Toucheo: Multitouch and Stereo Combined in a Seamless Workspace.

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ABSTRACT
We propose a new system that efficiently combines direct multitouch interaction with co-located 3D stereoscopic visualization. In our approach, users benefit from well-known 2D metaphors and widgets displayed on a monoscopic touchscreen, while visualizing occlusion-free 3D objects floating above the surface at an optically correct distance. Technically, a horizontal semi-transparent mirror is used to reflect 3D images produced by a stereoscopic screen, while the user's hand as well as a multitouch screen located below this mirror remain visible. By registering the 3D virtual space and the physical space, we produce a rich and unified workspace where users benefit simultaneously from the advantages of both direct and indirect interaction, and from 2D and 3D visualizations. A pilot usability study shows that this combination of technology provides a good user experience.

ACM Classification: H5.1 [Information interfaces and presentation]: Multimedia Information Systems. - Artificial, augmented, and virtual realities. H5.2 [Information interfaces and presentation]: User Interfaces. - Input devices and strategies.

General terms: Design, Human Factors

Keywords: Multitouch, stereoscopic display, 3D user interfaces

INTRODUCTION

Recent years have witnessed a keen interest for new input and output technologies. In particular, a widespread boom has occurred surrounding multitouch interaction on the one hand, and stereoscopic visualization on the other hand, noticeably with the extremely rapid market penetration of these technologies for the general public mass market. Direct multitouch interaction has shown many benefits for interaction with digital content. With good mappings, the intuitiveness of multitouch interfaces favors fast and easy interaction. At the same time, stereoscopic visualization, that has been dedicated to specific audiences and applications for a long time, is now becoming a standard display, and it tends to be well

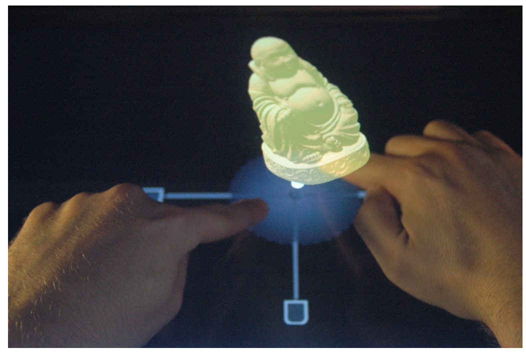


Figure 1: 3D stereoscopic objects and 2D monoscopic content are combined in a unified multitouch workspace.

accepted by large audiences. In this work, we lean on these current trends and we merge the benefits of both multitouch interaction and stereoscopic visualization into a new original unified workspace. Our system combines efficient direct multitouch interaction with co-located 3D stereoscopic visualization. Hence, users benefit from an immersive visualization of data while being able to interact with both 2D and 3D elements thanks to well-known, or new, touch-based 2D metaphors and widgets, within a seamless workspace. Figure 1 illustrates this workspace, where a user manipulates a 3D stereoscopic object from 2D gestures on a touchscreen.

In this paper, we first review the related work and technologies, and discuss their advantages and drawbacks. Afterwards, we describe both the hardware and software components of our setup. We then focus on interaction techniques and we present the dedicated transformation widget we have designed. A user study allows us to highlight the strengths and weaknesses of our setup. Finally, we describe an applicative scenario before concluding.

RELATED WORK

Interacting with 3D content on touchscreens is an inspiring challenge that has recently motivated interesting research work. Hancock et al. [12] proposed a technique where users manipulate 3D objects with one, two, or three fingers in shallow depth. Reisman et al. [18] extended the well known Rotate-Scale-Translate (RST) multi-touch technique to 3D. Martinet et al. have compared and improved these techniques [16]. In their approaches, Cohé et al. [8] and Kin et al. [14] adapted standard desktop interfaces to the multitouch paradigm. Hilliges et al. added *above-the-surface* interaction paradigms [13]. Even if these techniques enhance interaction with 3D scenes, they generally face the problem of 3D content being visualized on 2D flat screens.

Stereoscopic visualization associated with head tracking favors good perception of 3D content. This technology has been extensively used in VR, and it is now becoming widely available. One of the problems with such a display is the difficulty for the user to interact with, let alone to touch. Dedicated input devices and interaction techniques have been designed (see VR and 3DUI literature, e.g. [5]), but they are generally not integrated within widely distributed applications. Mirror-based display systems, such as the one presented by Schmandt [19], enable co-location between the interaction space and the visually perceived 3D scene. This allows exploiting proprioception and hand-eye coordination [1]. These systems are generally used with haptic devices, e.g. [15]. Such configurations allow one to directly address 3D points within the registered virtual and physical spaces, as well as to feel virtual shapes. With a semi-transparent mirror, the user can see both the real and the virtual environment at the same time. This has been exploited in AR scenarios, e.g. [4][17]. However, the applicative scenarios for such configurations are generally restricted to specific use, and the level of interaction is quite poor. As far as we know, mirror-based stereoscopic systems have never been exploited in conjunction with an additional touchscreen.

Recently, Benko et al. have proposed to combine touchscreens with stereoscopic visualization [3]. Their system is based on a DiamondTouch table used in conjunction with SeeThrough AR head-worn displays, and 3D tracked gloves. This system manages both 2D images projected on the table, and 3D visualization through the head-worn displays. Our approach shares some similar concepts with their work, and it is complementary. Whereas they have conceived their system to favor collaborative work, we have concentrate on a setup that maximizes the consistency and the seamless integration of 2D and 3D stereoscopic displays. Head-worn displays as used in [3] have substantial advantages, but they also suffer from many weaknesses, including a limited field-of-view and resolution, problems of lag and calibration, and so on. Our proposal oversteps these limitations by leaning on a new original optical configuration. Users wear light glasses, and they can interactively observe high-resolution monoscopic and stereoscopic content with a good visual comfort. We have also introduced new 9 DOF interaction widgets that take benefit of such a rich visualization space.

De la Riviere et al. have demonstrated a stereoscopic multitouch system [9]. In their approach, two head-tracked users directly interact on a large stereoscopic multitouch table. This setup revealed many promising uses. On the other hand, it suffers from some limitations. In particular, content occlusion is problematic when visualizing stereoscopic images. Selection is also a critical issue when stereoscopic visualization and touch input are jointly used in a unique setup. Valkov et al. [21][20] have focused on this problem, and they give recommendations for 2D touching of 3D stereoscopic objects. In their work, Coffey et al. [6][7] proposed an immersive setup where users interact on a horizontal touchscreen, while visualizing virtual environments displayed from a large vertical display located in front of them. Veit et al. [22] used a similar approach with a two-side workbench. The limitation of such approaches is that users need to change the focus between the interaction plane, and the 3D display. With our setup, users can refocus at two different depths without changing their viewing direction. This allows concentrating at visual content displayed at given depth, while keeping the context provided by the second depth plane.

All those attempts show that the conjunction of multitouch interaction and stereoscopic visualization is very promising. On the other hand, the previous work also shows that merging these technologies may be hard to perform, both in terms of hardware developments and design of efficient interaction techniques. Indeed, their achievements seem to be conflicting: immersive visualization makes the screen disappear and gives the feeling an object is located ahead of or behind the screen, while the touch input enables efficient interaction with any content that is displayed on the screen or the interaction plane. Moreover, the very nature of stereoscopic images conflicts with touch input, as two images are generated to force the eyes convergence and the associated depth perception, which is contradictory with single images displayed at screen depth to enable efficient and precise touch.

SETUP

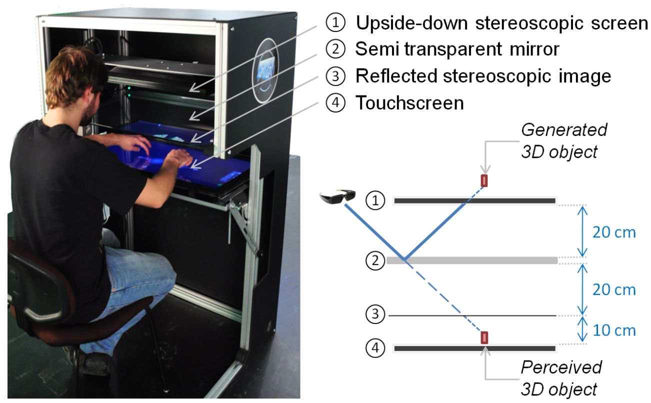
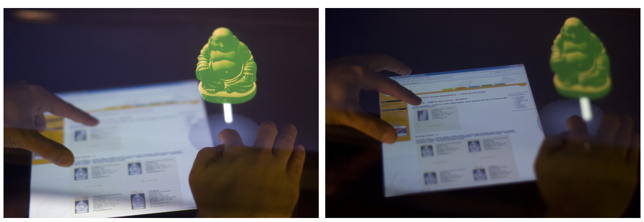


Figure 2: Physical setup

To overcome the limitations of the systems described in the previous section, we propose a new original setup. It relies on a multitouch screen on which users see a visualization and interact with monoscopic content. The stereoscopic visualization is provided by another 3D screen that is hung upside-down at the top of the system, and that is reflected on a semi-transparent mirror located between the user's head and the multitouch screen (see Figure 2). Hence, stereoscopic objects are perceived as if they were displayed above the hands, between the mirror and the touchscreen. The geometry of the system provides a large volume above the touchscreen where stereoscopic objects can be perceived. Head tracking ensures that virtual objects are displayed from a correct point of view, and that the parallax is physically correct for any of the real or virtual object within the workspace. By mapping the virtual stereoscopic volume to the physical space, we can then produce a rich and consistent interactive visualization space.

Regarding the taxonomy of Grossman and Wigdor [11], the input space is *2D Planar*, and both *2D Table* (perceived as *2D*) and *2D Heads Up* (percieved as *3D Volume*) are jointly exploited.

With this setup, users see in the same space the floating 3D objects, their hands, and the data displayed on the touchscreen. Our system inherently provides relevant occlusions clues. Indeed, the stereoscopic objects appear above the user's hands, while the monoscopic content remains below (see Figure 1). Contrary to standard immersive 3D systems that only rely on affecting the eyes convergence to simulate 3D objects depth, our proposal also takes advantage of eye accomodation, and its capability to focus at two different depths. This is illustrated in Figure 3. By changing the lighting conditions inside the system, as well as the brightness of the two screens, we are able to modify the ratio between reflection and transparency and, consequently, we can adjust the visibility of the 2D images, 3D images, and physical objects (e.g. hands).



(a) Focus on the 3D object (b) Focus on the touchscreen

Figure 3: The setup based on two physical displays provides natural focus separation.

Our current implementation is based on two 32" 1080p LCD screens, which are capable of stereoscopic visualization with shutter-glasses. We chose identical screens for colorimetric consistency purposes, even if stereo is enabled on the top screen only. A PQLab 32" multitouch sensor that is mounted on the bottom screen is used to detect finger gestures. The semi-transparent mirror reflects 70% of the light. Head-tracking is currently achieved with an electromagnetic sensor, but it will be replaced by an optical tracking solution to avoid wires. Our software plateform is based on Ogre3D and QT. It runs on a unique PC equipped with a Nvidia Quadro Fx 3800 graphic board. The user is sitting when interacting.

INTERACTION TECHNIQUES

The monoscopic touchscreen provides a direct multitouch interaction surface. Consequently, we benefit from the large variety of user interfaces that were previously designed for such systems. In particular, we take advantage of well known multitouch gestures for zooming and panning operations, for item selection, and even for application control. For example, Figure 3 illustrates the use of a web browser that is displayed on the touchscreen, and Figure 4 shows a standard color editor. Such widgets are embedded inside the immersive workspace, and they can be manipulated with standard touch gestures. Users are therefore able to interact in a fast and easy way with the content beneath the fingers, as they would do with a standard touchscreen.

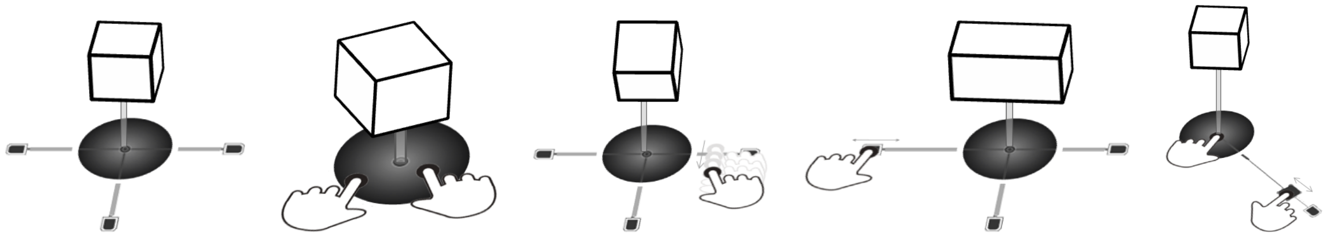
By default, the 3D objects are displayed and move on the monoscopic screen. They are therefore seen as 2D projection of 3D objects just like on any standard screen. A *double tap* gesture on a 3D object makes it appear as a stereoscopic object floating above the surface. A simple *z*-translation animation gives the impression that the object comes out of the touchscreen. The 3D representation of the object on the touchscreen disappears, and it is replaced by a 3D transformation widget located below the floating object. This widget is used to select the floating object, and to manipulate it. A virtual ray, similar to Glueck et al.'s position pegs [10], enforces the link between the manipulated 3D object and its associated transformation widget, as can be seen in Figure 3. It strengthens the direct relationship between the finger gestures and the object motion, giving an impression of "pseudo-direct" interaction, even if the object is not manipulated directly as in, e.g., [18].

Figure 4: Both standard 2D widgets and 3D widgets are used in the same workspace.

The 3D transformation widget is composed of a central disk and additional virtual controllers (see Figure 5). Dual-touch gestures on the central disk of the widget result in *RST* operations on a plane parallel to the touchscreen (*x*-*y* plane). *x* and *y* rotations are controlled by way of virtual rods located on the sides of the disk. The fingers crossing the rod would launch an inertial rotation around the rod axis, allowing the control of a single degree of freedom without affecting the others. Similarly, scaling widgets allow the control of the *x* and *y* scale factors. For *z* translations and scaling operations, we use an approach inspired from the balloon metaphor [2]. The user first touches the center of the disk with one finger, and then she or he adjusts the height and the size with a second finger. Hence, users are able to control 9 DOF (plus uniform scaling) of the manipulated 3D object. Figure 5 summarizes these control gestures. Note that all the transformations occur in the camera view frame. The transformation widget can be manipulated with multiple fingers at the same time. Two widgets can also be controlled with two hands for simultaneous manipulation of various objects.

USABILITY TESTING

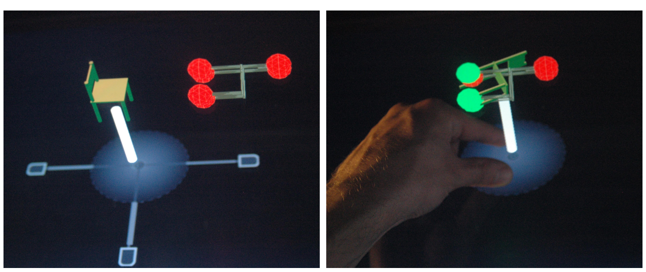
We conducted an experiment to obtain user feedback about our prototype. Sixteen volunteers (13 males, 3 females, mean age 27) participated in this study. None of them was familiar with stereoscopic visualization nor with large multitouch interaction. The participants were asked to complete a 3D docking task implying 9 Degree-Of-Freedom (3 translations, 3 rotations, 3 scaling), as illustrated in Figure 6. Note that



(a) (b) (c) (d) (e)

Figure 5: Gestures and corresponding transformations. (a) The widget is displayed on the touchscreen, below the floating object. A virtual ray links both the object and the widget. (b) One or two fingers on the central disk controls RST movements on the x-y plane. (c) Virtual rods are used for x and y rotations. (d) x and y scaling are controlled with dedicated widgets. (d) When touching the center of the disk, a new control widget appears. It allows controlling z translations and scaling.

we did not focus on precise manipulation in this pilot study, therefore the matching between the target and the manipulated object was quite tolerant. Each participant had to complete the task five times, with various target sizes, orientations and locations. Before starting, the participants were shown the basic usage of the interface. The whole experiment took approximatively between five and ten minutes by participant. After the experiment, the participants were asked to complete a questionnaire based on a five-point Likert scale. We also collected free-form comments.



(a) (b)

Figure 6: The 3D docking task. The spheres move from red to green when the alignment is correct within a tolerance area.

In this experiment, we were interested in the general feeling of the participants regarding the system. The participants reported they liked the system with an average score of 4.6, which demonstrates a stimulating and satisfying overall experience. The score for the global intuitiveness is 4. Almost none of the participants reported fatigue or sickness (1.1).

The perception of the depth was rated with an average score of 4.5, and the perception of the 3D objects obtained a 4.6. We did not use shadows nor specific shading to enhance depth perception. Even with our current basic experimental environment, participants did not encounter problems with the perception of the 3D environment. The need to move the head for observing the 3D scene has been rated as low (1.8). The participants tended to keep a fixed head-position. This may indicate that head-tracking is not mandatory once the initial head position has been detected. Note that we need to know the initial head position to correctly map the stereoscopic objects with the monoscopic ones. The low use of head movements may be explained by the inexperience of the participants. Also, the completion of the task did not require extensive head motion. The related mean scores are illustrated in Figure 7.

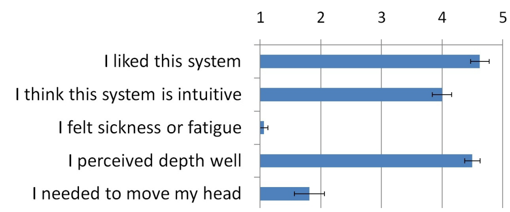


Figure 7: General feeling. Mean scores (1-fully disagree, 5-fully agree) and standard errors (1 SE above and below the mean).

We were also interested in interactions between the visualization of floating objects, the hands, and the widget displayed on the touch screen. The participants answered they were able to visualize well their hand with a score of 4.6. When asking if the hands were too much (resp. too little) visible, the score was 1.6 (resp. 1.5). The hands have not appeared to disturb the visualization of the 3D objects (1.4), nor the 2D objects (2). These results tend to show that the simultaneous visualization of real and virtual elements at different depths do not perturb users (see Figure 8). The simultaneous visualization of their hands and virtual environments may even help users complete the task. This should be studied in more depth in future experiments.

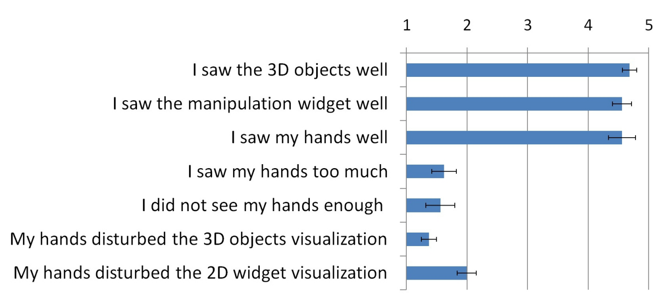


Figure 8: Interactions between the visual elements.

Concerning the widget and the manipulation metaphors (Figure 9), the participants reported they were mainly able to perform what they wanted to (4.2). The RST interface has been rated as easy to use with a score of 4.3. The score for the rotation (resp. scaling) widgets was 4 (resp. 3.9). The z widgets obtained a lower score (3.5). We think that one of the reasons is that the finger movements were sometimes stopped by the borders of the touchscreen. To solve this limitation, we afterwards replaced the initial z movements by circular movements. After having caught a dedicated handle, the user can now turn it around the center of the widget, as she or he would do with a crank handle, to modify the z parameter. Another problem was linked to the selection of the widget due to the parallax between the displayed 2D images and the sensitive surface where the touch inputs were detected. Because we know the position of the user's head, we could solve this problem by warping the input so it could fit exactly with the perceived display space. Note that the participants have practiced no more than 10 minutes with the widget before assessing it. From our experience, the use of the widget become very efficient after a short period of practice. This needs to be better evaluated in future longer experiments.

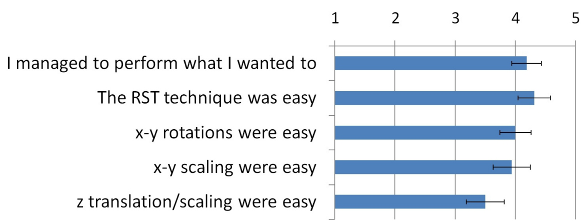


Figure 9: Manipulation widget.

3D docking tasks are generally hard to perform. One of the reason is the difficulty to perceive well the 3D structure of the objects and their relative positioning. Another one is linked to the control of 9 DOF. Our proposal address both of these difficulties. The participants had few problems with perceptual issues thanks to the immersive aspect of our system. They manage to complete the task quite easily thanks to the 2D widget and the associated touch gestures.

LIMITATIONS

In the free-form comments section of the experiment, some participants said that the overall environment was too dark. Indeed, the light coming from the stereoscopic screen is attenuated by the reflection on the semi-transparent mirror, as well as by the shutter glasses needed to produce stereo. In the future versions of our prototype, we will seek for screens that maintain a comfortable overall brightness. We also need to study in more depth colorimetric issues to ensure a perfect consistency taking into account the perturbation induced by the reflection. None of the subjects complained about the possible overlapping between the stereoscopic and the monoscopic content, maybe because the test application we proposed was quite simple. We nevertheless think that such conflicts may be problematic. Because we know the position of the viewer and the position of the 3D objects, we can compute the part of the 2D content that is supposed to be visible (resp. invisible). Hence, we can avoid conflicts, and provide very plausible environments.

Some participants also reported that they found the system bulky, and that they had difficulties to reach the rear part of the touchscreen because of the mirror. We will take these comments into consideration and we will work on ergonomics issues for the design of our future prototype. In particular, we will explore different touchscreen and mirror orientations. We will also work on different form-factors that would avoid the system to be perceived as bulky.

Finally, one of the limitations of our setup is the size of the stereoscopic volume. Compared to large VR screen installations [7] and HMD-based configurations [3], this volume is reduced with our setup. Note however that this volume is bigger than if the stereoscopic display was coming directly from a touchscreen having the same dimensions.

APPLICATION SCENARIO

To illustrate the benefit of our system, we have developed a demo application for a cultural heritage scenario where archaeologists have to reassemble broken objects by manipulating numerous virtual fragments. To complete this task, archaeologists first need to easily access libraries of objects. Then, they may want to sort, arrange, or annotate them. To do this, direct-touch interaction on a multitouch screen is particularly well suited. Similar tasks in fully immersive VR environments may be harder to complete. On the other hand, archaeologists need to precisely perceive all the shape irregularities or the texture variations of the 3D fragments to understand how they can fit together. This can be favored thanks to the immersive aspect of our system. Both stereoscopic visualization and head-tracking provide powerful visualization. The 3D transformation widget we have designed allows the full manipulation of any 3D object. By using two hands, archaeologists can manipulate two objects at the same time to estimate how well they match together (see Figure 10). This would be difficult to complete with a standard multitouch configuration as depth perception may be a true problem. While manipulating stereoscopic objects, archaeologists can still access various standard controls such as color editors, 2D documents, and so on. We believe that numerous other scenarios where the conjunction of both efficient interaction and good visual immersion would benefit from our setup, e.g. in architecture and medicine scenarios.

Figure 10: Two virtual fragments being manipulated with both hands for a reassembly task. *This figure is rendered in stereo with the views for both eyes visible.*

CONCLUSION AND FUTURE WORK

We have proposed a new system that combines both multitouch input and immersive visualization into a single unified workspace. This system relies on the strengths of each technology. It favors at the same time fast and easy interaction, 3D manipulation and camera controls, 2D system control, bimanual interaction, and immersive visualization. The original design of our setup takes advantage of eye accomodation and its capability to focus at different depths.

Our first usability testing was very positive. The participants enjoyed their experience with the system. This study has shown that the blending of stereoscopic display, monoscopic display, and real elements in the same workspace does not cause perceptual conflicts. It has also shown that our setup allows novice users to complete a 9-DOF docking task without many difficulties. User comments have highlighted some limitations of the system. Our future work will consist in improving the design of our prototype by leaning on ergonomics studies. In addition, we want to continue improving and inventing new interaction techniques to push forward the strengths of our system. We also plan to add a depth-camera to mix touch-based and 3D spatial interaction inside the same workspace.

Despite some current areas of improvement, we are convinced that, thanks to its unique blend of complementary displays and simple multitouch interaction schemes, our proposal could bridge the gap between powerful immersive virtual environments and efficient 2D desktop paradigms within a unified workspace.

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