Int J Interact Des Manuf (2012) 6:179–193
DOI 10.1007/s12008-012-0144-1

ORIGINAL PAPER

A comparative evaluation of human interaction for design and assembly of 3D CAD models in desktop and immersive environments

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Received: 9 June 2011 / Accepted: 20 January 2012 / Published online: 21 March 2012

Abstract Computer aided design (CAD) systems have become today the basic tools used to design and develop products in the industry. In current CAD software most of the editing commands are issued with the aid of widgets and alphanumeric data input devices, while research community is proposing the use of virtual reality environments for CAD modelling. This paper presents an experimental study which compares the performance and usability of a multimodal immersive VR (virtual reality)-CAD system with a traditional CAD system. A comparative analysis was done for the modelling and the assembling process of 3D models. The results obtained from this investigation have shown that, in spite of the variety of interface devices in the virtual environment which provide a natural interaction to the user, the modelling time is about the same compared with a traditional desktop interface. The assembling time, however, is shown to be much smaller for multimodal system. Furthermore, the multimodal interface poses a higher physical stress factor, the hand movement distance being on average 1.6–2.3 times greater than the desktop interface for modelling process and assembling process, respectively. A post-experiment questionnaire shows that the multimodal system produce a great satisfaction for users in modelling and assembly processes.

Keywords Virtual reality · Physical ergonomics · Multimodal interface · Movement pattern · CAD modelling

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1 Introduction

The modelling and assembly 3D CAD models with new interfaces of computer-aided design systems have been more and more a subject of research. These kinds of systems offer extremely rich modelling features and function which increase the productivity of designing new products. While the geometrical database is 3D since long time, the user interaction within this software has not significantly changed. Currently CAD tools use standard WIMP (Window, Icon, Menu, Pointer) desktop-based graphical user interfaces (GUI), and the interaction is made through keyboard, mouse and LCD display which are solely 2D devices. The interaction of desktop-based CAD modelling and assembling, however, is not very intuitive. Many authors [4,12,20,24,46,51,59] estimate that changing the interaction paradigm will unlock significant resources for improvements in terms of cognitive load and productivity.

Current virtual reality (VR) technologies provide new perspectives for user interaction with CAD tools. During the last two decades VR technology has evolved to a new level of sophistication and changed the ways scientists and engineers look at computers. VR technology gives the user a sense of presence in the virtual word, because it combines multiple interfaces to provide various sensations (visual, auditory, haptic, etc.), which enable users to become immersed and interact using natural human motion. Many research activities are currently focused to integrate CAD tools inside a VR-system in order to enhance the immersion feeling and user interaction interface [7,46,59]. Thus, VR–CAD systems have an enormous potential of improving the depiction of engineering data. Combining VR–CAD system with multimodal immersive interaction (using 6 DoF tracking, speech and gesture recognition systems), the deformation of the objects' shapes can gain directly and intuitively within a VE, avoiding explicit interactions within a classical WIMP interface.

Numerous applications use VR technologies only for visualization and analysis of previously created CAD models [4,26,46,47]. Another emerging category of VR design applications are the VR–CAD integrated systems, which allows to create, modify and manipulate 3D models directly in the VR environment [7,12,15,24,51,59]. Despite the intensive research activities, none of them produced yet a significant impact for the development of the next generation CAD systems. VR–CAD systems try to make more familiar the interaction into virtual environments (VE), for user [38] using, the direct 3D input device in design process of CAD objects. For this reason it is necessary to develop experimental research in order to evaluate the impact of virtual reality technologies in the design process, and analyse their advantages and shortcomings.

Evaluation is a way to measure the usability of a computer-based system. Usability is the ability to carry out tasks effectively, efficiently and with satisfaction. Virtual environments are usually accompanied by major changes in the workplace, so the ergonomics of the new workplace must be re-evaluated. Moreover, virtual environments present new concerns about the physical ergonomics [2,40]. The general goal of the multimodal VR–CAD system is to improve work processes in industrial design and assembling. The combination into a VR system of output devices usually used for 3D visualization with 3D input devices used for interaction involve natural hand motion and voice commands. Thus, all of these create a fully interactive and immersive environment for designers. In these virtual interactive environments, designers can walk through the virtual space, perceive the 3D objects, they, visually inspect and interactively sketch, while at the same time they are able to evaluate different shapes.

In this paper we present a comparative experimental study conducted to analyse the added value of direct spatial input compared to usage of 2D traditional user interface for the modelling and assembling process of geometrical 3D models.

This paper is organized as follows: Sect. 2 presents the context and previous work of comparative evaluations of the VR CAD with traditional workbench for modelling and assembling process. Section 3 presents the experimental systems architecture which we use to evaluate the performance and usability of the systems. In Sect. 4, we illustrate the evaluation of the system during the modelling and assembling tasks. Here we also analyse the experimental results and determine the performance and usability of both systems. We conclude and propose future works in Sect. 5.

2 Related work

In the past few years evaluation of usability and performance of VR–CAD systems for modelling and/or assembling has been an increasing subject of research. There are many individual works on the evaluation of VR system and traditional workbench paradigms. The majority of them have compared a VR system with traditional workbench just for modelling, and others just for assembling. Therefore, we split this section in three parts, and we classify the comparative evaluation of the systems after the required task, i.e. for modelling, for assembling and for both.

Evaluation of human interaction during the creation of 3D objects

Many approaches based on VR system for modelling are proposed to improve the designer skills in many fields, i.e., for artists, stylists [9], product engineering [33] etc. In many fields of research, virtual reality (VR) software tools and device interfaces for interaction creates a representation of a world the user can consider real and in which she/he can simulate different operations and actions. Any designer who uses VR 3D input interfaces is no longer limited to traditional 2D interfaces when making 3D designs [1,9,31].

Over the last years, different VR based systems have been developed, but not all of them can be considered as VR–CAD (solid/surface modelling) systems, some being designed only for providing better control on the objects with the use of virtual reality tools or for supporting the sketching process [23,28,34]. In the sketching process tri-dimensional spatial visualization is the core requirement for successfully developing the artists' skills [27]. Thus, the design of 3d model can create an effective strategy that supports the development of spatial skills using VR systems for 3D visualization. In order to develop a capacity for visual imagery and creativity it is important to combine VR interfaces for visualization with those of interaction. Many recent researches compare and evaluate VR visualization techniques. In [28], Keefe et al. presented four studies which investigate tools and methodologies for artist–scientist collaboration in designing multivariate VR visualization. Based on these studies, they proposed a formal methodology for successful collaborative VR visualization design that they expect to be useful in guiding future collaborations. Also, in [27], the authors describe for visualization the Cave-Painting's 3D brush strokes and they present several works of art created using the VR system for interaction with feedback from artists. The drawback of those two approaches is that there are suited for modelling compared only in terms of 3D visualization. Thus, there are tailored for artistic design. 3D modelling in design engineering involves sustained effort from an engineer because an engineer usually spends to create and assembly 3D models with high accuracy and precision at least 8 h per day at her/his job. From this point of view, a VR system must be able to enhance the comfort of the user; hence the user interaction should be done in a natural way. The interaction with 3D objects needs a two-way information exchange between the human and the product. Thus, in order to create a familiar interaction, the VR system needs to create an intuitive interaction between the human and the 3D object. The intuitive interaction is target-oriented from the human perspective [22,56]. In terms of human aspect of interaction [16] refers that tasks consist of a set of actions which are subordinated to sub-goals. A sub-goal can be part of a super ordinate conjoint goal which can be taken up by the motive of the task. The actions to achieve a task consist of a set of operations dependent on the task, because their results are not consciously anticipated as a goal. At a time, operations include several motions or single mental processes. Thus the 3D object perspective must be done in a simple way involve a set of simple operations in a shortly period of time. Involving the human natural interaction (e.g. voice, gesture, etc.) in design of 3D parts can create a more familiar interaction for the designer, meaning that the interaction between the designer and the 3D parts can be performed more intuitive and efficient [36].

In the industrial design field, many approaches such as [13,18] combine the virtual reality with augmented reality (VR/AR) technology. VR/AR technology [50] allows intuitive modelling and sketching directly in 3D environment in order to integrate the evaluation and creative stages of the design process, and the number of iterations is minimized. Florentino et al. [18] proposed an innovative approach based on VR/AR technologies for styling: a VR/AR software tool called spacedesign. A software tool based on 3D visualization VR/AR technologies, have some parameters (e.g. form, audio, and smell, colour, proportion, size, material and surface qualities [8]) which improve the user perception. These kinds of parameters have a significant effect on design and/or assembly of 3D objects in design process. Thus, improving the user's perception means that designer's reaction time to make operations is increased. However, 3D visualization issues such as: space positioning precision and reduced perception in depth direction etc., have been identified and yet to be solved [18]. Another drawback is that one has to work on a specific CAD system, meaning that the modules developed for one CAD system are not applicable to other systems.

All these aspects lead to an improvement in speed of the design process of a product, and the designer interaction in modelling and assembly process could be more ergonomic through embodiment knowledge of a product that provides flexibility and efficiency to designer [3]. In this paper, we evaluate all of the above aspects for a VR–CAD system compared with a 2D traditional system. In the following paragraphs, we will present several existing systems for CAD modelling and assembly, and we highlight the assessment of the existing systems.

VR systems for CAD parts modelling

Wu et al. [45] present a system for designing 3D parts used for ergonomics evaluation. They take into account numerous parameters of human interaction (action speed and acceleration, action frequency, and time to complete a task).

Johansson and Ynnerman [42] make a comparative evaluation of an immersive workbench with a desktop-VR and a traditional desktop system. The results have shown that participants using desktop-VR performed the test better than the rest. However, there was no statistically significant difference between the different platforms.

A comparative study of human performance is presented by Prabhat et al. [44], where the user's performance is compared in three different systems: traditional desktop, Fish-tank, and immersive VR system based CAVE. Evaluation results show that participants preferred the modelling in VR system. A similar evaluation is presented in the work of Wang et al. [58], where they evaluated a system based on desktop-VR with an immersive VR system, and their results demonstrated that desktop-VR system was better than immersive VR system.

Santos et al. [53] present a comparative evaluation between a VR system based HMD (head mounted display) and a traditional desktop. They used a large number of users for experiments to clarify the accuracy and usability of the systems. By analysing the evaluation results, the global users' performance was identified to be about the same in both setups.

Trika et al. [55] developed a VR system for modelling 3D parts, and they used it to enable the creation of shapes. This system maintains the knowledge of part cavities with their adjacencies and a representation of approximated polyhedrons of design features. A similar system was developed by Jeh and Vana [12].

Most of the above mentioned modelling systems present a performance comparison between different systems, but fail to take into account usability and stress factors that can possibly influence long-term use during the design of a product.

VR systems for assembling of CAD parts

Assembly planning and evaluation is an important component of the product design process in which details about how parts of the new product will be put together are formalized. Therefore, a designed assembly process takes into account various factors such as optimum assembly time and sequence, tooling and fixture requirements, ergonomics, operator safety, and accessibility.

Mizell et al. [35] presents a comparative evaluation of an Immersive VR system with traditional desktop. After evaluation, the participants performed significantly better in the VR system for assembling task. A similar case study was presented by Gruchalla [21], where users performed better in real-work using an immersive VR system as compared to a conventional desktop.

Kueline and Oliver developed a system [41] called Ivy that allows users, during assembling process to interact with designed parts using HMD system, trackers with 6 DOF (degree of freedom) and data gloves. Some similar systems such as the Raja's et al. [21] system, and the Ams's et al. [24] system, present case studies which report that the VR system improves users' performances.

Chu et al. [11] presents a quantitative analysis of a VR–CAD design system. They show that this system is easy-to-use and efficient compared with a traditional desktop because VR based CAD system present a multi-sensory input and output interaction. A similar VR–CAD system for assembling parts is presented by Wan et al. [57]. This system is composed from tracker device, force feedback data glove, voice commands, human sound, fully immersive CAVE together for optimization a complex assembly parts. The drawback of this system is that it is custom for assembling and misses an evaluation performance compared with other systems.

From the above literature survey, we can see that currently no modelling and assembly VR–CAD systems simultaneously has the following features: (1) focusing on the conceptual design stage, (2) providing an intuitive and user-friendly interface, (3) supporting arbitrary mechanism topologies, and, (4) providing full dynamic simulation capability.

Numerous VR systems [44], are developed, some which are designed just for modelling, while others for assembling. The number of multimodal VR–CAD systems developed for design and assembly are limited.

VR system for modelling and assembling

Various researchers have investigated human performance, in order to assess the effectiveness of force-feedback in VR applications used for modelling and assembling of 3D objects. Neugebauer et al. [39] presents a VR–CAD system developed for design and modelling that allows the user to interact in multimodal ways using voice commands and gestures. The same task was performed in a desktop system for evaluation of the VR–CAD system. The results show that the VR–CAD system improves by three times the performance to complete the task compared with a desktop system. The drawback of evaluation systems is that authors took into account just the time for task completion, and investigation of system usability factors, such as hand movements and fatigue, are missing.

Lukasa et al. [50] takes into account the usability of performance of the systems, but they compare two similar devices for interaction in VR–CAD system, not a VR–CAD systems with a traditional desktop.

None of the above presented works offer a complete evaluation from both the performance and usability points of view. The papers focus on evaluating the systems, the usability or the performance of either modelling or assembly systems. Our work reports the results of a comparative thorough evaluation between a CAD VR-based system and a traditional desktop CAD, for modelling as well as assembly user case scenarios.

3 Motivation and research questions

Modelling and assembly of 3D parts are often conceived as a complicated task which should be done by trained experts. With the developments of computer technologies, techniques such as computer aided design (CAD), virtual environments (VE) and virtual reality (VR) can create one of the most intuitive human–computer interfaces by providing multi-modal interaction and feedback. In the process of modelling and assembly of 3D CAD objects, the human interaction and feedback are involved. From this reason, our goal is to show that by utilizing a VR CAD system compared with a traditional system can be improved. Evaluation is a way to measure the usability of a system [6], and usability is the ability to carry out modelling and assembly tasks: effectively, efficiently and with satisfaction [25]. That is, the more successfully designers can accomplish their modelling and assembly, and the more satisfied they feel in carrying out their tasks, the more usable a user interface is judged to be. In a above chapter, we saw that a myriad of VR systems, traditional evaluation tools, methods, and techniques were evaluated. However, in terms of both modelling and assembly of parts, they are untested for the evaluation of VR–CAD systems based on cognitive, perceptual or technical factors. Cognitive processes were seen as the end-result of a one-way route from perception → cognition → action (verbal or/and non-verbal actions) [48]. In terms of cognitive psychology [19], the designer is considered as a cognitive system that efficiently designs and assembles the CAD parts through computer. The big advantage of the computer is that it can transform the input data into output data based on logical–mathematical operations. The cognitive interaction between the designer and computer is performed by input and output interfaces, and interaction techniques. The VR offers designers the ability to directly interact with the 3D model through 3D input interfaces using multiple channels of communication (e.g., voice, gestures) at the same time. To provide a better user experience in human–computer interaction multiple modalities are combined and a new class of interfaces emerges called “multimodal interfaces”. A definition of the multimodal interfaces is given in [52] by Sharon Oviatt who states: “Multimodal systems process two or more combined user input modes—such as speech, pen, touch, manual gestures, gaze, and head and body movements—in a coordinated manner with multimedia system output.”

A number of unanswered questions are posed by the above studies. From this reason, we want to evaluate if the 3D input and output interfaces are useful in modelling and assembly process. The first and most fundamental question is the following research question: “Is direct 3D input useful for the design engineers?” The utility of 3D input will be compared with the 2D input interfaces which usually are used for interaction with CAD models in traditional desktop workspace. In this paper, we will evaluate the utility of the input interfaces both in modelling and assembling process. Thus, the compared evaluation of input interfaces involve answering the following research questions: “What is the performance of 2D devices and direct 3D input for creation of 3D CAD models? But for assembling 3D objects?”

A designer needs to do some specific motion actions while interacting with input interface devices in order to perform the tasks of modelling and/or assembly of parts. Even if the virtual reality puts the designer in the loop of a real-time simulation, immersed in a world, however, hand movements for a long time can be a physical effort [38]. The physical effort of the hands plays a key role in the ergonomics fields and could cause fatigue and stressful factors for the designer. Thus, there was a necessity of comparing and evaluating VR–CAD system with traditional desktop workspace assessing the hand motion in the performance a task. Our comparative experiments also try to answer to another research question: Are the hand movements of designers a stress factor in the design process?

In a cognitive process, the perception triggers the interaction of human with the environment of interaction [17] based of sense of human. The human mind model carried out based on the perceived information from environmental and based on mind model the human acts through verbal action or non-verbal action depend of the task. In 3D modelling and assembly of parts, visual perception has an important role throughout the interaction. In most of the cases, commercial CAD systems still use 2D LCD displays for visualization. The disadvantage of these devices is the lack of depth perception of 3D models. For this reason, regarding CAD related activities, an evaluation study of the visual perception is necessary to be developed, that will highlight the impact of VR technologies on visual perception of 3D CAD models during the design process of products. Combining VR interfaces for 3D visualization with interfaces for interaction do convey the idea of a familiar interaction [54] and create an intuitive interaction for the designer [48]. Also, the perception of the designer will be improved giving the vibro-tactile haptic feedback, beside visual perception. Thus, we want to evaluated the intuitiveness level of the 3D input VR interfaces in modelling and assembly simultaneously process take into account a set of features and parameters which make the interaction intuitively. Thus, we are trying to answer to the following research questions: “Which interface of a VR CAD system is the most intuitive and natural interface in the design of 3D CAD parts?”

4 Experimental system architecture

To answer the research questions stated in the previous chapter, we propose to use an experimental system. Thus, we have devised and conducted an experiment to measure and record the movement patterns of participants [29] in the design process of a CAD model using two modelling and assembling techniques. The former is the traditional desktop workspace with 2D input (keyboard and mouse) and output (computer screen) peripherals. The modelling and assembling of parts are typically created by using a combination of keyboard and mouse (or other type of digitizer) input. Although the designs themselves are three-dimensional (3D) in nature, the keyboard is a one dimensional device and the mouse is a two-dimensional (2D) device, and therefore both devices are somewhat restricted. Figure 1 highlights the differences between the conventional CAD systems and multi-modal, multi-sensory CAD-VR systems. Conventional CAD systems need mapping process between I/O devices and the 3D geometric space. The latter technique consists of a multimodal immersive interface of an integrated CAD–VR system with direct 3D input. The results from this experiment will allow us to answer the four research questions.

Experimental apparatus

Traditional desktop workspace

The traditional CAD workspace used in the experiment consists in a desktop 3 GHz Intel Core 2 Duo workstation with a 22 in. LCD monitor, a standard keyboard and an optical mouse, and is running SolidWorks commercial CAD software [52]. For the purpose of capturing the head and hands movement the subject head and arms are fitted with 14 infrared reflective markers that are tracked by the 12 cameras of an OptiTrack optical tracking system [37]. The tracking of human motion is necessary to determine the body parts trajectory while performing a task.

Replacement of traditional WIMP interface

The conventional CAD systems are visualizing the generated models with a traditional CRT/LCD 2D display. The

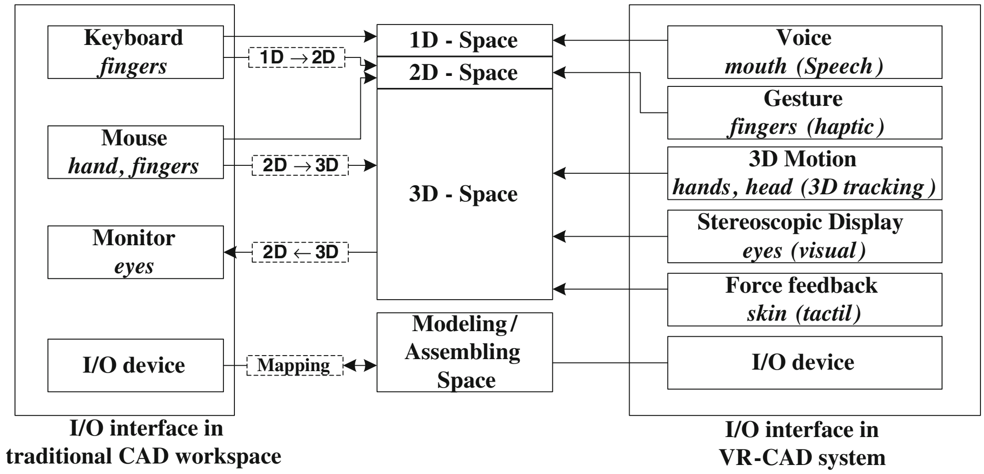

Fig. 1 User sensors used: CAD workspace (hand, finger, eyes); VR–CAD system (mouth, fingers, hands, head, eyes, skin)

disadvantage of this type of display for CAD systems is the lack of depth cues. In order to overcome this disadvantage we developed an innovative multimodal interface, VRSolid [20], capable of modelling and assembly 3D CAD parts using multiple sensorial channels (i.e. visual, tactile and verbal). The goal is to enhance user efficiency in the design and assembly processes by allowing creating, visualizing, "touching" and manipulating CAD models. It employs for generated CAD models visualization a multipurpose large-scale multi-wall architecture, able to provide two modes for the 3D visualization: four side CAVE-like and Holobench functionality. Replacement of the 2D mouse in the VRCAD multimodal interface has been made by using lightweight Pinch Gloves tactile gloves, OptiTrack optical tracking system and voice commands. Keyboard is still used in the CAD conventional system for input of the alphanumeric data. In the VRSolid system this device has been replaced with voice commands. Voice commands are discrete words that are transmitted by the user through the use of a microphone. Microsoft speech recognition API was used for the implementation of voice commands. In addition, alongside the OptiTrack optical tracking system, for the implementation of assembly operations in the immersive environment through gesture recognition, a pair of hand touch gloves (Fakespace Pinch Glove), is used.

VR multimodal interfaces

A multimodal interface based on virtual reality technologies [10] provides an alternative to the traditional interface that uses 2D display, keyboard and mouse. In our solution, various VR devices are used: a large scale multi wall projection system called Holo-CAVE or visual output; an optical tracker system for spatial tracking of user position and orientation; data gloves for fingers gesture recognition and voice

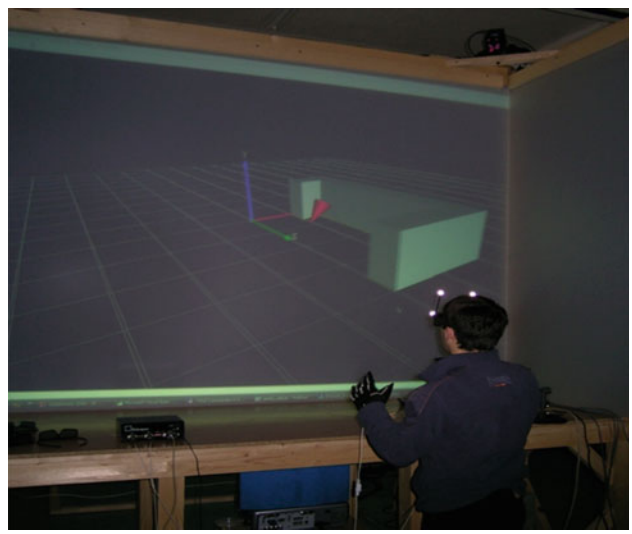

Fig. 2 Modelling of a part in the immersive environment

recognition for input commands (Fig. 2). The above presented solution, the VRSolid multimodal interface, enables modelling of solid objects by combining advantages of the VR technologies with available well-established Solidworks 3D CAD software [52]. The chosen approach is to keep current CAD functions implemented by the software vendor and augment them with a VR user interface for an intuitive and natural way of interaction.

The multimodal interface was designed to be used complementary with the commercial CAD system SolidWorks, in order to take advantage of the already existing basic CAD functions (i.e. parameterized geometry generations and visualizations).

The software configuration (Fig. 3) is has a distributed, highly modular, client–server architecture, based on the strict separation of its VR system management into three layers: a multi user server performs the administration of the 3D

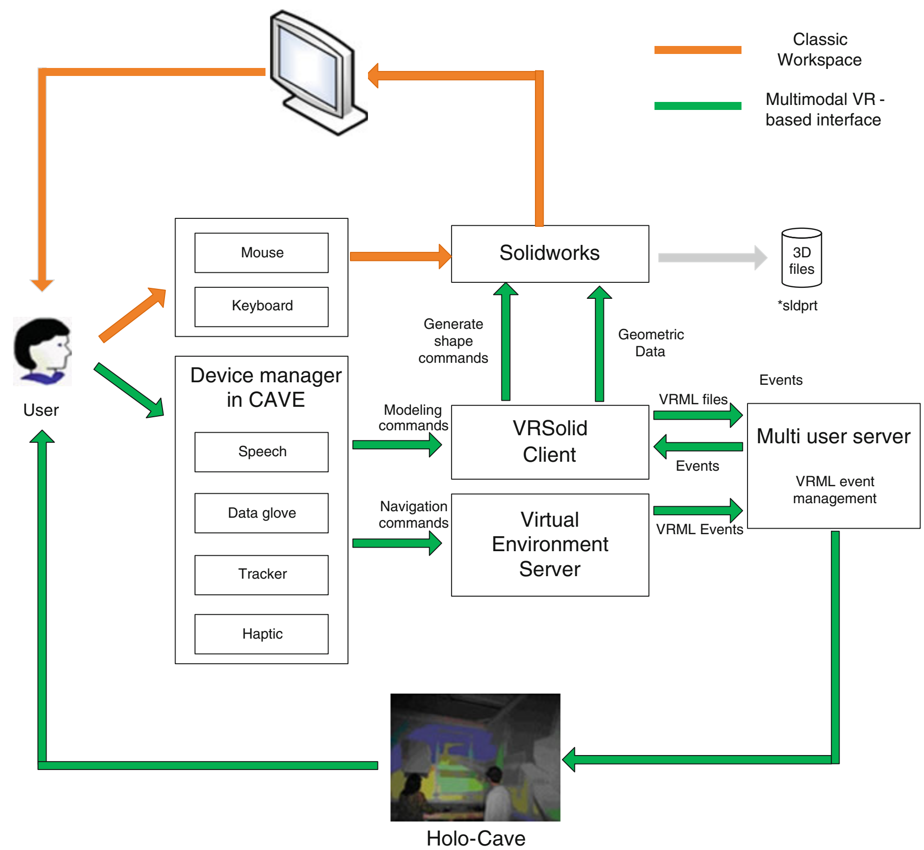

Fig. 3 Experiments set-up

model data and the users connected in the system, a virtual environment server coordinates local projections and navigation and VRSolid client provides the interface to the SolidWorks application and handles all the aspects of user interaction.

The VRSolid module retrieve and interpret command data from input devices, translate them in shape generation commands to Solidworks, retrieve model data from Solidworks, generate VRML files and sends them to the Holo-Cave visualization system. When the user creates an entity in the VR environment, the data is sent to the CAD solid modeller that executes the appropriate modelling command and via network the geometric and surface identification topological data is sent to the VR database. The result is the VRML file which contains all geometry information of the CAD models entities, discretized as triangle tessellations, and the topology structure stored as hierarchical relationships between parts, surfaces and tessellations. In this way each tessellation corresponds to only one surface and each surface corresponds to only one part. Each entity of the CAD model is treated as an individual object and has a unique identity that corresponds with the entity name from the CAD database.

The multimodal interface provides functions for creation of solids primitives (box, cone, cylinder, and sphere), extruding 2D closed profiles created previous and revolving a 2D profile around an axis.

The proposed configuration software is capable to display synchronized passive stereo 3D images on the multi-wall display environment and supports different VR devices.

Each client holds the entire 3D scene, with only positions and perspectives being different. It also provides methods by which objects in virtual environment can be manipulated, added, or removed. The 3D representation is VRML2.0 (virtual reality modelling language) and the stereoscopic rendering of 3D models is done by BS Contact Stereo viewer [5]. SolidWorks [60] offers an API (application programming interface) to create and access the CAD model data. The VR modules are implemented in C++ programming language.

Population

Eight volunteer participants (6 males, 2 females) from our department with a mean age of 23.7 years participated in our experiment. They were all familiar with the commercial SolidWorks CAD systems, but none of them had previous experience with VR spatial devices and/or with multimodal interfaces. Before the test we allowed each participant to understand, familiarize and optimize the settings of voice command and 3D spatial input. The users had 30 minutes prior to the experiment, for practicing both interaction modalities for modelling and assembly of 3D CAD models.

Experimental procedure

The experiment consists of two phases. The first phase required the subjects to model the simple part which is composed from two rectangle features, a cylinder and a blind pocket. The sample part was built on both traditional CAD system and multimodal immersive system. Every subject modelled the 3D part using a traditional desktop based commercial CAD.

The modelling process in the desktop interface can be break down in the eight major steps, which are repeated for each part's feature.

These steps are sequentially, and work in a closed-loop, as following: (1) select work plan, (2) 2D view mode selection, (3) select drawing option, (4) drawing 2D object, (5) select drawing option, (6) 3D view mode selection, (7) selection option for 3d modelling, (8) select a view part of the object to draw other object, then go to first step to modelling next part. Every user modelled the sample part using the above described multimodal interface in the following steps: the first box entity is created using the voice command "Rectangle" for activation of a 2D rectangle drawing feature. The 2D entity is drawn according with the movements of the tracked hand. Insertion of control points is made by voice command "Enter" or by a finger gesture (touching one of the glove fingers). Then, the user extrudes the 2D sketch by using the voice command "Extrude". After, the box is selected and the dimension is edited by moving the hand position or by specifying an alphanumeric value with the aid of "Number" vocal command followed by the specific digits and "Enter" vocal commands. The steps are repeated for the second box and cylinder feature.

In the second phase we asked the subjects complete a given positioning and rotating configuration of parts and to assemble a mechanical part, specifically a bearing on a spindle. The assembling process using the desktop system has the following steps: (1) grasp the object; (2) drag the objects by mouse; (3) attach mating constraints between parts; (4) repeat from (1) until final part is complete.

The VR–CAD system uses directly a homogeneous matrix for specifying the location and orientation of each part in the assembly, instead of indirect mating conditions. Virtual hand models are used to manipulate the virtual parts. Grasping and releasing hand gestures are identified through data gloves. The collision between the virtual hand and the virtual parts object is calculated continuously. If a collision with a part of the virtual environment is determined and a grasping gesture is issued at the same time, that item is attached to the virtual model of the hand. Thus the system has the possibility to manipulate a virtual object depending on the user's hand movements. When the user releases the model, the application recognizes this gesture, and the item is fixed in its new position and orientation. In this way, the user can directly manipulate all the components of the virtual environment.

5 Results and evaluation

For both modelling and assembling interfaces, we examine the performance and usability of the systems. Then, we analysed the overall body posture, body member's position and their movement pattern. For each subject, we measured the modelling and assembling completion time, the hand movement distance and the number of modelling commands: mouse clicking and keyboard key pressing, and voice commands for the desktop and multimodal interface, respectively. The results values from both processes are presented

Table 1 Experiment result values

Subjects	Modeling							Assembly					
	Time (s)		Distance (mm)		Commands			Time (s)		Distance (mm)		Commands	
	VR.	Desk	VR.	Desk.	Click	Keys	Voice	VR.	Desk.	VR.	Desk.	Clicks	Keys
1	61	67	14076.36	5521.00	33	12	8	144	259	5046.3	1976.4	187	43
2	81	69	11467.64	6550.90	38	10	9	97	278	3911.6	5034.7	212	33
3	63	78	7185.42	4198.30	29	14	11	123	459	4608.3	3744.6	306	22
4	100	81	18367.77	6317.30	36	16	14	83	219	3903.8	2481.1	101	23
5	92	63	13053.13	4432.15	34	13	8	64	250	3315.6	2044.9	202	36
6	122	75	12096.13	5000.27	37	11	10	134	302	3987.5	2148.4	123	40
7	66	92	11061.32	6211.01	35	19	15	117	288	4689.9	3744.6	223	32
8	69	79	9100.12	4012.57	30	9	8	102	362	3887.2	3004.1	223	28
Average	81.75	75.5	12075.99	5028.44	34	13	10.38	108	302.12	4209	3022.3	194.75	32,125
SD	21.55	9.19	3353.33	1013.5	3.2	3.29	2.77	26.71	76.02	594.50	1082.3	62.80	7.54

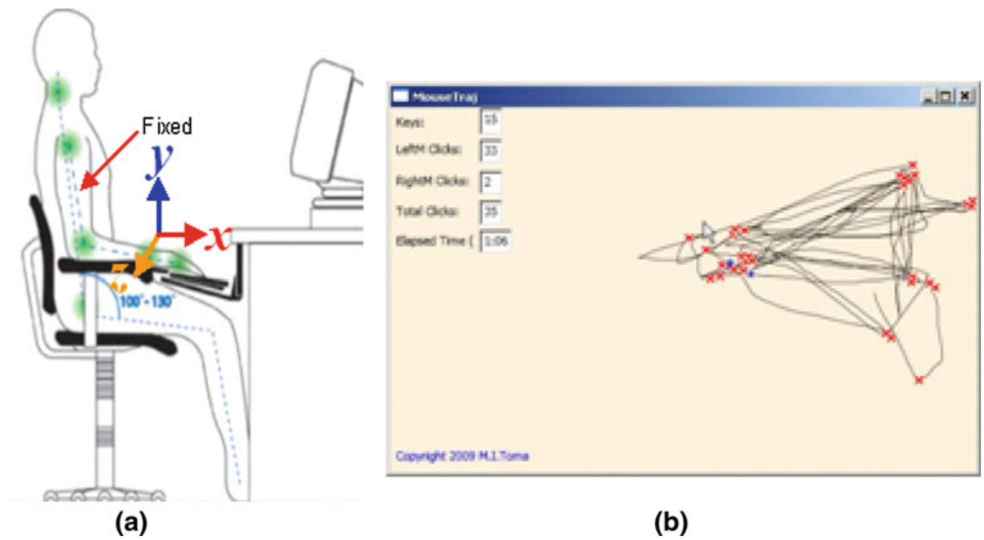

Fig. 4 **a** Body posture in traditional workspace, **b** hand movement pattern in traditional workspace

in Table 1. Moreover, the table contains average and standard deviation (SD) values for each result.

Hand movement distance and commands

Body posture is essentially fixed in both cases, but while in the desktop workspace all the subjects were seated on a chair with the elbow resting on the chairs' armrest, as in Fig. 4a, in the virtual environment all subjects preferred to stay standing in front of the wall, even though a chair was available.

In the traditional desktop case the head movement was almost negligible, the eye movement being sufficient to cover the entire screen. Subjects in the Holo-CAVE presented a slightly larger head movement, but in total still within a few centimetres.

The difference in control paradigm between the two cases resulted in quite different hand movement patterns. In traditional desktop workspace the left arm was predominantly static with the hand resting over the keyboard, while the right hand holding the mouse presented the highest movement rate and distance. The movement pattern consist of translations [53], mostly in the xz plane, corresponding to moving the mouse or the hand above the keyboard, and some translations on Oy axis, corresponding to mouse clicking or keyboard keys pressing. An example of the recorded right hand movement pattern for a subject using the traditional workspace can be seen in Fig. 4b. The pattern is obtained by capturing the mouse trajectory and clicks with an application developed in C# programming language, while the subjects were performing the experiment. The red crossed and blue stars represent left and right mouse clicks respectively.

When using VR-aided CAD system, all the subjects held their hands in front of their body, with the forearms perpendicular on the body. The movement was done from both the elbow joint and the hand joint, consisting of both translations and rotations of the hand.

Conventional CAD interfaces use a 2D mouse and keyboard to activate commands from the menu, interact with the 3D object and navigation in the virtual environment.

Compared with the traditional desktop workplace, larger hand movement distances can be observed for the multimodal interface, according to experimental results value from Table 1. For some subjects an increase in distance of three times was observed, while on average for this low complexity parts the increase in hand distance for the multimodal interface is 2.2 times.

Figure 5 shows that the command pattern is the same for both interfaces when run for modelling and assembly task; the keyboard and mouse commands were simply replaced by voice commands. For assembly task the commands pattern

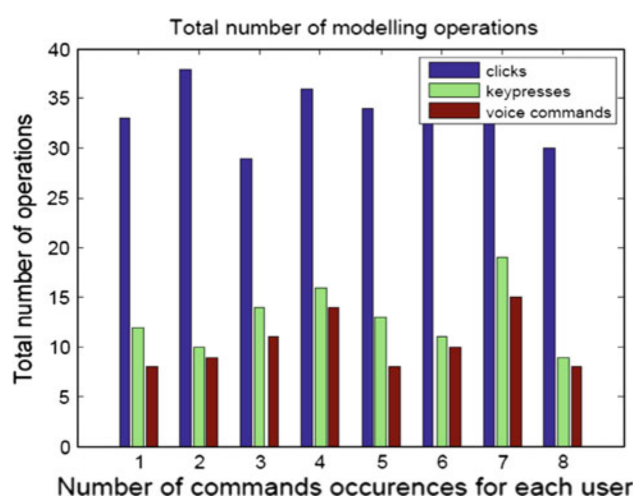

Fig. 5 Commands occurrence for modelling operation

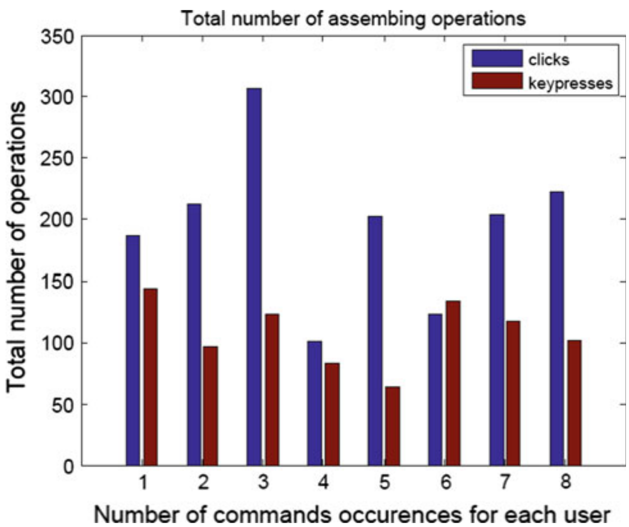

Fig. 6 Commands occurrence for assembling operation

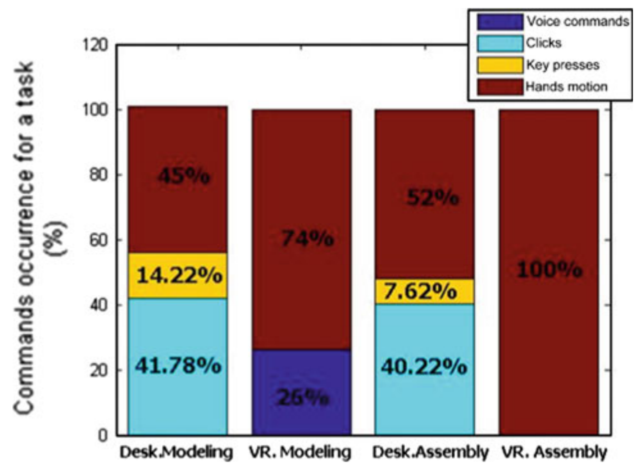

Fig. 8 The percentage of commands occurrence for a task

are depicted in the Fig. 6. The subjects used only gesture and hand movement in the VR–CAD system, and just mouse and keyboard commands in traditional workbench.

After a comparative statistical analysis for modelling and assembling task results, illustrated in the Fig. 7, a difference between VR system and desktop was observed. The figure shows the distance values box-plot, i.e. the minimum and maximum sample, median and first and third quartile. Average distance hand movements for modelling task were 12.07 m (SD = 3.35) for VR system and 5.02 m, (SD 1.013) for desktop, and for assembling task was 4.209 m (SD = 0.59) for VR system and 3.02 m, (SD 1.08). From these results, we can observe that VR system presents a physical stress factor for the modelling and assembling task, because the distance of hand movements is bigger for VR system than desktop.

Also, in Fig. 7, one can observe that the field variation is higher for VR system in the modelling task and in reverse higher for desktop in the assembling task.

A better highlight of subjects' physical effort is shown in Fig. 8, where we evaluated what percentage of a task takes each command (e.g. hands motion, clicks, key press and voice commands) used in the process of creating the 3D model.

The modelling process of a 3D part performed in the traditional workspace is composed of 45% for hand motions, 14.22% key presses and 41.78% mouse clicks, while a VR CAD system has 74% hands motions and the rest of 26% accounts for voice commands. The clicks and key presses commands from the traditional workspace were replaced in the VR CAD system by a combination of voice commands with hands motions.

For the assembly process the commands have a different percentage, i.e., in traditional workspace: 52% for hands motions, 7.62% for key presses and 40.22% for mouse clicks, and in the VR CAD system a task is accomplished just by hands motion.

The hands movements after a certain trajectory represented the preferred way to accomplish a task in both design processes for the VR CAD system. Thus, by observing the experimental result values from Table 1, their analysis displayed in Fig. 7 and the percentage of hand motions used to accomplish a task from Fig. 8, it is clear that the hand movements are more involved in the design process of 3D

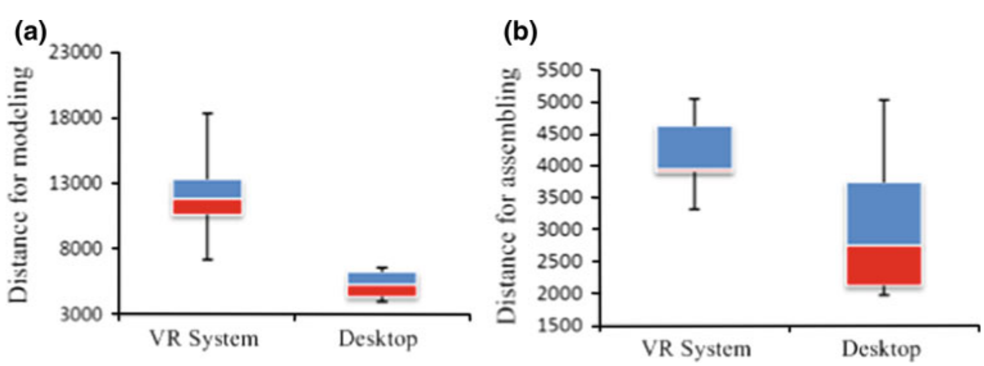

Fig. 7 Distance for accomplishing a task: **a** distance for modelling part, and **b** distance for assembling part

CAD part than other commands (e.g. clicks and key presses for traditional desktop system, and voice commands for VR CAD system, respectively). Considering that a design engineer usually spends at work at least 8 h per day designing and building 3D CAD parts the long trajectory performed by the hands can represent a factor of stress in the design process. In addition, we could observe in our experiment results that the speed of hands' motion for a task in the VR CAD system is much higher than it in traditional environment. However, it depends from designer to designer and on her/his experience as a designer. Accordingly, the reaction of hand motion is enhanced in the VR–CAD system compared with the traditional system, and the trajectory of hand in VE can be done on all 6 DoF, since it is not restricted at 2 DoF like in the traditional system case. Even if the hands motion in VR–CAD system are more familiar for a designer, a lot of repetitive tasks could create a stress factor for designers into a long design process of 3D CAD models. All the results of our experiment about the trajectory of hand motions indicate the presence of a stress factor in the modelling process using the VR–CAD system.

Task completion time

The time consumed for modelling and assembling of 3D components are shown in Fig. 9. The figure shows the time values box-plot, i.e. the minimum and maximum sample, median and first and third quartile. The time for modelling a part is about the same for both interfaces, slightly larger for the VR-based interface. Instead, for assembling parts there is a large difference between VR system and desktop. In experimental result values from Table 1, the time to accomplish an assembling task is three times higher than the time to accomplish a modelling task.

However, considering the higher hand movement distance and the hardiness of operation for the multimodal interface we can state that for complex parts the completion time will be even higher than the desktop interface. Figure 9 illustrated a comparative statistical analysed for modelling and assembling task.

Average task completion time for modelling process was 81.75 s (SD = 21.55) for VR system and 75.5 s, (SD 9.19) for desktop, and for assembling task was 108 s (SD = 26.71) for VR system and 302.12 mm, (SD 76.02). These results answer to the second research questions and they show that that performance of both systems is quite similar for modelling task, but a major difference can be observed in assembly process.

The performance of VR system is with three times greater than desktop system. The field variation observed in Fig. 9, is higher for VR system in modelling task, and for desktop in assembling task. However, subjects' performance was more disparate.

Results indicated that reaction time of designer interaction was better in VR CAD system than traditional desktop system in both design process for a performed task. Accordingly, the performance of the VR CAD system enhanced the design interaction in modelling and assembly process of 3D CAD parts. However, for assembly process the performance of the system was greater than modelling process because the interaction is performed just hand movements without voice commands and 3D visualization give more knowledge about 3D parts of the object which are intended to be assembled. Thus, we evaluate 3D visualization of VR CAD system in the following paragraph.

Evaluation 3D visualization

We evaluated the impact of 3D visualization in modelling and assembly processes of 3D parts in immersive and desktop environment. Our immersive environment is a VR CAD system based on sides' projection solution (CAVE). It allows optimum representation of design details at a 1:1 scale and thus offers a high degree of immersion. The 3D visualization is performed using effects of stereoscopy and monocular coding techniques on the cognitive manipulation of 3D

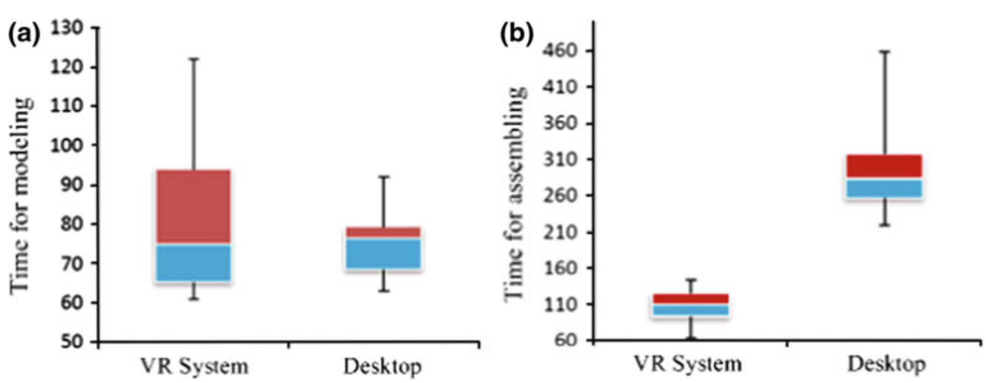

Fig. 9 Time for accomplishing a task: **a** time for modelling part, and **b** time for assembling parts

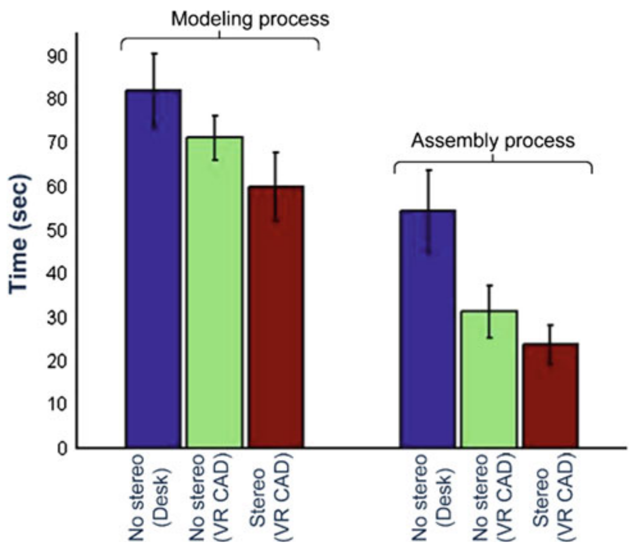

Fig. 10 Evaluation 3D visualization

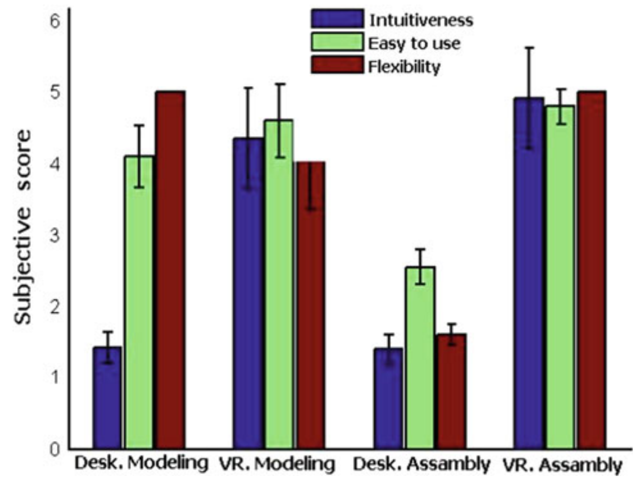

Fig. 11 Subjective average user opinion score

parts in the assembly process. We were interested to assess whether the positive effect of binocular disparity which we could observe in our experiments during subjects accomplished the tasks in VR CAD system.

Both processes were performed first without stereoscopic vision, and second with stereoscopic vision available, in the following conditions:

(a) *3D visualization in modelling process*: (1) 2D-desktop environment: no stereo; (2) VR CAD system-no stereo: perspective projection with the depth cues of relative size and overlap/occlusion; (3) VR CAD system-stereo: this condition made use of a pair of shutter glasses to provide disparity depth cues.

(b) *3D visualization in assembly process*: (1) rotation 3D part-desktop environment: no stereo; the rotation speed of parts with an angle about 270 degree using mouse and/or keyboard; (2) rotation 3D part-VR system: no stereo, the rotation speed with the same angle of 270 degree of parts using hands; (3) rotation 3D part-VR system: stereo, the rotation speed of parts with 270 degrees using hands and shutter glasses.

The results of the above conditions are summarized in Fig. 10. In both process, the main difference between conditions is found between “no stereo Desk” and “stereo VR CAD”. Also, the effects of stereoscopy can be observed when the same task was performed in the same VR CAD system, as when using the monocular technique it takes more time for the designer to accomplish a task than when using the stereoscopy technique. Another aspect that can be observed is that the stereoscopy technique gives the designer a better perception of the assembly process than the modelling process.

The above experiment results show that 3D visualization through stereoscopic technique enhanced the time to perform a task with 28% in the modelling process and with 44% in the assembly process. Thus, 3D visualization plays an important role in the creation process of 3D CAD models. The designer interaction is the most intuitive in the assembly process when using the stereoscopy technique and interfaces for 3D visualization in the VR CAD system.

Hence, 3D visualization through the stereoscopy technique is efficiently in the design process of 3D parts.

Subjective evaluation

In order to have subjective evaluation, we collected the user’s responses through a questionnaire. Thus, at the end of the each experiment task, an evaluation questionnaire was given to the subjects. The questionnaire had twelve statements about specific aspects of interaction with CAD systems, and it was split in three groups of four questions. First groups of question were devised to assess the intuitiveness aspect of interfaces of two systems, second group to assess how easy to use are the systems for both assembling and modelling process, and third group to assess which is more flexible to use in each process to accomplish a task. The subjects had to express their level of agreement with each statement by choosing from the following ratings: completely agree (5), somehow agree (4), neutral (3), somehow disagree (2), and completely disagree (1). The results of questionnaire are analysed in Fig. 11 and Table 2.

For modelling task, in comparison with the traditional CAD system the users appreciated the utilization of the VR multimodal interface as an interface for CAD database which offer an intuitive virtual environment where the user does not have to navigate through a series of windows and menus in order to achieve a desired action.

Table 2 Subjective user opinion score

Eight users	Experience (4.25) Modeling						Assembly					
	Desk.			VR.			Desk.			VR.		
	Intuitiveness	Easy to use	Flexibility	Intuitiveness	Easy to use	Flexibility	Intuitiveness	Easy to use	Flexibility	Intuitiveness	Easy to use	Flexibility
Average	1.42	4.10	5.00	4.35	4.60	4.20	1.40	2.55	1.60	4.92	4.80	5.00
SD	0.21	0.43	0	0.71	0.51	0.84	0.21	0.24	0.14	0.71	0.24	0
Average satisfaction	3.50			4.38			1.85			4.90		

In the modelling process, the users appreciate also the possibility to use the voice commands and gestures which provide a natural way of giving commands. However, all subjects perceived the multimodal interface as more psychically demanding because of the wide variety of interaction ways. Overall, they had the feeling that they performed slower than by using a desktop workplace, as proven also by the completion time. In modelling process, the majority of subjects, at a rate of 87%, agreed that the VR system is more flexible to use than desktop.

In Table 2, for assembling task the satisfaction degree for VR system was greater than desktop, and also most of the subjects (80 %), saw that VR system is much easier to use than desktop. All subjects (100%) saw that VR system for assembly process is much flexible to use than desktop. The questionnaire shows that the majority of participants prefer an immersive VE to a desktop system. Compared to the desktop the users had no problems with initial orientation in the virtual world and with interaction devices. In addition, the questionnaire has an open-end question where subject could freely say opinions about modelling and assembly 3D parts carried out in both systems from our experiment. The user answers were very enthusiastic about VR system. We could remark several observations, such as: (1) direct 3D interaction with the 3D parts is much easier than interaction in 2D. (2) The interaction is more intuitive in VR CAD system for assembly 3D parts using stereoscopy for 3D visualization and force feedback for user interaction. (3) In design task of 3D parts, the speech has proven to be very useful. Voice commands for majority of subject created a more familiar interaction. (4) The users indicated that they preferred VR CAD system in the modelling and assembly process of 3D parts. Analysing the open-end responses of subjects, we observed that the voice commands the most intuitive and natural interface of VR CAD system in modelling process and stereoscopically visualization in assembly process.

Following above comparative assessments of the 3D input and output device of the VR system with 2D input devices of the desktop workspace, we could be seen that that 3D input and output have the potential to be more effective than 2D conventional interfaces because they give a superior perception and investigation of 3D shapes and models. Compared to traditional keyboard and mouse interface, multimodal interfaces provide flexible use of input modes and allows the users a choice of which modality or their combinations to use and when. Multimodal interfaces used in our experiment are thus perceived as easier to use and more accessible, provide better performance and robustness of interaction and are suited for modelling and assembly CAD parts.

In our experiment, the 3D visualization render through VR interfaces for visualization and stereoscopic technique enhanced the perception of designer in interaction process with 3D CAD parts. Analysing our results in order to accomplish a task, we could claim that the perception is higher in assembly process than modelling process.

Even if in the VR CAD system, the perception is enhanced and direct 3D input/output interfaces for interaction are more flexible that mouse and keyboard from traditional workspace, the subject involved in the experiments felt a little bit tired their arms after all accomplished tasks.

6 Conclusions

VR technologies represent very useful tools to visualize and interact with 3D models in the modelling and assembling process. Its integration within the product engineering applications represents the research challenge for the next future. In this paper a comparative study regarding modelling and assembling of 3D CAD models in multimodal VR interface and traditional desktop environment was presented. The advantages of immersive multimodal modelling compared with the traditional CAD interface are: better perception of the depth of the objects using immersive Holo-Cave visualization system, natural and intuitive interaction modalities by using of the voice recognition and gestures. But despite of these advantages this approach did not prove to be a powerful tool because it did not succeed to provide a considerable improvement to the operator efficiency and involves more physical movement of the hands.

Design and modelling using a VR based multimodal interface has advantages like the use of natural methods of interacting, use of real scale modelling, and real-time fully immersive and interactive visualization [12,14,30,32]. All these make VR an ideal tool for modelling and assembly of 3D CAD models.

However, our results show that for the creation of the sample part the traditional 2D desktop interface is still preferred over the multimodal VR-based interface. All the subjects completed the task in comparable time frames in both environments, but in the VR-based interface the hands movement was over a significant higher distance, and stressed more muscles than the traditional desktop interface. In the future work we will try to develop new improved VR-based interface by reducing the movement of the hand, but keeping the immersive feeling in the 3D environment.

Acknowledgments This paper is supported by the Sectorial Operational Programmer Human Resources Development (SOP HRD), financed from the European Social Fund and by the Romanian Government under the contract number POSDRU/88/1.5/S/59321 for author (1), POSDRU/89/1.5/S/59323 for author (2) and by INCOGNITO project number PNII—IDEI 608/2008, funded by CNCSIS—UEFISCDI (Romanian National University Research Council) for author (3).

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