A STEREOSCOPIC AUGMENTED REALITY SYSTEM FOR THE VERIDICAL PERCEPTION OF THE 3D SCENE LAYOUT

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Abstract: The recent diffusion of the stereoscopic 3D technologies has yielded the development of affordable and of everyday use devices for the visualization of such information. This has paved the way for powerful human and computer interaction systems based on augmented reality environment where humans can interact with both virtual and real tools. However, an observer freely moving in front of a 3D display could experience a misperception of the depth and of the shape of virtual objects. Such distortions can have serious consequences in scientific and medical fields, where a veridical perception is required, and they can cause visual fatigue in consumer and entertainment applications. Here, we propose a novel augmented reality system capable to correctly render 3D virtual objects, without adding significant delay, to an observer that changes his position in the real world and acts in the virtual scenario. The correct perception of the scene layout is assessed through two experimental sessions with several observers.

1 INTRODUCTION

In the last decade, there has been a rapidly growing interest in technologies for presenting stereo 3D imagery both for professional applications, e.g. scientific visualization, medicine and rehabilitation system (Subramanian et al., 2007; Ferre et al., 2008; Knaut et al., 2009), and for entertainment applications, e.g. 3D cinema and videogames (Kratky, 2011).

With the diffusion of 3D stereo visualization techniques, researchers have investigated the benefits and the problem associated with them. Several studies devised some specific geometrical parameters of the stereo acquisition setup (both actual and virtual) in order to induce the perception of depth in a human observer (Grinberg et al., 1994). In this way, we can create stereo pairs that are displayed on stereoscopic devices for human observers which do not introduce vertical disparity, and thus causing no discomfort to the users (Southard, 1992). Yet, other factors, related to spatial imperfections of the stereo image pair, that yield visual discomfort have been addressed. In (Kooi and Toet, 2004) the authors experimentally determined the level of discomfort experienced by a human observer viewing imperfect binocular image pairs, with a wide range of possible imperfections and distortions. Moreover, in the literature there are several works that describe the difficulty of perceptually rendering a large interval of 3D space without a visual stress, since the eyes of the observer have to maintain accommodation on the display screen (i.e., at a fixed distance), thus lacking the natural relationship between accommodation and vergence eye movements, and the distance of the objects (Wann et al., 1995). The vergence-accommodation conflict is out of the scope of this paper, however for a recent review see (Shibata et al., 2011).

Besides the previously cited causes of discomfort, another well-documented problem is that the 3D shape and the scene layout are often misperceived by a viewer freely positioned in front of stereoscopic displays (Held and Banks, 2008). Only few works in the literature address the problem of examining depth judgment in augmented or virtual reality environments in the peripersonal space (i.e. distances less than 1.5 m). Among them, (Singh et al., 2010) investigated depth estimation via a reaching task, but in their experiment the subjects could not freely move in front of the display. Moreover, only correcting methods useful in specific situation, e.g. see (Lin et al., 2008; Vesely et al., 2011), or complex and expensive systems (Cruz-Neira et al., 1993) are proposed in the literature. Nevertheless, to the knowledge of the authors, there are no works that aim to quantitatively

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analyze the 3D shape distortions, their consequences on the perception of the scene layout, and to propose an effective and general solution for an observer that freely moves in front of a 3D monitor.

In entertainment applications, such distortions might not be a serious problem, even if they can cause visual fatigue and stress, but in medical and surgery applications, or in cognitive rehabilitation system and in applications for the study of the visuo-motor coordination, they can have serious implications. This is especially true in augmented reality (AR) applications, where the user perceives real and virtual stimuli at the same time, thus it is necessary that the rendering of the 3D information does not introduce undesired distortions.

In this paper, we propose an AR system capable to minimize the 3D shape misperception problem that arises when the viewer changes his/her position with respect to the screen, thus yielding a natural interaction with the virtual environment. The performances of the developed system are quantitatively assessed and compared to the results obtained by using a conventional system, through experimental sessions with the aim of measuring the user's perception of the 3D shape and the effectiveness of his/her interaction in the AR environment.

The paper is organized as follow: in Section 2 we describe the geometry of the standard stereoscopic 3D rendering technique, the misperception associated with the movements of the observer, and our solution; Section 3 describes the AR system we have developed; Section 4 presents two experimental sessions to validate the proposed approach; the conclusion and future work are discussed in Section 5.

2 THE GEOMETRY OF THE STEREOSCOPIC 3D RENDERING TECHNIQUE

2.1 The Standard Approach

To create the stereo 3D stimuli for the conventional approach, we have adopted the stereo rendering, that uses the method known as "parallel axis asymmetric frustum perspective projection", or off-axis technique (Bourke and Morse, 2007; Grinberg et al., 1994), the technique usually used to generate a perception of depth for a human observer. In the off-axis technique, the stereo images are obtained by projecting the objects in the scene onto the display plane for each camera; such projection plane has the same position and orientation for both camera projections (see Fig. 1).

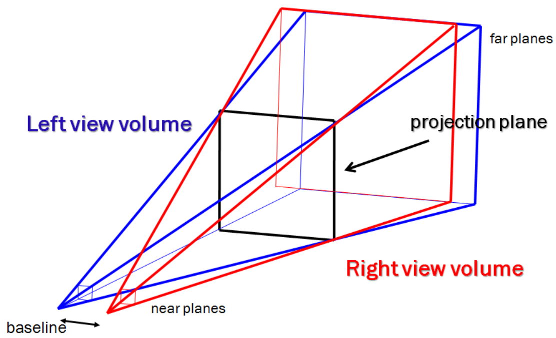


Figure 1: The two skewed frustums for the off-axis technique.

We have also taken into account the geometrical parameters necessary to correctly create stereo pairs displayed on stereoscopic devices for human observer (Grinberg et al., 1994). In particular:

- the image planes have to be parallel;
- the optical points should be offset relative to the center of the image;
- the distance between the two optical centers have to be equal to the interpupillary distance;
- the field of view of the cameras must be equal to the angle subtended by the display screen;
- the ratio between the focal length of the cameras and the viewing distance of the screen should be equal to the ratio between the width of the screen and of the image plane.

Moreover, as in (Kooi and Toet, 2004), one should take into account the problem of spatial imperfection that could cause visual discomfort to the user, such as:

- crosstalk, that is a transparent overlay of the left image over the right image and vice versa;
- blur, that is different resolutions of the stereo image pair.

The previously mentioned rules are commonly considered when designing stereoscopic virtual reality systems. Nevertheless, when looking at a virtual scene, in order to obtain a veridical perception of the 3D scene layout, it is necessary that the observer must be positioned in the same position of the virtual stereo camera. If the observer is in the correct position, then the retinal images, originated by viewing the 3D stereo display and the ones originated by looking at the real scene, are identical (Held and Banks, 2008). If this constraint is not satisfied, a misperception of the object's shape and of the depth occurs (see Fig. 2(a) and Fig. 3).

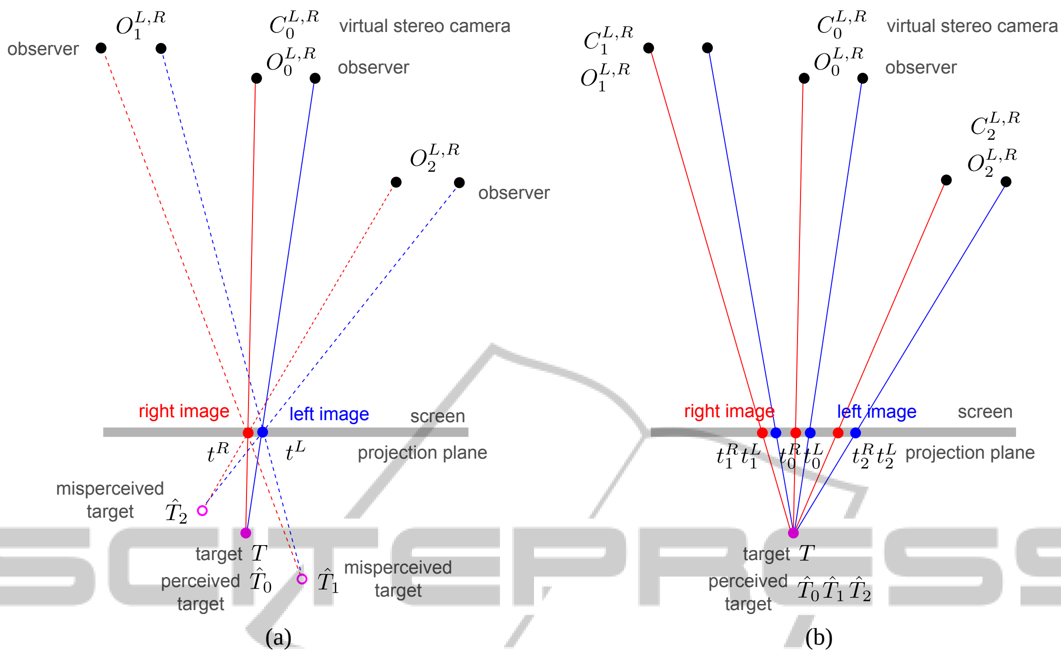


Figure 2: A sketch of geometry of the stereoscopic augmented reality environment when using the standard stereo rendering technique (a), and when using the proposed approach (b). (a) In the virtual environment a target is positioned in T, and a stereo camera is placed in $C_0^{L,R}$, thus generating the left and right projections t^L and t^R on the projection plane. A real observer in the same position $O_0^{L,R}$ of the virtual camera will perceive the target correctly, whereas he will misperceive the position ($\hat{T}_1$ and $\hat{T}_2$) of the target when looking at the screen from different positions ($O_1^{L,R}$ and $O_2^{L,R}$). (b) In the proposed technique, the virtual camera is moved accordingly to the different positions of the observer. This yields different projections of the target (t_0^L, t_0^R; t_1^L, t_1^R; t_2^L, t_2^R) on the projection plane, thus allowing a coherent perception of the target for the observer.

2.2 The Proposed Approach

In Figure 2(a), a virtual stereo camera positioned in C_0 (for the sake of simplicity, we omit the superscript, i.e. C_0^L and C_0^R denote the positions of the left and right cameras, respectively) determines the left and right projections t^L and t^R of the target T on the projection plane. An observer located in the same position of the virtual camera ($O_0 = C_0$) will perceive the target in a position $\hat{T}_0$ coincident with the true position. Otherwise, an observer located in a different position ($O_i \neq C_0$) will experience a misperception of the location of the target ($\hat{T}_i \neq T$). This also causes a deformation of the 3D shape, as it is schematically shown in Figure 3 for a simple target represented by a horizontal bar. When the observer is in a location different from the position of the virtual camera, he misperceives both the depth of the object and its spatial structure.

To overcome this problem, the system we have developed, and that we present in this paper, is capable of compensating for the movement of the observer by computing his/her position with respect to the monitor, and consequently moving the virtual stereo camera (see Fig. 2(b)). For each different position of the observer a corresponding stereo image pair is generated, and displayed on the screen. Thus, the observer always perceives the 3D shape of the objects coherently. Moreover, to maintain a consistent augmented reality environment it is necessary to have a virtual world that is at each moment a virtual replica of the real world. Thus, the screen and the projection plane should be always coincident.

3 THE PROPOSED AUGMENTED REALITY SYSTEM

3.1 Software and Hardware Components

Considering the availability of commercial products with high performances and affordable costs, we decided to use off-the-shelf devices to design and develop our AR system. Specifically, we use the Xbox Kinect, a motion sensing input device developed by Microsoft for the Xbox 360 video game console.

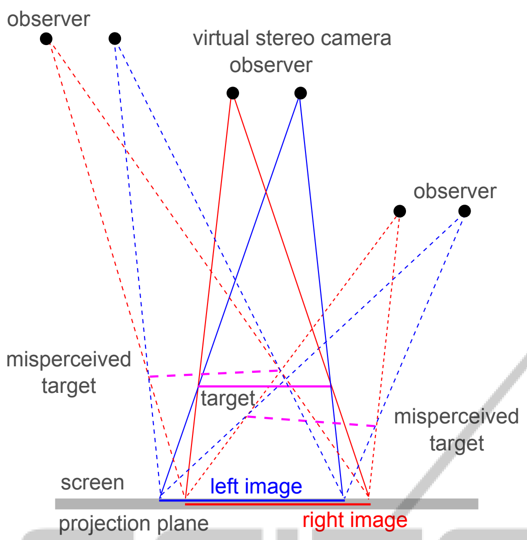


Figure 3: The deformation of the 3D shape when displaying a horizontal bar with the standard technique. For a comparison with the experimental results see Fig. 7(b).

Based on an RGB camera and on an infrared (IR) depth sensor, this RGB-D device is capable of providing a full-body 3D motion capture. The depth sensor consists of an IR projector combined with a monochrome camera.

The main features of this device used for the development of the system are:

- Frame rate: 30 Hz;
- Depth image size: VGA (640×480);
- Depth resolution: 1 cm at 2 m distance from the sensor;
- Operation range: from 0.6 m to 3.5 m;
- Color image size: VGA (640×480);
- Horizontal Field of View: 58 deg.

All the software modules are developed in C++, using Microsoft Visual Studio 10. To render the stereoscopic virtual scene in quad buffer mode we use the Coin3D graphic toolkit[1], a high level 3D graphic toolkit for developing cross-platform real time 3D visualization. To access the data provided by Microsoft XBox Kinect, we use the open source driver (version 5.0.3.3), released by PrimeSense[2], the company that developed the 3D technology of the Kinect. The localization and the tracking of the head and the hand rely on the framework OpenNI[3] (version 1.3.2.1), a set of open source Application Programming Interfaces (APIs). These APIs provide support for access to natural interaction devices, allowing the body motion tracking, hand gestures and voice recognition.

The processing of the images acquired by Kinect RGB camera is performed through the OpenCV 2.3[4] library.

Both the development and the testing phases have been conducted on a PC equipped with an Intel Core i7 processor, 12 GB of RAM, a Nvidia Quadro 2000 video card enabled to 3D Vision Pro with 1 GB of RAM, and a Acer HN274H 3D monitor 27-inch.

3.2 System Description

Figure 4 shows the setup scheme of our system. The XBox Kinect is located on the top of the monitor, centered on the X axis, and slightly rotated around the same axis. This configuration was chosen because it allows the Kinect to have good visibility on the user, without having the Kinect interposed between the user and the monitor. To align the two coordinate systems, we performed a calibration step by taking into consideration a set of world points, whose coordinates are known with respect to the monitor coordinate system, and their positions acquired by the Kinect. In this way, it is possible to obtain the angle α_y between the Y axis of the Kinect coordinate system and the monitor one. In the setup configuration considered for the experiments presented in Section 4 the value of α_y is about 8 deg.

The proposed system, during the startup phase, is responsible to recognize and track the position of the skeleton of the user. After the startup phase, each time new data is available from the Kinect, the system performs a series of steps to re-compute the representation of the 3D virtual world, and to achieve the interaction with the user. These steps can be summarized as follows:

- Positioning of the stereo camera of the virtual world in the "tracked" position of the user's head, obtained from the Kinect. The stereo camera has a fixed angle of view, far wider than the one that is created between the real user and the monitor, that is his/her "window" on the virtual world. For this reason, once repositioned the camera, our system changes the viewport to display on the monitor only the portion of the virtual world that the camera sees through the area that represents the monitor in the virtual world. Just as if we are looking through a window.
- Detection of the position of the index finger of the user, through a light marker, in the image plane of the Kinect RGB camera. This can be achieved

[1] www.coin3D.org
[2] www.primesense.com
[3] www.openni.org
[4] opencv.willowgarage.com

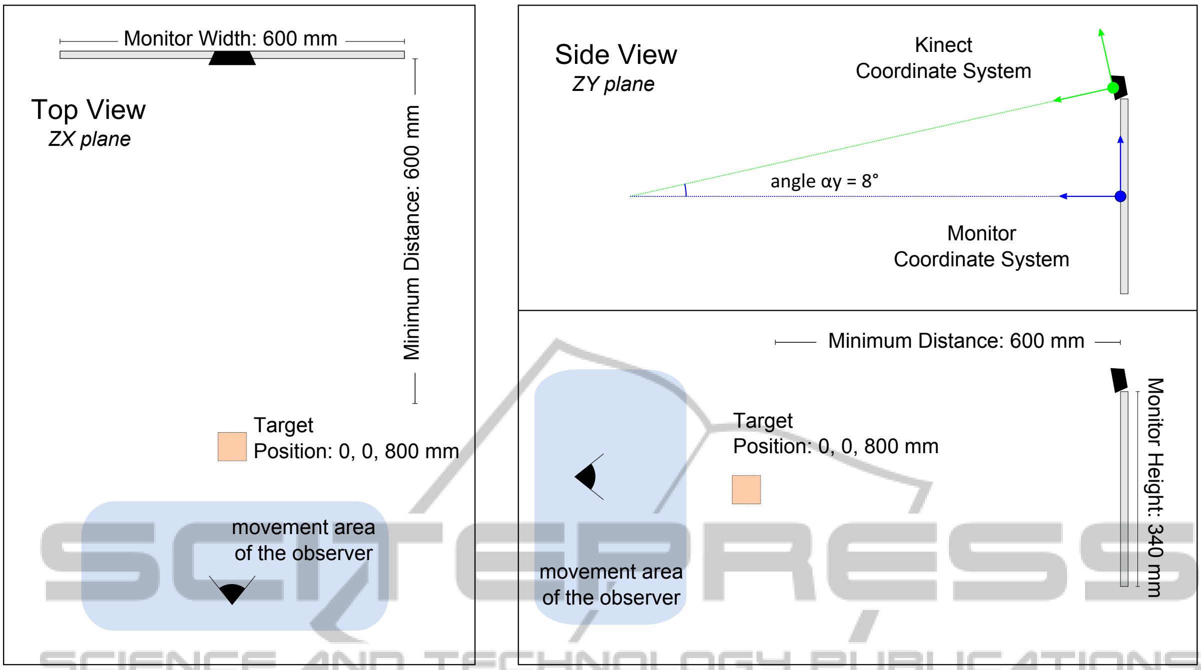


Figure 4: The developed setup for the augmented reality system. The reported measures refer to the specific setup considered for the experimental results. The position of the target is the same of the one of the experiment shown in Figure 5.

first by obtaining the position of the hand from the skeleton, produced by OpenNI libraries, and then performing a segmentation and a tracking of the light source in the sub-image, centered in the detected position of the hand. This image processing step is based on the color information, and is performed by using OpenCV libraries.

- Computation of the position of the finger in the real world by combining its position in the image plane and the corresponding depth (from the Kinect D camera). The spatial displacement between the RGB and D cameras has been taken into account.

The computed 3D position both of the head and of the finger have been stabilized and smoothed in time through a small averaging window over 5 frames.

In order to evaluate the precision of the measurements of the system we performed a test session, from which we derived an uncertainty of about 1 cm (at 1 m of distance from the sensor) on the three axes in real world coordinates, both for the head and the finger localization.

4 EXPERIMENTS AND RESULTS

To quantitatively assess the proposed augmented reality system, and to verify if it effectively allows a veridical perception of the 3D shape and a better interaction with the user, we have performed two types of experiments. In the first one, the observer was asked to reach a virtual target (i.e. the nearest right bottom vertex of a frontal cube whose width is 2.5 cm), in the second one, the task was to trace the profile of a virtual horizontal bar. In both cases, the scene has been observed by different positions, and we have acquired the position of the head and of the finger during the execution of the tasks. The experiments have been performed both by using a standard rendering technique (in the following denoted as tracking OFF) and the proposed approach that actively modifies the rendered images with respect to the position of the observer's head (in the following denoted as tracking ON). The virtual scenes have been designed in order to minimize the effects of the depth cues other than the stereoscopic cue, such as shadows and perspective. It is worth noting that since we use a real finger to estimate the perceived depth of a virtual object, we obtain a veridical judgment of the depth. If the task is performed by using a virtual finger (a virtual replica of the finger), we obtain a relative estimation of the depth, only.

For the experiments six subjects were chosen, with ages ranging from 28 to 44. All participants (males and females) had normal or corrected-to-normal vision. Each subject performed the two tasks looking at the scene from 5 different positions both in

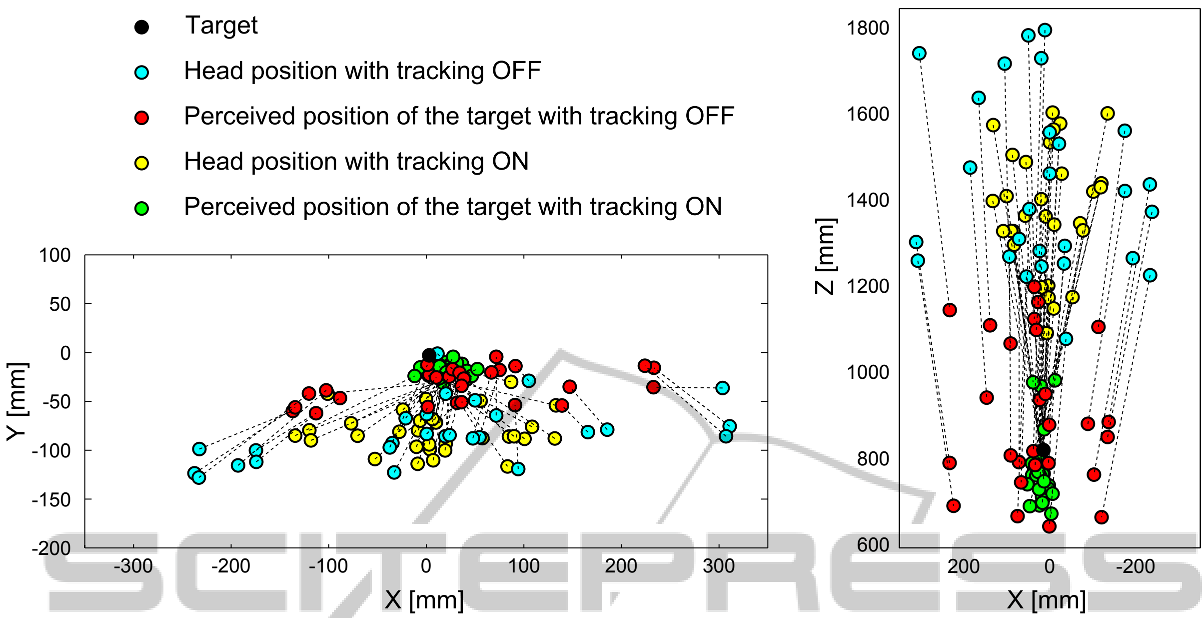


Figure 5: Perceived positions of the target point, and the related head positions for the reaching task. The perceived positions of the target with our tracking system enabled (green circles) are less scattered than the ones using a conventional system (red circles).

tracking ON and in tracking OFF mode.

4.1 First Experiment: 3D Position Judgment

Figure 5 shows the results of the first experiment.

When the tracking is ON, the positions of the observer's head (represented by yellow circles) are spread in a smaller range than the positions acquired when the tracking is OFF (represented by cyan circles). This happens since, as a consequence of the active modification of the point of view, the target could not be visible from lateral views. This behaviour is consistent with real world situations, in which objects that are seen through a window disappear when the observer moves laterally. Nevertheless, the perceived target points when the tracking is ON (green circles) are less scattered than the perceived positions of the target point when the tracking is OFF (red circles), also taking into account the more limited movements of the observer in the first situation.

Table 1 shows the mean errors and their standard deviations of the perceived points. The tracking of the head position of the observer and the re-computation of the stereo pairs projected onto the screen, performed by our system, yield a consistent reduction in the error of the perceived position of the target and in its standard deviation.

A graphic representation of the scattering areas of the perceived points with respect to the movements of the observer in the two situations is shown in Figure 6.

Table 1: The mean error and the standard deviation values (expressed in mm) of the perceived position of the target for the first experiment. The actual position of the target is $(12.5, -12.5, 812.5)$.

	X	Y	Z
tracking OFF	81 ± 68	22 ± 16	146 ± 119
tracking ON	14 ± 10	6 ± 5	74 ± 43

It is worth noting that the area where the target is perceived, when our tracking system is enabled, is very small, thus indicating a veridical perception of the virtual object. In particular, when the tracking is OFF, the mean and the standard deviation values of the perceived 3D points, expressed in mm, are $(34\pm104, -34\pm17, 898\pm168)$, whereas we obtain $(21\pm15, -17\pm6, 774\pm76)$ with the tracking ON. Since the positions of the observers are uniformly distributed in the work space, the perceived positions of the target are uniformly distributed around the actual target position (see Fig. 2), thus yielding mean values comparable between the two systems. The misperception is represented by the spread of the perceived positions of the target, that it can be quantified by the standard deviation values.

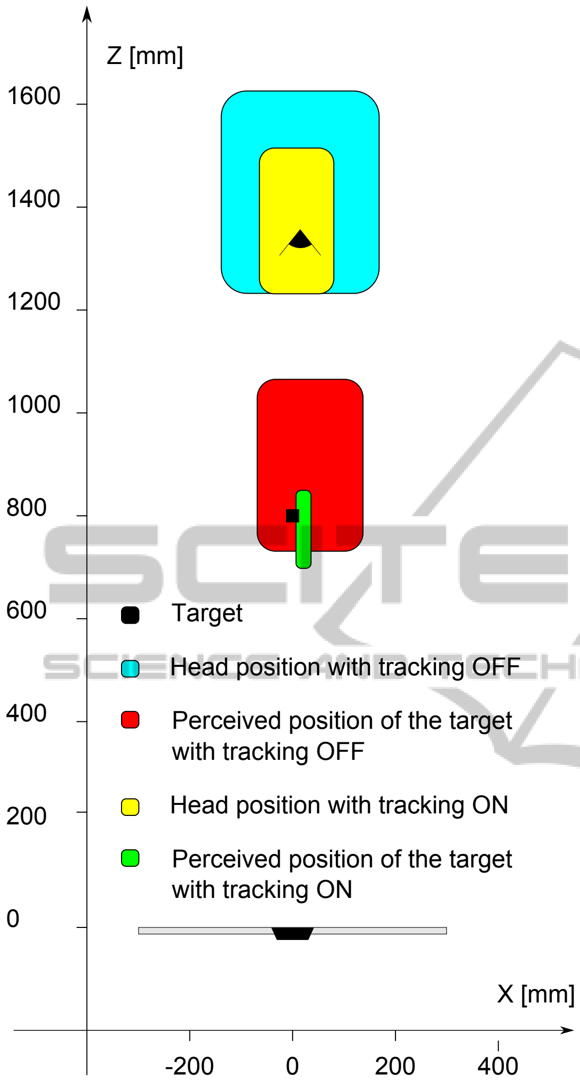


Figure 6: Graphic representation of the results of the first experiment. The boxes are centered in the mean values of the head positions and of the perceived positions of the target. The size of the boxes is represented by the standard deviation values. The smaller size of the green box represents a veridical perception (i.e. without misperception) of the position of the target.

4.2 Second Experiment: Shape Perception

Figure 7 shows the perceived start and end points of the bar traced in the second experiment.

The considerations on the positions of the head done for the previous experiment are still valid. When our system is enabled, the perceived positions of the bar are less scattered than in the conventional system. This is confirmed by the mean error and the standard deviation values of the perceived mid point of the bar, shown in Table 2.

Table 2: The mean error and the standard deviation values (expressed in mm) of the perceived mid point of the horizontal bar for the second experiment. The actual position of the mid point of the target bar is $(0,0,800)$.

	X	Y	Z
tracking OFF	47±47	26±29	149±88
tracking ON	9±6	13±8	76±73

Moreover, when the tracking is OFF, the observer misperceives the orientation of the horizontal bar, as we have previously discussed (see Fig. 3). Table 3 confirms that with the proposed system the mean error and the standard deviation of the perceived orientation of the bar are reduced. The same applies for the perceived length of the bar.

Table 3: The mean error and the standard deviation values of the perceived length and orientation (angle with respect to the horizontal bar) for the second experiment. The actual length of the target bar is 100 mm, and the orientation is 0 deg.

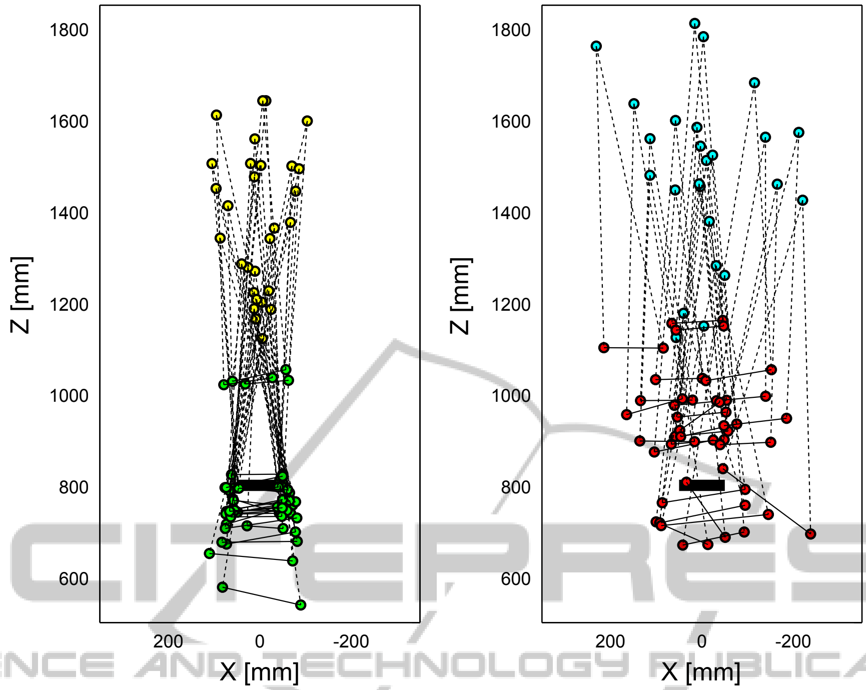
	length (*mm*)	angle (deg)
tracking OFF	36±38	11±13
tracking ON	26±22	7±5

5 CONCLUSIONS AND FUTURE WORK

A novel stereoscopic augmented reality system has been developed and presented in this paper. Such system allows a coherent perception of both virtual and real objects to an user acting in a virtual environment, by minimizing the misperception of the depth and of the 3D layout of the scene. This is achieved through a continuous tracking of the position of the observer and a consequent re-computing of the left and right image pair displayed on the screen.

In the conventional systems, when the user freely moves in front of the screen, distortions of the shape and of the distance of virtual objects occur. This issue is relevant when an accurate interaction of a real observer in a virtual world is required, especially in scientific visualization, rehabilitation systems, or in psychophysical experiments.

The proposed system relies on off-the-shelf technologies (i.e., Microsoft XBox Kinect for the tracking, and a 3D monitor with shutter glasses for the rendering) and it allows a natural interaction between the



(a) (b)

Figure 7: Perceived positions of the target horizontal bar, and the related head positions (denoted by the yellow and cyan circles for tracking ON and tracking OFF, respectively) for the tracing task. The perceived positions of the end-points of the target bar with our tracking system enabled (green circles) are closer to the actual values, than the ones obtained by using a conventional system (red circles).

user and the virtual environment, without adding significant delay in the rendering process.

The performances of the developed augmented reality system has been assessed by a quantitative analysis in reaching and tracing tasks. The results have been compared with the ones obtained by using a conventional system that does not track the position of the head. The results confirmed a better perception of the depth and of the 3D scene layout with the proposed system.

As a future work, we plan to improve the techniques used to render the stereoscopic environment and to track the user in the scene. Moreover, in order to further validated the proposed system, an extensive experimental phase is foreseen, with a larger number of participants and with different tasks.

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