Evaluation of a Haptic-Based Interaction System for Virtual Manual Assembly

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Abstract. This paper describes a mixed reality application for the assessment of manual assembly of mechanical systems. The application aims at using low cost technologies and at the same time at offering an effective environment for the assessment of a typical task consisting of assembling two components of a mechanical system. The application is based on the use of a 6-DOF interaction device that is used for positioning an object in space, and a haptic interface that is closer to reality and is used for simulating the insertion of a second component into the first one while feeling a force feedback. The application has been validated by an expert user in order to identify the main usability and performance problems and improve its design.

Keywords: Virtual Manual Assembly, haptic-based interaction, VR system evaluation.

1 Introduction

Virtual reality tools and technologies are demonstrating to be useful and effective in various phases of product development. Several examples can be reported demonstrating the successful use of Virtual Reality (VR) for the early evaluation of various aspects of products, such as functional, ergonomics, usability, etc. [1]. Particularly complex are those situations where it is necessary to validate the interaction of humans with the designed products. Accessibility, reachability, usability are just few examples of issues where it is necessary to investigate the interaction of the user with the product. Most of VR systems based on pure visualization of objects do not allow us to fully validate these aspects. The recent introduction of haptic interfaces allows us to perform better and more comprehensive tests, including ergonomics and usability tests [2]. An additional situation where it is required the interaction of humans and products concerns the validation of the manual handling of products, such as assembling and disassembling and maintenance.

Several research works have addressed issues related to VR systems for the simulation of assembling and disassembling of components only based on digital simulation of the task, possibly including digital mannequins, but without any intervention from real users. Other works have integrated haptic technologies for the analysis of assembly tasks. The aim of the work presented in this paper is demonstrating the

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effectiveness of VR technologies for the validation of manual assembly processes in manufacturing industries. In particular, we address the problems related to the design review and validation of assembly of mechanical components. Currently mechanical systems tend to be compacted and occupy very limited space in order to allow more space to other components with which the users interact with. This fact generates assembling and disassembling problems, accessibility as well as maintenance problems. CAD tools allow engineers to perform static tests of parts assembling. They allow them to check collisions and interferences but do not allow the validation of assembling/disassembling procedures, i.e. mating trajectories, which are typically performed manually by skilled operators. Recently we are witnessing the development and evolution of sophisticated VR technologies in markets like games and infotainment. Actually, these technologies are performing although available at low and reasonable prices due to the dimension of their markets. Our intention is testing the use of these technologies in the technical and engineering domain related to product development, integrated with typical CAD-Computer Aided Design and PLM-Product Lifecycle Management tools. Our purpose is developing a mixed and heterogeneous experimental workbench where various technologies and interaction modalities can be easily developed and tested. This paper presents the workbench that has been implemented for the evaluation of assembly tasks performed by skilled operators. Typically assembly tasks are performed by operators by using both hands. The idea of our research is including the users (designers and individual assembly operators) in the validation loop so that functional, ergonomics and usability issues related to the assembly tasks can be tested in the virtual environment, before actually building the physical components constituting the system. This can be achieved providing users with two 6-DOF haptic devices for the manipulation of two components to assemble. Actually, this solution is quite expensive to implement. Therefore, we have been spurred to find an alternative solution but equally effective. Observing a real user during the assembly of two parts we have noticed that most of the times one hand is used to position and hold an object, and the other hand is used to insert a second object into the first one with sometime very complex trajectory guided by the force feedback generated by the contact between the two mounting parts. Therefore, we have thought of using a 6-DOF interaction device to position a part of a system, and a 6-DOF force feedback device for handling and assembling a second part or for simulating a machine tool, such as a drill, a welder, a wrench, etc. The VR environment has been tested by an expert user in order to identify main usability and performance issues. The final goal is accessing how effective would be a virtual manual assembly over a real physical assembly task, and compare human factors aspects.

2 Related Works

This section reports an overview of the virtual/mixed reality systems that make use of haptic interfaces for assembly simulation or manipulation tasks for testing or training purposes. Abhishek S. et al. [3] outline the problematic in virtual assembly applications that mainly regard the graphic visualization and rendering of the virtual scene, collision detection, physics-based modelling and haptic interaction. Stereo viewing, head tracking and instrumented glove interaction are all common components of many virtual reality applications.

Jayaram S. et al. [4] have developed VADE (Virtual Assembly Design Environment) a VR-based engineering application that allows engineers to plan, evaluate, and verify the assembly of mechanical systems. The Inventor Virtual Assembly system developed by Kuehne and Oliver [5] allows designers to interactively verify and evaluate the assembly characteristics of components directly from a CAD application.

The evolution of haptic technologies [6,7] has allowed researchers to study new interaction approaches between the users and the virtual tools concerning assembly tasks that may be performed through one-hand or two-hands. Applications based on two-hand interfaces have proved to be more effective and actually allow the implementation of additional tasks that cannot be performed by one hand alone.

The Sensable Phantom™ haptic device [8] has been used in several applications, like in virtual milling machines [9] and assembly training in the aeronautic environment where the device is used to simulate mounting and dismounting operations of different parts of an aircraft [10]. Recently it has been proposed a system that integrates mixed-reality and haptic feedback [11] based on the use of the Haptic Workstation™. The system consists of four devices manufactured by Immersion Corporation (www.immersion.com) and is able to acquire the position of the hand and to add force feedback for each finger in one direction, and it is also able to simulate the weight of the grasped objects. The major issue is related to the fact that the mixed-reality techniques based on optical see-through head mounted display are not precise enough to overlap correctly the real and virtual worlds. Another haptic device, which is used in the research presented in this paper, is the Virtuose manufactured by Haption (www.haption.com). The device has been used to develop an application described in [12] that consists of a complex virtual simulation dedicated to virtual assembly. The HapticMaster by Kyushu Institute of Technology, is used as a haptic interface in a tele-operation application. The user controls a manipulator on the basis of force and torque feedback provided by sensorized end-effectors; [13].

3 The Study Case

The Virtual Reality interactive workbench developed aims at simulating a typical environment where operators perform assembling tasks of mechanical components. The environment resembles the corresponding real environment and tasks without exactly replicating it. In fact, the purpose is allowing operators to test the efficiency and effectiveness of the workbench, its usability and intuitiveness.

We have developed a Study Case for performing manual tasks in a virtual environment. The scenarios are based on a combination of a virtual reality system and a haptic interface. The user can see the scene represented in real scale on a wall visualization system; his position is detected by a tracking system that allows him to change his point of view in respect to the scene. He can interact with the virtual objects using an input device, and can feel force feedback when grabbing and handling virtual components and virtual tools through the use of the haptic interface.

The Study Case consists of a two hands assembly task. Some components that are part of a mechanical system are positioned on a table. The system demonstrates the assembly procedure consisting of grabbing, holding and positioning a component (component A), grabbing a second component (component B) and assembling the two components. The user repeats the same task. He grabs and positions the component A using a 6-DOF interaction device, and then he grabs the component B using a 6-DOF haptic device, and assembles the component B into the component A.

4 The Virtual Reality System

We decided that the close correspondence between real and virtual is required for the hand that is performing the "primary" tasks. The primary task is the manipulation of the object (component B) to insert into the other component (component A). In this specific context the interaction with objects directly mimics the real world. Through the use of the haptic device, the user can feel the weight of the object and the collisions that occur when performing the insertion of the second object into the first one. Instead, the task performed with the other hand doesn't need to have a faithful resemblance with reality. An interaction device may be used for handling and orienting the first subject. Haptic feedback is not necessary, although appropriate feedback is required for informing the user about the system and the objects status.

Then, the application should have some features that help the user during the execution of the tasks. In particular the application should provide the following.

User's presence. The user should be represented in the virtual world by means of a visual representation. The interaction mainly consists of the manipulation of objects and occurs through the use of 6-DOF devices. The user's presence may be represented by visual rendering of the position and orientation of the device.

Haptic feedback. Haptic feedback is the sense of touch occurring when the user comes in contact with an object. Haptic feedback to user's interaction with scene objects may be provided either through the haptic device or through visual, sound, tactile (vibration) feedback.

Feedback of users' actions and on the effect of actions on objects. The user should be informed about the actions he is performing and about the effect that these actions have on the virtual objects.

Interactive techniques. Specific interaction techniques may be used for quickly reaching objects, zooming, and others.

Realistic graphical representation. The system should render photorealistic details of components that are important for the task that the user has to perform.

Information about the status of the environment and objects. The user should be always informed about the status of the environment and of the objects.

Affordances. The application should provide suggestions about usage, functions, actions to perform on objects.

4.1 Hardware and Software Components

The Virtual Reality system used for implementing the application consists of a real scale, stereoscopic visualization environment including an optical tracking system, and a haptic device. The hardware components of the system are shown in Figure 1.

The haptic interface consists of the Virtuose 6D35-45 ™ device from Haption. It is a 6-DOF haptic device with a large force-feedback field on all 6 DOF. For what concerns the input device simulating the use of the second hand we have used the relatively low cost WiiRemote™ device by Nintendo™. The Wii-mote has 3-axis accelerometer which transforms the user's physical motions to activities in the virtual environment. There are 12 buttons on the Wii remote. The Wii-mote is also equipped with a speaker. A very simple mechanism provides haptic feedback through vibration. It has an IR sensor and is connected to a computer via a Bluetooth wireless link. The tracking system is based on the use of ARTrack™. It is used for acquiring the user's head position and orientation. Three IR-cameras are oriented towards the user's working space. Some markers are positioned on the stereo glasses worn by the user. The user can move his head in order to see the objects in the virtual scene with different orientations and distance. The visualization of the virtual scene is provided by the Cyviz Viz3D™ display system (www.cyviz.com). A single PC with an nVidia Quadro FX5600™ graphics card provides the stereo image pairs and a CYVIZTM 3D stereo converter. Users wear simple polarized glasses to see the stereoscopic scene.

For what concerns the software platform, the application is based on Virtools from Dassault® Systèmes, which is a development system for creating interactive 3D applications. The Virtools allows developers to create immersive experiences based on stereo viewing scenes displayed on power walls integrated with a head-tracking

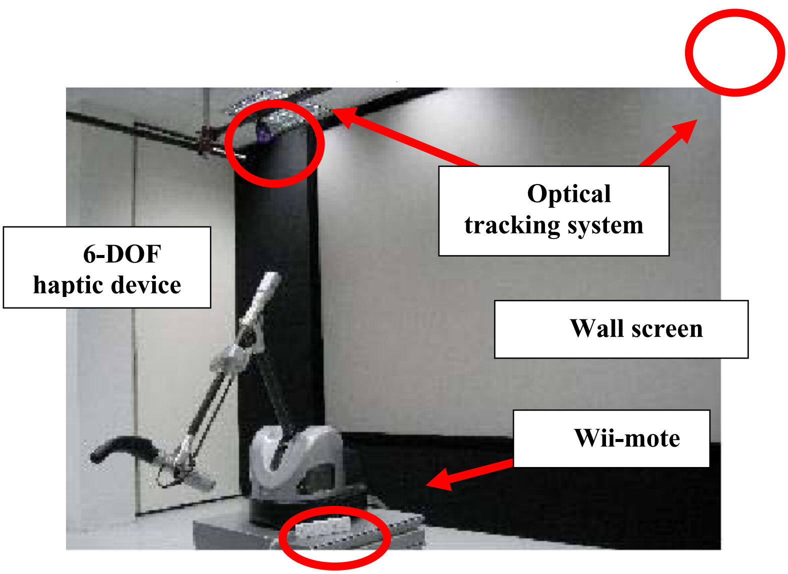

Fig. 1. Hardware components of the VR system

system and a real-time 3D application with haptic interaction (using IPP Interactive Physics Pack). It is possible to import several types of 3D files like: 3D XML (Dassault® CATIA®), 3ds Max®, Maya®, XSI®, Lightwave® and Collada®.

4.2 Study Case Implementation

This section reports the description of its implementation and the features of the study case described in § 3. The application displays some components of the mechanical system that are positioned on a table. The Wii-mote and the 6-DOF haptic devices are rendered on the screen through a visual reference frame (see Figure 2). The application demonstrates the assembly procedure consisting of grabbing, holding and positioning a component (component A), grabbing a second component (component B) and assembling the two components.

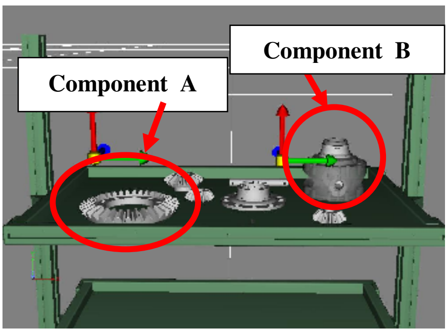

Fig. 2. Components of the mechanical system to assemble manually: the components are positioned on a table

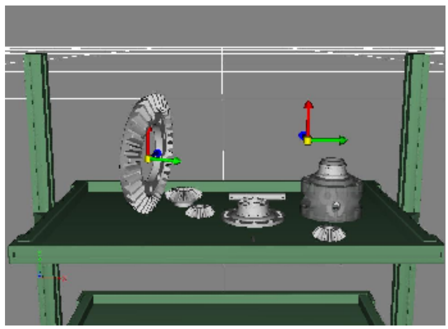

Fig. 3. Wii-mote is used to grab component A

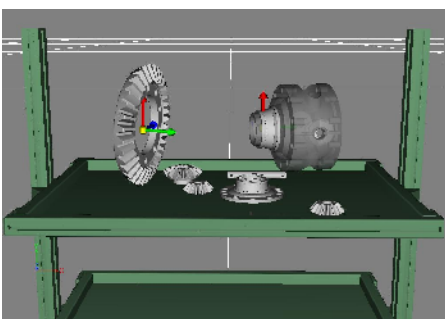

Fig. 4. Assembling task of two components: component A is hold using the Wii-mote and B is inserted into A using the haptic device

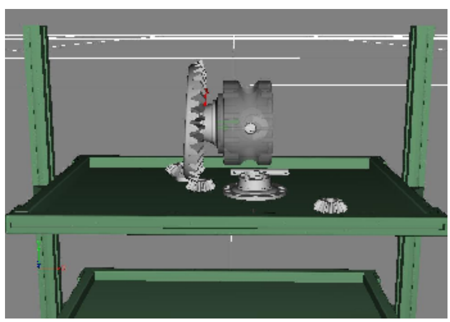

Fig. 5. Final assembly of the two components

The use's task consists of assembling the two components. First, the user grabs and positions the component A using the Wii-mote device (see Figure 3). The application provides feedback when the component A is grabbed: the component is highlighted in a different colour. Then, the user grabs the component B using the 6-DOF Haption haptic device. The application performs haptic feedback during the manipulation, so that the user can feel the weight and inertia of the grabbed objects. Then, the user starts assembling the component B into the component A (see Figure 4). When the two components collide the application provides proper feedback: the haptic device provides force feedback and the Wii-mote provides tactile feedback through vibration. The task is completed when the component A and B are properly assembled.The application records the tasks performed by the user. The data recorded are: trajectories of the two interaction devices, user's viewpoint, and trajectories of the manipulated objects.

5 Validation and Discussion

We are interested in testing the usability of the environment, according to the effectiveness, efficiency and satisfaction with which users reach the targeted objectives with the application context. According to Nielsen, heuristic evaluation can be performed by one usability expert although studies have shown that the effectiveness of the method is significantly improved by involving multiple evaluators [14]. In this first phase of the development and set-up of the system we have decided to run a preliminary evaluation asking an expert user to test the system, and using some of the heuristics proposed by Sutcliffe and Gault [15] for the evaluation of VR applications. The heuristics considered for assessing the quality of the application are the following (Table 1).

Table 1. Heuristics and description

Heuristic	*Description*
1. Natural engagement	Interaction should be as natural as the one in the real world.
2. Compatibility with the user's task and domain	The behaviour of objects should correspond to users' expectations of real world objects.
3. Natural expression of action	The virtual environment should be explored in a natural manner.
4. Close coordination of action and representation	The application should update the virtual environment without delay after user's movements and actions.
5. Realistic feedback	The effect of users' actions on virtual objects should be immediately visible.
6. Faithful viewpoints	User's head movements should coherently change the viewpoint without delay.
7. Navigation and orientation support	The application should support users in navigating and orienting themselves within the virtual space.
8. Support for learning	The application should provide explanations on how to interact with the virtual objects.
9. Sense of presence	The user should naturally feel as being in a real world.

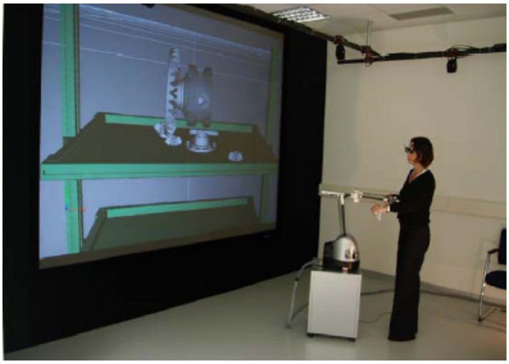

Fig. 6. Expert user assembling the components

The user is a mechanical engineer expert in using 3D application and with some expertise in using haptic devices and in assembly of parts (Figure 6).

The evaluation of the VR application started with the familiarization with the application and the interaction devices: the stereoscopic visualization wall, the change of viewpoint, the use of the two interaction devices. Then, the user was asked to perform the task: grab component A, then grab component B and assemble the two components. When the task was successfully performed, the user was asked to list the problems and to relate them to heuristics, also assigning a rate from 1 (very poor) to 4 (very good). The results are reported in Table 2.

Table 2. Heuristic rating and description of the problems

Heuristic	*Rate*	*Problems*
1. Natural engagement	2	No natural feedback is performed on the left hand.
2. Compatibility with the user's task and domain	3	Information when the task is completed.
3. Natural expression of action	3	Limited navigation within the virtual space due to fixed position of the haptic device.
4. Close coordination of action and representation	4	-
5. Realistic feedback	3	Force feedback is provided only on one hand.
6. Faithful viewpoints	4	-
7. Navigation and orientation support	2	Not intuitive. Rotation around y-axis is not activated directly but by means of pad.
8. Support for learning	2	Little assistance during the task execution.
9. Sense of presence	3	No realistic representation of the user

Then, we have mapped the less satisfactory aspects of the application into a list of features that may be improved. Table 3 lists the features and the related issues to address, including a reference to the heuristic that has originated it.

The following improvements have been taken into account in the implementation of the new version of the application.

Interaction. We may think of using sounds for mimicking the noise made by the various components when colliding also considering the kind of material they are made of, and also using sound for informing the user when the assembly is successfully completed. The navigation within the scene is going to be improved by adding functionalities for reaching objects, zooming the scene, etc. In addition, we are planning to implement a mechanism that moves the haptic device along a trajectory parallel to the virtual screen. The interaction limitations due to the use of the Wii-mote for moving and rotating the first component will be solved with the integration of devices equipped with a gyroscope capability.

Table 3. Classification of problems in respect to application features and importance rating

Application feature	*Issue*	*Heuristic*
1. Interaction	Provide feedback when the task is completed.	3
	Improve user's navigation within the virtual scene.	2
	Improve interaction performances of the Wii-mote.	7
	Better represent user's presence within the scene.	9
2. Action feedback	Improve feedback on virtual representation of Wii-mote and its interaction with object.	5
3. Haptic feedback	Better haptic feedback provided on the left hand.	1, 5
4. Affordances	Not enough assistance during task is provided.	8

Action feedback. The Wii-mote and the 6-DOF haptic devices are currently represented through a visual reference frame. A more intuitive and realistic visual representation may be implemented.

Haptic feedback. The aim of the application was to use a low cost device for providing feedback to the user about the actions performed on the secondary component during the execution of the assembly task. Tactile information, supported by the Wii-mote device, would be used more carefully to convey information about contacts and collisions with other components or with the environment.

Affordances. The object's affordance should also be improved, so that objects suggest how they can be used, also in perspective of more complex assembly tasks.

6 Conclusions and Future Works

This paper has described a low cost application developed for testing a mixed reality approach for the evaluation of manual assembly of mechanical systems. An application for evaluating manual assembly tasks typically require the simulation of haptic manipulation performed with both hands. In order to reduce the cost of the application, and limiting the application architecture to the use of one single 6-DOF haptic device, which is currently a rather expensive equipment, we have proposed a configuration where a Wii-mote device is used for positioning a first component and a 6-DOF haptic device used for performing the assembly of a second object into the first one. Major usability problems of the application have been identified through low cost tests by using a simple but effective evaluation methodology and involving one single expert user. From the results of this initial and preliminary evaluation we have modified the design of some features of the assembly application. Following activity plans to involve several evaluators for testing the system, with the aim of performing a more formal and comprehensive evaluation of the application. Once the platform has been set up and evaluated, we plan to implement additional industrial oriented applications also integrating other low cost interaction devices that in the meantime will become available. We are also planning to use the data recorded about assembly tasks performed by users for playing back the user's task using a virtual human with the aim of performing more accurate ergonomics analysis about user's postures and discomfort without engaging and bothering real users with exhausting testing sessions. The same data may be used for training purposes with novel users.

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