

Visuo-haptic set-up for usability analysis of industrial products

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Abstract

Virtual Reality (VR) technologies are able to support and facilitate the Participatory Design of industrial products by allowing designers to involve the final users of a product at the early design stages, without the need of a physical mock-up and with the advantage of being able to assess several design options.

In some previous works, we have described a methodology and a system (called VP2PaD: Virtual Prototyping oriented to Participatory Design) for the usability evaluation of an industrial product based on the use of virtual prototypes. One of the main limitations of VP2PaD is the absence of tactile feedback, which complicates the user's interaction with the interface of the virtual product. This paper presents the continuation of these works, describing the first steps in the development of a new system, based on a haptic device and an augmented reality display, that aims to improve the effectiveness of VP2PaD, especially in terms of user-friendliness of the interaction devices. Thanks to the haptic device, the user may feel the presence and the contact with interface widgets like buttons and knobs. Moreover, with augmented reality the virtual product may be displayed in a real context and the user may see his/her own hand touching the digital objects.

This approach presents several challenges related to the implementation of the visuo-haptic augmented reality setup. The rendering pipeline has to be modified in order to delete the haptic device from the scene and, at the same time, to display correctly the real hand avoiding any wrong occlusion by the virtual objects. In order to solve these problems, we consider Image-Based Rendering (IBR) techniques. The elimination of the haptic device from the augmented reality scene, together with the collocation of the user's hand and the virtual object, notably enhance the friendliness of the interface. As a result, the user can focus on testing the virtual product, without distractive elements from the setup.

Keywords: *Participatory Design, Augmented Reality, Haptic, Visuo-haptic, Image-Based Rendering*

1. INTRODUCTION

The earliest industrial VR applications merely provided the visualisation of the virtual prototype (VP) in VR, in order to perform an aesthetical validation of the product [1]. VP visualisation in VR is crucial to exploit the overall appearance of the product, but it can also be useful in order to perform some analyses, such as parts reachability, cabling, design, assembly, validation, etc. [2]. An overview of the possible utilisation of VR in the industrial field has been presented in [3], describing both a taxonomy of all the

employments of VR in industry and, in particular, some recent progress of Virtual Prototyping.

More recent VR applications in the industrial field try to simulate in VR the behaviour of the industrial products. In this way it is possible to use VR not only for aesthetical purposes, but also to discover any functional flaw of the VP [4].

One of the most promising applications of VR in the product development process is the usability evaluation, thanks to VR, this task may be realized since the early conceptualisation phases of the product.

The usability of an industrial product is the most important characteristic in helping the designer to define the compatibility between design and user [5]. But the notion of usability may not be separated from the notion of assessment of the usability itself. That is why it is important to have interactive prototypes to carry out the assessments.

In previous work [6, Design for usability in virtual environment] we have validated the reliability of a usability test in a virtual environment. The user is facing a virtual prototype, and interacts with the product interface through a virtual interface. The tests verified that VR devices do not distort the usability assessment of the product. In fact, during the experiment, either with real or virtual interaction, the same difficulties of functional understanding of the product interface were noticed in all users, revealing some design errors in the product interface.

In order to generate the sensation of an immersion into a virtual environment, it is necessary to simulate all the perceptive stimuli coming from the real world. At present, it is still particularly difficult to simulate tactile stimuli and reactions coming from real objects. Whereas simulations based on visual stimuli are particularly effective (the sight has the privilege of being the sense *par excellence*). The user easily learns how to code a visual stimulus as the effect of an action, thus becoming aware of such correspondence that he/she will be able to reproduce in the future. The user's training phase, carried out before the interaction with the virtual prototype, notably improves the user's familiarity with the virtual interface.

During the adjustment of the system, we particularly focused on the design of a product/user interaction as similar as possible to the real one. A large number of tests were carried out, in order to simulate tactile feedback (not implemented in the set-up used); the experimental evolution led to a perceptive solution (sufficiently immediate in terms of cognition) of the hand-virtual interface collision obtainable through both a visual and sound feedback [7, A new approach to participatory design: usability tests in virtual environment].

The set-up used to carry out the research (Fig. 1) is based on a retro-projected screen for passive stereoscopy visualisation; a 5th Dimension Technologies Data Glove with 15 sensors through which the user may

activate various control panels; a 3D joystick through which the user may control both the selection of objects and the points of view; a tracking device (Ascension Flock of Bird) with two sensors: one connected to the glove to determine position and orientation of the user's right hand, and another one used for head tracking or placed inside the 3D joystick to improve navigation tools.

The limitations of this set-up are related to the lack of haptic feedback during the interaction with the interface. This lack prevents the user from evaluating the real dexterity and/or the level of force required to make a selection. This set-up allow only to assess strictly efficacy, efficiency and satisfaction of use related to the understandability of the product interface.



Fig. 1. Use of the SenseGraphics system for the PUODARSI project [8]

Starting from this consideration we are currently planning to evaluate in future tests the benefits related to the presence of force feedback. But the integration of haptic devices requires to completely change the previously used set-up.

Our idea is to employ low-cost devices like a Sensable Phantom Omni that ensure 6 Degrees Of Freedom (DOF) in positional sensing and 3 DOF in force rendering. For the visualization we intend to use an Augmented Reality (AR) environment to allow the user to see the virtual product into a real context. The use of AR could improve the visualization but, as it will be discussed later in greater detail, the visuo-haptic feedback is not completely natural, as the user is distracted by the vision of the haptic device.

Instead of simply merging the augmented VP into the real scene, we propose to modify the rendering pipeline and delete the haptic device from the scene. In order to solve this challenge, we consider Image-

Based Rendering (IBR) techniques, which would provide correct visuo-haptic integration in the AR-based environment.

2. RELATED WORK

The state of the art presented in this section concerns three different research fields that are involved in the present research. Since there is an ample literature in each field, we have limited the analysis only to the aspect strictly related to the topic of our interest.

2.1. Haptic interaction

Unlike the other human senses, the haptic or tactile system has the unique property of providing bidirectional communication with the environment [9]. Haptic rendering [10] is the technology of computing interaction forces that allow interacting with a virtual object in a way that mimics the interaction with real objects.

Haptic devices allow the perception of physical contact with the simulated virtual objects in augmented reality [11]. In the past few years several commercial and laboratory haptic devices have been developed. For the purposes of this project, we have relied on the Phantom Omni haptic device from SensAble Technologies Inc. (www.sensable.com) Such device allows for the rendering the interaction with the virtual environment through a tool, which in our case is the virtual prototype.

From the many algorithms for rendering contact between a tool and the rest of the virtual environment, we have selected multi-threaded algorithms that compute accurate contact in a slow (visual) thread, and employ a linearized contact model in a fast (haptic thread), both for rigid [11] or for deformable tools [12].

2.2. Augmented Reality

Augmented Reality (AR) applications visualize virtual objects superimposed on the physical scene [13]. These applications are based on HMD technologies and see-through visualization systems.

AR applications are implemented in many domains such as assembly, maintenance and repair of complex equipment, cultural heritage and entertainment. A comprehensive review of augmented reality can be found in [14, A Survey of Augmented Reality] and [15].

In [16] it has been pointed out that the advantage of VR in prototyping is clear

when there is a presence of both virtual and real objects, such as in the visualization of data related to CAE analysis which have been realized on existing products, or also on a physical prototype. Starting from this statement we intend to evaluate how the AR can be a valid instrument also in the usability analysis of VPs.

Other researches like [17], employed augmented reality and tangible interaction in a novel approach to virtual prototyping of digital handheld products, which is called tangible augmented prototyping. The proposed approach is aimed at generating and utilizing prototypes of digital handheld products using and functional behaviour simulation. The prototypes can represent not only the primary function but also other functions such as looking nice in aesthetic shape and keeping good in overall structure.

In the PUODARSI project [8] a visuo-haptic interface has been used for shape modification. It is based on the SenseGraphics 3D-IW immersive workbench that consists of a Phantom haptic device integrated with a stereo visualization system including a CRT monitor, a semi-transparent mirror and some stereographic shutter glasses. This configuration is more ergonomic compared to HMDs that users are not keen on wearing for long periods. But the SenseGraphics system does not include a tracking system allowing detecting the user's point of view. Consequently, it may happen that the point of contact between the haptic device and the virtual surface does not correspond.

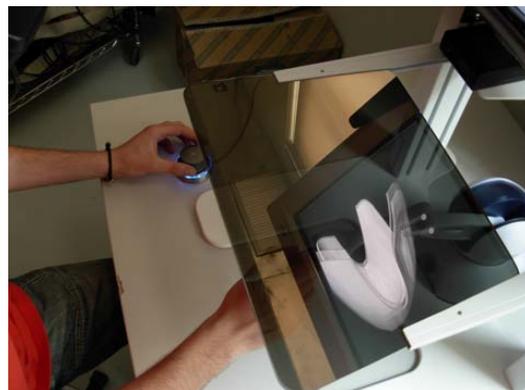


Fig. 2. Use of the SenseGraphics system for the PUODARSI project [8]

2.3. Image-based rendering

Image-Based rendering (IBR) appeared about 15 years ago [18] as a revolutionary technique in the general field of Computer

Graphics. In fact, IBR techniques soon showed the potential to generating photorealistic images directly from a set of input images of the same scene. IBR allow to capture the complete appearance of a real or digital scene, representing this information, and then using this representation to render images of the scene from new camera positions. In other words given a set of images acquired from known viewpoints, IBR allow to synthesize the image which would be seen from a new viewpoint.

IBR technique can be implemented through different approach. Strategies for view synthesis are divided into those which explicitly compute a 3D representation of the scene, and those in which the computation of scene geometry is implicit. The first class includes texture-mapped rendering of stereo reconstructions [19], the second class generally assemble the pixels of the synthesized view from the rays sampled by the pixels of the input images [20]. In the implicit approach the interpolation of the input images is computed in the domain of the *plenoptic* function, a function that maps the colour of each ray departing in every direction from each point of the scene [21]. Starting from these reference works many IBR solutions based on the *plenoptic* function were presented. In these works it is possible to recognize two main groups. On one side we can consider those implementations that could reach a photorealistic result [22] [23], on the other side those solutions that attempt to a Real-time implementation [24] [25].

The Unstructured Lumigraph [26] fuses the explicit and the implicit approach giving the possibility to merge known 3d geometry information in an unknown scene, and collecting the input images samples without a precise structure.

3. VISUO-HAPTIC SET-UP

The set-up that we want to develop for usability tests is based on a visuo-haptic interaction that allows the users to verify both the shape and the functions of the virtual product. Our visuo-haptic set-up integrates and uses a haptic device in an AR context. In **Errore. L'origine riferimento non è stata trovata.** the interaction scenario related to our visuo-haptic system for VP is shown. The engineer defines the product behavior as a

mathematical model that describes how the product responds to the user actions. There are several techniques to describe the behavior like finite state machine, Petri net, etc. In some cases also a physical model of the product is needed because the product behavior may involve also some aspects related to the mechanics e.g.: moving parts that require a multi-body simulation.

We may generalize the problem thinking that the system able to describe the product behavior is a Knowledge Based Environment because it captures and stores the engineering knowledge about the product. The KBE is connected to the VR system that creates the Virtual Environment (VE) in which the product is represented and simulated. The users interact with the VE through a Head Mounted Display and a haptic device that allow them, respectively, to observe the digital representation of the product and to control the elements of the product's interface (buttons, knobs, levers, etc.).

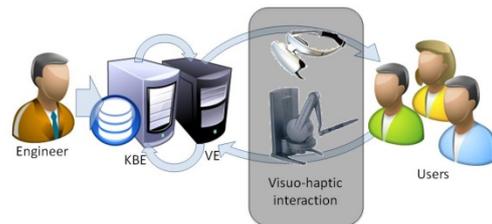


Fig. 3. The interaction scenario

An AR system can be implemented using different hardware configurations. One of the most widespread solutions is the optical see-through Head Mounted Display (HMD). These systems combine computer-generated imagery with "through the glasses" image of the real world, usually through a slanted semi-transparent mirror. Another option to show digital data on a real scene is with the video see-through approach. One or two cameras can be employed to transform a normal HMD into a simulated see-through display.

We employed this kind of device for two reasons. The first is that it is much easier to match the video latency with the computer graphics latency. Moreover, the video see-through device allows us to implement a marker-based optical-tracking system using the two cameras mounted on the HMD [27].

The video see-through HMD has been created starting from an eMagin Z800 HMD. This visor has a pair of OLED displays with native resolutions of 800x600 pixels each, and supporting 8 bits per pixel.

The unit offers a 200:1 contrast ratio. Further, the visor is equipped with a gyroscope for the head tracking. The visor has been modified to mount two Pointgrey Flea2 1394b cameras. These cameras have a 1/3" color CCD sensor, with a resolution of 1024x768 pixels and a 30Hz frame-rate.



Fig. 4. The visuo-haptic set-up

The utilization of AR in our setup aims to satisfy two needs: first, we want to visualize the VP immersed in a real context, in order to make the product presentation more similar to reality; second, we want the user to be able to see his/her hand which acts directly on the product, rather than a digital hand which replicates his/her movements. In fact, in the VR set-up used until now, the user wears a glove which allows us to replicate the user's hand movements inside the virtual environment. The difficulties in the system usage are due to the fact that some users make too much effort to create a correlation between the movement of their hand and the movement of the virtual one, and this fact complicates the test execution for people who are not familiar with computers.

The new set-up, thanks to AR, will instead allow the user to see his/her hands that get near and touch the virtual product, receiving – thanks to the haptic device – a force feedback that gives him/her the sensation of being able to touch the object.

In order to make the set-up efficient, it takes a perfect synchronization of the visual and tactile answer of the system. Moreover, it would be convenient if user could not see the haptic device, also because the device could partially be hidden by the visualization of the VP.

This aspect represents one of the main challenges in this moment, because we believe that only an effective integration of the haptic and visual parts could give birth to the implementation of a system which can put the user in the position of doing the

tests in a more natural way, without being hampered by the experimental set-up.

4. INTEGRATING AUGMENTED REALITY AND HAPTICS

The realization of the system requires the definition of an architecture in which three different modules are integrated. These modules provide respectively:

1. Haptic rendering;
2. Product behavior simulation;
3. Visual rendering;

The modules work at different refresh rates, hence a synchronization is needed. The haptic rendering requires a refresh rate at least equal to 1000 Hz. On the other hand for visual rendering a refresh rate of 30 Hz is enough. Finally, the product behavior simulation, based on the rules and the models defined in the KBE, may be executed at a variable frame rate depending on the nature of the simulation.

Moreover the integration of haptic device in an AR context requires a calibration able to exactly align haptic and world coordinate systems as described by Harders et al. [28] [29].

Keeping in mind that any error in this process would greatly diminish the usability of the system, and compromise user interaction with the VP [30], we have implemented a simple calibration procedure based on the work of Vallino and Brown [31].

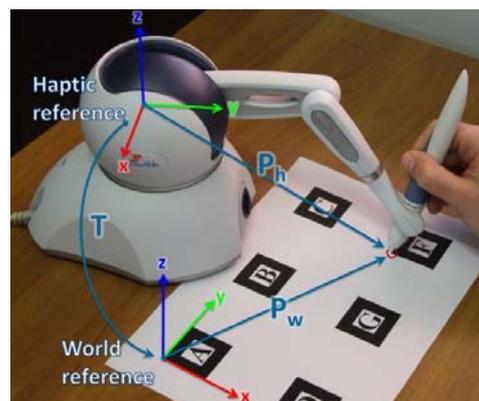


Fig. 5. Phantom interactive calibration in AR

The calibration procedure starts requesting to the user to put the phantom pen's tip upon the corner highlighted in AR with a red flashing ring (Fig. 5). When he/she points the correct position, he/she should press a pen's button to store the position, and move to the next point. The procedure

automatically asks for all available corners, but the user can skip to store the position of an unreachable point.

When a point is selected, the system automatically stores both the two vectors \mathbf{P}_w and \mathbf{P}_h , defining, respectively, the position in the world and the haptic reference frame. \mathbf{P}_w and \mathbf{P}_h are expressed in homogeneous coordinates. In particular, \mathbf{P}_w is already known because it is defined for the multi-marker AR set-up. The \mathbf{P}_h vector can be retrieved directly using the driver of the haptic device, which internally computes it by evaluating the direct kinematic function over the current angular encoders' configuration.

When the interactive calibration phase is terminated, an optimization algorithm computes the affine transformation \mathbf{T} minimizing the following objective function:

$$f_{obj}(x) = \sum_i^N (P_h^i - T(x) P_w^i)$$

The resulting transformation is then used to align the haptic reference in respect with the world reference.

5. NEW AUGMENTED RENDERING PIPELINE

The correct visualization of the augmented scene requires the deletion of the haptic device from the real scene and, at the same time, to correctly display the virtual objects, avoiding any wrong occlusion. To reach this goal we need to modify the standard rendering pipeline, usually employed in AR applications, adding both capabilities of deleting the haptic device and repainting the scene background.

We have, initially, evaluated the possibility to implement a mono-chromatic filtering technique (also known as chroma key), usually employed in cinema or television effect. Coloring the device with a uniform color (typically green or blue) would allow us to detect a mask to delete the device from the scene.

An alternative solution could be reached by coupling a direct kinematic model and a 3D model of the device. The spatial configuration of the virtual model is constantly updated taking into account the values of the encoders present on the haptic device. The filter mask could be derived with an off-line rendering of the virtual device. This rendering can be transformed in a mask that represents the pixels to be deleted. For repainting the

scene background we are following the idea of IBR (Image Based Rendering) techniques to synthesize the *haptically* scene image consistent with the current user's point of view. At the moment, we are just trying to implement some of the works described in the state of the art, keeping major interest for those promising a real-time result. After the selection of the most suitable IBR algorithm we expect to implement a specific rendering pipeline able to integrate the real scene with some parts calculated by the IBR and some others given from the rendering of the virtual objects.

Before the rendering starts, a preparation of the working environment is required. The steps needed are the following:

- 1) Calibration of the two cameras in order to compensate for image distortion, to retrieve the projection matrix and to determine the relative positions of the camera (needed for stereo tracking).
- 2) Collocation of the markers for video tracking in the environment.
- 3) Acquisition of N images (from N different poses) of the scene without the haptic device.
- 4) Collocation of the haptic device and registration with respect to the reference system defined by the markers.

After the preparation of the environment, the system starts to work executing the following pipeline for each frame.

- 1) Acquisition of the *Real Scene View* (RSV) through the cameras mounted on the HMD (Fig. 5a).
- 2) Calculation of the Point Of View (POV) of the camera using the marker-based tracking.
- 3) Acquisition of the haptic device configuration (angles of each encoder).
- 4) Off-screen rendering of the virtual haptic device reproducing the configuration of the real one. This rendering is used to generate a mask needed to delete the haptic device from the scene (Fig. 5b).
- 5) Synthesize the New View (NV) for the current pose of the POV using the IBR algorithm. The NV is calculated only in the pixels needed to delete the haptic device. These pixels are defined in the mask calculated at the previous step (Fig. 5c).
- 6) Augmenting the RSV with the rendering of the digital objects and obtain the Augmented Scene View (ASV).

7) Merge the ASV view with the NV to obtain the frame to show to the HMD (Fig. 5d).

The pipeline has to be repeated for each camera of the HMD.

The following figures illustrate a possible application of the new augmented rendering pipeline where a Phantom Omni is deleted from the scene while a virtual model of a DVD player is added.

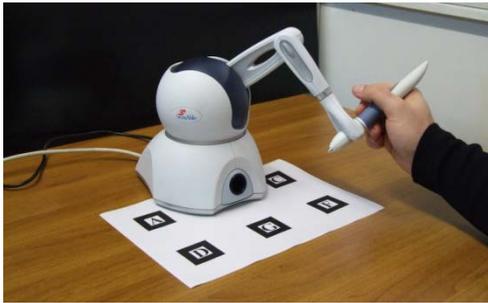


Fig. 5a: The real scene acquired by the camera

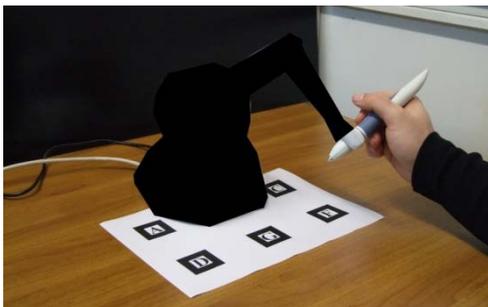


Fig. 5b: Mask of the haptic device

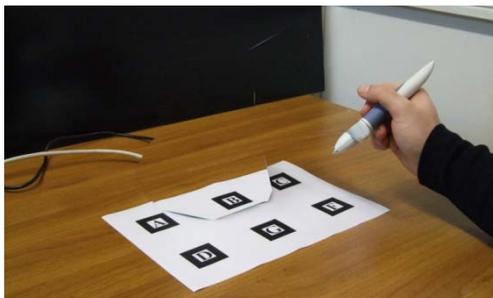


Fig. 5c: Image synthesis by IBR

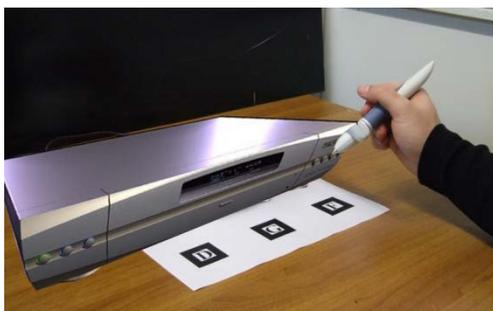


Fig. 5d: Augmenting the real scene

6. CONCLUSIONS

The present paper describes the first steps toward the development of a visuo-haptic set-up for the usability analyses of industrial products in an AR environment. The research, at the moment, is tackling the problem of deleting the haptic device from the scene. We believe that it is essential to resolve this problem in order to improve the sensation for the user to be able to touch the product by acting on the various elements of the interface.

We approached this problem by defining a pipeline rendering that is able to delete undesired real objects from the scene and to add some virtual object taking correctly into account the occlusion between physical and digital objects. Future works will regard the implementation of this algorithm in a shader in order to have a sufficient frame rate. Then we may complete the development of the pipeline and start to carry-out some tests with the users.

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