INTERNATIONAL CONFERENCE ON ENGINEERING DESIGN, ICED'09
24 - 27 AUGUST 2009, STANFORD UNIVERSITY, STANFORD, CA, USA

VISUALIZATION PLATFORMS FOR CONCEPTUAL DESIGN

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ABSTRACT
In the research described in this paper, we used structured rule based analytical method, questionnaire survey method and expert evaluation method to systematically identify suitable visualization platforms for conceptual design tasks by taking into consideration technological affordances and usability demands. Comparatively, the structured analytical method we developed and used in this work focuses more on technological issues, takes into account typical working situations and is based on unambiguous sets of rules which the user only need to apply. It has been shown that there is no particular type of visualization technology that fulfils all visualization demands in conceptual design. Also, it has been concluded in all three studies that the design tasks that require space imagination such as deciding on how the final design should look like, reviewing the ergonomics of the designs and assembly verification can be accomplished aptly by using design support systems equipped with 3D displays. Like it is the case for other design support tools and technologies, proper choice of visualization platform or technology for conceptual design is critical for the reason that there is a real danger of inappropriate selection, which can actually compromise rather than improve designers' performance.

Keywords: 3D Design, product visualization, computer aided design, conceptual design.

1. INTRODUCTION
The importance of visual imagery is well recognized in many fields of application [1]. Traditionally, flat-screen two-dimensional (2D) displays are used to display 2D or three-dimensional (3D) models generated by computer based design support systems, variously known as Computer Aided Design (CAD) systems, Computer Aided Design and Manufacturing (CAD/CAM) systems, or Computer Aided Engineering (CAE) systems. It is widely known that these flat-screen 2D displays coupled with Windows, Icons, Menus and Pointing (WIMP) style graphical user interfaces do not provide proper support for interactive visualization of 3D virtual models [2], [3]. Lack of truly 3D information, inability to enable viewers to feel presence of imagery, and lack of means to enable direct contact or interaction between viewers and the displayed 3D virtual models are some of the shortcomings frequently cited. As a result, practitioners in engineering design as well as in other fields of applications have in recent years been attempting to take advantage of the capabilities of the emerging 3D display technologies such as 3D glasses, head or helmet mounted displays (HMDs) and other stereoscopic displays.
Recent advancements in computing and computer graphics areas have lead to creation of a large variety of 3D display systems with a wide range of capabilities. As a result, the 3D visualization scene is currently characterized by a large variety of competing display concepts and technologies. There are three main types of 3D displays: (a) stereoscopic displays (which use various methods to convey separate image to each eye and create illusion of 3D), (b) autostereoscopic displays (which display 3D images viewable without the need of wearing 3D glasses, goggles, helmets or other stereo view enhancing devices), and (c) volumetric displays (which create 3D imagery in three physical dimensions via emission, scattering or relaying illumination from well-defined regions in space) (Figure 1). Some of these technologies are now applied in several application fields, including in engineering design; mostly as non-interactive visual display units for displaying models, diagrams and animations. Some of them are applied in some specific stages of the design process for various purposes, including for reviewing the ergonomics of designs, simulation of product use and evaluation of designs. It is widely perceived that these 3D displays are useful in the conceptual phase of the

(a) (b) (c)

Figure 1. Examples of stereoscopic displays (a) 3D glasses - filter two images to create 3D effect (b) HMD - worn on the head or as part of a helmet. Has small display optic unit (i.e. lenses and semi-transparent mirrors) in front of each eye. Has the potential to display different image to each eye. (c) Autostereoscopic display - optical material e.g. parallax barrier, lenticular lens plate or LC shutter is placed in front of the LCD screen to create 3D effect

design process [4]. However, only very limited studies have been conducted to identify which conceptual design tasks specifically require 3D visualization devices or to establish whether, for instance, if a 3D display is required, which type of display would be more appropriate. Many reported works only focus on the analysis and justification of the need for these visualization devices without indicating clearly, for instance, what kinds of 3D visualization devices are required in the execution of various conceptual design tasks. Proper selection of display technologies is critical because there is always a real danger of making inappropriate choice, which can actually compromise rather than improve the designer's performance.

The work reported in this paper therefore focused on the identification of appropriate types of visualization platforms for various tasks and subtasks in the conceptual phase of the design process. The specific objectives were twofold: (i) to study the conceptual design literature and to prepare a comprehensive list of conceptual design tasks; and (ii) to identify the types of visualization platforms needed for each task. Our approach can be described as follows. Based on a literature study, we first identified and compiled a comprehensive list of conceptual design tasks and subtasks. We then conducted three separate studies, namely analytical evaluation, questionnaire survey and expert evaluation to identify the appropriate types of 3D visualization technologies for conceptual design tasks.

This paper is structured as follows. The following section concisely reviews related research. Section 3 describes in details the three studies we conducted to identify appropriate types of 3D visualization platforms for conceptual design tasks. Section 4 discusses the results. It ends with some conclusions and brief description of future work.

2 RELATED WORK

Many publications mention entertainment, advertisement, medical diagnosis, military training and engineering design as potential areas where many emerging 3D displays could be applied. Some of these displays are already being applied in engineering design, but mainly for passive visualization to support tasks such as reviewing the ergonomics or aesthetics of designs. Identification of the basic operations for interactive 3D visualization in these application fields has been the focus of some researchers. Several studies on how users interact with images displayed by these systems have been conducted by some computing, computer graphics and human computer interaction (HCI) researchers, as well as by the developers of 3D displays. In some of these studies, some basic interactive 3D visualization operations performed by viewers when visualizing virtual objects have been identified by following several different approaches. For instance, Foley et al. [5] classified the basic operations that can be performed in virtual environments as selection, positioning, orientation, generation of paths, quantification, and inputting text string. Darken and Durost [6] assert that the above classification by Foley et al. [5] is accurate as a lexical description of interaction operations in general. Balakrishnan et al. [7] through exploration and experimentation with physical mock ups and props identified the basic operations that an interactive volumetric display system must support and that should be considered when developing user interaction style as selection (choosing one or more objects), moving (placing object in 3D scene), rotating (orienting an object in the 3D scene), scaling (shrinking or enlarging an object), navigating (pan, tilt or zooming an image), commanding (issuing commands via menu-item

Table 1. Examples of basic interactive 3D visualization operations proposed in the literature

Operation	Description
Selection	Choosing one or more objects/geometric elements such as points, lines and curves
Positioning	Placing virtual objects or its elements in a virtual space
Orientation/ rotating	Adjusting (angular) of an object in the 3D scene
Paths generation/moving	Moving an object around in virtual workspace
Quantification	Specifying quantity of virtual objects/geometric elements
Inputting text string	Annotating a 3D virtual object
Scaling	Shrinking or enlarging virtual object
Navigating	Pan, tilt or zooming a 3D virtual object
Commanding	Executing commands via menu-item selection or text entry
Filtering	Adjusting scene contents to better view or interpret 3D information
Specifying geometry	Stating how the object look like/dimensions
Connecting entities	Assembling virtual objects

selection or text entry) and filtering (adjusting scene contents to better view or interpret all 3D information). Furthermore, there have been some dedicated attempts directed towards defining how viewers may interact with virtual objects when designing in 3D space. For instance, Horváth et al. [8] created some hand-motions language words that could be used in spatial shape conceptualization to accomplish tasks such as selection of geometric elements (such as points, lines and curves); specification of geometry; positioning of virtual objects or its elements; scaling of images; connecting entities and assembling virtual objects. There are several other similar related works.

It can be said that most of the basic operations mentioned by both the computing/computer graphics/HCI researchers and by the developers of the emerging 3D visualization systems are not tied to particular application fields or processes. Much of the research has been devoted to developing interaction techniques for low level tasks such as object selection, navigation, and manipulation; targeting a wide range of applications such as entertainment, advertisement, travel and way-finding [9]. Engineering design, however, is relatively a significantly different and complex process which involves numerous unique tasks; most of which require interactive visualization. The question now, which has not been dealt with in sufficient depth is: what tasks can be supported by using the sorts of basic 3D visualization operations mentioned above (see also Table 1)?

The basic operations summarized in Table 1 have been identified by following approaches such as exploration and experimentation with physical mock-ups and props, brainstorming, common sense reasoning, and expert judgment. These approaches and several others can also be followed to identify conceptual design tasks or subtasks that can be accomplished by using the proposed basic operations (Table 1). These include using methods such as analytical assessment, questionnaire survey, expert evaluation, empirical evaluation, and observation. In general terms, each of these approaches is limited in one-way or another. For instance, in questionnaire survey and expert evaluation methods, subjective opinions are often collected and responses can be biased; in empirical evaluations the experimental environments are often different from typical working situations while analytical assessment and observation methods are often narrow focused. In the following section, we describe the three different approaches we followed in determining appropriate types of visualization platforms for conceptual design tasks.

Table 2. Conceptual design tasks

ID	Task
T1	Search for new product ideas/solution principles [11]; [14]; [15]
T2	Generation of alternative solution principles/ideas [10], [11]; [13]; [16]
T3	Building working combinations/combining solution principles/ identification of subsystem/sub functions [11]; [16]
T4	Assembly verification/determination of preliminary layout/arrangement of component [11], [16]
T5	Deciding the appearance of the final product (aesthetics of product) [16]
T6	Determination of the basic need/formulation of functional requirements and other requirement and constraints [11], [12], [13], [15], [17]
T7	Modification of the solution concept [13]
T8	Determination of production technique [16], [17]
T9	Determination of functions of the products/operational scenario [16]
T10	Determining type/plan of production [13], [16]
T11	Preliminary engineering analysis [13]
T12	Market investigation [13], [16], [17]
T13	Determination of the needs/elaboration of specifications [11]
T14	Derivation of properties of alternative solutions (simulation)/development of prototypes plans [10], [16], [17]
T15	Evaluation of concept against technical criteria [11], [15]
T16	Evaluation of concept against economic criteria [11], [15]
T17	Determination of if properties of solution have been met [10]
T18	Selection of optimum solution, concept, components or based on outcomes of evaluation (decision making) [10], [11], [14]
T19	Investigation and definition of the user group [13]
T20	Determination of underlying engineering principle [13]
T21	Determination of functions of the product/function structures [11], [13]
T22	Preliminary determination of costs [17]
T23	Standards review [17]
T24	Safety review [17]
T25	Determination of type of product on global level [13]
T26	Determination of process type on global level [13]
T27	Studying the ergonomics of the product [18]
T28	Re-checking if a preliminary design is a rational solution/conforms with market and production requirements [12], [13], [17]

3 CHOOSING VISUALIZATION PLATFORMS FOR CONCEPTUAL DESIGN TASKS

Conceptual design is an activity in the early stages of the product design process that follows after preliminary market and feasibility studies, and precedes detail design. It is often a complex undertaking that involves numerous specific tasks. We therefore conducted a comprehensive literature survey and identified tasks involved in conceptual design. We also closely examined the existing models of product design which typically provide higher-level guidelines and descriptions of conceptual design tasks - see e.g. [10], [11], [12], [13]. We found that there is some sort of general consensus in the literature on what tasks should be accomplished during conceptual design and we managed to identify twenty-eight tasks (see Table 2).

We applied (i) a tailor-made analytical evaluation method, which focused more on technological aspects, and (ii) the questionnaire survey and expert evaluation methods, which took into consideration usability aspects as well to determine the appropriate types of visualization platforms for conceptual design tasks.

3.1. Systematic Technology Analysis Method

In the following sub section, we analyze three types of displays, namely: 2D displays, stereoscopic displays and volumetric displays and identify key performance characteristics of each type of display. These performance characteristics are then used as yardsticks in judging if a given type of display system is appropriate for a given task. They also essentially represent and describe capabilities of specific types of display devices. These performance characteristics have been derived from various sources including, for instance, from the literature and from first hand observations. In using these performance characteristics as criteria in reasoning about the selection of appropriate types of displays for conceptual design tasks, they are first crafted in Boolean query formulation and then applied as inference rules in the form of **IF** (..Boolean Expression..) **THEN** (..Type of Display..) statements. This method is regarded as an information/data driven method because it depends on the available information/data.

3.1.1 2D Displays

Standard CRT computer monitors or television monitors can display both 2D and 3D images. Flat panel, vector, and storage tube displays (i.e. a special monochromatic CRT whose screen has a kind of 'memory') or professional video monitors and projectors can also display 2D and 3D images. Some of these displays are commonly used in design offices by designers to visualize models generated by CAD systems. The embedded software makes models appear 3D, and viewing does not require additional techniques (such as LC shutter glasses, etc.) to compensate for loss of depth information. What also happens is that several software and graphics rendering techniques such as shading, shadowing, and texturing are employed on 2D displays to increase realism of images and to make them appear 3D. The reality, however, is that in principle, they are still 2D images appearing on flat 2D screens and they are not volumetrically represented. Furthermore, interaction with the displayed images is tied to 2D input devices such as mouse and keyboard. These factors make these displays inadequate for supporting activities that require space imagination or knowledge of volumetric data. The performance characteristics ($^{2D}\Delta$) that influence selection of 2D display as a visualization platform for a given task can therefore be defined and expressed as follows.

$$^{2D}\Delta = \begin{pmatrix} ^{2D}\delta_1 \\ ^{2D}\delta_2 \\ .... \\ ^{2D}\delta_i \end{pmatrix} \qquad (1)$$

Where: $^{2D}\delta_p$, with $p = 1, 2, \ldots i$ are clauses that describe technological performance characteristics of 2D displays. For example, in the case of 2D displays, we have identified three main performance characteristics ($p = 3$); which are $^{2D}\delta_{\square}$ = embedded software makes images appear 3D/increase realism of images; $^{2D}\delta_2$ = images are not represented volumetrically, and $^{2D}\delta_3$ = images appear behind the screen (i.e. are neither accessible nor immersive). Certainly, other clauses describing technological performance characteristics of 2D displays can also be formulated and included in this list. The Boolean relationship (β_{2D}) that set conditions that must be fulfilled in selecting a 2D display as a visualization platform for a given task can therefore be formulated as follows.

$$\beta_{2D} = \left(^{2Dt}\delta_1\right) AND/OR \left(^{2D}\delta_2\right) AND/OR \left(^{2D}\delta_3\right) \qquad (2)$$

The selection is therefore done based on this Boolean relationship as follows:

IF *(β_{2D})* **THEN** *(2D Display)* (3)

Reasoning in this case involves using the set of clauses in $^{2D}\Delta$ as inference rules in the Boolean relationship (β_{2D}) to conclude on whether to select a 2D display as a visualization platform for a particular task. This basically involves searching the inference rules (i.e. $^{2D}\delta_p$, with $p = 1, 2, \ldots i$) until at least one is found for which the **IF**-clause is known to be true. The **THEN**-clause can then be executed, which in this case results into the statement "*2D Display*".

3.1.2. Stereoscopic Displays

We classify stereoscopic displays into two groups (a) mediated stereoscopic displays, and (b) autostereoscopic displays. Mediated-stereoscopic displays are those 3D displays in which viewer's 3D vision or in some instances illusion of immersion is enabled by using stereo enhancing viewing gears. Examples of these gears include HMDs [19], [20] and 3D glasses. HMDs are widely used in virtual reality (VR) environments to produce correct stereo perspective. However, in VR environments, viewers are typically isolated from the real-world view. Nevertheless, viewers can experience the sensation of being completely surrounded by high-resolution spatial video and audio (i.e. the feeling of immersion). Mediated stereoscopic visualization technologies have in recent years attracted attention of many people because of their capability to provide viewers with intuitive and realistic images. Various manufacturers offer a wide variety of HMDs and head tracking systems with different performance characteristics, but many of them are known to be encumbering and clumsy to use. Although mediated stereo displays provide better depth perception, better realism and sensation of immersion than standard computer monitors, these are not the only required features or capabilities for effective product visualization [21]. One of the downfalls of these devices is that the images seen by viewers do not occupy actual volume of space. Furthermore, mediated-stereoscopic displays typically provide visual cues using relative size, superposition, and a wide range of lighting techniques. In contrast, the human visual system works in real time, and this enable humans to interpret images promptly. Also, humans' ability to perceive depth through stereopsis, motion parallax, focus, and eye convergence is obviously more reliable than with mediated stereo displays.

Autostereoscopic displays use completely different 3D vision enabling methods. Viewers experience 3D views without using 3D glasses, helmets or other stereo view enhancing devices [22]. Halle [23] grouped autostereoscopic displays into three categories: (i) re-imaging displays, which are based on lenses and mirrors - which re-project existing images to new locations or depths; (ii) parallax displays, which emit directionally-varying image information; and (iii) volumetric displays, which display images in spatial volume (for more details refer to Section 3.1.3). 3D impression in parallax displays is created by movement parallax (i.e. image consists of 2D projections of photographic or synthetic images). Parallax displays are the most common autostereoscopic displays.

Both mediated stereoscopic and autostereoscopic displays enable 3D vision. However, one of the main limitations of these devices is that they display images that do not actually occupy volume of space and which are not geometrically volumetric. The underlying techniques only enable human eyes to experience illusion of 3D vision.

Based on the above analysis, the technological performance characteristics (${}^{St}\Delta$) that influence the selection of a stereoscopic display as a visualization platform for a given task can therefore be defined and articulated as follows.

$$ {}^{St}\Delta = \begin{pmatrix} {}^{St}\delta_1 \\ {}^{St}\delta_2 \\ \cdots \\ {}^{St}\delta j \end{pmatrix} \tag{4} $$

Where: ${}^{St}\delta_q$ with $q = 1, 2, \ldots j$ are clauses that describe technological performance characteristics of stereoscopic displays. For example, in this case, three key performance characteristics that influence the selection of stereoscopic displays most ($q = 3$) can be can be identified, namely, ${}^{St}d$□ = uses optic techniques to display illusive 3D images; ${}^{St}\delta_2$ = image data not volumetric, and ${}^{St}\delta_3$ = the device can display immersive images. Obviously many other clauses can also be identified and added to this list. The Boolean relationship (β_{st}) that steers the selection of a stereoscopic display as a visualization platform for a given task can therefore be formulated as follows.

$$ \beta_{St} = \left({}^{St}\delta_1\right) AND/OR \left({}^{St}\delta_2\right) AND/OR \left({}^{St}\delta_3\right) \tag{5} $$

The selection of stereoscopic display can therefore be done as follows:

IF *(*β_{st}*)* **THEN** *(Stereoscopic Display)* (6)

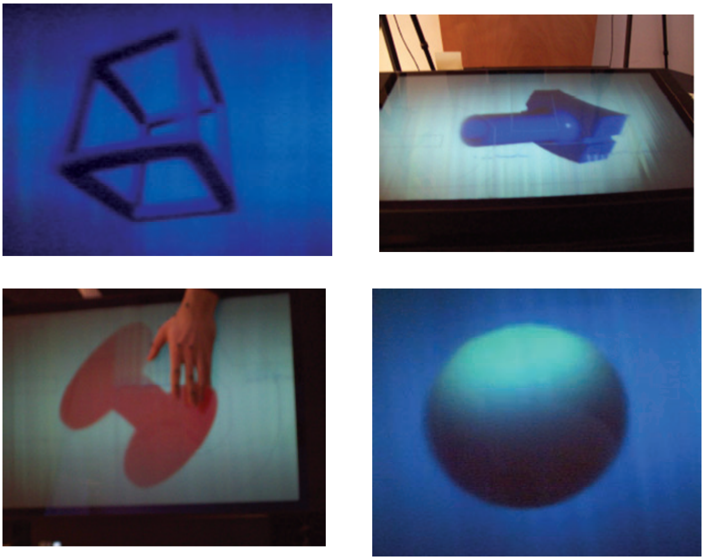

Figure 2. Holographic 3D virtual models generated by HoloVizio 128WD display (www.holografika.com). Holographic images are generated in a two-stage process, i.e. (i) conversion of 3D image description into holographic fringes, and (ii) modulation of light by the fringes

Reasoning in this case involves using the set of clauses in ${}^{St}\Delta$ as inference rules in the Boolean relationship (β_{st}) to conclude on whether or not to select a stereoscopic display as a visualization platform for a particular task. Basically, this involves searching the inference rules (i.e. ${}^{St}\delta_q$ with $q = 1, 2, \ldots j$) until at least one is found for which the **IF**-clause is known to be true. The **THEN**-clause is subsequently executed, which in this case results into the statement "*Stereoscopic Display*".

3.1.3 Volumetric displays

The techniques employed in volumetric displays can broadly be classified as: (i) swept-volume based techniques, (ii) static-volume based techniques, and (iii) holographic techniques. Swept-volume techniques involve sweeping 2D images in a spatial volume at higher frequency than the viewer's eyes can see [24]. Due to visual persistence, the viewer perceives a 3D view. Examples of swept volume display systems include the Perspecta display (http://www.actuality-systems.com/) and Felix 3D display (http://www.felix3d.com/). In holographic displays, images are generated by reproducing diffraction of light from 3D scenes [25], [26]. There are two types of holographic display methods: (a) optical holography, and (b) electro-holography. In optical holography [27], 3D images are created by using coherent light to record an interference pattern. Illumination light is modulated by the recorded holographic fringe pattern, subsequently diffracting to form a 3D image. In this case, hologram production is a three-stage process that involves recording, developing and reconstruction of images. In electro-holography on the other hand (Figure 2), 3D images are generated from 3D image description of objects. In this case, image generation is a two-stage process, which involves: (a) computations (in which the 3D image description is converted into holographic fringes), and (b) optical process (in which the fringes modulate light). The defining characteristic feature of volumetric displays is that they can generate 3D virtual models in actual volume of space. These virtual models can be 'hogelized' images, or can even be created by sets of 3D primitives. In the light of the above discussion, the performance characteristics (${}^{Vo}\Delta$) that influence the selection of volumetric display as a visualization platform for a given task can be defined and expressed as follows.

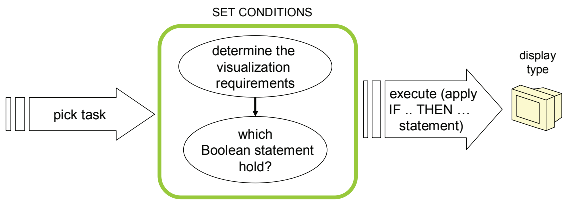

Figure 3. The process of determination of the appropriate types of visualization platforms for conceptual design tasks by following the systematic technology analysis method

$$^{Vo}\Delta = \begin{pmatrix} ^{Vo}\delta_1 \\ ^{Vo}\delta_2 \\ .... \\ ^{Vo}\delta_k \end{pmatrix} \quad (7)$$

Where: $^{Vo}\delta_r$ with $r = 1, 2, ... k$ are clauses that describe technological performance characteristics of volumetric 3D displays. For instance, for volumetric displays, three main performance characteristics ($r = 3$ in this case) can be identified as: $^{Vo}\delta_{\square}$ = images occupy real three physical dimensions in space; $^{Vo}\delta_2$ = image data are addressed volumetrically, and $^{Vo}\delta_3$ = images are not immersive. Other clauses can also be identified and added to this list. The Boolean relationship (β_{Vo}) that specifies technological performance conditions to be fulfilled for a volumetric display to be selected as a visualization platform for a given task can therefore be formulated as follows.

$$\beta_{Vo} = \left(^{Vo}\delta_1\right) AND/OR \left(^{Vo}\delta_2\right) AND/OR \left(^{Vo}\delta_3\right) \quad (8)$$

The selection expression can therefore be defined as follows:

IF *(β_{Vo})* **THEN** *(Volumetric Display)* (9)

Reasoning in this case involves using the set of clauses in $^{Vo}\Delta$ as inference rules in the Boolean relationship (β_{Vo}) to conclude on whether to select a volumetric display as a visualization platform for a particular task. This basically involves searching the inference rules (i.e. $^{Vo}\delta_r$ with $r = 1, 2, ... k$) until at least one is found for which the **IF**-clause is known to be true. Then, the **THEN**-clause is executed, which in this case results into the statement "*Volumetric Display*".

3.1.4 Using the Systematic Technology Analysis Method to Select Appropriate Types of Visualization Platforms for Conceptual Design Tasks

We followed the steps shown in Figure 3 to determine the appropriate visualization platforms for various conceptual design tasks. According to this procedure, the visualization requirements for each task are formulated first and then matched up with the performance characteristics that influence the selection of display devices. The most applicable Boolean relationship is then chosen and substituted in the '**IF** .. **THEN** ….' statement. For example, suppose the task under consideration is ergonomics review (i.e. T27 in Table 2). The main requirement in ergonomic review is that the display should enable viewers to imagine volumetrically and in some instances to attain the feeling of being immersed. This means that of the three Boolean relationships, either β_{Vo} or β_{St} fulfils this key requirement more sufficiently, and the appropriate type of display would therefore be either volumetric display or stereoscopic display. The inference rules and Boolean relationships mentioned

	T1	T2	T3	T4	T5	T6	T7	T8	T9	T10	T11	T12	T13	T14	T15	T16	T17	T18	T19	T20	T21	T22	T23	T24	T25	T26	T27	T28
Volumetric Displays	●	●	●	●	●		●	●	●		●	●		●	●			●			●			●	●	●	●	●
Stereoscopic Displays	●	●	●	●	●		●	●	●		●	●		●	●		●	●			●			●	●	●	●	●
2D Displays						●				●			●			●			●	●		●	●					

Conceptual design tasks (see Table 2)

Figure 4. Aggregation of the results of systematic analysis– appropriate types of visualization platforms for conceptual design tasks

in Sections 3.1.1, 3.1.2 and 3.1.3 were applied in the identification of appropriate types of displays for the conceptual design tasks listed in Table 2. The results are summarized in Figure 4.

3.2. Comparison of the Systematic Technology Analysis Method Results with Questionnaire Survey and Expert Evaluation Results

3.2.1 Questionnaire Survey

We conducted a study to find out how the results of the systematic analysis method described in the previous section compares with questionnaire survey results. Eleven subjects, all of them graduate students with both general design experience and firm knowledge of 3D visualization technologies participated in this study. We first held a formal awareness session to introduce: (i) to the subjects various types of 3D display technologies and systems, and (ii) the conceptual design tasks listed in Table 2. This session was intended to enable the subjects to reach an adequate and common level of understanding of conceptual design and of the state of the art of 3D display technologies, and how the available displays could be used in practice. We then gave the subjects questionnaires with the list of conceptual design tasks shown in Table 2 to fill in and to indicate which type of display would be most appropriate for each task. We also asked them to assume that the basic operations shown in Table 1 can be performed when using any display in question. Furthermore, we provided them with chunks of information about these technologies and systems in various forms, including in video, picture and text forms for referencing.

We observed from the collected data that there was some consensus among the subjects in some aspects. We also observed some similarities with the results of the systematic analysis method presented and discussed in Section 3.1.4. For instance, all subjects felt that tasks such as ergonomics evaluation and aesthetics review can better be accomplished by using volumetric 3D displays, just like was also the case in the systematic technology analysis method. Similarly, subjects also felt that task such as preliminary cost analysis, evaluation of concept against economic criteria, investigation and definition of user group, determination of needs and standards review can better be accomplished by using 2D displays.

3.2.2. Expert Evaluation

In another follow-up study, we conducted expert evaluation [28] to investigate the extent to which 3D volumetric displays support conceptual design tasks. HoloVizio 128WD display

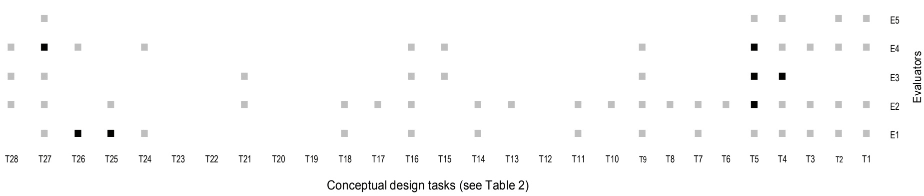

Figure 5. Expert evaluation findings- aggregation of views of experts: black squares = supported fully; grey squares = supported partially; empty provisions = cannot be supported

(http://www.holografika.com/) - a display system for the 3D design support environment in our research group - was a representative volumetric display in this study. Five expert evaluators (all of them with long design experience and firm knowledge of the existing and emerging 3D visualization technologies) participated in this study. They first familiarized themselves with the HoloVizio 128WD display before expressing their opinions. An electronic form with the list of conceptual design tasks shown in Table 2 was used to gather opinions of these expert evaluators. The evaluators were asked to indicate if the HoloVizio 128WD display can fully or partially support conceptual design tasks by using the basic operations shown in Table 1. Detailed description of this study is available in [29]. The views of the expert evaluators were aggregated as shown in Figure 5. Black/dark squares in Figure 5 indicate that the respective expert evaluators feel that the corresponding conceptual design tasks can be supported fully by the experimental system; grey squares indicate that the respective expert evaluators are of the opinion that the corresponding conceptual design tasks can only be supported partially by the HoloVizio 128WD display. Empty provisions indicate that the respective expert evaluators believe that the corresponding conceptual design tasks cannot be supported at all by the HoloVizio 128WD display. It can be seen that these results are highly consistent with the findings of both systematic analysis method (Section 3.1.4) and questionnaire survey (Section 3.2.1). The tasks identified in this study that can be supported well by the HoloVizio 128WD display have also been singled out in the other two studies as tasks that require 3D volumetric displays.

4 DISCUSSION

The 'triangulated' studies described in the previous section have shown that all conceptual design tasks require at least some sort of visualization devices. Visualization demands in conceptual design generally vary. Some tasks require merely passive 2D visualization devices while others require interactive 3D visualization devices. 2D displays are generally adequate for tasks that do not require knowledge of 3D information such as building working combinations and determination of preliminary product cost. These studies have also shown that some tasks in the conceptual design process need 3D visualization devices. These findings are in line with the general understanding in the areas of visualization that there is no single visualization technology that suits all visualization needs [30]. Basically, conceptual design is a problem solving and creativity process, and normally involves consideration of aesthetics, functionality, ergonomics, assemblability, safety and many other aspects of products, and requires considerable research, modeling, thinking, interactive adjustment, and redesigning. It is known that humans (read: designers) are naturally spatial thinkers, who perceive and comprehend world better in 3D [31] and obtain over 70% of sensory input visually [4]. It is therefore expected that 3D displays would have huge impact in design, in particular by providing appropriate support in accomplishing tasks that require space imagination.

There have been notable advancements in computing and computer graphics areas in recent years, and the capabilities of processors; displays and input devices have improved enormously. These advancements could be beneficial in many fields of application, including engineering design, especially in conceptual design. However, the major downside of most of the available 3D visualization technologies and systems with regard to support of 3D objects design in 3D space is that they are limited in terms of interactivity, and they lack proper user interfaces. In fact, most of the 3D displays presently used in design serve primarily as passive visualization tools, although some of them allow very limited direct interaction. Interaction with the images displayed on some of these devices is possible only by using 2D input devices such as keyboard or mouse; via WIMP style graphical user interfaces. For 3D displays to provide effective support, numerous technological challenges need to be dealt with first, including, for instance, the challenges of: (i) improving interactivity and user interfaces, (ii) setting up formal methodological framework for designing in 3D space by using interactive 3D displays, and (iii) having in place proper software and hardware technologies that will be the backbone, binding together different display and natural input technologies.

5 CONCLUDING REMARKS

In the research described in this paper, we used three different approaches to systematically identify the appropriate types of visualization platforms for conceptual design tasks by taking into consideration both technological affordances and usability demands. The results of these studies have been compared and found largely to be in harmony. Comparatively, the structured analytical method we developed and used focuses more on technological aspects. It takes into account typical work situations and is based on unambiguous sets of rules which the user only need to apply; which makes it a straight forward and rational, less subjective and more focused method. It is, however, overly formal approach for making comparisons. The gold standard approach should be, for instance, comparing how different visualization platforms perform in a real design task. It has been shown in these studies that some conceptual design tasks certainly need 3D visualization devices. All three studies have suggested that tasks that require space imagination such as deciding on how the final design should look like, derivation of properties of alternative solutions, evaluation of the ergonomics of designs and assembly verification can be accomplished aptly by using design support systems equipped with 3D displays. Overall, it is evident from these studies that visualization requirements differ among tasks, and as can be expected, there is no one specific visualization technology which is precisely suitable for all conceptual design tasks. It is important, however, to mention that the 3D display systems on ground are still plagued by numerous limitations, and there are still many research and development challenges ahead, including, for instance, the challenge of developing proper multimodal input means and user interfaces for 3D visualization devices that would allow viewers to effectively take full advantage of the features and capabilities of these technologies.

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