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ORIGINAL ARTICLE

Floating autostereoscopic 3D display with multidimensional images for telesurgical visualization

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Abstract

Purpose We propose a combined floating autostereoscopic three-dimensional (3D) display approach for telesurgical visualization, which could reproduce live surgical scene in a realistic and intuitive manner.

Methods A polyhedron-shaped 3D display device is developed for spatially floating autostereoscopic 3D image. Integral videography (IV) technique is adopted to generate real-time 3D images. Combined two-dimensional (2D) and 3D displays are presented floatingly around the center of the display device through reflection of semitransparent mirrors. Intra-operative surgery information is fused and updated in the 3D display, so that telesurgical visualization could be enhanced remotely.

Results The experimental results showed that our approach can achieve a combined floating autostereoscopic display that presents 2D and 3D fusion images. The glasses-free IV 3D display has full parallax and can be observed by multiple persons from surrounding areas at the same time. Furthermore, real-time surgical scene could be presented and updated in a realistic and intuitive visualization platform. It is shown that the proposed method is feasible for facilitating telesurgical visualization.

Conclusion The proposed floating autostereoscopic display device presents surgical information in an efficient form, so as to enhance operative cooperation and efficiency during operation. Combined presentation of imaging information is promising for medical applications.

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Keywords Autostereoscopic display · Floating display · Integral videography · Telesurgery · Combined display

Introduction

To promote safety, accuracy, and practicability of surgery, minimally invasive surgery (MIS) have been proposed with the development of various medical technologies [1]. As part of the improvement of efficiency, accuracy and security of MIS techniques, a variety of telesurgical systems have been developed and applied [2,3]. Earlier studies include "Lindbergh operation", a laparoscopic cholecystectomy that was performed on a patient in Strasbourg, France by a surgeon from New York [4]. However, for medical and technical reasons, telesurgery is still an underutilized technique at present [5].

As an essential part of information presentation, display device is an important part in telesurgery. Typically, multichannel images are separately presented in operation room (OR), making it difficult for users to coordinate information across multiple screens [6]. OR integration is a promising solution to address the long-standing problem of segregated data display [7]. It is extremely helpful for telesurgery to obtain as much information as possible for accurate reconstruction of operation scene. However, viewers could only acquire circumscribed information of OR on limited monitors currently [8,9]. Therefore, a display device with multidimensional presentation and flexible customization capability is desired under these circumstances.

Besides limited information available, most traditional telesurgical display devices present only two-dimensional (2D) images. They are incapable of providing depth information (stereo and motion parallax) to the viewers. To compensate for these drawbacks, various three-dimensional (3D) displays have been widely used in OR as an auxiliary part of microscope to offer detailed spatial data nowadays [11]. This could help surgeons in making critical spatial judgement, e.g. spatial relation of vessels or nerves [10]. However, these 3D displays rely on glasses and surgeons have to put on or take off the glasses; hence, surgeons need to switch between 3D and 2D perception, which may cause visual fatigue. Such inconvenience would interrupt operation, decrease efficiency, and result potential safety risks as surgeons may get fatigue easily due to a constant need of adapting to different visualization methods [12]. On the other hand, autostereoscopic 3D display is a promising and attractive alternative. This technique does not require glasses for visualization among many other merits [13]. Integral videography (IV) is a kind of autostereoscopic 3D display that has been proposed and applied in medical application [14]. However, due to the narrow viewing angle of IV autostereoscopic 3D display, the observers can obtain limited 3D information with a single IV display. Furthermore, medical image data, such as CT, MRI, contain total 360° 3D morphological and structural information. Glasses-free autostereoscopic 3D display has advantages over 2D and glasses 3D displays for clinical applications.

In this study, we propose a polyhedron-shaped display device with combined 2D and autostereoscopic 3D display capability for telesurgical visualization. This glasses-free floating display has a larger viewing region, so that several surgeons can simultaneously observe these intuitive floating 3D images from various viewpoints. Different 2D and 3D displays can also be combined in the display system to present information captured by different sources concurrently. In addition, movement of surgical instruments can be updated in real time to remote viewers in 3D for surgical navigation. Furthermore, traditional sagittal, axial, and coronal views can also be presented together with 3D images.

Materials and methods

System configuration

The telesurgery is conducted at two sides: OR side and remote side (Fig. 1). At the OR side, 3D data acquisition, image segmentation, 3D reconstruction, and surgical planning are done before operation. Navigation system and imaging equipment are used to monitor the patient and surgical process during the operation. At the remote side, the proposed polyhedron-shaped display device is used to reconstitute the surgical scene in OR. We develop algorithm of IV image rendering and software for this telesurgical visualization. Four semi-transparent mirrors reflect the 2D and 3D fusion images displayed on horizontal plane and different contents or different perspectives of the same content are shown on four facets of the display device. According to specific needs, the users could choose and stand facing a desired view. Hence multiple users observe the floating autostereoscopic display from surrounding areas. In this way, real-time surgical scene is remotely reproduced in such a realistic and intuitive manner.

Floating autostereoscopic 3D display

We use IV technique for autostereoscopic display and 3D surface model is extracted from 3D volumetric data for IV

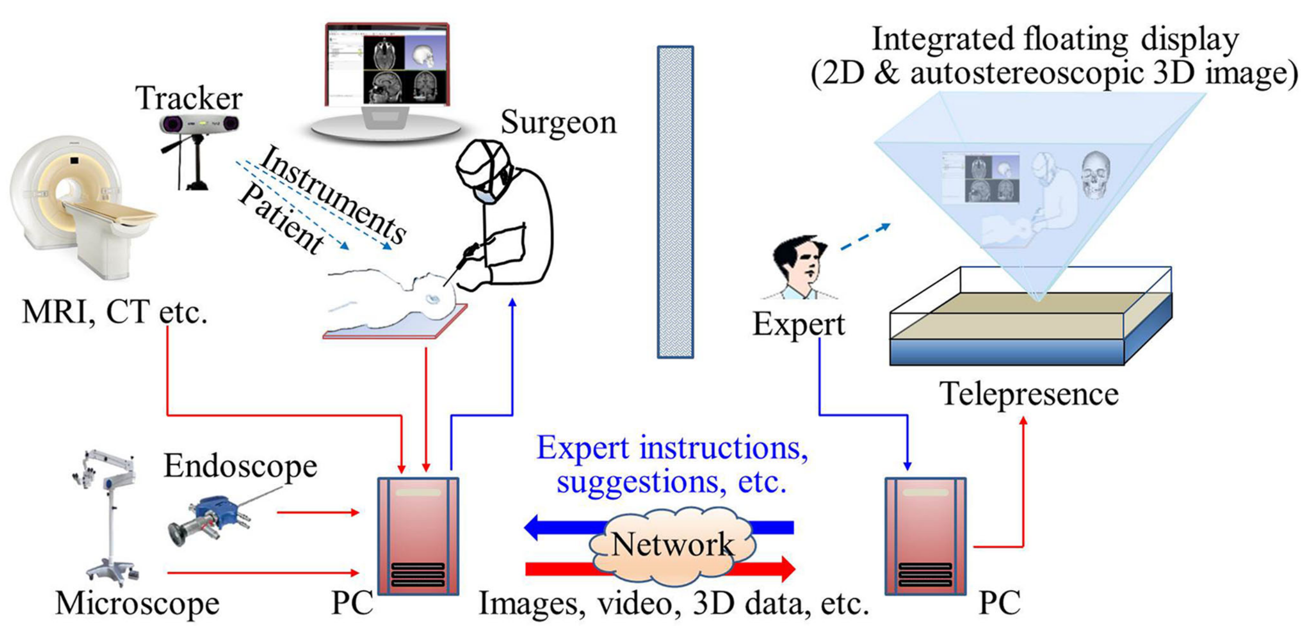

Fig. 1 System overview of telesurgical visualization system

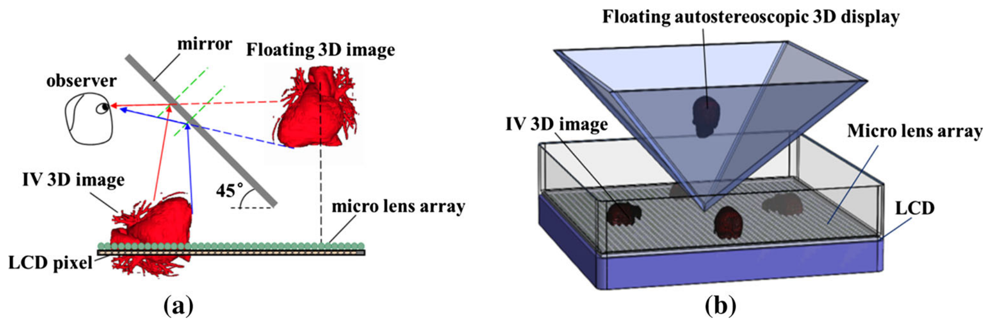

Fig. 2 **a** Fundamental principle of floating display by semitransparent mirror reflection (one side), **b** polyhedron-shaped floating display device

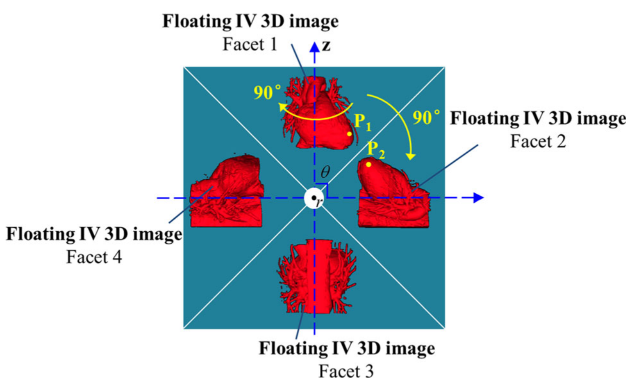

Fig. 3 Orthogonal arrangement of IV images corresponding to four mirrors

rendering. 3D volumetric data are acquired, segmented and reconstructed before or during operation, and 3D data can be DICOM files from MRI, CT, etc. Here IV has some unique advantages: (1) geometrical accuracy (showing image depth); (2) visibility of full parallax and continuous viewing points over a wide area; (3) no need of special glasses or tracking device for 3D vision; (4) simultaneous observation by several people; and (5) compact system configuration and relatively simple implementation [14].

We adopt triangular semitransparent mirrors to build the polyhedron-shaped floating display (Fig. 2). The semitransparent mirror is 45° tilted with respect to horizontal plane, so that image centerline of the 3D object lies exactly on vertical centerline. According to the symmetry principle of mirror imaging, distance from the object on the horizontal plane to the central point is equal to the distance from its image on the vertical plane to the central point. Therefore, the observer could see a floating 3D image when standing in front of the display device.

In this study, we adopt moving view point (MVP) algorithm to render surface models and fusion of multimodality images for real-time IV display [15]. The four 3D images to be displayed on four facets are rendered from four directions of the 3D model (Fig. 3). The relationship of adjacent 3D images is illustrated as:

$$P_2 = R_{(r)}(\theta) R_z(\theta) P_1 \tag{1}$$

where P_1 is a point in floating IV 3D image Facet 1, for example, a prominent point on the heart model; and P_2 is the same anatomical point in floating IV 3D image Facet 2. In other words, floating IV 3D image Facet 2 is a rotated version of floating IV 3D image Facet 1. As adjacent images are orthogonal to each other, hence $\theta = 90°$. Thus, different perspective of a 3D object, i.e., left, right, front and back, could be presented simultaneously. When the image is updated in real time, the other three relevant IV elemental images are also regenerated simultaneously. An observer could hence obtain complete information of the 3D object.

Combined 2D and 3D display of multimodality images

Conventional multiple 2D displays are sparsely placed one by one in a row, and each presenting only one perspective of the object without depth information. In this study, we use the polyhedron-shaped display device to present and update four orthogonal perspectives of the fusion image (Fig. 4) simultaneously. Four perspectives of the 3D data are rendered from

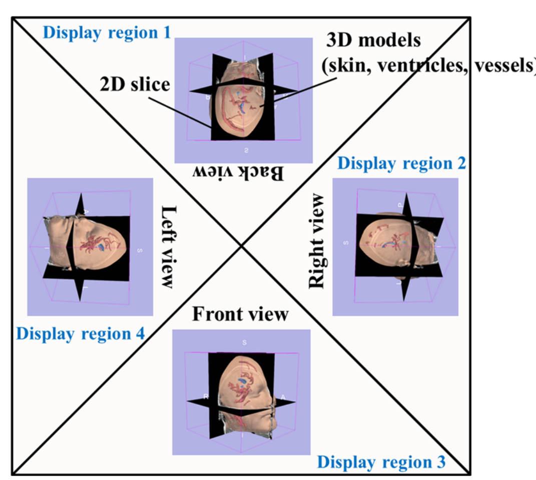

Fig. 4 Arrangement of 2D/3D fusion image for polyhedron-shaped display

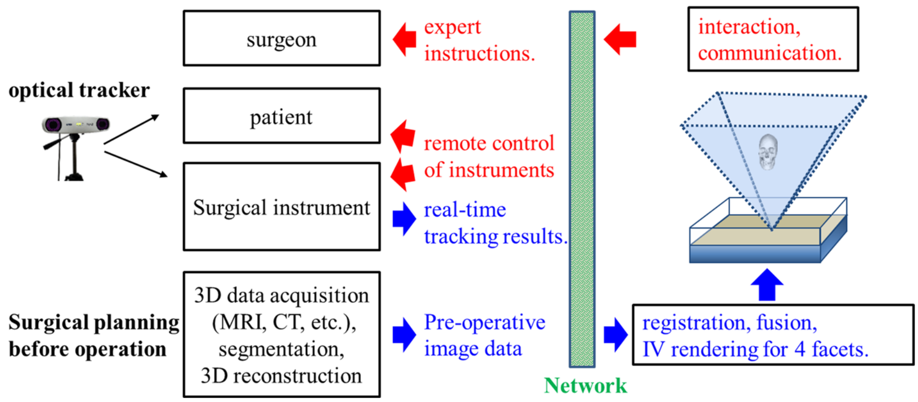

Fig. 5 Workflow of the polyhedron-shaped display for telesurgical visualization

four orthogonal directions and presented by four triangular mirrors. Therefore, alternative perspectives are provided for several users in an efficient form. Entire structural information of a 3D object can be observed from surrounding area of the display device.

Meanwhile, as we know, multimodality imaging sources are used in OR, such as microscope, surgery video, surgical navigation, anesthesia machine, patient monitor, etc., and these image-based contents can be grouped for better understanding. The placement of fusion images from multichannel sources are arranged elaborately according to the features of image source and the need of surgeons. For example, surgery-related displays are allocated to one side, while monitoring-related displays are allocated to another side of the display device. Therefore, relevant multimodality images are presented together for effective perception and optimized utilization of space.

Workflow of the display for telesurgical system

The proposed display device provides an information presentation method for telesurgery. A bit different from conventional telesurgery, this combined display shows images in an intuitive form and the viewer obtain entire information from surrounding area of the polyhedron. The procedures using this combined floating display for telesurgery are as follows (Fig. 5):

1. Before operation, acquire 3D data (MRI, CT, etc.) of patient. Segment the data and reconstruct to obtain 3D models of interest.
2. Place navigation tracker and register the surgical instrument and patient to the 3D atlas.
3. Transmit real-time surgical data and images of various equipments in OR to remote side via network.
4. At the remote side, according specific needs of surgery, manage the display of four facets with the software we developed.

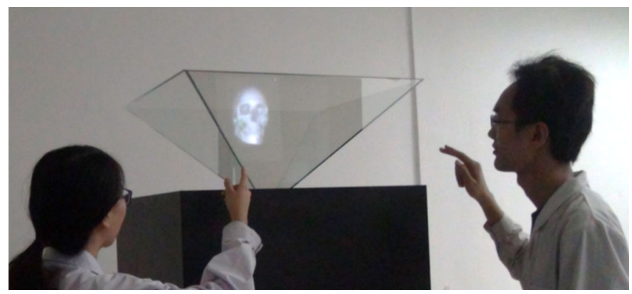

Fig. 6 Experimental setup of the floating autostereoscopic 3D display device

5. Surgeons and mentors choose desired position of the polyhedron-shaped display device for telesurgical guidance.
6. Surgeon controls instruments according to the provided information, and the mentor gives instructions according to what he/she sees and his/her professional experience.

The proposed display device has glasses-free 3D visualization capability, which is an important advantage (structural precision, comfort, etc.) for telesurgery. With this surgical navigation system, 3D spatial relationship between surgical instrument and patient is tracked. Both the target object and surgical instrument are presented in 3D form on the polyhedron-shaped display device at the remote working site simultaneously.

Experiment and results

We manufactured a prototype device to validate the proposed display approach. The polyhedron-shaped floating autostereoscopic 3D display device is shown in Fig. 6. The floating autostereoscopic display is realistic and intuitive, and it could be observed by several persons simultaneously. We can obtain information from different perspectives around the 3D display.

Table 1 System specifications and parameters

Items	Value
Polyhedron dimensions	
Pyramid width	70 cm
Pyramid height	30 cm
Vertex angle of every isosceles triangle	70.5°
Surface inclination angle	45°
Facets	4
3D image	
Size (width:height:depth)	Within 241 mm × 185 mm × 50 mm
IV display	
LCD	9.7 in. diagonal, resolution 1536 × 2048 pixel
Micro lens arrays	Pitch: 2.32 mm, focal length: 3.3 mm

Four semitransparent mirrors were fabricated to build the polyhedron-shaped display device. Detailed specifications and parameters are shown in Table 1. To guarantee the facets accurately tilted at 45°, vertex angle of every isosceles triangle is 70.5°. The final inverted pyramid part was 30 cm in height and 70 cm in width. Multiple high-definition (HD) LCDs (LG LP097QX1-SPC1, 1536 × 2048 pixel, 9.7 in., and 264 pixels per inch) were used to display images from various sources. A set of micro lens arrays (MLA) were manufactured according to optimal design to build high-quality IV autostereoscopic display.

We designed and performed experiments to evaluate feasibility and effect of the proposed method. Surrounding floating 3D display effect, combined display effect and capability, and real-time instrument tracking performance were verified. The pictures and movies were captured by a digital video camera (SONY, HDR-TD10).

Floating autostereoscopic 3D display viewable from surrounding area

To evaluate surrounding view and motion parallax of the developed IV display device, we used a CT scanned human head (256 × 256 pixels times 94 slices) to extract surface model for generating IV elemental image. IV elemental image rendered to generate the 3D display is shown in detail (Fig. 7a, b). Four IV images were placed around the center, and each IV image corresponds to its mirror facet on the polyhedron. 90° rotation around centerline of the object itself and 90° around the center of LCD were used here. We used hexagonal lens array to get full-motion parallax, maximally utilized pixels in the LCD and minimalized IV image flipping. The surrounding view can be observed from four directions to obtain full information of the object from four autostereoscopic 3D images (Fig. 7c–f).

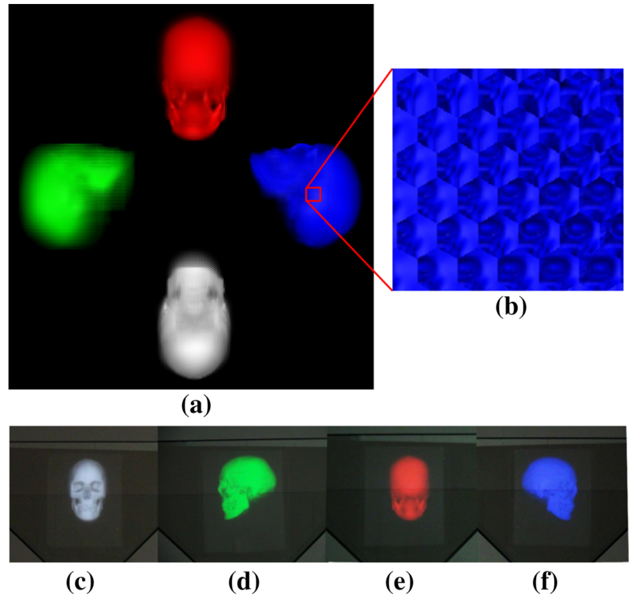

Fig. 7 **a** Rendered IV elemental images, **b** details of IV elemental image, and 3D display of the four images. Pictures are captured from different directions of the polyhedron-shaped display: **c** front, **d** left, **e** behind, **f** right

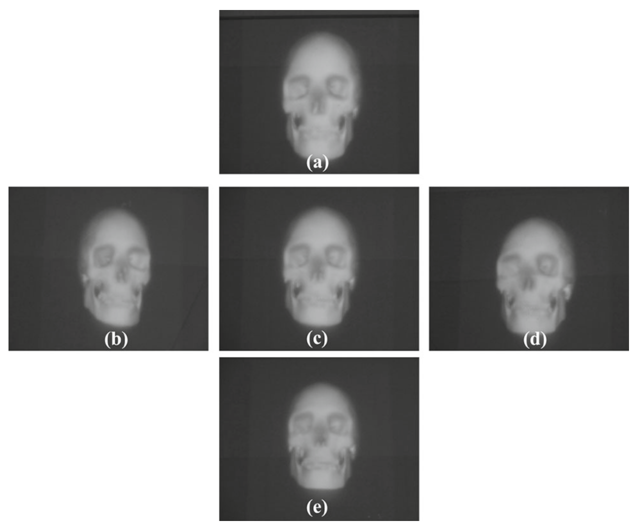

Fig. 8 Parallax of autostereoscopic image taken from various perspectives: **a** upper, **b** left, **c** center, **d** right, **e** lower

The floating autostereoscopic image is of glasses-free 3D property. In the experiment, we used IV display system with viewing angle of 57°, and the 3D Image depth is about 50 mm according to our measurement [13]. Full-parallax effect and floating capability can be clearly observed from different directions. The 3D display keeps still in 3D space when viewpoint move up, down, left, and right (Fig. 8a–e).

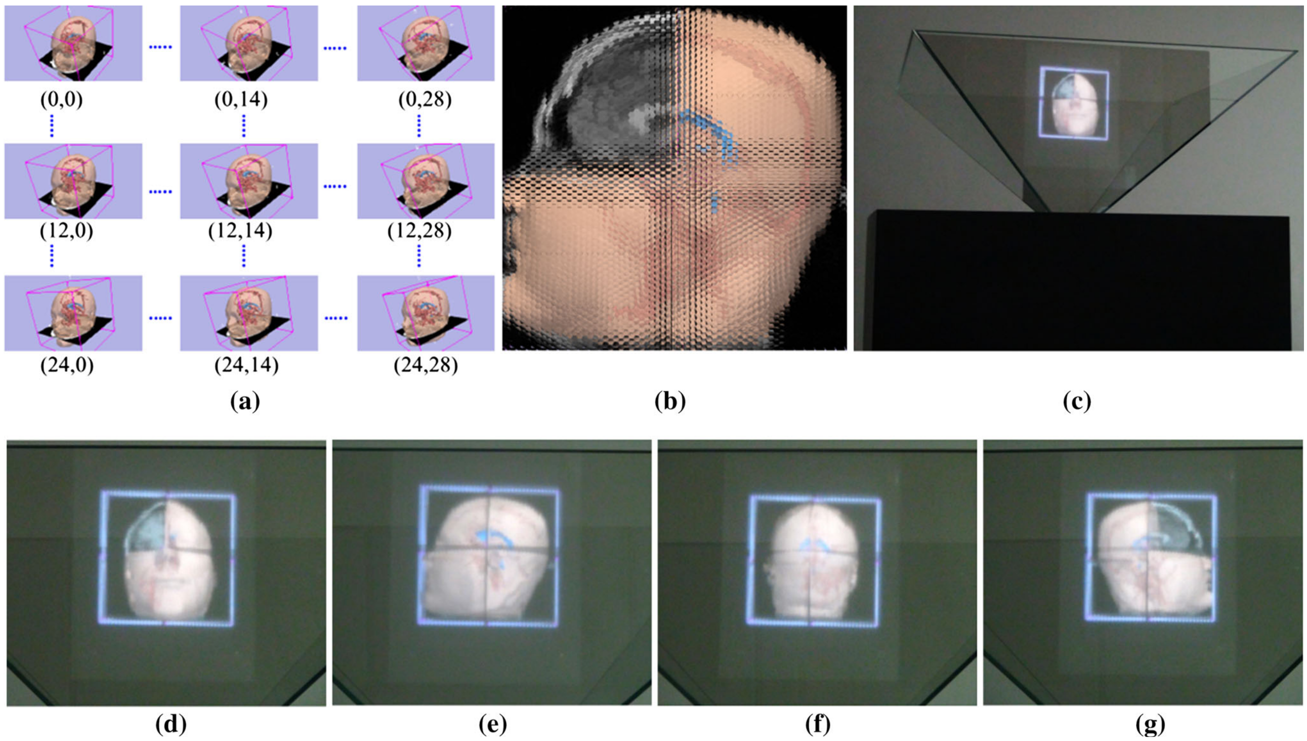

Fig. 9 Autostereoscopic 3D display of fusion image. **a** Multiple viewpoints images captured in 3D Slicer, **b** rendered IV elemental image, **c** IV 3D display of the fusion image, and detailed show of autostereoscopic 3D display with the polyhedron-shaped display, pictures taken from four directions: **d** front, **e** right, **f** behind, **g** left

Floating autostereoscopic display of 2D and 3D fusion image

To validate visualization of fusion images, we rendered IV of 2D and 3D fusion images. The 3D volume data and models are obtained from 3D Slicer [16]. We used tcl script to capture images of multiple viewpoints (29 × 25 viewpoints, resolutions 146 × 121 pixel). The captured images were redistributed to obtain IV elemental image.

The captured images for IV rendering from arrays of viewpoints in 3D Slicer are shown in Fig. 9a, and IV elemental image is shown in Fig. 9b. The displayed floating 3D images of different directions are shown in Fig. 9d–g. The 2D slices were fused into the 3D model. Meanwhile, we could see that different views of the fusion image are simultaneously shown in the polyhedron-shaped display.

Real-time instrument tracking and telepresence

We implemented simulation of surgical navigation with a skull phantom and a simulated instrument (Fig. 10a). The 3D model was extracted from CT scanning data of the phantom. Optical tracker was used for obtaining position and pose of the instrument. 3D display of the phantom and surgical instrument was floating in 3D space (Fig. 10b). The relationship between patient and surgical instrument was obtained and accurately updated in real time according to the movement of surgical instrument. Meanwhile, autostereoscopic 3D images of different perspectives are presented in different planes of the display device (Fig. 10c–f). In addition, viewers could control mouse and keyboard to rotate and scale the target.

Real-time performance is one of the important points for telesurgical system, and time is mainly exhausted in computation, data transmission, and 3D display. IV rendering needs a lot of computation. In this study, we implemented IV rendering using GPU parallel computing, so real-time performance of IV display could be largely improved. We used a workstation with a high-performance graphics card to run the real-time MVP algorithms and telesurgical visualization software. The CPU and GPU are an Intel Xeon E5-1607 (3.00 GHz) and a NVIDIA GeForce GTX970. Algorithms are developed using Microsoft Visual Studio 2010 platform and C++ programming.

We performed tests of IV rendering speed. We did translation, rotation and zooming of the model, and counted time cost of each step during IV updating. The statistic result of consecutive 1000 measurements is shown in Table 2, and durations are expressed in milliseconds (ms). The result showed that virtual capturing of multiple viewpoints in OpenGL 3D space (29 × 25 viewpoints,

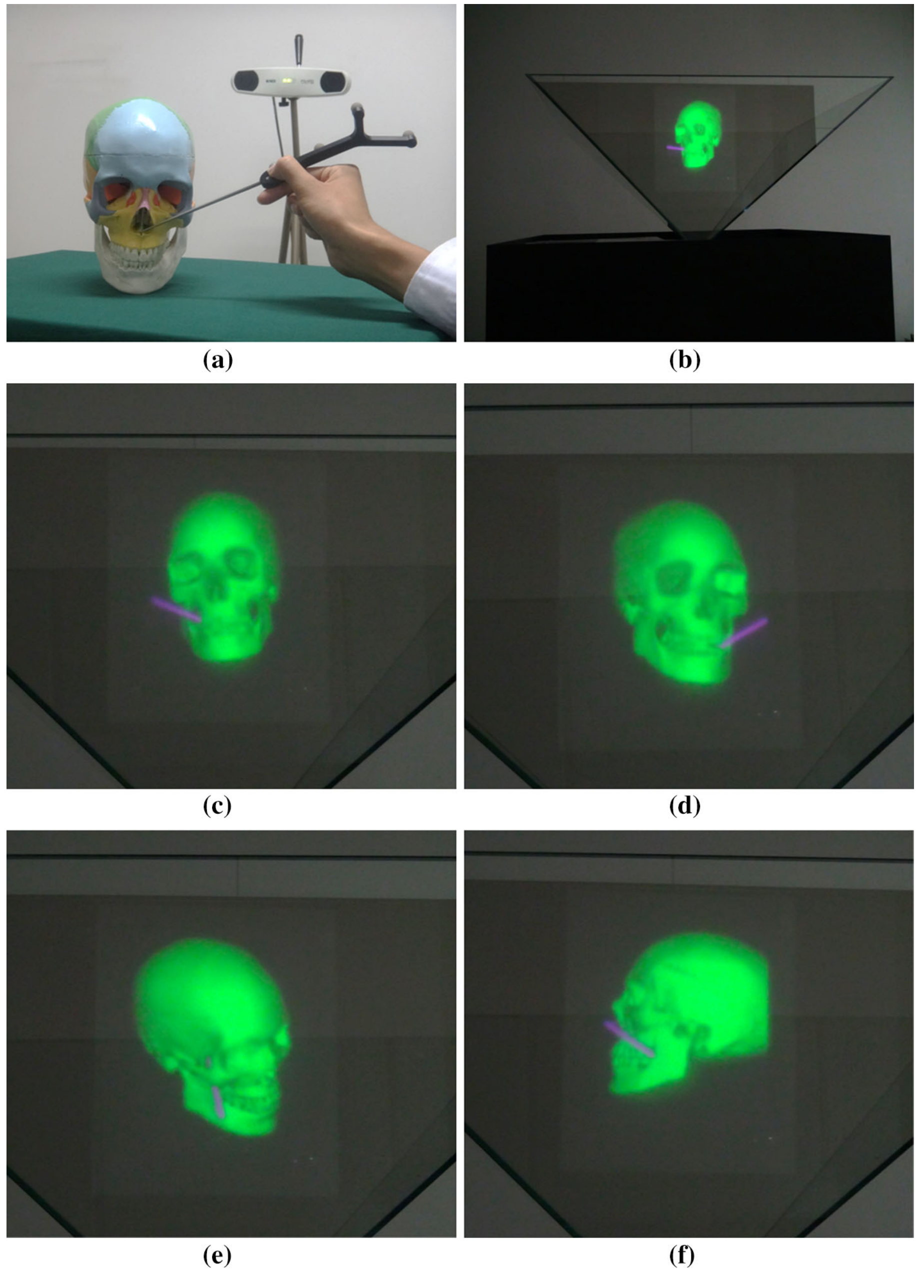

Fig. 10 **a** Setup of surgical navigation simulation, **b** IV 3D display of the phantom and surgical instrument, **c**–**f** detail show of the autostereoscopic 3D display. Spatial position and pose of the surgical instrument are updated in real time, and different perspectives of images could be presented

Table 2 Rendering time of IV autostereoscopic display ($n = 1000$)

IV elemental image rendering	Cameras placement and setup	Virtual capturing of multiple viewpoints in OpenGL 3D space	Pixel redistribution
Mean (ms)	0.3 ± 0.16	22.3 ± 2.6	1.3 ± 0.52

resolutions 146×121 pixel) consumes the most time, followed by pixel redistribution. Hence average update rate of IV rendering during the test is 41.8 frames per second (FPS) for this skull model (Polygons: 91,108, Vertices: 273,324). In this experiment, no perceivable display lag appears.

Discussion

We have demonstrated a combined floating display for telesurgery, which could reproduce live surgical scene in a realistic and intuitive manner. It addresses numerous aspects of operative application: animated reappearance, instrument tracking, and navigation view replay. Information could be shared simultaneously between surgeons and remote receivers in an efficient form. Therefore, efficiency and precision of MIS could potentially be promoted.

We adopted semitransparent mirrors to achieve realistic floating display effect. The feature of semitransparent mirror enables objects behind the semitransparent mirror to be observed simultaneously, which can be used to achieve better visual perception. The ratio of reflectance to transmittance (RTR) is critical for display effect (contrast, luminosity). If transmittance is too much, the reflected image will be weak as the background becomes obvious. As the priority of display is to show the target as clear and bright as possible, it is thus essential to carefully select a proper RTR and ambient light strength.

The proposed display device presents real-time images inside four triangular facets of the polyhedron-shaped display. When neighboring images are orthogonal to each other, the entire structural information of 3D object can be presented with this single display device. Moreover, in another relevant research previously, we developed a polyhedron-shaped floating autostereoscopic display that has continuous a 360° viewpoint without flipping between facets [17]. It can also be adopted to build a combined display although hardware and software are a bit more complicated.

The limitation of traditional 2D display (i.e., without depth information) could be overcome by using IV autostereoscopic display. Although the resolution is not as high as current 2D display, IV 3D display is applicable in some cases, especially where intuitive depth information is needed. Resolution of IV autostereoscopic display is determined by pixel density of LCD and precision of MLA. Many researchers have proposed method to promote fineness of IV autostereoscopic display [13,18,19]. We anticipate that with the advancement of LCD pixel density and MLA accuracy, together with development of algorithms, the weakness of IV resolution may be overcome. Hence our proposed display device can be adopted in more medical application.

As an essential application, stereoscopic endoscope can be achieved through a variety of methods, such as structured light technology, structure form motion (SFM) method, binocular vision technology, time of flight (TOF) technology, etc [20]. 3D model can be constructed from direct 3D acquisition or software post-processing, such as texture mapping [21]. Because IV autostereoscopic display can interface with various 3D data, such as DICOM data, volumetric data, CG generated model (stl, obj, etc.), stereoscopic information from endoscope can also be presented by IV autostereoscopic 3D display. The proposed display device can show multimodality image information simultaneously in an efficient way. Therefore, we can achieve real-time floating autostereoscopic 3D display of endoscopic image with the proposed system to present entire information of targets.

The telesurgical application is of more potential significance, and medical robot and its counterparts have attracted more and more attentions [22]. The proposed display device has glasses-free 3D visualization capability and compact structure, which is an important strength (comfort and structural precision) for telesurgery. With the advancement of autostereoscopic display and relevant technologies, we will further improve resolution, accuracy, real-time performance, etc., and hope that our proposed display device can be adopted in more medical application.

Conclusion

A display device with integration of multidimensional display capability for telesurgical visualization was developed. This form of display presents multiple perspectives of multimodality fusion images in a combined display device, and the IV autostereoscopic 3D display has full parallax and can be viewed by multiple persons simultaneously. The proposed floating display reproduces remote operation scene and surgical information in a realistic and intuitive form, and these 2D and glasses-free 3D capabilities can also be easily configured according to specific needs. Information obtained by operating surgeon could be shared in real time with telesurgical mentors and surgeons, enhancing intra-operative interaction and cooperation. Therefore, this combined presentation of visualization information is promising for telementoring and telesurgery. Furthermore, it could be utilized as a visualization method for other medical applications.

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Compliance with ethical standards

Conflict of interest The authors declare that they have no conflicts of interest in the research.

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