A Shared Immersive Virtual Environment for Improving Ship Design Review

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Abstract. Ship design review (DR) involves extensive collaborative and participatory processes and requires all DR actors (designers, stakeholders, end-users) to manage a large complex decision space in addition to coping with heavy cognitive demands. Here, we present a novel system whose purpose is to optimize the balance between ship DR complexity and the users' cognitive effort. The system exploits the power of interactive multi-user immersive 3D environments based on efficient immersive Virtual Reality Mock-Ups (VRMU) obtained directly from 3D CAD models. The remote multi-user cooperative interaction is supported by tools like Oculus Rift and Oculus Touch, as well as by avatars to overcome geographic distance and increase social proximity. This will likely facilitate joined decision processes and, through enaction, the visualization of environmental features (error/feature detection, information search), thus promoting the project development towards success.

Keywords. Immersive Virtual Reality, CAD, ship design, design review, multi-user

ACM Classification[1] Keywords. H.5.1. Information interfaces and presentation (e.g., HCI): Artificial, augmented, and virtual realities

1. Introduction

Modern technology based on advanced computer systems has in recent years transformed the way in which products are designed. The most important factor in this has been the widespread availability of specialized IT solutions, which has enabled a more cooperative product development process by facilitating both the collaborative design (interaction between designers) and participatory design (interaction between designers and stakeholders).

Such solutions are particularly important for the shipbuilding industry due to the complexity of products as well as the organizational structures of companies that design and realize them. Consequently, a large number of designers and other stakeholders normally involved in the design process means that proper execution of design review (DR) sessions, during which a design is carefully evaluated, is critical to the overall success of the project.

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Conventional design review systems enable users to access information predominantly via standard visual channels (either passive 2D or 3D-CAD rendered images), which allow for single user-to-interface interaction (stand-alone systems), thus forcing the actors of a DR session to be physically present in the same geographical place. However, enaction through immersive Virtual Reality (VR) can offer added value to DR technology, enabling remotely connected multiple users to access information, mutually interact in real time [1] and actively experience the self-generated optic flow [2]. Current requirements for an efficient DR system [3] specify that remote actors should be in touch within the shared environment and smoothly interact with the multimedia content. This is becoming possible and affordable as the consumer market of multimedia systems offers highly adaptable visualization and interaction tools (e.g., Oculus Rift, Oculus Touch, Space Mouse).

The system presented here integrates such tools with a new highly adaptable rendering engine that supports the fast and efficient creation of large scale shared 3D immersive virtual worlds from 3D CAD models through innovative algorithms. With respect to standard CAD, the real-time creation of Virtual Reality Mock-Ups (VRMU) from CAD models provides a more efficient way of sharing design information among experts (e.g., designers, engineers) and non-expert participants (e.g., stakeholders, end-users) in DR sessions, thus moving even the review of large scale design towards a true collaborative-participatory user-centered design [4]. There is indeed an increasing interest in assessing the effectiveness and psychological impact of multi-user exploration for extensive collaborative and participatory processes involved in DR [5].

2. System overview

The system is supported by a stereo projector connected to a standard PC equipped with a Core i7 6800K CPU, 16 GB RAM and an nVidia GeForce GTX 1080 graphics card that, for the multi-user purpose, can be networked with other PCs. Each PC can be interfaced with different hardware devices (such as the Oculus Rift head-mounted display, the Oculus Touch controllers, and 3Dconnexion Space Mouse) through custom-made modules to enable a deep immersive experience, joined-presence and interactivity.

The core software of the system is based on a custom-designed, stand-alone desktop application that provides: (1) the interactive, visual rendering of the 3D design to be reviewed during the DR session (i.e., immersive VRMU), and (2) the data processing engine that takes care of converting and optimizing the 3D models supplied as input, thus bringing design data from a CAD model into the real-time visualization environment.

In particular, this latter module needs to quickly convert and process input files, because CAD models are usually encoded in formats and data structures (e.g., industry standard STEP format) that are not suitable for direct GPU-accelerated rendering. Unlike other software tools that require from the user to go through a long and often difficult process of 3D model conditioning (conversion, simplification, correction, and level-of-detail management), our application does this automatically. As a result, very large and/or highly detailed CAD models can still be processed quickly, and 3D rendering is always smooth, even when performed in immersive VR through Oculus Rift headsets. The automatic conversion module is thus meant to be easy to use, and it doesn’t require any specific CAD knowledge in order for it to be used effectively. It is meant to implement the zero learning time usability heuristic [6], i.e., even non-technical stakeholders and end-users who are interested in participating in DR sessions can quickly learn how to use it and become active participants in the review process, alongside with designers and engineers.

Both the rendering engine and the data processing modules are coded in C++14 and use OpenGL 4.5 directly. Common open-source helper libraries, such as Boost, glm, and Assimp, are used throughout the code base.

2.1. Typical use

Figure 1 depicts the typical workflow of processes supported by the system as subdivided into three steps.

(1) *Project setup.* The designer/engineer sets up a collection of CAD files and parameters that define the default content of the 3D scene and configures the various modes of interaction and displays. Sensible default values are provided, so that the inexperienced user can still get a fully usable 3D scene by just specifying the set of input files, leaving all of the other parameters at default values. Although this step is usually done only once, the user is free to modify and refine the project at any time, thus optimizing the balance between user control and system flexibility [6].

(2) *Build process.* CAD files are automatically optimized and converted into a VRMU ready to be either visualized on a projector or shared through Oculus Rift based immersive reality. If necessary, the result of the build process can be exported and shared with other users. It is worth noticing that the exported files are encoded in a proprietary, encrypted format, so they can be safely shared also with stakeholders that are not authorized to access the original CAD data.

(3) *Design review*. Users play the 3D scene and can review the design.

The application can be installed on a disconnected workstation, operating in single-user mode, or it can be networked to enable the interaction between multiple users, each connected to a different remote workstation equipped with an Oculus Rift device. It should be noted that, while this is a feature that is already present in some VR-enabled video games and social applications, it is still not common in ship DR [7].

During the DR session, users can explore the 3D design, mark features with a 3D pointer, take screenshots and notes, measure distances and angles, and interact with other users in the VR world. Combining Oculus Rift with Oculus Touch sensors in an optimal manner allows the users to track (and store) in real-time finger/hand positions and bending angles as needed to provide precise 3D pointing performances as well as manual estimates of the objects' shape properties (i.e., depth). Fast tracking of head position/orientation is needed for fast perspective correction in order to provide a deep immersive experience during the DR sessions.

At the end of the DR session, all users automatically receive an activity report in PDF format. Sessions can also be played back in non-interactive mode, and can be saved in a persistent fashion when the application is closed.

Since DR is an inherently iterative process, care has been taken to ensure that no manual work is required to update the 3D scene when the original CAD files change. As a result, the software automatically detects changes in input files, and simply repeats the build process whenever they occur.

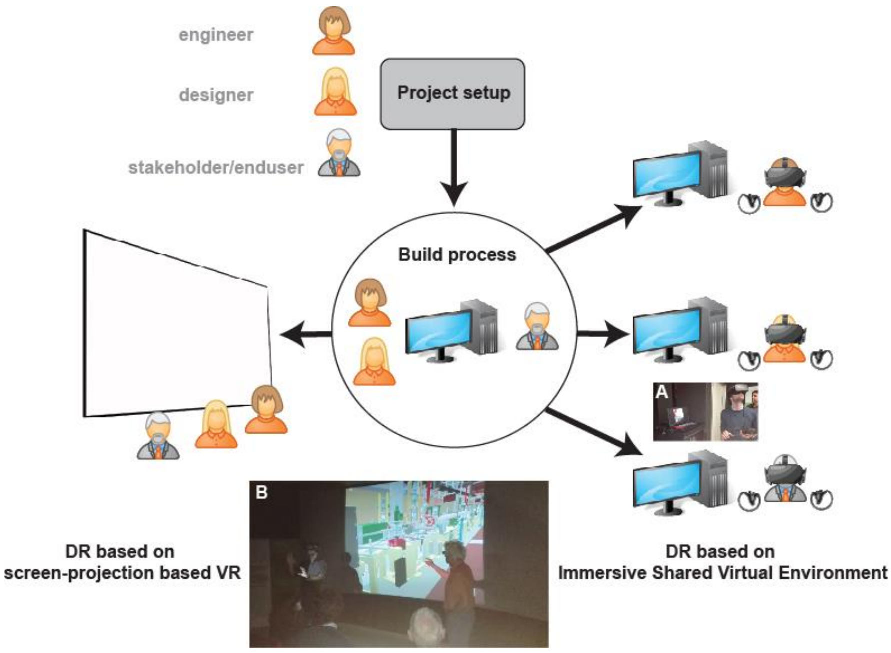

Figure 1. Processes supported by the system. The project setup is delivered to the build process during which a main workstation converts the 3D CAD models into a VRMU. DR sessions can be supported by both a conventional stereo-projection screen (example in picture B) and an Immersive Shared Virtual Environment mediated by multiple Oculus Rift devices.

2.2. Performance

The performance of the software satisfies the following 4 requirements, all fundamental to achieve an optimal flow of the immersive experience during immersive DR [8]:

(1) Compatibility with industry-standard 3D file formats, such as STEP's AP203 and AP214 application protocols. Since the rendering engine works on triangle meshes, a large number of mesh formats are also supported, as they usually allow for faster loading and decoding times;
(2) The time it takes to produce a 3D scene suitable for review after one or more changes have been made to the original CAD model is short enough not to interfere with the DR process itself. For example, in a test, an entirely new 3D scene (.dgn file the size of 236Mb) that included 6,000,000 polygons was rendered in 175 seconds;
(3) No manual conversion, simplification, spatial partitioning, or other optimization is required on the original CAD models to make them "VR-ready";
(4) The software is able to capture all of the original geometric details while still producing a smooth rendering experience, regardless of the number of input files or the complexity of input data.

It should be emphasized here that requirements (2), (3) and (4) are hard to meet by simply relying on existing 3D conversion tools and rendering engines, as they are usually developed with different goals in mind. Platforms like Unity, for example, are primarily meant for building applications that work on predefined 3D content that has been carefully crafted and optimized prior to packaging. By contrast, this software automatically accepts almost any kind of 3D input without requiring any manual work on the 3D content itself. Furthermore, straightforward rendering of triangle meshes does not guarantee that requirement (4) will be satisfied, because rendering performance depends vastly on the amount of triangles sent to the GPU.

2.3. Processing and rendering

A top development priority for a production system is the development of automatic conversion tools that guarantee data consistency [8]. This was done by implementing a custom-made engine and processing tool. The engine relies on modified versions of well known data structures and simplification algorithms that were fused together in a generalized, content-agnostic data structure and associated rendering algorithms.

Different simplification techniques are applied automatically to different parts of the 3D model in order to create a multi-resolution spatial tree, where a number of representations are created for each tree node. The rendering engine then traverses the tree to extract the optimal representation of each node among the ones that were constructed in the processing step. In order to select the optimal representation, four factors are considered in real time:

(1) The maximum geometric error that we can afford to display for that particular node, given its location in clip space and its pixel coverage on the screen;
(2) The amount of (compressed) data that must be streamed in from the disk or the network in order to load that representation, if it's not already present in memory;
(3) The type and amount of resources (main RAM, video RAM, shader instructions, etc.) that are consumed when that representation is rendered;
(4) Hardware performance, mainly GPU bandwidth and shader processing speed.

All of the above information is combined and a score is assigned to each representation. Then, a global optimization step is performed on the whole tree in order to balance resources and avoid stalling individual GPU stages, for example, by selecting too many representations that rely on ray marching with heavy fragment shader usage, and too few simple triangle streams that require more bandwidth but less shader instructions.

The technique described above leads to real-time rendering performance of about 90 frames per second required by the Oculus Rift headset, even when exploring very large or highly detailed 3D models (e.g., 6,000,000 polygons).

2.4. User interface

In order to enable effective and affordable interaction with the scene and between expert and non-expert participants while wearing the Oculus Rift, a web-based graphical user interface was implemented inside the virtual world supporting the direct manipulation of graphical menus and icons [9]. The interface implements the *model-world* metaphor to provide the user with a maximally affordable model of its functioning, logical structure and contents [10]. According to such a metaphor, the interface is characterized by:

(1) Innovative *graphical* solutions inspired by the use of every-day multimedia tools, such as tablets: the user can enable a “virtual tablet” that appears in their hand when pressing a predefined button on the Oculus Touch controller. The same user interface can be replicated on a real tablet or web browser when VR headsets are not employed;
(2) Intuitive *selection* solutions inspired by the use of own body to point and interaction with tools, by implementing a modified ray casting technique with the Oculus Touch controller emitting a laser pointer casting on the GUI;
(3) Effective functional requirements based on the *workbench* metaphor [11] used to store, recover, combine, send, and listen/visualize in real time to annotations of audio/video materials encountered by the DR participants while sharing their immersive VR experience.

2.5. Instrumented mode

The software can run in a special instrumented mode that provides additional features targeted at researchers, such as:

(1) Definition and control of experiments, self-contained state contexts that can be started and stopped by the researcher while the user is running the DR session;
(2) Automation in the VR scene by means of event-based scripting, that can affect either the global state or a single experiment;
(3) Full per-frame raw state logging, including position and orientation of all objects and actors in the VR scene, as well as recording of events and manually-inserted marks.

The raw log can be further processed to extract more meaningful measurements, such as hand/head movement kinematics, locomotion paths, the distance between users or the duration of tasks carried out during experiment runs.

3. Human productivity in design review

The development of a system based on shared immersive virtual environments is supported by comprehensive investigations of aspects related to human productivity in order to provide understandable, useful, self-consistent functions to maximize the likelihood that DR will be completed successfully. In this respect, one needs to ask whether shared immersive virtual environments of this type, though functionally effective, would constitute a challenge for DR, given that human users must interact with the system and adapt to it.

This can lead to interesting dynamics in the dyadic adaptation between each user and the “intelligent” multisensory system or display, possibly facilitating the processes of information selection and decisions making that are fundamental in DR, thus reducing the cognitive load and promoting the project development towards success. Facilitation is expected as challenging psychological effects should be involved due to social interaction between avatars within shared immersive virtual environments:

(1) Social facilitation, with the joined presence between virtual actors being shown to be positively related to motor and cognitive performance in exergames [12];
(2) Social proximity, known to modulate decision making in both economy [13] and military [14] fields, but whose effects on ship design remain to be determined;
(3) Enhancement of the perceived user-system cohesiveness, as it has been proved that team cohesiveness and entitativity improve performance on various tasks, including the cognitive ones [15];
(4) Active 3D viewing, known to disambiguate several 3D properties of environmental objects (i.e., shape, depth, slant) through self-generated (not passively observed) optic-flows [2].

However, facilitation cannot be taken for granted when considering shared immersive virtual environments relative to real life interactions [16]. For instance, as regards proxemics, it has been found that social interactions within shared immersive virtual environments are systematically distorted relative to real life conditions [17], though leading to similar effects of gender and age [18].

With regard to research of human productivity in a collaborative immersive environment, the system has multiple purposes:
(1) To build upon a new multisensory immersive VR model that lowers the cognitive demands involved in large scale DR;
(2) To provide a useful platform for testing and evaluating the performance of human adaptation to innovative multisensory systems allowing for mutual learning situations, which will likely provide insights for a better understanding of the human sensorimotor learning processes in shared immersive virtual reality environments;
(3) To provide guidelines, evaluation criteria, and recommendations for the design of adaptable and usable multimedia systems for DR.

4. Conclusions

An innovative system capable of managing a shared immersive virtual environment described in this paper has the potential to streamline the process of design evaluation (i.e., design review sessions) by automatically importing complex 3D CAD models, which do not require prior simplification or optimization, and projecting them in virtual reality in real-time.

Promising initial testing of the system, which has focused primarily on the technical requirements for smooth management of 3D models, implies that an increase in productivity is possible. However, the relative contribution of social and psychological factors needs to be considered in order to properly understand the possible advantages of this technology based on shared virtual environment for supporting DR-participants' interaction.

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