APPLICABILITY OF SYNTHETIC ENVIRONMENTS FOR PRODUCT DESIGN

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Abstract: This paper studies the applicability of Synthetic Environments (SE) for dynamic prototyping in the early phase of product design. For this purpose, a simple SE, built with commercial off-the-shelf (COTS) technology, was employed to support the design of the lid of an X-Ray machine. Psychological experiments, statistical analysis of questionnaires, and user interviews indicated that for the design problem concerned, the SE was a proper substitution of the physical prototype, although the participants experienced difference in sense of presence. To further improve the applicability of SE, a design strategy of intuitive user interface is proposed for dynamic prototyping in SE to facilitate the communication among stakeholders with various knowledge backgrounds.

Key words: synthetic environment, product design, dynamic prototyping, industrial design, validation

Abbreviations

API	Application Programming Interface
AR	Augmented Reality
CORBA	Common Object Request Broker Architecture
COTS	Commercial Off-The-Shelf
DCOM	Distributed Component Object Model
DP	Dynamic Prototyping
IPQ	IGroup Presence Questionnaire
MANOVA	Multiple ANalyses Of VAriance
MR	Mixed Reality
RW	Real World
SE	Synthetic Environment
SME	Small and Medium Enterprises
STEP	Standard for the Exchange of Product model data
UI	User Interface
VE	Virtual Environment
VR	Virtual Reality
XML	Extensible Markup Language

1- Introduction

Virtual Reality (VR) is often used as a notion of a group of technologies to create artificial environments that the human users interact with multi-sensory modalities in visual, haptic, or even smell, taste, etc. Such an environment is called Virtual Environment (VE). A related term is “Mixed Reality” (MR), referring to environments where both virtual and physical objects are included.

Although different researchers and organizations may have somewhat different concepts with the same term, “Synthetic Environment” (SE) in a general sense refers to any deliberately constructed artificial environment as a replacement to the real and natural environment in which an operator can navigate or interact as if in the real world (RW) [A1][RB1][RA1][IP1]. As a simulation of its RW counterpart, in most cases its construction is based on VR technologies. SE may be used as a general term referring to a superset concept of virtual reality, virtual environments, teleoperation, telerobotics and augmented reality [DM1].

In this paper, the term “SE” in the narrow sense within the scope of the specific research project, is limited to the application domain of Industrial Design, especially in the early stages of the design process like the conceptual design phase where the SE is assumed to have wider margin of (hypothetical) advantages.

1.1 – Development of VR and SE

The concept of VR can be traced back to the pioneer research work by Ivan Sutherland [S1] in 1963 in which a computer display was described as a window into a virtual world. As early as 1967, the development of one of the first multimodal VR systems GROPE [BO1] was started. But it’s not until the 1990s when the booming advancement in commercial computer hardware started to accommodate the requirements of VR applications thus the new opportunities offered by VR technology were widely recognized and research activities proliferated. However, criticism over the applicability of VR also paralleled the advancements. For instance, in 1995, Cobb et al [CD1] stated that VR technology is "a solution looking for a problem" in contrast to Brooks, who in 1994 had a largely positive view that "it almost works" [B1] in a public lecture cosponsored by the Royal Academy of Engineering and the British Computer Society in London.

The earlier applications of SE were mostly confined in military mission and critical system simulations because of the high cost of equipments and complicated technology. With the rapid development of computer technologies, the application of SE spread into academic, commercial, industrial and educational domains.

In a review of the state-of-the-art VR technologies and application systems in 1999, Brooks [B2] already concluded that "VR is now really real". Many successful VR application systems for industrial product simulation were described and discussed in this review report, covering the application domains of military, medical, mechanical industry and scientific research.

One example of the research projects that resulted in a successful general purpose commercial VE product is CAVE. It allows multiple persons to experience a stereoscopic visual space constructed with image projections on full-view screens according to the tracked body position and movement of the viewers [A1].

The most successful applications of VR technologies might be aircraft cockpit simulators for pilot training, car simulators for driver training, movies special visual effect making and computer video games, where level of immersion and presence is regarded as the key point to judge the success. Many researchers made insightful reviews of SE applications [A1][DM1][B2][SC1][BC1][SC2], where at the time of those reports, most featured SEs still cost too much for Small to Middle Enterprises (SME) applications. For example, a commercial VR display system like CAVE cost about $300,000. RAVE cost about $500,000, and less expensive variants like Future Lab's PC CAVE Linux PC cluster with nVidia graphics cards cost less than $100,000 [BC1]. While high-end advanced CAVE cost from $250,000 to $1.5 million, the cost to build a low-end CAVE-like system can be reduced to about $20,000 in the year 2006, but with lower speed, graphic quality and level of immersion [L1].

1.2 –Application of VR and SE in Product Design

The development in video game industry further helped to reduce the costs with mass production of technologies and equipments previously only available in high-end VR systems. This popularized VR concepts and technologies into the society and stimulated more research on potential applications. The research work of this paper is also one of these attempts to explore and contribute knowledge on the possibility and methodologies to build applicable SEs with currently available VR technologies to improve the industrial product design processes.

SE already found many applications in product design to support the prototyping of vehicles [C1], the design on a virtual workbench [WD1], production planning [DF1][MS1], and haptic virtual product assembly [HV1], etc. However, these applications are limited to the later stages of the product design process for dynamic simulation based on the relatively matured prototype of products.

In Biocca and Levy's book [BL1], VR was investigated as a communication media in the general sense. It allows the presentation of design information in a way that it is comprehendible regardless of discipline or training, whereas consequences of design choices can be experienced rather than imagined. Such an SE can serve as a collaborative workspace for designers.

For example, Antonya and Talaba [AT1] presented recently one of the first VR applications for product analysis stages. Bordegoni and Cugini [BC2] demonstrated a possible application in the conceptual stage, using haptic clay modelling.

Bowman and McMahan [BM1] made a convincing assertion about the reason of success after a brief review of successful VR projects, that "they all fulfil requirements in their respective domains and improve on alternatives for meeting those same requirements in some way". They observed that there is already a trend toward lower-cost, commercial off-the-shelf (COTS) VR systems.

Jimeno and Puerta's detailed review [JP1] provided the most updated overview of VR applications in design and manufacturing. Cecil and Kanchanapiboon's survey [CK1] is quite comprehensive specifically on virtual prototyping (VP). There are also similar projects employing MR for evaluation of engineering design, such as Mixed Environments for Review and Generation of Engineering Designs (MERGED) [WK1], with relatively high level of immersion and an evaluation plan focused on comparison between MR and VR solutions.

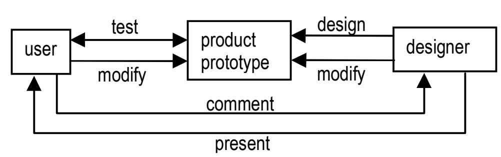


Figure 1: Dynamic Prototyping in Synthetic Environment

2- Dynamic Prototyping with SE

Prototyping refers to the design process of making mock-ups of the product for testing and evaluation purposes. In most of the cases the costs of physical prototypes are very high so a digital virtual prototype is preferred thus the designer can modify the prototype with lower costs than a physical prototype. Moreover, the prototyping process may also employ physical and/or virtual prototype, with 3D scanning and rapid prototype manufacturing (such as stereo lithographic 3D printing) techniques to support seamless modification migration, or with Augmented Reality

(AR)[FA1][OY1] to impose virtual modifications on physical prototypes. Such a process is called Dynamic Prototyping (DP).

Figure 1 illustrates the DP process in the SE. The designers present their design of the product through the prototype in the SE to the product end users (and other stakeholders), and the users test the product design by interacting with the prototype in the SE and comment to the designers by direct modification on the prototype. The consequences of the desired modifications can be visualized and simulated instantly. The major enhancement of such a DP process to the conventional design process is the closer involvement of the end users and other non-designer stakeholders in the design process.

One example of the virtual DP research reported by Niesen [N1] in 1999 was a MR environment for vehicle operator interface design. It included an industrial robot, force feedback joysticks, levers and other control hardware components in conjunction with graphics to create an environment which can be readily reconfigured and tested without lengthy design changes.

In Brooks' review [B2] of VR application systems, he observed the following industrial application requirements: "The most strongly desired tools are geometry manipulation tools, ways of easily specifying interactions with the design. … The great desire is for interfaces simple enough for the occasional user to participate in model changing." This means the inclusion of non-designer roles in the DP process is desirable, which we perceive as requirements of both a supporting framework of process integration, as well as intuitive user interfaces for the occasional users.

3- Applicability of SE

Although the development of VR technologies enabled successful application of SE in many fields, SE is still not commonly employed in industrial product design processes of SME. In the following, the applicability of SE for product design will be discussed regarding potential benefits as a communication tool with intuitive user interface to support user-centred dynamic prototyping, employment of industrial standard technology to improve cost effectiveness and flexibility, and most important, whether a simple SE can be a valid replacement of the physical prototype.

3.1 – SE as a Communication Tool

Because the different roles in the product development process have different knowledge backgrounds and different levels of expertise, which is an intrinsic problem regarding the multi-disciplinary characteristic of industrial design, obstacles in communication of requirements and design concepts are often the causes of delayed, faulty, mismatched, inferior, or even failed products.

One of the possible benefits of SE to product design process is to provide low-cost prototyping methods to speed up design evaluation feedback loops and to achieve optimization of the product design by enhancing communication in the design process including all the stake-holders of different roles like customers (product end users), marketing personnel, designers, engineers, business management personnel, etc.

Especially at the earlier stages of the product design process, such as the conceptual design phase, normally both the design concepts and the available prototype is uncertain and ambiguous. The requirements and solutions are general, vague and conceptual rather than accurate, concrete and specific, which is hard to communicate without help of intuitive models. High impact changes are still under consideration thus intensive communication of design concepts are critical for decision making among the different stakeholders of the product development group.

When SE is studied on the application background of industrial product design, it includes not only theories and techniques about virtual or mixed-reality simulation of objects, but also those about accessibility of the technologies by the human users who interact with them, specifically, all the stakeholders participating in the product design and development process. Such an SE must be simple in configuration, non-obstructive to the design process and accessible to all stakeholders without specialized training.

Cruz-Neira et al. (1992) [CS1] stated in bold characters in their report of the CAVE VE system, that "One of the most important aspects of visualization is communication. For virtual reality to become an effective and complete visualization tool, it must permit more than one user in the same environment." This means that the communication feasibility is not only a merit provided by a VE or in our case, an SE, but also an indispensable component of the SE to make it "effective and complete".

Likewise, we also regard the SE as a tool for communication of concepts and ideas, for either traditional prototype evaluation, or collaborative, interactive user-centred dynamic prototyping. The simulation of the product is one-way communication to present the product information to the stakeholders. Intuitive interaction methods without intrusion into the communication are promising to break the obstacles in the other direction to ease the expression of modifications of complex product features requested by different roles, in addition to traditional verbal and sketch drawing approaches. So we need to consider the intuitiveness of user interaction in SE from a communication point of view.

3.2 – Intuitive User Interface

Most of the researches in VE/SE user interface were based on one of the following assumptions:

a. The VE itself is a more intuitive user interface for most users, thus most of the researches focused on application of VE as an intuitive interface to certain tasks.

b. 3D user interaction techniques should be improved to simulate the real world activities the closer the better to be intuitive to the user. This led to efforts to provide higher level of immersion and presence.

But these are not always true for all application cases. Especially for industrial design engineering tasks, the efforts needed in deployment of an SE in the design process might be an obstacle preventing the designers and engineers from working effectively within the high immersive VE. Furthermore, the intuitive interaction techniques for the purpose of highly immersive 3D VR experience may block the design concept communication when it doesn't fit the conventional work flow.

Professional CAD user interfaces which can manipulate the product model in an accurate way normally requires certain level of training before the user can operate them at will without interrupting the design concept formation and communication. On the other hand, intuitive user interfaces normally can't provide handles for highly accurate design modification.

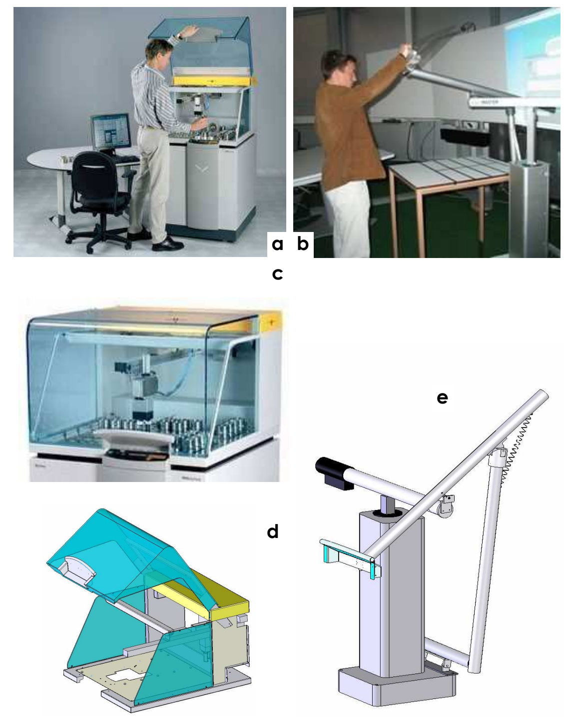
To solve this problem, Nassima Ouramdane et al. (2006) [OO1] suggested splitting the VE space into three zones in which a specific interaction model is used: a free manipulation zone, a scaled manipulation zone and a precise manipulation zone. In the free manipulation zone, rough intuitive operation is supported; while in the precise manipulation zone, a more complex but more accurate interface assisted by virtual guides is supported.

We propose a different approach to solve this problem. Since different roles with different backgrounds have different senses of intuition, it's highly possible that one type of intuitive interface for one role turns out to be intricate for another role. For example, the designers may feel difficult to understand or operate with the UI of an engineering software although the engineers feel it quite intuitive. Thus, different roles should be presented with different customized interfaces. Naturally, the designers and engineers feel more comfortable with the CAD software interfaces of their daily use. So in the SE, it should be possible for different roles to manipulate the common product model through different intuitive interfaces of their choices.

3.3 – Cost Effectiveness

Up to now, the fact that successful high-level SEs are often too heavy-weight and specific for product design applications persists to be an obstacle of pervasive application of SE techniques in product design processes of SME.

Hopefully with the development of technology, low-cost, relatively standardized SE components will become available and, consequently, become accessible for SME. In order for this to be accepted by the industry, a flexible SE should be able to be configured for a range of application purposes. Components should be able to be plugged in or removed and designs be altered; hence, various SEs can be created on demand, rather than one dedicated implementation. This will decrease deployment costs and increase the applicability to product design requirements which is versatile in nature. For this to be possible, a universal integration platform of hardware and software modules for construction of SE should be established based on industrial standard technologies for data exchange and interoperability, such as STEP, XML and CORBA / DCOM.



a) real world **b)** synthetic environment
c) physical prototype **d)** visual simulation **e)** haptic simulation

Figure 2: Real Environment vs Synthetic Environment

3.4 – Validation of Applicability

Before a cost effective simple SE system can be accepted as applicable in the early stages of product design in SME, the following questions must be answered:

1. Whether a simple SE can be constructed with COTS products with relative low costs
2. Whether it can replace the physical prototyping method commonly employed in industry

As the first step, we tried to evaluate the validity and applicability of such a simple SE to a practical industrial product design case.

4- Case Study

4.1 – Experiment Setup

Overview

In the case study, an experimental SE was constructed for a commercial product design problem proposed by one of our industrial partners. Visual and haptic simulation was provided to support design evaluation of the compartment lid of an X-ray spectrometer which should be ergonomically optimized for end users with different body features, physical conditions, safeguard requirements, as well as work preferences. This case is chosen to be simple for implementation yet sufficient for our experiment targets, instead of a full fledged SE. The experiment setup were shown in photos of Figure 2, and the hardware and software configurations of the SE are illustrated in Figure 3 and 4 respectively. All of the major hardware, software components and technologies employed to construct the system are COTS products and current general practice, except the customized extension arm for the haptic device.

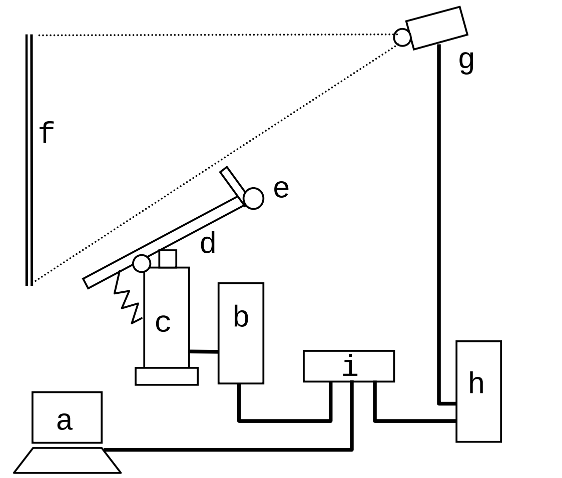
Visual Simulation

The product operated in RW is shown in Figure 2a, and the MR prototype is evaluated in an SE as shown in Figure 2b. A dynamic 3D model (Figure 2d) as visual simulation of the motion of the lid (Figure 2c) was generated on a generic Wintel desktop PC (Figure 3h, AMD Athlon 64 3500+; 2.21 GHz, 1 GB RAM, nVidia GeForce 6800GT; 256MB). A projector (Figure 3g) was connected to the PC to display the animation on a wall screen (Figure 3f).

The 3D model of the lid was imported from the CAD software (I-DEAS) used by the designers in an industrial standard data exchange format (STEP) into a 3D CAD desktop software (SolidWorks) which served as both 3D Modeling Engine and 3D Visual Rendering Engine (Figure 4). After some manual clean-up and simplification, the motion parameters of the model components were defined to make a dynamic model fit for direct simulation inside the CAD software utilizing its built-in 3D rendering capabilities. 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 (Figure 4). Through the SolidWorks API library, the visualization is controlled by the Visual Simulation Logic code (Figure 4) written in C++. This approach simplified the integration work by avoiding the step to transfer the dynamic model into a dedicated 3D rendering engine, but also causes bigger visual latency than a dedicated 3D rendering engine.

Haptic Simulation

The force feedback simulation was rendered with a haptic device, FCS-CS HapticMaster (Figure 3c), which is capable of simulation of forces up to 250N in 3 degrees of freedom, within a workspace of two translations and one rotation of 0.36m, 0.40m and 1 rads respectively. A rotating arm with a variable length and gear ratio was installed as an end-effector to extend the motion range of the HapticMaster (Figure 2e). To evaluate the design of the lid handle, a physical prototype was mounted on the rotating arm, as shown in Figure 3e. The Haptic Master was programmed to model and simulate the behavior of the virtual lid on the HapticMaster controller computer (Figure 3b) and the simulation process was controlled through the API library of HapticMaster by Haptic Simulation Logic code (Figure 4) running on a laptop PC (Figure 3a, Dell Inspiron 6400). The parameters of the haptic model can be adjusted by changing data in a text input file for dynamic prototyping of the force features.



a: haptic simulation computer
b: HapticMaster controller computer
c: HapticMaster computer
d: mechanical extension
f: screen
g: projector
h: visual simulation
i: 100Mbps Ethernet switch

Figure 3: Hardware Configuration

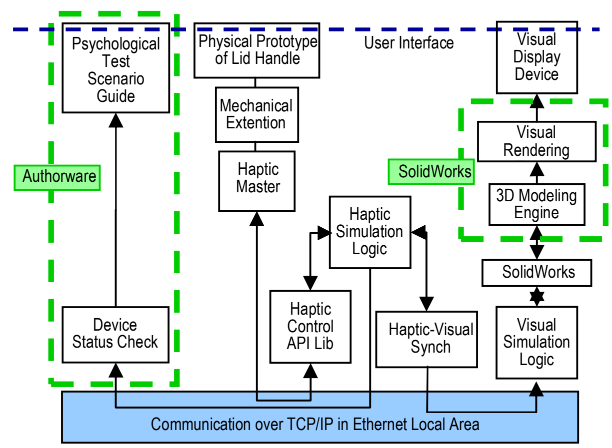


Figure 4: Software Configuration

Synchronization and Integration

In order for the visual simulation to be synchronized in response of the user operation on the haptic end-effector, communication between the visual and haptic simulation modules is necessary.

Because of the performance limitation of the consumer grade graphic card used in the visual simulation computer (Figure 3h) and the internal 3D rendering engine of CAD software which is not optimized for real-time rendering, the frame rate of real-time 3D rendering of the dynamic model fluctuates between 16 – 22 fps and can be sometimes slower than the rate of data received (down-sampled from the high-rate physical data) from the Haptic-Visual Sync module (Figure 4). This can cause intermittent data loss. User Datagram Protocol (UDP) is chosen for communication between the visual and haptic simulation modules, since possible intermittent data loss can be well recovered by updated data of the new position of the lid, thus the visual simulation can always catch up with the most recent status of the haptic device to achieve an as-fast-as-possible real-time simulation.

Through the Haptic-Visual Synchronization module (Figure 4), the Haptic Simulation Logic module sends the current position of the lid to the Visual Simulation Logic module for the dynamic 3D model to be updated with the lid's new position.

According to Brooks [B2], system latency between the user motion and the visual response is more critical than visual rendering quality to the level of immersion achieved. Based on his experience with the flight simulator, latencies of greater than 50 ms was perceptible, while latencies of 150 to 250 ms won't ruin the feeling of immersion depending on the type of simulation.

In the system's pilot test, without any tuning, the visual-haptic latency was as big as over 300ms and apparently noticeable to the user. After upgrading the video card driver and code optimization in the simulation logic to avoid unnecessary graphic updates, the latency was reduced to around 45-63ms, which is marginal to perceptible as observed in our test. The visual haptic latency was caused mainly by the graphic updating of the dynamic 3D model in SolidWorks software (GraphicsRedraw2 API call), while the other time costs like network transmission and data processing were negligible.

Besides, in the psychological experiment (described in Section 4.2) to evaluate the validity of the SE, the participants were required to conduct some predefined tasks guided by an interactive Test Scenario Guide module (Authorware script in Figure 4). The Test Scenario Guide module got device status input data from the Haptic Simulation Logic module through the Device Status Check module using file semaphores that were shared in Common Internet File System (CIFS, protocol used for Windows Network File Sharing).

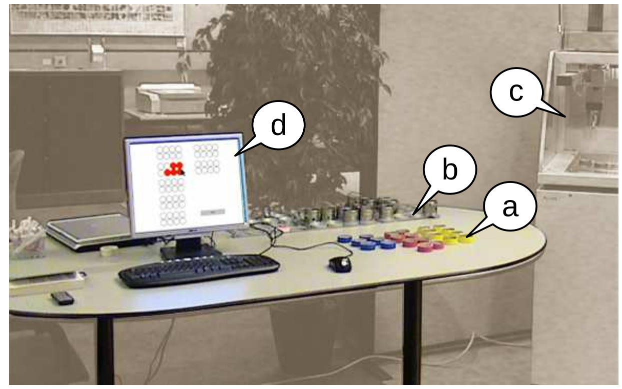
4.2 – Validation Experiment

In order to verify whether such a simple SE described above can be used as a valid replacement of the RW physical prototype for the product design evaluation purpose, a validation experiment was conducted. This kind of validation is often related to the measurements of immersion and presence.

Immersion and Presence

Immersion and Presence are two related important factors concerning design and evaluation of an SE. According to Mel Slater's definition [SW1], "immersion" refers to the objective level of sensory fidelity a VR system provides, while "presence" refers to a user's subjective psychological response to a VR system. Quite some researches [SS1] has been done in quantitative study of immersion and presence in VE, such as Meehan et al [MI1] and Pausch et al [PP1], which provided experimental approaches to evaluate the validity and applicability of an SE.

Although higher level of immersion often bring better feeling of presence hence better task performances, empirical research demonstrated that the level of immersion is not always the most important factor affecting the feeling of presence [BM1]. Furthermore, in certain application cases, the feeling of presence is not required because it won't help the user performance in the tasks. On the contrary, intentional abstract, unrealistic visual presentation might even help the user to get better understanding of the critical features of the simulated objects [BM1]. Another example is a recent research result reported by [SV1], in which the authors presented certain cases where a non-realistic third-person perspective may induce higher sense of presence because of easier manipulation of the virtual objects.



a) sample cups **b)** tray **c)** machine lid (the physical one in this photo) **d)** experiment guide

Figure 5: Psychological Experiment

Based on these related research results, we propose that an SE to aid product design should not try to implement as higher level of realism or immersion as possible, but to provide an efficient minimal system for the targeted design tasks.

The sense of presence can be assessed in many ways that can be roughly divided into two categories: subjective and objective measurements [IR1][NE1]. Subjective post-test rating scales, or questionnaires, have been most commonly used in research experiments about presence in VR. There are a large number of presence questionnaires available that researchers can use to evaluate the sense of presence in VE, e.g. [WS1][S2][SF1]. One questionnaire is specifically interesting, because it is constructed from other presence questionnaires: The IGroup Presence Questionnaire (IPQ) [DB1]. The IPQ consisted of 14 items and 3 subscales: (1) Spatial presence – the sense of being there; (2) Involvement – attention to the real and virtual environment; and (3) Realness – the judgment of realism of the environment.

In the current study, the SE was evaluated by comparing the users' sense of presence and subjective workload to those in the RW. An adaptation of the IPQ was posed to the users after they had performed a task similar to the practical operation with the product, in both the SE and the RW. Logically, we expected the users to indicate higher level of presence in the RW with significantly higher scores on each subscale for the RW than those for the SE.

Experiment Procedures

Sixteen participants (9 males and 7 females) joined the individual experiment. All participants were non-expert users (regarding knowledge of the prototype product) in the age of 19 to 30 (with an average of 24) and reported no physical limitations.

Participants were guided to take part in two experiment sessions on different locations, one in the SE and the other at the work site of the real machine. The order of the sessions was counterbalanced; i.e., half of the participants started in the SE and the other half in the RW.

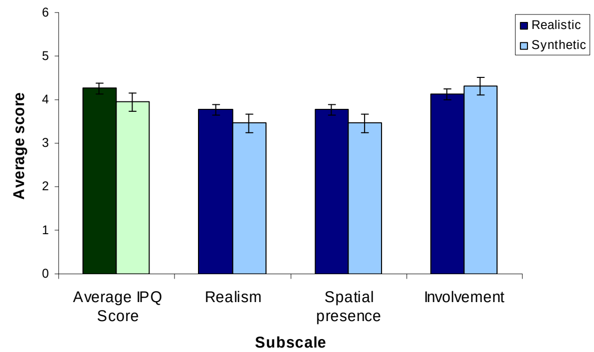
Each session started with a short explanation of the task to perform. The task was designed based on interview with expert users of the machine to resemble the typical user operations of the X-Ray machine in practice (See Figure 5), i.e. the actions of a) preparation of a number of sample cups (with colored labels, Figure 5a) for material analysis on designated positions of the tray (Figure 5b), opening the machine lid (Figure 5c), putting the tray into the designated positions in workspace of the machine, and taking the tray out of the machine. After the task explanation, the participants were guided by Psychological Test Scenario Guide software running on a laptop computer (Figure 5d) to start with two practice trials followed by an unrestricted number of experimental trials with a 20 minute time constraint without any human intervention. The participants were instructed to perform as many experimental trials as accurately as possible within the time limit.

After each session, a self rating on the sense of presence (IPQ) was collected. The IPQ assessed the experienced presence in the environment on a 7-point Likert scale. In this questionnaire, the experience of presence is expressed in three dimensions: Spatial presence, realism, and involvement with the environment.

Results

A Multiple ANalyses Of VAriance (MANOVA) was run on the resultant data, regarding the questionnaire, to investigate differences between the two environments. MANOVAs were preferred rather than ANalyses Of VAriance (ANOVA), because the subtasks could not be treated independently from each other.

Participants reported to experience more presence in the RW compared to the SE. A significant difference between the two environments was displayed: The average IPQ scores of presence in the RW (M = 4.26) were higher than those in the SE (M = 3.95), $F(3, 28) = 3.83$, $p = 0.02$. Data analysis showed a significant difference in two of its three subscales. More realism was reported in the RW (M = 3.77) than in the SE (M = 3.46), $F(1, 30) = 5.11$, $p = 0.03$. In addition, higher level of spatial presence in the RW (M = 4.88) was experienced than in the SE (M = 4.08), $F(1, 30) = 7.02$, $p = 0.01$. However, users did not report a higher involvement in the RW (M = 4.13) compared with the SE (M = 4.31), $F(1, 30) = 1.06$, $p > 0.05$. In Figure 6, the rotated scores on the IPQ and on its separate subscales are depicted; e.g., a score of 0 equals "not realistic at all" while a score of 6 denotes "very realistic".



On the left (in green) the average scores of IPQ are depicted. On the right (in blue) average scores of the separate subscales are shown

Figure 6: The rotated scores on the IGroup Presence Questionnaire (IPQ) for both environments.

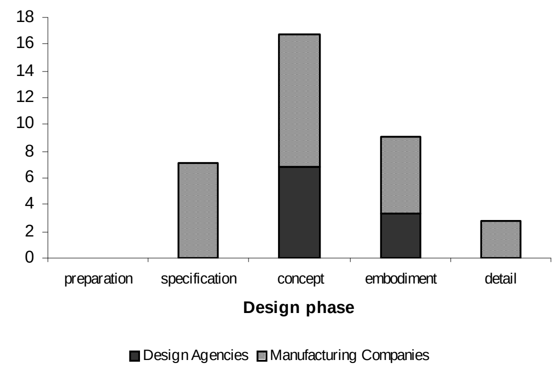


Figure 7: Application phase preferences; scores normalized to total number of answers.

The results indicate that users only partly reported a difference between the SE and the RW. Although the users sensed a difference for the subscales of spatial presence and realism, they did not for involvement. In accord with our expectation, users scored the sense of presence in RW significantly higher than that in the SE. Furthermore, average scores of IPQ in the SE were very close to those of the RW: The differences in mean scores were small. Taking these small differences into account, we can still feel safe to say that such a simple configuration of SE is a comparable replacement of the RW counterpart in respect to the users' subjective experience of the environment.

4.3 – User Interview

Besides the evaluation with psychological experiments, group interview sessions were also conducted with a different group of experienced designers and engineers (including experts from the product designer and manufacturer companies) to collect further subjective evaluation of applicability of SE in a product design process. In these sessions, first the participants got an experience in the sample SE system by operating it. Then, the haptic parameters were adjusted according to their desire to provide them a basic idea of the feasibility of DP in SE. After that, they were asked to compare this with their current work practice and propose the possible applicability of such an SE in the product design process. A semi-structured approach was adopted, which enabled the participants to produce unlimited feedback.

One of the interesting information we got from the interviews were the deemed applicability of SE to different phases of product design process, as shown in Figure 7. About 47% (17 out of 36) participants perceived the SE to be applicable to the concept design phase, in contrast to 25% (9 out of 36) for the embodiment design phase, 19% (7 out of 36) for the specification and requirement definition phase, 8% (3 out of 36) for the detail design phase. This showed high level of acceptance in the designers and engineers user group on SE application in the concept design phase.

Another important feedback is from the designers group: "Leave creativity with designers". It's not a common practice so they won't expect the users to provide design solutions in the design process. Normally the users only provide requirements. Nevertheless, the applicability of an SE aided DP process to help design concept communication was recognized and desirable. For example, normally it's difficult to imagine the designed force feedback or to describe the desired force feedback of the machine lid without instant tuning and testing of the dynamic prototype in the SE. This empirical statement is in accord with our discussion in section 3.1 regarding the SE as a communication tool between different stakeholders with different knowledge and skills.

The interviewees also expressed a common concern about the cost of the SE for both hardware and software development and integration. Being the most expensive component employed in this experiment setup, HapticMaster is still not common equipment seen in SME. Nevertheless, standardization of such hardware equipments may reduce the production price and with better solutions to the other applicability problems except this hardware cost issue, deployment of such devices may be popularized.

5- Conclusions

To summarize, the research presented in this paper showed that a simple SE configuration based on COTS products can provide a valid replacement of a physical prototype for product design. User interviews indicated that the dynamic prototype in such a simple SE is regarded as an applicable medium to support the design concept communication in a user-centred design process. This is especially the case in the concept design phase and when incorporating non-designer stakeholders. To improve the applicability of SE for product design, further research is proposed for:

a. Investigation of intuitive user interfaces adapted to different stake-holders to enhance the advantage of SE in supporting design concept communication in a dynamic prototyping process.
b. Study on the effects of different levels of presence to the validity of a prototype in SE. This knowledge can help people to determine the minimal configuration that is in-expensive yet valid in certain application cases.
c. Quick integration framework for lower implementation costs of SE applications in SME.

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