Synthetic Environments for Cooperative Product Design

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Abstract. Synthetic Environments (SE) facilitate an easy setup of various virtual realities since they are component-based and relatively easy maintainable. Through three stages, involving various types of stakeholders, the feasibility of SEs for cooperative product design (CPD) was explored: 1) Semi-structured group interviews with 19 engineers and designers assessed SE's potential for CPD; 2) Implementation of a SE; 3) Comparison of a SE with its real counterpart, through: a) an experimental task and b) questionnaires to determine the task performance, the mental workload, the experienced spatial presence, involvement, and realness. 16 participants had a similar task performance, mental workload, and involvement but differed in experienced realism ($F(1,30)=5.11$, $p=.03$) and spatial presence ($F(1,30)=7.02$, $p=.01$). This research emphasizes the benefit of SE for CPD, which can increase the communication, speed and quality of CPD. Hence, a first step is made towards a new era of CPD.

Keywords: Frameworks, reference models, architectures, tools and systems for cooperative engineering; Industrial scenarios, case studies of cooperative engineering: in mechanical engineering.

1 Introduction

In January 1963, Ivan Sutherland defended his PhD-thesis "Sketchpad-A Man-Machine Graphical Communication System" [1] in which he introduced an advanced display as a window into a virtual world. Since this milestone, the opportunities offered by VR technology have been recognized and expanded. In parallel, however, criticism emerged; e.g., in 1995, Cobb, D'Cruz, and Wilson [2] stated that VR technology is "a solution looking for a problem". Numerous advantageous VR applications have been presented for product design, the current field of application [3,4]. However, these applications are limited to the later stages of the product design process, which is supported by the available CAD models of products and their dynamic simulations.

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We pose that it is a major challenge to exploit VR for the earlier stages of the product design process. In these stages, design information is uncertain and ambiguous and high impact changes are still under consideration. Henceforth, the inclusion of all stakeholders in the design and decision process is important [5]. VR allows the presentation of design information in a way that it is comprehendible regardless discipline or training, whereas consequences of design choices can be experienced rather than imagined.

With the rise of recent technology, low-cost, relatively easy maintainable VR has become available and, consequently, became accessible for Small and Medium Enterprises. In this line, we introduce Synthetic Environments (SE): flexible mixed reality setups as a possible method to enhance Cooperative Product Design (CPD) with various stakeholders involved; e.g., managers, designers, engineers, manufacturers, and end-users. In Section 2, group interviews with 19 designers and engineers, assessed the potential of SE. Section 3 describes the implementation of a SE. In Section 4, the SE is validated by comparing it with its real counterpart. Last, a general discussion presents the pros and cons of the project accompanied by some advice for future research.

2 Group Interviews

To acquire an overview of possible improvements SEs can bring to CPD, semi-structured group interviews were conducted with 19 designers and engineers. The sessions started with an explanation of the concept SE. In four groups, the participants were asked to imagine an SE for CPD and compare it with their current practice.

2.1 Method

With each group, four interview sessions were conducted, preceded by one pilot session. The reactions of the groups were noted and displayed on a big central screen. The complete sessions were also recorded on video.

In the introduction round, each designer was asked to tell about his specific tasks in the development of a recent product. Second, the designers gathered around the SE configuration of the X-Ray machine lid and experienced how the behavior of the lid can be simulated for a wide range of future product configurations. Third, the envisioned usage of SEs for CPD was explained. The topics discussed were: 1) the definition and generic model of SEs, 2) exemplary SEs, and 3) the expected advantages and difficulties of SEs. Fourth, using a tablet PC and a drawing program, each group member expressed his ideas and presented them on a large central screen. The session was finished with a discussion.

2.2 Results

The video recordings (and their transcriptions), the schematic notes, and the drawings made during the brainstorm were coded and scored on frequency of mentioning, using the code categories: type of users, type of activity, type of product, design phase, accessibility, and project characteristics. The expressed requirements for the SE were subdivided in model requirements, procedure requirements, and interaction rquiments.

All participants indicated the SE’s usage as vehicle for communication among various stakeholders and, the possible faster design process as the main advantages of SEs. In addition, various reasons for applying SEs were mentioned; e.g., supports early (low fidelity) prototyping and, consequently, enables more exhaustive testing and experience with the products in development.

In Table 1, the users, activities, and products that typically define a future application of SEs are summarized. In line with current design practice, product developers are considered the most important users of the envisioned SEs. They expect to use SEs for reaching agreement among stakeholders throughout the design process, especially in the case of complex operational behavior. Designers see the most opportunities for SE in brainstorming sessions during the concept phase of the design process. Among them, designers from manufacturing companies see a more general benefit for SEs opposed to designers from design agencies.

To ensure an efficient support by SEs for CPD, visualization models, their usage, and interaction forms have to meet a set of requirements. In line with the researchers’ view on what makes an SE, designers foremost want SE models to be interactive. When used, they warned that the creativity-part of design work must remain in the hands of the designers; e.g., ideas for including users in the creative phase of CPD were not considered fruitful. When interacting with a virtual model, most power was appointed to SEs, where product models could be generated quickly. Specifically, CAD system interactions were considered too slow for the envisioned use of SEs.

Table 1. Application situations for Synthetic Environments (SE)

Type of users	Type of activity
- Product developers	- Reach agreement
- Non-technical stakeholders	- Determine (hidden) specs
- Technical stakeholders	- Converge between design options
- Product users	- Characterize design options
	- Diverge between design options

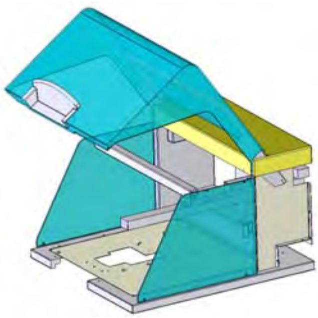
In general, the 19 engineers and designers see advantages in the usage of SEs for CPD. Especially, rapid prototyping, high level interaction, and communication support among various stakeholders during the design process are denoted as benefits. This sustained the envisioned advantages of SEs for CPD. Therefore, the second stage of the study was executed: the development of a SE to conduct a case study.

3 Technical Configuration

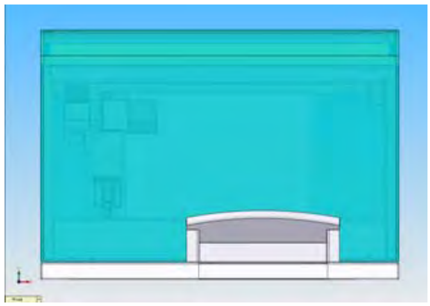
In the case study, an Axios material analysis machine using X-ray fluorescence from the company PANalytical should be under investigation. A model of the lid of this machine was constructed. The latter required a synchronized haptic and visual simulation. In addition, the configuration should be both low-cost and realistic. Figure 1a and 1b show the machine and its 3D CAD representation. The SE is presented in Figure 1c and 1d, which show both its haptic and visualization component. Figure 2 provides a schematic overview of the complete SE, dedicated to the case study.

The real environment

SE’s haptic simulation



3D CAD representation



SE’s visualization

Fig. 1. Realistic Environment vs. Synthetic Environment (SE)

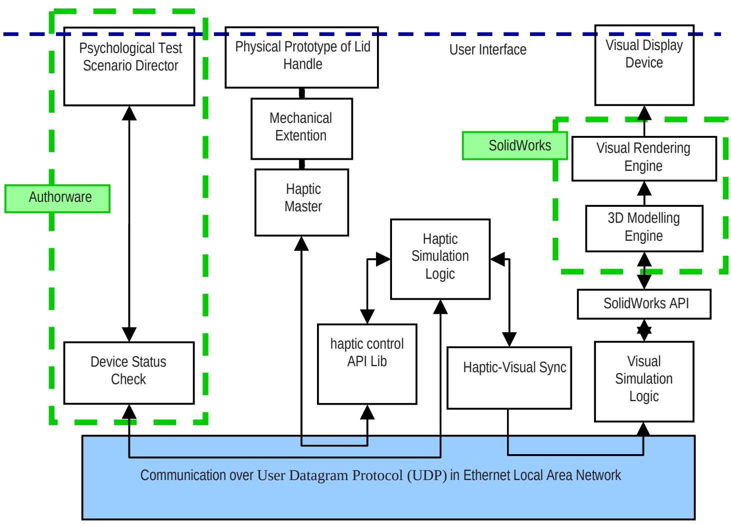


Fig. 2. Configuration of the Synthetic Environment (SE)

3.1 Haptic Simulation

For a realistic haptic simulation of the machine lid, a FCS-CS Haptic Master is used (see also Figure 3), which enabled the simulation of forces up to 250N in 3 degrees of freedom, within a workspace of two translations and one rotation, respectively of 0.36m, 0.40m, and 1 rad.

To enable adequate, realistic handling of the lid, the Haptic Master was extended using a rotating arm as an end-effector, with a variable length and gear ratio, as shown in Figure 3d. A grip from a real X-Ray machine was connected to the rotating arm (see Figure 3e). Using the C++ API of the Haptic Master, the behavior of the virtual lid was modeled and controlled. This model ran on a dedicated PC (see Figure 3b).

3.2 Visual Simulation

The visualization was rendered on a dedicated PC connected to a projector (see Figure 3h and 3g), which displayed the dynamic model of the lid on a screen (see Figure 3f). The visualization started with the I-DEAS CAD model of the lid that was converted to the ISO standard "Standard for Exchange of Product model data" (STEP) and, subsequently, was imported into SolidWorks' 3D CAD software, which served as 3D Modelling Engine and 3D Visual Rendering Engine; see also Fig. 2. The 3D Modeling Engine defines and updates the 3D model according the real-time simulation situations of the virtual prototype. The 3D Visual Rendering Engine is responsible for the shading and visual presentation of the 3D model through the Visual Display Device. Through the Solid-Works API library, the visualization is controlled by the Visual Simulation Logic code written in C++, as is all denoted in Figure 2.

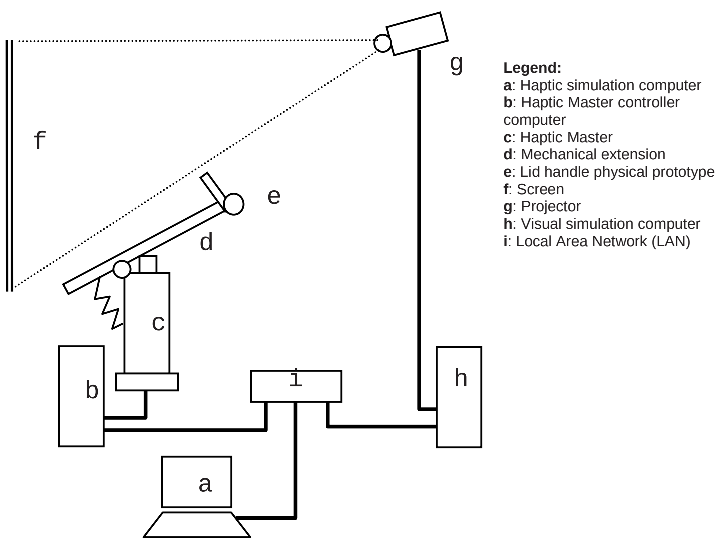


Fig. 3. Scheme of the Synthetic Environment's (SE) hardware configuration

3.3 Synchronization

To achieve real-time synchronization, the haptic simulation and visualization, the User Datagram Protocol (UDP) is used for data transmission over the Local Area Network (LAN); see also Figure 2 and 3i. Through the Haptic-Visual Synchronization module (see also Fig. 2), the Haptic Simulation Logic module communicates the current position of the lid to the Visual Simulation Logic module; consequently, the dynamic 3D model is updated with the new position of the lid and its visualization is updated on the screen.

To enable a smooth, realistic interaction between users and SE, it is crucial to have a latency of less than 50ms between different modalities, the visualization and the haptic master in our case [6]. After an upgrade of the video card driver, a latency of 40 ms was realized, well below the threshold.

4 Validation of a Synthetic Environment

A SE should elicit the same behavior as they would have in reality. Then, and only then, the SE could truly play a role of importance in communication processes among several stakeholders in CPD. For this reason, we developed an experimental setup that could compare a SE with a real representation of our case.

4.1 Presence

Most research on user behavior in VR environments is related to the concept of presence [7]: the user's psychological response to a virtual environment. Presence is sometimes confused with immersion [7]: the objective level of sensory fidelity that a virtual environment provides.

The sense of presence can be determined through various subjective (subjective post-test rating scales and questionnaires) and objective measurements [8]. We choose the IGroup Presence Questionnaire (IPQ) [9], which consists of three subscales: (1) Spatial presence – the relation between the virtual environment as a space and the user's own body; (2) Involvement – the awareness allocated to the environment; and (3) Realness – the sense that an environment is real.

Since some researchers demonstrated an increased sense of presence will result in a decrease in mental workload [10], we controlled for this using the Rating Scale Mental Effort (RSME) and an objective assessment: a secondary task. This is a n additional task, that can serve as an indicator for the amount of effort allocated to the main task in the SE. The more effort is dedicated to the main task, the more performance on the secondary task will decrease.

4.2 Method

Subjects and materials: Sixteen participants (9 males and 7 females) volunteered in the research against monetary compensation. The participants' age ranged from 19 to 30 (average: 24). None of them reported any physical limitations. A PC running Authorware 7.01 (Macromedia, Inc.), was used to guide participants and record the necessary data. On a 17" flat screen the experimental task was presented. Participants responded through a standard QWERTY keyboard and mouse.

General procedure and design: Participants were submitted to two sessions: an SE and a real environment (RE), held on different locations. The order of the sessions was counterbalanced; i.e., half of the participants started in the SE and half in the RE. The RE contained the real X-Ray machine lid. The SE contained a simulation of it, as described in Section 3. Each session started with a short explanation of the task. Subsequently, the participants were required to take place behind the computer. The experiment started with two practice trials followed by an unrestricted number of experimental trials with a 20 minute time constraint. The participants were instructed to perform as many experimental trials as accurately as possible within the time limit.

Experimental task: Based on an expert interview, an experimental task was constructed that represented the use of the X-Ray machine in practice: the preparation of the sample material in cups to the performance of a scan. As a secondary task, the memorization of characters was added to assess the invested mental workload in the experimental task, see also Figure 4.

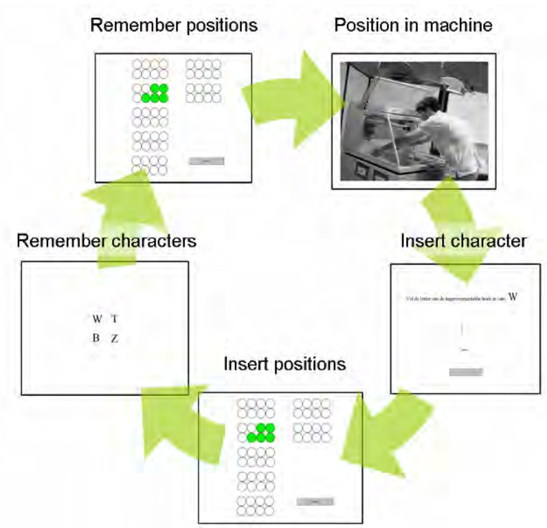


Fig. 4. The experimental task: 1) presentation of four characters in an imaginary square; 2) presentation of the locations of the cups, using a color); 3) Position the tray inside the machine; 4) participants were asked to insert the character as previously presented in the opposite corner; 5) Last, participants indicated where they had put the cups in the machine

Each trial started with a five second presentation of four unique, randomly drawn, black characters in an imaginary square on a white background. The participants were required to remember these letters with their positions on the screen. This was followed a presentation of seven 2x4 grids of black circles; each resembled the possible tray position in the X-Ray machine. In one of these grids, for a period of three seconds, one to eight of its circles were randomly colored red, blue, or yellow, with the prerequisite that the color was not used in the previous trial. Participants were asked to remember (1) the position of the tray in the machine, (2) the location of the sample cups within a tray, and (3) their color. Next, a real tray had to filled and placed in the machine in the same manner as was presented just before. Then, one of the four characters of the memory task was presented in the center of the screen. Here, the character presented previously in the opposite corner of the imaginary square had to be inserted. At the end of the trial, participants had to indicate where they had put the cups in the machine.

Questionnaires: After each session, the RSME and IPQ were collected, as described in the previous section.

4.3 Results

Three separate Multiple ANalyses Of VAriances (MANOVAs) were run on the resultant data, one regarding the experimental task and one regarding each questionnaire. MANOVAs were preferred above ANOVAs, because the subtasks could not be treated independently from each other.

Experimental task: Although participants were immersed in distinct environments, their performance did not differ on the experimental task. There was no significant effect of environment on the percentage of errors made in the experimental task on average ($F(3,28)=.98$, *ns*), nor for each subtask separately: Positioning the sample cups ($F(1,30)=.03$, *ns*), positioning the tray in the X-Ray Machine ($F(1,30)=.03$, *ns*), and the memory task ($F(1,30)=.10$, *ns*).

Questionnaires: After each session, participants were instructed to rate their invested mental effort for the experimental task in general and for three subtasks separately, using the RSME. There was no significant difference between environments in general ($F(3,28)=.66$, *ns*). Furthermore, there were no significant differences between environments for the separate ratings: the task in general ($F(1,30)=.58$, *ns*), the positioning of the cups ($F(1,30)=.19$, *ns*), the interaction with the machine lid ($F(1,30)=1.06$, *ns*), or the memory task ($F(1,30)=.01$, *ns*). On the IPQ, participants reported to experience more presence in the RE compared to the SE. A significant difference between environments was revealed: The IPQ scores on presence in the RE ($M=4.26$) were higher than in the SE ($M=3.95$), $F(3,28)=3.83$, $p=.02$. Data analysis revealed a significant difference in two of its three dimensions. Participants reported to experience more realism in the RE ($M=3.77$) than in the SE ($M=3.46$), $F(1,30)=5.11$, $p=.03$. In addition, they reported more spatial presence in the RE ($M=4.88$) than in the SE ($M=4.08$), $F(1,30)=7.02$, $p=.01$.

5 Discussion

The research line presented aimed to explore the use of flexible, highly interactive Synthetic Environments (SE) for CPD. First, designers and engineers were asked to judge the applicability of SEs for the early stage of CPD. This was done through group interviews. As a consequence of the positive reactions on the SE, a SE was developed for a specific design case was implemented. Next, a study was conducted to validate the implemented SE by comparing it to the real situation. The SE proved to be comparable with the real environment with respect to experienced workload and task performance. However, the participants fold more present in the RE than in the SE.

The designers and engineers that were interviewed indicated that in potential SEs can be very useful in the early stages of CPD. In particular, SEs can diminish the time required for the overall design process by supporting the communication processes among the various stakeholders; e.g., engineers, designers, managers, end-users. SEs were acknowledged especially useful in the design of products and for complex operational behavior. Moreover, the interviewees emphasized that it is important that an SE supports fast iterative and interactive operations.

As stated, the validation of the SE revealed that human performance is comparable in both the SE and the real environment. No evidence was found for any difference in the amount of errors in the experimental task between both environments. Furthermore, there was no significant difference in mental effort – objective as well as subjective – between these environments. On the other hand, this study did reveal a significant difference on the sense of presence between the two environments. This is in contrast with earlier findings of Draper and colleagues [10], who suggested a correlation between mental workload and the sense of presence. Hence, for the application of SEs in CPD, SEs are well capable to provoke the same human performance as in a real environment while an impaired sense of presence is experienced. For future research it is interesting to determine, what factors do affect communication in SEs.

This line of research showed that (low-cost) SEs can trigger realistic behavior and can facilitate the communication among various stakeholders, especially in the early phases of product design. It promises to be an affordable and feasible method, which increases the communication, the speed and the quality of the design process. With that, it is possibly a first step towards a new era of CPD.

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