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ASTOR: An Autostereoscopic Optical See-through Augmented Reality System

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ABSTRACT

We present a novel autostereoscopic optical see-through system for Augmented Reality (AR). It uses a transparent holographic optical element (HOE) to separate the views produced by two, or more, digital projectors. It is a minimally intrusive AR system that does not require the user to wear special glasses or any other equipment, since the user will see different images depending on the point of view. The HOE itself is a thin glass plate or plastic film that can easily be incorporated into other surfaces, such as a window. The technology offers great flexibility, allowing the projectors to be placed where they are the least intrusive. ASTOR's capability of sporadic AR visualization is currently ideal for smaller physical workspaces, such as our prototype setup in an industrial environment.

KEYWORDS: augmented reality, optical see-through, autostereoscopy, holographic optical element, system, projection-based

1 INTRODUCTION

The combination of real and virtual objects in Augmented Reality (AR) requires see-through displays, which can be either video or optical see-through. Video see-through head-mounted displays (HMDs) are significantly more popular than optical see-through HMDs primarily because of availability and calibration issues. However, optical see-through displays are the preferred choice in many applications in which a "direct" view of the world is desirable. Navab, for instance, discusses the need for optical see-through displays in industrial applications due to safety and security reasons [8].

The intrusiveness of the current display technology is a problem in current AR systems. While there have been significant advances in this research area, resulting in increasingly smaller head-worn-displays, such as the displays developed by Minolta [7] and MicroOptical [14], we believe that the area of projection-based AR is fairly unexplored and has great potential in terms of achieving AR with minimal intrusion.

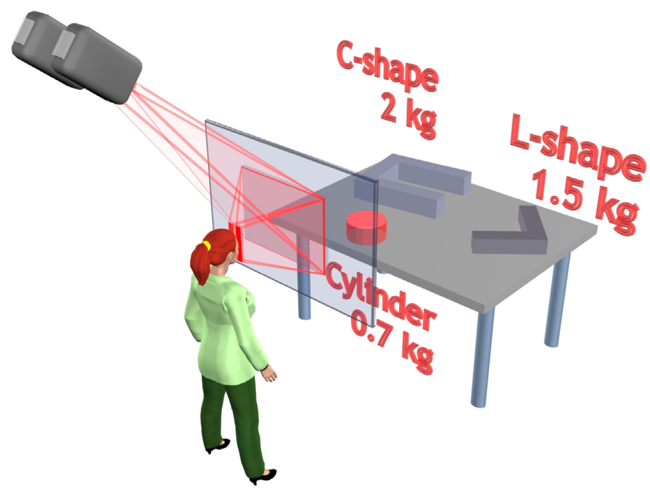

Figure 1. The principle of the display used for our autosteroscopic optical see-through augmented reality system. A smaller transparent holographic optical element (30×40 cm) in the center of the larger window separates the two projected views, so that each eye is presented with a different perspective, thus creating a stereoscopic effect. The annotations and the cylinder represent virtual objects.

This paper presents a novel projection-based AR system with an optical see-through display where a *holographic optical element* (HOE) is used for autostereoscopy. The details on the HOE are provided in a previous paper [6]. This is a "walk-up-and-use" 3D AR system where the user does not have to wear any equipment, since different images will be seen depending on the user's position.

In the remainder of this paper we present related work in Section 2, followed by a description of the technology in Section 3. We discuss our prototype AR system, set up in an industrial environment in Section 4. Finally, we provide conclusions and future directions in Section 5 and 6.

2 RELATED WORK

The AR community is continuously striving for ubiquitous, minimally intrusive AR systems. While most AR systems employ video see-through HMDs, it is also possible to run AR applications on handheld computers [12, 16]. A handheld computer is far less intrusive than an HMD but inherits many of the disadvantages of video see-through displays. AR can also be achieved through direct projection of graphics onto real-world objects [11], but this does not allow the introduction of arbitrarily positioned virtual objects in 3D space, such as annotations. Bimber et al. realized the potential of projection-based AR systems and implemented a back-projection system using a semi-transparent mirror [3]. In contrast to our approach, their use of a semi-transparent mirror limits the possible projector configurations and requires the user to wear shutter glasses. Another setup combines a static hologram with a dynamic stereographic display where either a lenticular sheet display or active shutter glasses are used [2]. The display solution we use may also play the role of the dynamic display in such a setup and would in contrast have the potential to offer an autostereoscopic system without the need for tracking. As such it could also be used in multi-user applications.

Wuest and Lakes [17] used an HOE in a stereographic see-through display and suggested its application in head-up displays for aircraft and automobiles, or as a visual aid to machine assembly or surgery. Ando et.al. [1] show a very similar display and demonstrated it in a HMD for AR. The HOE used is, however, quite different from the one used by us since one hologram recording is required for each perspective view, which may affect the image quality when more than two views are desired.

3 THE AUTOSTEREOSCOPIC AR SYSTEM

Autostereoscopic displays, in contrast to conventional AR displays, do not require the viewer to wear optical aids. One class of autostereoscopic displays is *multiview* displays, which apply some optical system to send a number of 2D views of a scene to separated portions of the 3D space. The number of views for a 3D display has, of course, to be at least two; one for each eye. More views provide the possibility to "look around", i.e., to move and see the scene from a different angle without the use of a tracking system.

The *Interaction Table* [6] is a multiview system that uses an HOE as the component separating the views and can be used in a see-through configuration. The views are displayed in real-time using digital projectors in a method similar to the one described by Newswanger [9]. Previous work has used Newswanger's technique [13, 15, 18] with the HOE illuminated in transmission, while our version works in reflection.

The HOE in our system forms a holographic image of a light-diffusing screen. When the HOE is illuminated, the light will reflect as to create a real image of the diffusing screen floating in front of the HOE plate (See Figure 1). The diffusing screen can be made extended in the vertical direction and narrow in the horizontal direction, such that its image will form a vertical slit. The HOE will produce one slit image for each light source (i.e., projector) that illuminates it. The light from the left projector in Figure 1 will thus pass through the right slit. The image produced by the projector is focused on the HOE and will only be visible when viewed through the slit. In the same way, the image produced by the right projector can only be seen through the left slit. The slits can be lined up side by side through adjustment of the relative projector positions. Using the same HOE, more projectors can be added to increase the number of perspective views and enlarge the viewing zone. The same HOE used in this work is used with four projectors in the current Interaction Table prototype, which allows the user to move between three stereoscopic views.

The HOE is produced in an ultra-fine grain silver-halide emulsion, taking advantage of the high sensitivity and large formats available for this material. The size of the first prototype HOE is 30×40 cm. The contrast was measured to 94:1 and found to be largely dependent on the contrast of the projectors [5]. The ratio of light level outside the viewing slit to that in the slit can be used as a cross-talk measure. It was found to be 0.7 % and is dependent on hologram quality [5]. The use of a grainless holographic material, such as dichromated gelatin or a photopolymer, would decrease the scattering and could thus reduce the cross-talk.

The projectors are mounted on geared stands and are calibrated by the manual alignment of a projected line-art graphics pattern. The HOE needs no alignment since a lateral displacement will have little effect on the 3D image.

This display is suitable for AR applications since it provides good see-through capabilities, more than sufficient brightness, and does not physically interfere with the real scene seen through it.

Hardware

Consumer-grade projectors (HP iPAQ 3800, 1024×768 pixels) provide reasonable keystone correction control and their dimensions allow them to be mounted close to each other while maintaining adequate cooling conditions. Each projector is driven by a separate computer (2.5 GHz CPU, 256 MB RAM, NVIDIA GeForce4 MX 440-SE). The opti-

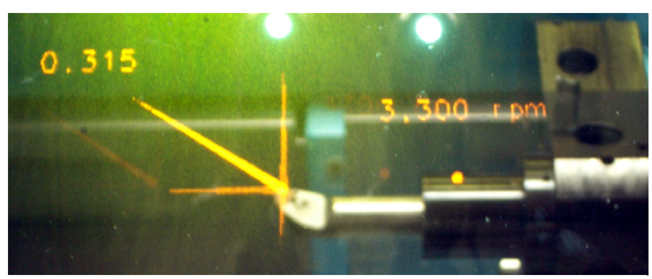

Figure 2. A view of the lathe, as seen through our optical see-through display. Here, additional annotations and visualization supplement the view. Our autostereoscopic display makes it possible to experience real and virtual objects in 3D without

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cal see-through requires only simple graphics to be rendered, which allows our application to run at interactive framerates of at least 30 fps.

Software

We extended the architecture by Gustafsson and Lindfors [4], which, most importantly, provides calibration and perspective management, so that the correct view of the scene is rendered to each projector. Java3D is used for rendering and Java Remote Method Invocation for communication in a client/server architecture over TCP/IP.

Unit [10] is a modular dataflow framework that we use for interactive control. Its support for various input devices allows direct and convenient interaction through physical buttons, sliders and knobs, which is especially useful in our 3D application where a mouse-based user interface with widgets would be impractical.

4 PROTOTYPE SETUP

We have tested our system in a proof-of-concept setup on an industrial lathe (SMT Swedturn 300). This machine provides a rich set of measurement data from the lathing operations it performs. The operator overlooks the operation through a large safety window while a computer to the left of the machine provides measurement data and means for manual control. Values that could be of interest to the operator are for example: cutting forces, revolutions per minute (rpm), tool operating times, temperatures, positioning, clamping pressures and tailstock pressures.

During informal interviews with production engineers that are using the machine for manufacturing research, it became evident that their current setup forced them to divide their attention between the machine and the control computer. Our proposal for an AR approach, with measurement data visualized next to the relevant parts in the machine, received enthusiastic responses from the production engineers. In particular, they liked the idea of simultaneously being able to monitor the values and the movement in the machine.

An operator typically inspects values and program execution on multiple machines in-between other tasks. This sporadic need for AR visualization makes it unreasonable to require the operators to wear head-mounted-displays or shutter glasses.

Our current prototype setup uses two projectors and an HOE mounted on a stand in front of the safety window. The operator can look through the HOE and see various measurements seemingly next to the relevant parts in 3D (See Figures 2 and 3). The HOE could even be integrated into the safety window, since it can be manufactured as a transparent plate or film. This still allows the safety window to be arbitrarily large regardless of the size of the region providing the AR visualization.

5 CONCLUSIONS

In this paper we described a novel autostereoscopic optical see-through AR system. An HOE makes it possible to simultaneously display different images on a single transparent surface where each image is visible only within a small viewing angle, which allows each eye to be presented with a different perspective.

The number of views are not only limited to the number of projectors used, but they are also constrained to lie along the horizontal axis, meaning that our display suffers from the image distortions inherent in all horizontal-parallax-only displays [4]. In addition to the lateral distortion, the apparent depth position of an image point will change when the viewer moves closer to or farther away from the HOE. The image points will hence not have an absolute mapping to the real world since their position will vary somewhat as the viewer moves around. For the type of applications we have tested, where the viewer remains reasonably stationary, we find the positioning accuracy to be more than satisfactory.

The current prototype can only show monochrome red images but the development of a color version should be straightforward after a color-capable HOE has been manufactured, since we expect that the same off-the-shelf projectors can be used without additional hardware.

The HOE requires the user to focus on the display and the objects behind it at the same time, which is a disadvantage compared to half-silvered mirrors. This makes our display more suitable for small work spaces. We did not experience any noticeable problems in our experiments, where the user was 40-80 cm in front of the display, and the objects were 20-80 cm behind it.

Many display characteristics, such as projection angles and

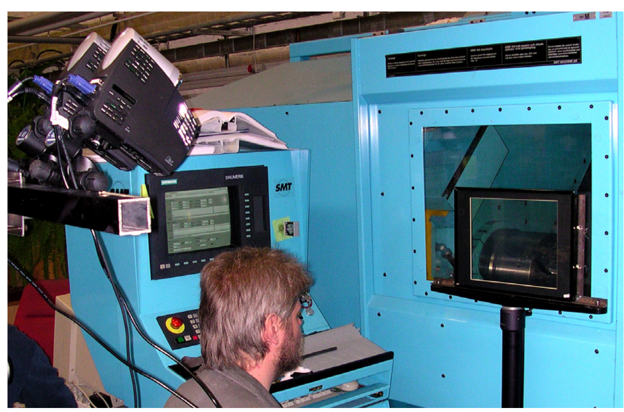

Figure 3. The prototype setup. Two projectors provide different views of the scene, which the holographic optical element (HOE) directs to each of the operator's eyes. This could allow the operator to see measurements next to relevant parts in the machine instead of having to read them off the control computer to the left. The HOE is mounted in a frame in front of the machine, but could, since it is transparent, be integrated into the safety glass in the future.

support for front- and back-projection, can be chosen when the HOE is manufactured. This provides the system with flexible configuration possibilities and allows the projectors to be placed at the most convenient location. As illustrated in Figure 1, the system does not require that the angle of incidence is equal to the angle of reflection.

6 FUTURE WORK

We are currently investigating methods to increase the number of views in a cost-effective manner. This can be done through the addition of off-the-shelf projectors or by other optical means. The research on the manufacturing of the HOE is also work-in-progress where we aim to develop a larger, full-color HOE and formally evaluate its performance. It is also possible to manufacture an HOE that could be illuminated in transmission, i.e., the projectors can be placed behind the HOE.

Our ongoing work involves addressing the limitations of the horizontal-parallax-only display. In our effort to avoid having the user to wear any equipment we are currently investigating vision-based techniques to acquire the user's position relative to the display. Eye tracking and distance sensing would allow the projection to be corrected as the user moves vertically or varies the distance to the display.

Additionally, we are working on more advanced AR applications for our industrial machine. Examples include displaying real-time force data as 3D vectors and to build an interactive simulator for the NC programming language (Numerical Control is a language for controlling industrial machine operations). This would allow the operators to safely simulate their programs with virtual machine parts in the physical work space, without the risk of damaging the equipment.

Autostereoscopic optical see-through system would be useful in numerous situations where sporadic access to AR data is desirable and could become an interesting alternative to traditional HMD-based AR.

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REFERENCES

1. Ando, T., Yamasaki, K., Okamoto, M and Shimizu, E. Head-mounted display using a holographic optical element. *Proc. SPIE Vol. #3293, Practical Holography XII*, 1998, pp. 183-189.
2. Bimber, O. Combining Optical Holograms with Interactive Computer Graphics. *IEEE Computer*, January 2004, pp. 85-91.
3. Bimber, O., Encarnação, L.M., and Schmalstieg, D. Augmented Reality with Back-Projection Systems using Transflective Surfaces. *Proc. EUROGRAPHICS 2000*, vol. 19, no. 3, 2000, pp. 161-168.
4. Glaser, I., Anamorphic imagery in holographic stereograms, Optics Comm., 7, 1973, pp. 323-326.
5. Gustafsson. J. Lindfors. C. Mattsson, L. Kjellberg, T. Large Format 3D Interaction Table. *Proc. SPIE, Vol. #5664, Stereoscopic Displays and Virtual Reality Systems XII,* 2005, pp. 589-595.
6. Gustafsson, J. Lindfors, C. Development of a 3D Interaction Table. *Proc. SPIE, Vol. #5291 Stereoscopic Displays and Virtual Reality Systems XI,* 2004, pp. 509-516.
7. Kasai, I., Tanijiri, Y., Endo, T., and Ueda, H., A forgettable near eye display, *Proc. ISWC'00*, 2000, pp. 115-118.
8. Navab, N. Industrial Augmented Reality (IAR): Challenges in Design and Commercialization of Killer Apps. *Proc. ISMAR 2003,* 2003, pp. 2-6.
9. Newswanger, C., Real time autostereoscopic display using holographic diffusers, *United States patent no. 4,799,739*, 1989.
10. Olwal, A. and Feiner, S. Unit — Modular Development of Distributed Interaction Techniques for Highly Interactive User Interfaces. *Proc. GRAPHITE 2004*, 2004, pp. 131-138.
11. Raskar, R., van Baar, J., Beardsley, P., Willwacher, T., Rao, S., Forlines, C. iLamps: Geometrically Aware and Self-Configuring Projectors. *ACM Transactions on Graphics (TOG)*, ISSN: 0730-0301, Vol. 22, Issue 3, 2003, pp. 809-818.
12. Rekimoto, J. NaviCam: A Magnifying Glass Approach to Augmented Reality Systems, *Presence: Teleoperators and Virtual Environments*, 6, 4, 1997, pp. 399-412.
13. Sakamoto, K., Okamoto, M., Ueda, H., Takahashi, H. and Shimizu, E. Real-time 3D color display using a holographic optical element. *Proc. SPIE Vol. #2652, Practical Holography X*, 1996, pp. 124-131.
14. Spitzer, M.B, Rensing, N. M., McClelland, R., Aquilino, P. Eyeglass-Based Systems For Wearable Computing. *Proc. ISWC'97*, 1997, pp. 48–51.
15. Trayner, D. and Orr, E. Autostereoscopic Display using Holographic Optical Elements. *Proc. SPIE Vol. #2653*, 1996, pp. 65-74.
16. Wagner, D., Schmalstieg, D. First Steps Towards Handheld Augmented Reality. *Proc. ISWC*, 2003, pp. 127-137.
17. Wuest, D. and Lakes, R. S. Holographic optical element for projection of stereo images. *Applied Optics*, 31, 1992, pp. 1008-1009.
18. Yamasaki, K., Okamoto, M., Ando, T, Kitagawa, T. and Shimizu, E. Color multiplex imaging 3D display system using holographic optical element. *Proc. SPIE Vol. #3956, Practical Holography XIV,* 2000. pp. 205-210.