaction. They suggested that these issues may be enhanced using game mechanics to provide more engaging and intuitive environments, which may also result in reduced task times and improved design-making. Lee et al. [6] explored 3D architectural and engineering design tools from a usability point of view and concluded that CAD systems have become overly complex since they are composed of several hundred menu items, which causes too much cognitive load on the users. The best practices they suggested for 3D design environments included maximization of workspace, graphical richness, direct manipulation, familiarity, and minimalistic design.

Game engines seem to offer solutions for minimizing the above-mentioned limitations and promoting best practices in building design. For example, games have been shown to generate cognitive engagement in engineering design due to their inherent interactivity, and they may even inculcate confidence [5]. Game engines allow for the development of real-time walk-through applications, using which different users can freely inspect different versions of building designs. This can add to the realism and immersion. Buildings can also be displayed under different lighting conditions, which is important, as there is evidence that buildings can be difficult to even recognize under different lighting conditions and methods of presentation [7, 8]. Game engines also have built-in multiplayer features with avatars and collision detection, which can be utilized in developing real-time collaborative systems for building design with communication and object manipulation features.

Game engines also offer advanced possibilities for creating virtual reality (VR) applications. Despite their potential in diverse tasks, VR systems have been used in construction mostly to explore finished designs rather than to create new ideas [9]. However, Moloney and Amor [10] suggested that game engine-based collaborative virtual environments are suitable to supporting the early stages of design where teams can collaborate and evaluate iterations at a relatively low level of detail. They emphasized the possibility for both synchronous and asynchronous communication, supporting participatory and iterative design, as well as making intuitive of design decisions as the main motivators of using a collaborative virtual environment for building design. Recently, Lin et al. [11] studied VR-based design in practice and demonstrated that a BIM/VR based solution could increase communication efficiency, facilitate visual interactions, and ease decision-making in hospital design. Systems for collaborative multi-user VR such Glue [12] and Fake [13] have entered markets, but the related user needs in the context of construction remain largely unexplored in the literature.

The current paper contributes by presenting a user needs based approach for designing tools for interaction and virtual design and review meetings for the construction industry. A process for utilizing a game engine (Unreal Engine) in design and review of buildings is suggested. Based on the approach and a user-centered design process, a prototype platform and a set of tools for collaboration in building design were developed based on interviews and regular discussions with architects and designers.

2 An approach for bringing building information models to game engines

We have developed a process and methods for bringing building information models to game engines in order to be able to view and manipulate them in virtual reality. In our process, there are two ways to bring the building information model with its metadata (e.g. manufacturer, material, and price for each component) into a game engine. If the Unreal Engine is used, the Datasmith add-on for Unreal Engine can be used to import a building information model or its parts. Datasmith is a collection of tools and plugins, which directly supports bringing content from more than 20 modeling formats into Unreal Engine 4. For example, if a model or a part of it has been created with Autodesk's Revit software, it can be imported into the Unreal Engine with metadata directly in Revit's native format. Figure 1 below illustrates the proposed process for brining building models into game engines.

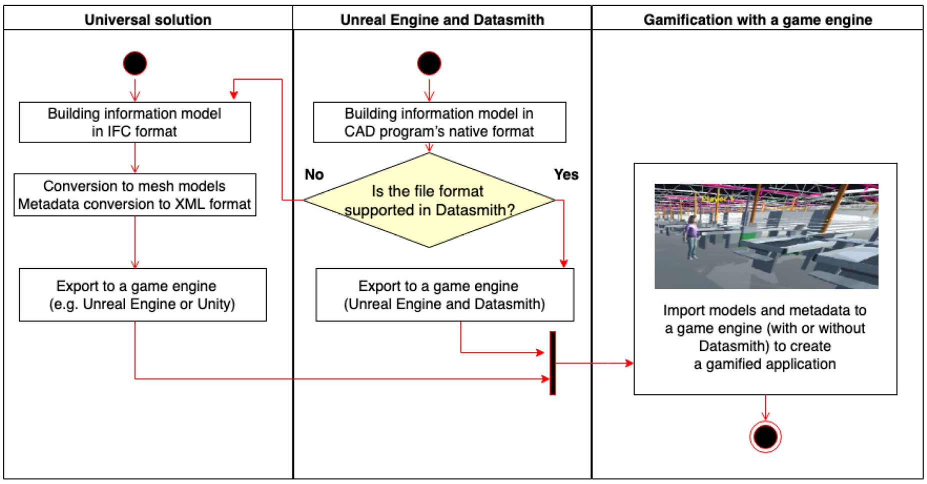

Fig. 1. A process for bringing building information models into game engines.

For a universal solution working with all the game engines and CAD software, the Industry Foundation Classes (IFC) format is the only possible option. The IFC format is the standard data storage and data transfer format for BIM. The IFC format is not based on meshes (polygon structures), and game engines do not support it as such for performance reasons. Thus, IFC models must first be converted into a mesh format supported by game engines. The IFC format also supports the inclusion of metadata, while pure mesh-based models do not contain metadata. In the process we have developed, the IFC sub-models of the building data model are converted into the mesh-based Wavefront OBJ format with the IfcOpenShell open source software. In addition, the IFC models are translated into Extended Markup Language (XML) using the same software. Then the metadata they contain can be read directly into the game engine with an XML parser along with the data model. In the game engine, the models and associated metadata are linked to each other using common identifier fields (e.g. id or name). We have developed a computer program to support this process and convert data models into a format that is supported by game engines.

3 Platform and tools for collaborative design meetings in VR

3.1 User-centered design

To support the development of the current platform, called Virtual Construction, a user centered design process was followed. First, the context of use was specified by identifying the most important stakeholder groups, including architects, different groups of designers, as well as the clients and the end users of the building. Next, user needs were investigated. In total, 10 employees from four different companies forming an alliance in the construction and architecture industry participated in the iterative process focusing on user needs. The participants included both senior and junior personnel, as well as manager level personnel and hands-on designers.

Table 1. Summary of identified user needs for a virtual building design platform

Need category	***Needs***
General	Need for an integrated communication and visualization solution. Need for real-time information, plans always updated and shared.
Visualization	Immersion and walk-in (to examine the model like a real building). Easy navigation and wayfinding within the entire 3D model. Sketching by drawing and adding simple objects. Changing textures and colors “on the fly”. Seeing behind structures (e.g. locations of pipes). Decoration by easily adding and moving stock objects. Simulation of lighting options and different times of day and year.
Communication	Synchronous design meetings and asynchronous communication. Communicate in the model using voice and chat (“like in Skype”). Awareness of others and their locations in the model. Pointing and highlighting parts of the 3D model. Leaving feedback messages to 3D objects.
Access control and crowdsourcing	Default user group of all project members and private groups. Involving end users of the building, “design your own work room”. Crowdsourcing the design of public buildings. Access control with high information security. Easy versioning and version control.
Special needs	Supporting design for accessibility. Scenario and simulations for building evacuation.

First, a design meeting focusing on the requirements of each company for collaborative virtual technology was arranged. Next, four in-depth user interviews were conducted. The interviewed persons were: a senior architect, a junior architect, a senior building designer, and a designer of industrial structures. The semi-structured interviews concentrated on understanding their work processes, communication during the processes, current use of tools and technology, and ideas for improved or new tools. The identified requirements and ideas were listed and categorized. The most central need categories and needs are summarized in Table 1 above. Interactive tools were designed based on the requirements. The designs were refined iteratively in the context of monthly meetings and special events (e.g. live demonstrations) over the course of more than one year.

3.2 Technology

The frontend application of the Virtual Construction platform was implemented using Unreal Engine 4 due to its superior visualization capabilities and more straightforward compatibility with CAD software. The server side backend was programmed using Node.js. HTTP calls and web sockets are used for communication between the frontend application and the backend. The system uses Vivox voice services for voice chat. The system has been tested with both HTC Vive Pro and Oculus Rift virtual reality headsets.

3.3 Interactive tools

In virtual reality, the Virtual Construction application is optimized for the HTC Vive headset and its two motion-tracked handheld controllers (HTC Vive Wands). The viewpoint is changed by head movements, and basic pointing and selecting is carried out with the dominant hand controller using raycasting. The user points the ray from a virtual raygun towards the object to be selected and presses the primary button (HTC Vive Wand trigger) with the index finger. If an action with the selected tool can be performed on the object, its outlines are shown when pointed at, allowing the user to rapidly browse objects. Dragging objects is possible by pointing and selecting the object, holding the trigger down, moving the controller and releasing the trigger. In the default mode, virtual hands for moving objects are displayed.

The different tools implemented can be accessed from a radial menu activated by pressing the menu button of controller. The menus and dialogs are operated using two hands so that the 2D menu or dialog can be moved with the non-dominant hand, and pointing and selecting items is carried out with raycasting as in interaction with the 3D objects. The default method for moving both shorter and longer distances in virtual reality is to teleport to visible locations. This is achieved by pressing the controller touchpad button, moving the controller so that the ray ends at a desired position on ground or floor, and releasing the touchpad button. Thus, the technique used for moving is a type of specified coordinate movement [14].

Interaction and communication techniques. The different interaction and communication techniques designed and implemented for VR are displayed in Figures 2 and 3 below. Fairly detailed descriptions are given for each technique to give the readers the possibility to adopt the techniques in their VR developments.

Adding, resizing, and erasing objects and shapes. The item catalog tool displays a menu of available 3D design objects. When pointed and selected, the added objects appear in front of the user and the move tool becomes active. Basic shapes (e.g. cubes, spheres, cylinders) can be added similarly using the add shape tool and their dimensions and colors can be changed in a dialog. Objects can be erased using the erase tool simply by pointing and selecting the object.

Manipulating objects. Using the raycasting based move tool, objects can be grabbed and moved horizontally or lifted vertically by moving the controller. In the depth dimension, they can moved by pressing up and down on the main controller touchpad when grabbed. Light objects can also be moved and lifted in the default mode (virtual hands) by dragging them with one of the controllers. Heavy objects can be dragged along the floor in this mode by grabbing them with the controller and using the four touchpad buttons to walk in four dimensions with the object.

Snapping, aligning, and rotating. When moving objects, they can be snapped to and aligned orthogonally with any surface of the building (e.g. floor, wall, ceiling) by moving them close to the surface using the respective snap and align tools. While being moved, objects can also be rotated along the floor by pressing left or right from the controller touchpad or rotated on all three axes in a specific dialog using sliders.

Measuring distances. Distances can be measured between two points by pointing and selecting starting and ending points on surface. Multiple distances between points can be measured in a row similarly using the measure path tool. Using the freehand measurement tool, the user points a starting point with the tip of the ray gun and start dragging, while the system shows the distance in meters. Using the measure normal tool, the user points and selects a single point on a surface to measure against surface normal (e.g. wall to wall or floor to ceiling).

Hiding and unhiding objects. A common need is to see through surfaces or objects blocking a view. Using the hide tool, surfaces and objects can be hidden by pointing and selecting them with the primary controller. All the hidden objects can be unhidden at once by selecting the unhide option from the menu.

Fig. 2. Descriptions and illustrations of the developed interaction techniques.

Avatars, chat, and voice. Users are represented by simple avatars, whose appearances can be tailored for different users or user groups. Designers are used to using chat and voice communications in design meetings and expressed a need for these features for synchronous communication within the 3D model. These features can be activated and deactivated from the tools menu, and the messages are visible/audible to users within the entire 3D model.

Pointing. A typical need was to be able to point at specific locations in the 3D model while communicating with others. Using the pointer tool, a spherical marker is displayed at the end of a ray to grab other users' attention. To support awareness of other users' activities, raycasting is also always visible to other users when the other tools are used.

Drawing on a surface or to air. Drawing can be used as a tool in synchronous or asynchronous communication. Using the draw to surface tool the user points the ray towards a surface, moves the controller, and the system draws, when the primary button is pressed. The draw to air tool is used similarly, but instead of a surface, the drawing appears to the location of the tip of the virtual ray gun.

Leaving messages and feedback. Asynchronous communication between users emerged as a user need. The user selects the relevant location from a surface by pointing and selecting and gives structured or free form feedback using a 2D dialog. A marker (e.g. a 3D exclamation mark) appears next to the surface to mark the message location. Messages can be read by pointing the marker when using the show object info tool.

Taking screenshots. Using this tool, a preview of the screenshot contents appears above the ray gun and the user can refine the view by moving the dominant hand controller and press the trigger to take a screenshot. The screenshot tool can be launched from the message dialog and screenshots can be attached to messages and feedback. There is also a similar standalone screenshot tool for taking screenshots rapidly and saving them to disk.

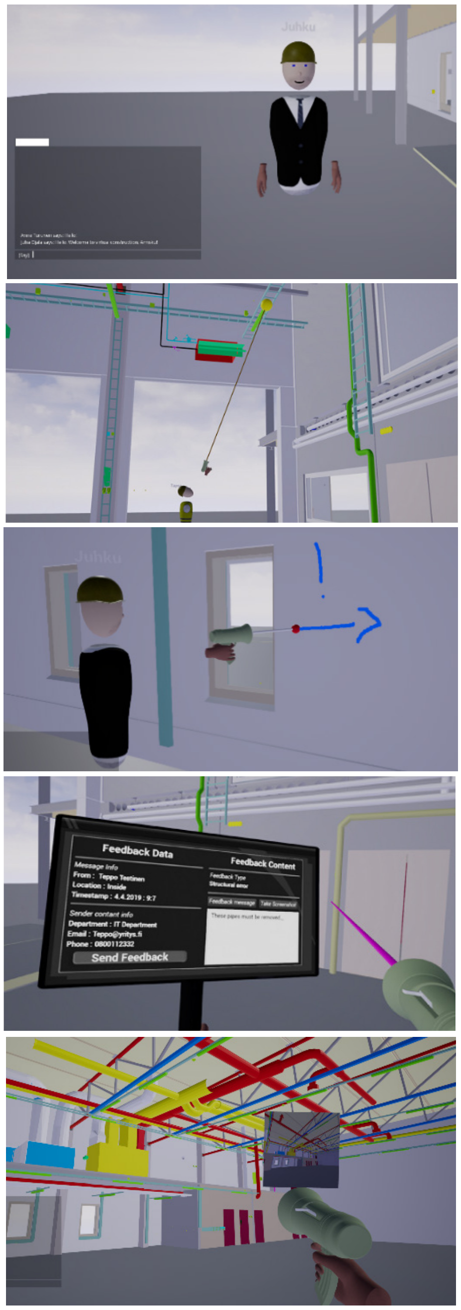

Fig. 3. Descriptions and illustrations of the developed communication techniques

Floor plan and guidance. Using the map tool, a 2D architectural floor plan of the premises appears on a sign on the user's non-dominant hand (Figure 4, left). The architectural plan can help in understanding the overall design of the building. It also acts as a map, in which the user's current location is indicated, and the user can point and select a destination on the plan with the raygun and the trigger. The user gets guidance to the selected location. The user can also see the locations of other users in the same virtual model. The guidance is drawn as arrows on the floor on walkable routes (Figure 4, right). If the user points the map with the raygun and selects a location with the touchpad button, he/she is directly teleported to that location.

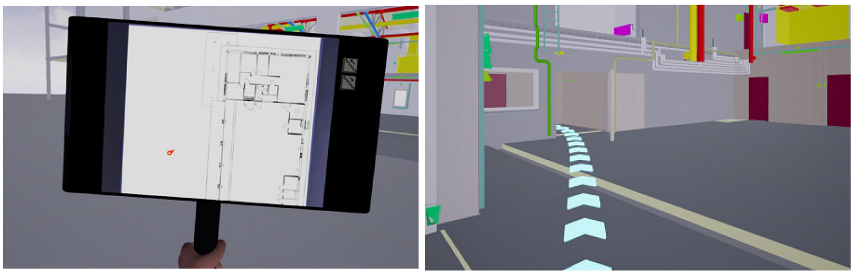

Fig. 4. The floor plan (left) and route instructions to a destination (right)

Crowdsourcing and voting. Opinions and votes can be gathered from the end users of the building or the general public in the case of public buildings. After completing a registration, end users can inspect the model freely, leave location-specific feedback (see Figure 3), and participate in voting. Voting buttons can be added to rooms (Figure 5). After selecting the voting button, the user can toggle between predefined alternatives for, for example, furniture, layouts, materials and colors, or lighting by selecting the number of the option in the voting dialog, and give her/his vote after inspection.

Fig. 5. Buttons can be added to rooms for toggling between alternatives and voting.

Scenarios for visualization. The developed platform allows the selection of one of the (currently eight) available visualization scenarios to display 3D models of buildings under different lighting conditions from the menu. An example of visualizing a building under normal lighting conditions and in an evacuation mode is presented in Figure 6.

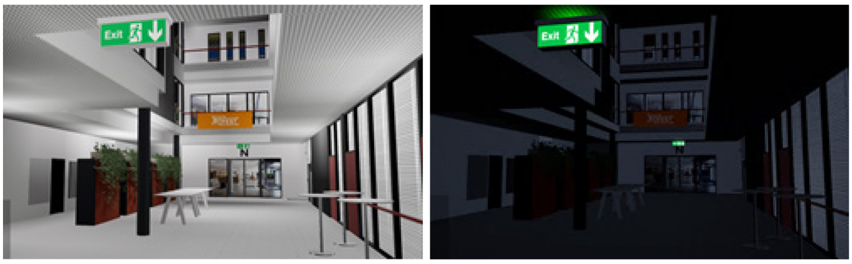

Fig. 6. A building interior in normal lighting and in an evacuation scenario

4 Conclusion

The introduction of virtual design meetings and asynchronous communication within 3D models has potential for significantly improving visual design and communication during construction projects, resulting in more desirable buildings. This article described our approach for bringing building information models to game engines and utilizing the advanced features of the Unreal 4 game engine to develop a platform with tools for collaboration and visualization of buildings.

The Virtual Construction platform was developed based on the principles of user-centered design, which ensured that the platform was developed based on real needs of companies operating in construction industry. It was noticed early that different stakeholders in the construction industry have different user needs for a virtual collaboration platform. The user needs were found out by involving 10 senior and junior members of staff from the participating companies in an iterative development process with monthly group discussions and four in-depth interviews.

The identified user needs for a virtual platform for construction can be roughly categorized to needs for advanced immersive visualizations, needs for advanced virtual tools for both synchronous and asynchronous communication, needs for access control and crowdsourcing, and special needs including designing for accessibility and evacuation, which are obligatory design issues in construction projects. The participants also expressed the general need for an integrated solution for communication, visualization and modification of plans collaboratively in real time.

The current solution already implements many features based on the most important needs expressed by the participants of the current study. The tools for virtual reality were designed from scratch based on the user needs and capabilities made possible by Unreal Engine 4, and they are reported in this article in detail. Naturally, existing ideas have also been utilized. For example, drawing and annotations have been previously found to enhance collaboration in design review meetings [15]. We suggest that the current approach and tools developed based on matching user needs to features of a game engine offer a noteworthy alternative to existing systems and developments.

The logical next step is to test the developed tools in a study involving real construction projects. In the future, the current platform can be extended into a more holistic system for managing digital twins of buildings. In addition to the design phase, game engine based visual solutions bring potential benefits in the construction and maintenance phases. For example, the current platform could also support augmented reality based viewing of building 3D models in the construction phase and visualizing measurement data from completed buildings in the maintenance phase.

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