Wearable Augmented Reality Optical See Through Displays Based on Integral Imaging

Emanuele Maria Calabrò[1], Fabrizio Cutolo[1(✉)], Marina Carbone[1], and Vincenzo Ferrari[1,2]

[1] EndoCAS, University of Pisa, Via Paradisa, 2, 56124 Pisa, Italy
{emanuele.calabro,fabrizio.cutolo,marina.carbone, vincenzo.ferrari}@endocas.unipi.it
[2] Department of Information Engineering, University of Pisa, Via Caruso 15, 56122 Pisa, Italy

Abstract. In the context of Augmented Reality (AR), industrial pioneers and early adopters have considered the wearable optical see-through (OST) displays as proper and effective tools in applications spanning from manufacturing and maintenance up to the entertainment field and the medical area, because they provide the user with an egocentric viewpoint maintaining the quality of the visual perception of the real world.

The common OST displays paradigm entails intrinsic perceptual conflicts owing to mismatched accommodation between real 3D world and virtual 2D images projected over semitransparent surfaces. Such paradigm is suitable for augmenting the reality with simple virtual elements (models, icons or text), but various shortcomings remain in case of complex virtual contents. The major shortcoming is due to the tedious and error prone calibration methods required to obtain geometrical consistency, pivotal in many of the aforementioned fields of application. These shortcomings are due to the intrinsic incompatibility between the nature of the 4D light field, related to the real world, and the nature of the virtual content, rendered as a 2D image.

In this paper we describe a radical rethinking of the wearable OST displays paradigm by generating, through integral imaging technique, the virtual content as a light field, in order to overcome the typical limitations of the traditional approach. This paper describes the hardware components and an innovative rendering strategy in more details in respect to a previous work. Furthermore we report early results with the implementation of the integral imaging display using a lens array instead of a pinhole array.

Keywords: Augmented Reality · Integral imaging · Optical see through · Light fields

1 Introduction

Augmented Reality (AR) based on visual enhancements represents an emerging technology whose growing penetration in the consumer market is nowadays possible both owing to all the frontier research carried out in the past and to the increased availability

P. Perego et al. (Eds.): MobiHealth 2016, LNICST 192, pp. 345–356, 2017.
DOI: 10.1007/978-3-319-58877-3_44

of hand-held devices with breakthrough hardware capabilities, like smartphones and tablets.

Wearable AR devices, commonly referred to as head-mounted displays (HMDs), provide the user with a natural egocentric viewpoint and allow him/her to work hands free. HMDs can be either binocular or monocular, depending on whether they provide stereovision or not.

As demonstrated by the huge number of publications in the medical area, AR is a promising technology in the field of image-guided surgery since it may constitute a functional and ergonomic integration between navigational surgery and virtual planning [1–13]. In this field of application, wearable devices offer the most ergonomic solution for those medical tasks manually performed under user's direct vision (open surgery, introduction of biopsy needle, palpation, etc.).

As a general rule, the quality of an AR experience depends on how well virtual content is integrated into the real world spatially, photometrically and temporally [14]. The fundamental condition for an AR surgical navigation system is to guarantee the geometric coherence in the augmented scene (i.e. registration) [15]. The HMD AR capability can be accomplished using either an optical or a video see-through method.

With a video see-through HMD, the real-world view is captured with external cameras rigidly fixed in front of the HMD, and the virtual content generated by a virtual camera is electronically combined with the video representation of the real world. An accurate registration between the virtual and the real scene is obtained through different methods [7, 10].

With optical-see-through HMDs, the real world is not mediated by external cameras, but it is generally observed through semi-transparent surface of projections placed in front of the user's eyes where the virtual information is projected. The optical see-through paradigm of HMDs (Google Glass, Microsoft HoloLens, Epson Moverio, Lumus optical) is still the same described by Benton [16]. A straightforward implementation of the optical see-through paradigm comprises the employment of a beam combiner to merge real view and virtual content. The user's own view is herein augmented by rendering the virtual content on a 2D micro display and by sending it to the beam combiner. Lenses can be placed between the beam combiner and the display to focus the virtual 2D image so that it appears at a comfortable viewing distance on a Semitransparent Surface of Projection (SSP) (Fig. 1) [17, 18]. As an alternative, the use of high-precision waveguide technologies allow the removal of the bulky optical engine placed in front of the eyes [19].

The industrial pioneers, as well as the early adopters of wearable AR technology properly considered the camera-mediated view as drastically affecting the quality of the visual perception and experience of the real world [20]. By contrast, optical see-through systems provide the user with a natural view of the real world with full resolution.

Although the optical see-through HMDs were once at the leading edge of the AR research [20], the degree of adoption and diffusion in many applications has slowed down over the years due to technological and in particular perceptual limitations.

In optical see-through HMDs, the user is indeed forced to accommodate his/her eye for focusing all the virtual objects on the SSP placed at a fixed distance. On the other hand, the focus distance of each physical object in the 3D world depends on its relative

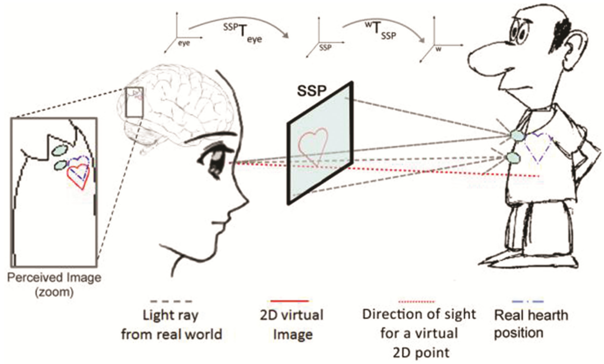

Fig. 1. Schematic of a standard optical see-through HMD display. A semi-transparent surface of projection (SSP) displays the virtual 2D image (heart). The user perceives light rays from the world combined with the 2D virtual image. The perceived image of the 2D virtual image can be misaligned in respect to the real view of the world (see the heart peak) due to user dependent calibrations issues.

distance from the observer and may dynamically vary over time. This means that, even if an accurate geometric registration of virtual objects to the real scene is attained on the 2D SSP plane, the user may not be able to view both elements in focus at the same time.

The second major shortcoming of the standard optical see-through HMDs is related with the geometric registration required to obtain a geometrically consistent augmentation of the reality, which is an essential condition in medical and surgical application. The spatial alignment of the virtual content with the real 3D world needs for: (a) the tracking of the HMD SSP relative to the real world (in Fig. 1); (b) a user-specific calibration for estimating the relative pose between HMD SSP and user's eye, namely the extrinsic calibration (in Fig. 1); (c) the definition of a projective model of the virtual viewpoint which is consistent to the human eye projective model, namely the intrinsic calibration.

State-of-the-art methods for tracking the HMDs (a), yield accurate results in terms of HMD pose estimation, whether they exploit external trackers or not. Differently, the calibration step needed to estimate user's eye pose in relation to the SSP (b) often entails a tedious and error prone method [21–24]. Further, this process should be repeated each time the HMD moves causing a change in the relative position between SSP and user's eye, and it should be autonomous and real-time. Current and more advanced calibration methods [25], albeit they work in real-time, do not incorporate the user-specific and real-time estimation of the eye projective model (c), which can change over time with the focus distance due to the accommodation process.

In real world, under the simplifying assumptions of geometrical optics, each point emits, transmits or reflects light rays in all directions. The light rays flowing in every direction along every point in space can be described as a light field (LF). Light rays directions in a 3D environment can be parameterized with a 5D (plenoptic) function [26], whereas light rays directions crossing a surface are parameterized with a 4D function (e.g. 2 dimensions for defining the position on the surface and 2 dimensions for defining the zenith and the azimuth angles).

A user wearing a traditional optical see-through display perceives the chromatic information of some of the light rays coming from the real world and crossing the semi-transparent surface SSP of the HMD. If we consider the real light field crossing the SSP, the rays perceived by the user through the SSP are a function of the pose of the real world in relation to the SSP, the pose of the SSP in relation to the eye, and of the actual projective model of the eye. The user perceives the virtual information as coherently aligned with the real world if the following condition is met for all the pixels on the SSP. A light ray along the direction passing through a point in the 3D real world and the eye's center, intersects the SSP in a display pixel, and the virtual information rendered in that pixel must match with said point in the 3D real world (Fig. 1). In this regard, the goal of the calibration routine is hence to determine where to render the 2D virtual image so to match the 4D light field perceived.

The major shortcomings of the standard optical see-through HMDs are due to the incompatibility between the nature of the 4D light field, related to the real world, and the nature of the virtual content, rendered as a 2D image on the SSP.

A recent feasibility study demonstrated that an optical see-through HMD based on light field displays potentially solves the perceptual conflict due to mismatched accommodations intrinsic to standard optical see-through HMDs [27]. The efficacy of the proposed method was demonstrated in conjunction with a proof-of-concept monocular prototype, which combined emerging freeform optical technology and microscopic integral imaging.

In a recent feasibility study by our group [28], unlike the work by Hua et al. [27], our focus was not only aimed at solving the perceptual conflict due to mismatched accommodation, but also at dealing with the geometric registration problem affecting the standard implementations of the wearable optical see-through paradigm. Our hardware implementation is a scaled version of the one described in [29], including an innovative rendering strategy that will allow the implementation of small, thus wearable, devices.

This new paper describes the hardware components and the rendering strategy in more details in respect to the previous work. Furthermore we report early results with the implementation of the integral imaging display using a lens array instead of a pinhole array.

2 Methods

2.1 Integral Imaging

Integral Imaging (or integral photography) is a technique dating back to 1908 allowing the acquisition and reproduction of a light field [30, 31]. There is a growing interest in light field acquisition, processing and display nowadays, based on the availability of plenoptic cameras and the growing up of the know-how on the matter.

An integral imaging (II) display is able to optically reproduce a full-parallax view of the scene. An integral imaging based display is composed by the coupling of a 2D

Display Panel (DP) (for example an LCD based display) with a 2D Parallax Array (PA) consisting in a lens array or a pinhole array. The PA is positioned ahead the DP at a fixed distance. The light rays emitted by DP pixels are forced to pass through the Center Of Projections (COP) (Fig. 2). The DP is populated by a 2D array of sub-images that are defined elemental images (EIs). Each EI is coupled with a corresponding COP. Each pixel of each EI describes the chromatic information for the light ray passing through the coupled COP and the pixel itself. Therefore, each couple of EI/COP can be described as a projecting element of light rays passing through the COP. The integration of all the EI/COP couples simulates the light field LF passing through the whole array of COPs.

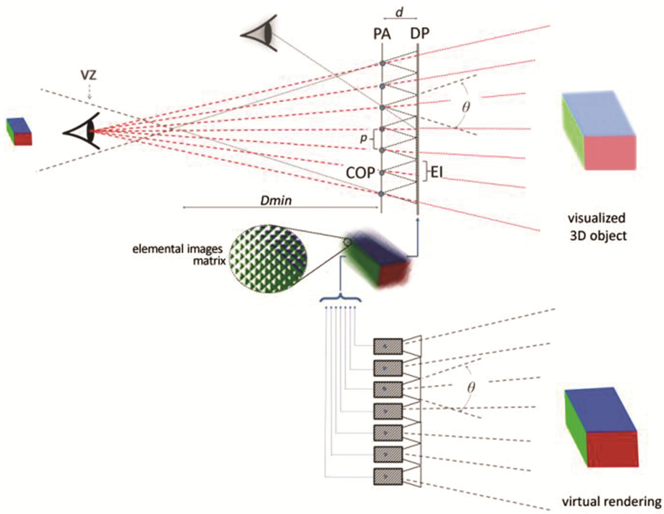

Fig. 2. (Up) Integral Imaging display and (Down) Elemental Images virtual rendering. PA is the parallax array that forces the light rays to pass through the center of projections COPs. Light rays are emitted by each pixel of each elemental image EI on the display panel DP. An array of virtual cameras are placed in a virtual scene to look the EIs virtual content. Each virtual camera acquires the chromatic information coming from different directions and passing through its center of projection. The result is that the user that looks at the integral imaging display will perceive the simulated light field corresponding to the virtual scene. Note that when the point of view is beyond the viewing zone VZ, the user view is double or distorted as some perceived light rays contain correspond to adjacent EIs (wrong).

The array of EIs can be generated by a direct grabbing from the world employing dedicated cameras (LF or plenoptic cameras) or deploying virtual rendering [30]. In the latter case, EIs can be generated simulating a bidimensional array of virtual cameras observing a virtual 3D scene. Each virtual camera acquires the chromatic information of virtual scene light rays crossing the camera center of projection. The virtual cameras array acquire the information for each EI/COP couple of the LF display. If the virtual cameras position, orientation and angle of view exactly replicates the COPs position, display orientation and aperture angle θ of the LF display, the system allow for the visualization of the virtual content in a natural fashion as the elemental images EIs acquired by the virtual cameras are naturally coherent with the LF display.

2.2 Hardware Description

The selected hardware components are: an HAIER w970 6′ Smartphone used as display panel DP (1280 × 720 resolution and 0.1038 mm pixel size); a 3 mm Plexiglas panel covered with a semi-transparent film as beam combiner and a parallax array PA. Two different kind of parallax array were employed. The first is a pinhole array realized printing over a transparent acrylic sheet a black mask with transparent white holes of 0.1 mm diameter and pitch 0.9339 mm. The second one is a lenses array by Fresnel Technologies microlens sheet (item #630), with lens focal length 3.3 mm and lens spacing 1.0 mm.

All the components where embodied in a plastic 3D printed case implementing a display as described in [29], where a semi-transparent mirror, acting as beam combiner (BC), is posed at 45° in front of the II display, see Fig. 3. The BC allows fusion of the virtual light field generated by the II display with the real world light field. The half mirror allows the user's eye to perceive both the real light field and the virtual light field emitted by the II display since the virtual light field is 90° rotated and projected directly in front of the user.

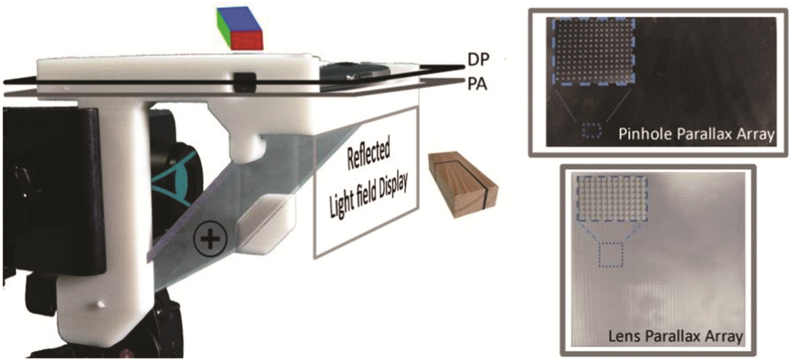

Fig. 3. The experimental integral imaging display: a smartphone display is used as DP and a lenslet array or a pinhole array as PB, (placed below the DP). The beam combiner BC "+" consisting in a half mirror rotates the light field in front of the user's eye. A camera is placed at the user's eye position to acquire the AR results.

If the virtual LF generated by the II display matches with the real LF, the real world and the virtual one are both perceived by the user as consistent from any viewing angle, hence regardless of the eye's projection model and independently from its pose relative to the HMD, all without performing any calibration. We confirmed this hypothesis with an experiment. On a wooden parallelepiped the borders of a virtual colored ones was marked. A mechanical calibration allowed placing the wooden parallelepiped in the correct position and orientation. A real camera was placed in correspondence of the user eye to acquire the scene. We acquired three pictures sliding horizontally the real camera approximately 2 cm left and right in respect to the central position (Fig. 4). The coherence between virtual and real content is clearly reached and maintained despite the point of view movements confirming that no calibration is needed.

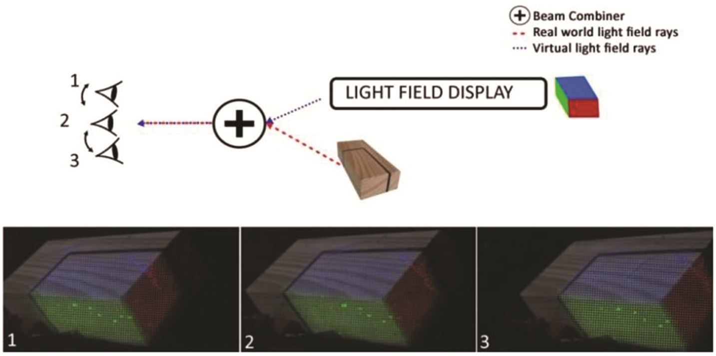

Fig. 4. Both a real object and the display were hold steady to acquire the images. A real camera placed in correspondence of the user's eye was sided in three horizontal position (with 2 cm acquisition steps) to demonstrate that without any eye-display calibration the coherence is naturally achieved.

Since in this experiment we employed as parallax array a pinhole array, the images has to be acquired in reduced light conditions in order to perceive the virtual reality. Using the lens array allowed us to work with normal lighting conditions (Fig. 5).

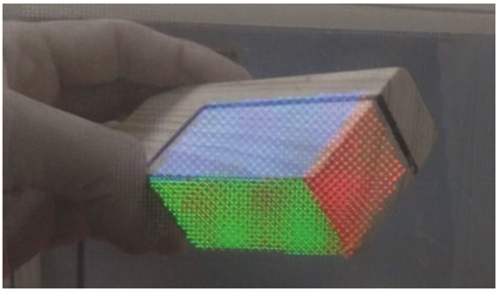

Fig. 5. The AR scene using the lens array: the improved brightness is clearly visible and the scene is comfortably visible in normal lighting conditions.

2.3 EIs Rendering and Limits of the Traditional EIs Arrangement

An off-line rendering of the elemental images EIs was achieved through a Python routine integrated in Blender 2.75a (www.blender.org), and generating a perspective image of the virtual 3D scenario for each EI. The perspective images were obtained by using an array of virtual cameras whose number, spacing, field of view, orientation, and frustum shape, were all opportunely fixed to match the specific LF display hardware parameters (Fig. 2). A 73 × 33 × 28 mm virtual parallelepiped with colored faces is rendered with an orientation of 45° along the X and Y axes (Fig. 2).

Theoretically, high visual quality could be achieved increasing the density of the COPs and/or the number of PPI (pixels per inch) for the EIs. Nonetheless, technological limits are present. As a general rule, referring to Fig. 2, once set the COPs pitch and the EIs PPI, the visual quality of the rendered image strictly depends on the width of the solid angle defined by the COP/EI pair (θ) [32]. In more details, referring to the standard EIs arrangement depicted in Fig. 2, with each EI centered on the coupled COP, given a certain PPI, the angular resolution (~PPI/θ) increases by decreasing the angle θ that means increasing the distance *d* between the PA and the DP.

Nevertheless, *d* affects also that range within which the viewer can see a full resolution image, defined as Viewing Zone (VZ) [30]. If the point of view is moved beyond the VZ, some of the perceived rays contain chromatic information which refer to wrong elemental images pixels (Fig. 2), thus the resulting perceived image appears distorted or doubled. VZ lower boundary (Dmin) is directly defined by L (longest display panel), by p, and by d according to the following equation:

$$Dmin = \frac{Ld}{p} \tag{1}$$

In our setup, if we set d = 7 mm a Dmin of about 100 cm is imposed, indeed: Fig. 6a, showing a good result, was grabbed by a real camera 100 cm away from the LF display, which is clearly a uncomfortable viewing distance in the direction of a wearable implementation. On the other hand, the same image acquired with the same hardware setting from about 15 cm produces a distorted image as the viewpoint is outside the VZ lower boundary as visible in Fig. 6b.

If we reduce d to see the display at distance 15 cm without distortions, we obviously reduce the visual quality as demonstrated in Fig. 6c.

The distance of the viewing zone is proportional to d and so a too large d determines a bulkiness display. With the traditional elemental images arrangement, the designer should have to increase d to obtain high visual quality, but there is a limit due to the fact that increasing d the minimum distance between the eye and the display Dmin also increases, with the consequent need to implement a cumbersome display.

2.4 The Innovative EIs Arrangement to Improve Visual Quality

An innovative strategy that partially allows separating the visual quality output (angular resolution as a function of d) from Dmin, has been proposed by the authors and first presented in the previous work [28].

The key idea behind the proposed new modality consists in a new arrangement of the EIs taking into account the ideal eye position in respect to the display. It is reasonable to force the eye position approximately in the center of the display at a certain distance D.

In particular, as shown in Fig. 7, each EI is centered with the direction pinpointed by the center of the eye in its ideal position and by the corresponding COP. The rendering

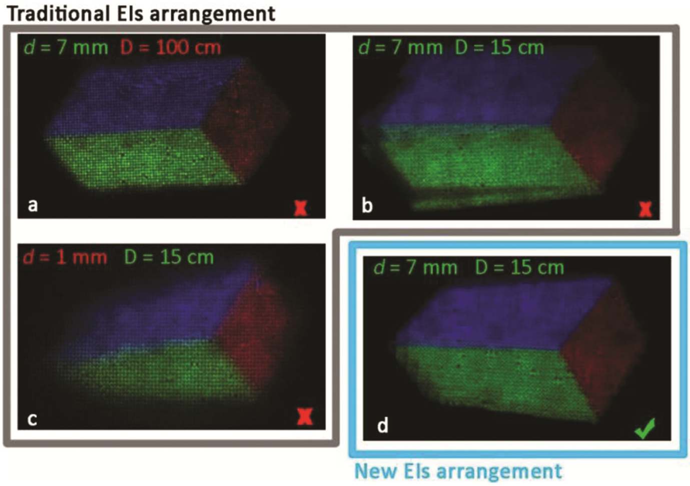

Fig. 6. Different renderings varying d and D with traditional EI arrangement (a, b, c), and an example of the results obtained with the new EI arrangement (d). A black screen was placed behind the reflected LF display so only virtual reality is visible in the picture.

of the EIs is obtained adapting the frustum of the virtual cameras to the new geometries. In this way, a higher value of d is permitted, thus allowing a higher visual quality and guarantee a VZ, around the ideal eye position, in which the eye can be placed to still rightly see the rendered images. In this case a large d reduces the VZ and vice-versa

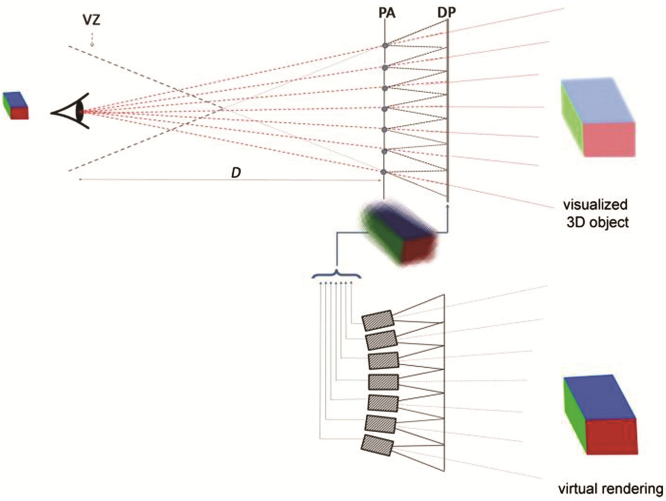

Fig. 7. Improving visual quality with the optimized EIs arrangement. In the new arrangement the EI is centered with the direction crossing the coupled COP and the eye. Virtual cameras position, angle of view and frustum shape are consequently coherently set.

(Fig. 7), so a huge d imposes a more precise positioning of the eye, but no inferior limit in the distance between the eye and the display (Dmin) are imposed.

Figure 6d shows the image rendered with the strategy described above and acquired at a viewpoint distance D = 15 cm with d = 7 mm. According to the figure, the efficacy of the proposed method ensures good image quality also at low distances between user's viewpoint and display.

3 Conclusions

The common optical see-through displays paradigm entails intrinsic incompatibility between the nature of the 4D light field, related to the reality and the nature of the virtual content, rendered as a 2D image on the display.

In this paper we describe a radical rethinking of the wearable optical see-through displays paradigm by generating, through integral imaging technique, the virtual content as a light field, in order to overcome the typical limitations of the traditional approach based on 2D images projected over semitransparent surfaces. Our hardware implementation, consisting in a semi-transparent mirror positioned at 45° in front of an Integral Imaging display, is a scaled version of the one described in [29].

The Integral Imaging displays visual quality relies on: parallax barrier pitch, display PPI, and by the distance d between display and parallax barrier. To obtain high visual quality, large d are required and, with the traditional EIs arrangement, a minimum distance between the eye and the display is forced by an inferior limit proportional to d itself (Eq. 1). For this reason, the miniaturization and the achievement of high visual quality are conflicting objectives.

The proposed rendering strategy based on a new EIs arrangement, which takes into account the ideal eye position in respect to the display, allows increasing the visual quality avoiding inferior limits for the distance between the eye and the display itself (that determine a bulky display). Note that in this EIs arrangement the knowledge of the ideal eye position is required, but the eye can be moved in the VZ maintaining the same visual quality without any distortion in the perceived image.

The presented work is a feasibility study and the implementation of a complete device based on the proposed approach still needs further research and complex technical developments. Two key issues are mandatory to go towards a wearable device: real-time rendering of the light field and real-time tracking of the real scene. In our current implementation we do not implemented tracking of the real scene (the object was mechanically calibrated) and rendering is off-line. Anyway, both issues were previously investigated and there are different possible solutions, which may be integrated with the proposed set-up [29, 33].

References

1. Badiali, G., Ferrari, V., Cutolo, F., Freschi, C., Caramella, D., Bianchi, A., Marchetti, C.: Augmented reality as an aid in maxillofacial surgery: validation of a wearable system allowing maxillary repositioning. J. Craniomaxillofac. Surg. **42**, 1970–1976 (2014)

2. Kersten-Oertel, M., Jannin, P., Collins, D.L.: The state of the art of visualization in mixed reality image guided surgery. Comput. Med. Imaging Graph. **37**, 98–112 (2013)
3. Cutolo, F., Badiali, G., Ferrari, V.: Human-P*n*P: ergonomic AR interaction paradigm for manual placement of rigid bodies. In: Linte, C.A., Yaniv, Z., Fallavollita, P. (eds.) AE-CAI 2015. LNCS, vol. 9365, pp. 50–60. Springer, Cham (2015). doi:10.1007/978-3-319-24601-7_6
4. Rankin, T.M., Slepian, M.J., Armstrong, D.G.: Augmented reality in surgery. In: Latifi, R., Rhee, P., Gruessner, W.G.R. (eds.) Technological Advances in Surgery, Trauma and Critical Care, pp. 59–71. Springer, New York (2015)
5. Ferrari, V., Cutolo, F., Calabrò, E.M., Ferrari, M.: HMD video see through AR with unfixed cameras vergence. In: International Symposium on Mixed and Augmented Reality – ISMAR (2014)
6. Cutolo, F., Parchi, P.D., Ferrari, V.: Video see through AR head-mounted display for medical procedures. In: International Symposium on Mixed and Augmented Reality – ISMAR (2014)
7. Ferrari, V., Megali, G., Troia, E., Pietrabissa, A., Mosca, F.: A 3-D mixed-reality system for stereoscopic visualization of medical dataset. IEEE Trans. Biomed. Eng. **56**, 2627–2633 (2009)
8. Meola, A., Cutolo, F., Carbone, M., Cagnazzo, F., Ferrari, M., Ferrari, V.: Augmented reality in neurosurgery: a systematic review. Neurosurg. Rev. 1–12 (2016). doi:10.1007/s10143-016-0732-9 [epub ahead of print]
9. Abe, Y., Sato, S., Kato, K., Hyakumachi, T., Yanagibashi, Y., Ito, M., Abumi, K.: A novel 3D guidance system using augmented reality for percutaneous vertebroplasty. J. Neurosurg. Spine **19**, 492–501 (2013)
10. Ferrari, V., Ferrari, M., Mosca, F.: Video see-through in the clinical practice. In: 1st International Workshop on Engineering Interactive Computing Systems for Medicine and Health Care, EICS4Med, vol. 727, pp. 19–24 (2011)
11. Ferrari, V.: Letter to the editor on "designing a wearable navigation system for image-guided cancer resection surgery". Ann. Biomed. Eng. **42**, 2600–2601 (2014)
12. Cutolo, F., Carbone, M., Parchi, P.D., Ferrari, V., Lisanti, M., Ferrari, M.: Application of a new wearable augmented reality video see-through display to aid percutaneous procedures in spine surgery. In: Paolis, L.T., Mongelli, A. (eds.) AVR 2016. LNCS, vol. 9769, pp. 43–54. Springer, Cham (2016). doi:10.1007/978-3-319-40651-0_4
13. Parrini, S., Cutolo, F., Freschi, C., Ferrari, M., Ferrari, V.: Augmented reality system for freehand guide of magnetic endovascular devices. In: Conference Proceedings of IEEE Engineering in Medicine and Biology Society 2014, pp. 490–493 (2014)
14. Sielhorst, T., Feuerstein, M., Navab, N.: Advanced medical displays: a literature review of augmented reality. J. Disp. Technol. **4**, 451–467 (2008)
15. Holloway, R.L.: Registration error analysis for augmented reality. Presence Teleop. Virt. **6**, 413–432 (1997)
16. Benton, S.A.: Selected Papers on Three-Dimensional Displays. SPIE Optical Engineering Press, Bellingham (2001)
17. Rolland, J.P., Cakmakci, O.: The past, present, and future of head-mounted display designs, pp. 368–377 (2005)
18. Holliman, N.S., Dodgson, N.A., Favalora, G.E., Pockett, L.: Three-dimensional displays: a review and applications analysis. IEEE Trans. Broadcast. **57**, 362–371 (2011)
19. Mukawa, H., Akutsu, K., Matsumura, I., Nakano, S., Yoshida, T., Kuwahara, M., Aiki, K., Ogawa, M.: Distinguished paper: a full color eyewear display using holographic planar waveguides. SID Int. Symp. Dig. Tech. Papers **39**, 89–92 (2008)

20. Rolland, J.P., Holloway, R.L., Fuchs, H.: A comparison of optical and video see-through head-mounted displays. Telemanipulator Telepresence Technol. **2351**, 293–307 (1994)
21. Tuceryan, M., Genc, Y., Navab, N.: Single-point active alignment method (SPAAM) for optical see-through HMD calibration for augmented reality. Presence Teleop. Virt. **11**, 259–276 (2002)
22. Genc, Y., Tuceryan, M., Navab, N.: Practical solutions for calibration of optical see-through devices. In: International Symposium on Mixed and Augmented Reality, Proceedings, pp. 169–175 (2002)
23. Gilson, S.J., Fitzgibbon, A.W., Glennerster, A.: Spatial calibration of an optical see-through head-mounted display. J. Neurosci. Meth. **173**, 140–146 (2008)
24. Kellner, F., Bolte, B., Bruder, G., Rautenberg, U., Steinicke, F., Lappe, M., Koch, R.: Geometric calibration of head-mounted displays and its effects on distance estimation. IEEE Trans. Vis. Comput. Graph. **18**, 589–596 (2012)
25. Plopski, A., Itoh, Y., Nitschke, C., Kiyokawa, K., Klinker, G., Takemura, H.: Corneal-imaging calibration for optical see-through head-mounted displays. IEEE Trans. Vis. Comput. Graph. **21**, 481–490 (2015)
26. Levoy, M.: Light fields and computational imaging. Computer **39**, 46–55 (2006)
27. Hua, H., Javidi, B.: A 3D integral imaging optical see-through head-mounted display. Opt. Express **22**, 13484–13491 (2014)
28. Ferrari, V., Calabrò, E.M.: Wearable light field optical see-through display to avoid user dependent calibrations: a feasibility study. In: SAI Computing Conference (2016)
29. Liao, H., Inomata, T., Sakuma, I., Dohi, T.: 3-D augmented reality for MRI-guided surgery using integral videography autostereoscopic image overlay. IEEE Trans. Biomed. Eng. **57**, 1476–1486 (2010)
30. Stern, A., Javidi, B.: Three-dimensional image sensing, visualization, and processing using integral imaging. Proc. IEEE **94**, 591–607 (2006)
31. Lippmann, G.: Epreuves reversibles donnant la sensation du relief. J. Phys. Theor. Appl. **7**, 821–825 (1908)
32. Park, S.-G., Yeom, J., Jeong, Y., Chen, N., Hong, J.-Y., Lee, B.: Recent issues on integral imaging and its applications. J. Inf. Disp. **15**, 37–46 (2014)
33. Wang, J., Suenaga, H., Liao, H., Hoshi, K., Yang, L., Kobayashi, E., Sakuma, I.: Real-time computer-generated integral imaging and 3D image calibration for augmented reality surgical navigation. Comput. Med. Imaging Graph. **40**, 147–159 (2015)