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Bio-inspired multimodal 3D endoscope for image-guided and robotic surgery

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Abstract: Image-guided and robotic surgery based on endoscopic imaging technologies can enhance cancer treatment by ideally removing all cancerous tissue and avoiding iatrogenic damage to healthy tissue. Surgeons evaluate the tumor margins at the cost of impeding surgical workflow or working with dimmed surgical illumination, since current endoscopic imaging systems cannot simultaneous and real-time color and near-infrared (NIR) fluorescence imaging under normal surgical illumination. To overcome this problem, a bio-inspired multimodal 3D endoscope combining the excellent characteristics of human eyes and compound eyes of mantis shrimp is proposed. This 3D endoscope, which achieves simultaneous and real-time imaging of three-dimensional stereoscopic, color, and NIR fluorescence, consists of three parts: a broad-band binocular optical system like as human eye, an optical relay system, and a multiband sensor inspired by the mantis shrimp's compound eye. By introducing an optical relay system, the two sub-images after the broad-band binocular optical system can be projected onto one and the same multiband sensor. A series of experiments demonstrate that this bio-inspired multimodal 3D endoscope not only provides surgeons with real-time feedback on the location of tumor tissue and lymph nodes but also creates an immersive experience for surgeons without impeding surgical workflow. Its excellent characteristics and good scalability can promote the further development and application of image-guided and robotic surgery.

1. Introduction

Thanks to the development of 5G technology, remote assisted robotic surgery is becoming possible, which can effectively solve the problem of uneven distribution of medical resources. Remotely controlled robotic systems based on image-guided technology provide a stable operation platform and enhance the capabilities of surgeons performing accurate surgery [1]. Endoscopes [2–8], as the eye of a surgical robot, provide surgeons with medical images of human anatomy and play important roles in remote assisted robotic surgery. In fact, long before robotic surgery, endoscopic minimally invasive surgery has attracted significant interest in current medicine for less operative pain and complications, smaller incisions, and faster recovery times.

However, most endoscope systems only have a single function and remain a practical and unmet need for simultaneous and real-time multimodal imaging of three-dimensional stereoscopic,

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multispectral [9], and even polarization [10]. Specifically, simultaneous and real-time 3D imaging of both color and NIR fluorescence is necessary for intraoperative visualization and location of tumor tissue, lymph nodes, and vital structures without impeding surgical workflow [11]. Most NIR fluorescence endoscopes work with dimmed surgical illumination, which significantly impedes the surgical workflow: surgeons stop the operation, turn off or dim the white lights, observe the tumor margins with NIR instrumentation, and then continue the surgery under visible illumination without NIR fluorescence image guidance or dim illumination [12]. The drawbacks of these instrumentations are mainly reflected in the following three aspects: (1) impeding surgical workflow; (2) unable to achieve simultaneous and real-time imaging of both color and NIR fluorescence under normal illumination; (3) only obtaining 2D images. The unimpeded surgical workflow shortens the operation time and reduces the operation risk. Simultaneous and real-time 3D imaging of both color and NIR fluorescence under normal illumination can provide surgeons with real-time feedback and comprehensive three-dimensional information during the operation. It will greatly improve the success rate of surgery and reduce the recurrence rate through complete tumor tissue resection [13]. To overcome these problems, some great ideas have been proposed [14,15]. Unfortunately, the complete endoscope system with simultaneous and real-time imaging of both color and NIR fluorescence has not been integrated.

Here, we demonstrate that a bio-inspired multimodal 3D endoscope with simultaneous and real-time 3D imaging of both color and NIR fluorescence can be designed by combining the excellent characteristics of human eyes and compound eyes of mantis shrimp. Different types of eyes have been developed in nature after 500 million years of evolution [16]. Many artificial vision systems and sensors, such as color-polarization sensor [17,18], hemispherical electronic eye camera [19], compound eye cameras [20–22], eagle eye camera [23], are inspired by biological vision systems. Meanwhile, many technologies have been proposed for 3D imaging [24–26], such as computed tomography (CT), magnetic resonance imaging (MRI), optical coherence tomography (OCT), structured light, time of flight (TOF), binocular imaging, and light field imaging. Among them, the binocular imaging inspired by the human eye can create an immersive experience for surgeons, making it a promising solution for endoscopic image-guided surgery or robotic surgery. High-resolution imaging is another excellent feature of the human eye apart from stereo imaging, shown in Fig. 1(a).

There is also a compound eye vision system except for the monocular system like the human eye in nature [27]. Many insects have a pair of compound eyes, such as dragonflies, bees, fruit-flies, grasshoppers, and mantis shrimp, etc. The compound eye of these insects, which is a sophisticated imaging device that consists of a mosaic of tiny optical units called ommatidia [28], allows insects to see a different world from humans. For example, the compound eyes of bees can see ultraviolet light, making it easier to distinguish whether flowers are rich in nectar. While the compound eyes of mantis shrimp can not only detect multispectral information but also recognize polarized light [18]. It has proven that simultaneous and real-time imaging of color, NIR fluorescence, and even polarized light in nature is feasible. The mantis shrimp's compound eye shown in Fig. 1(b) is divided into three parts: two hemispheres (DH/VH) and a mid-band section (MB). The mid-band section with 6 rows of ommatidia is where most of the spectral discrimination takes place. Lines 1-4 are sensitive to the spectrum, while lines 5-6 can see the polarized light. The microvilli array in the rhabdoms of the ommatidium is dichroic and selectively transmits light of a specific wavelength and polarization. This characteristic provides a feasible solution for simultaneous and real-time multispectral and polarization imaging. Therefore, a dichroic multiband sensor inspired by the mantis shrimp's compound eye is proposed in this article. While it is easy to integrate polarization imaging into this sensor so that it has good scalability. The bio-inspired multimodal 3D endoscope which the optical part like the human eye and the sensor inspired by the mantis shrimp's compound eye is shown in Fig. 1(c). Figure 1(d) shows the panoramic view of the multimodal 3D endoscopic imaging system. This multimodal

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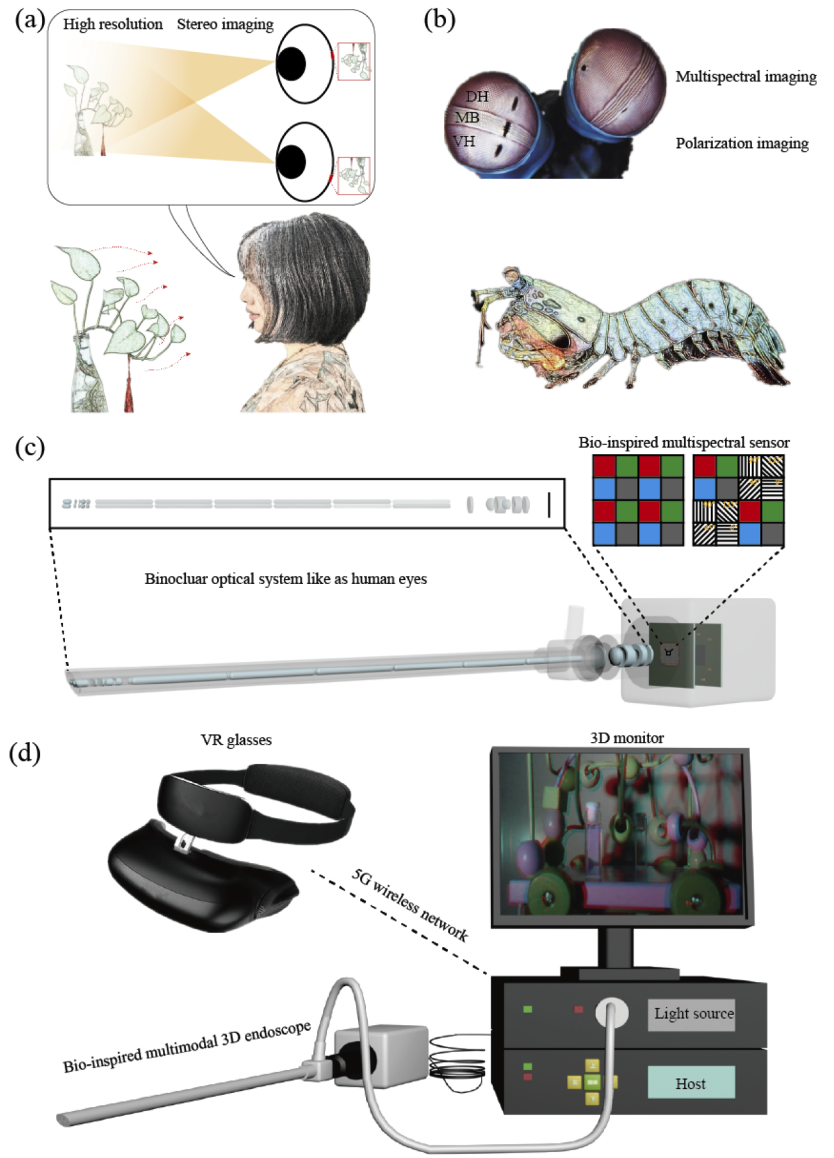

Fig. 1. Schematic illustration of the bio-inspired multimodal 3D endoscope for color and near-infrared fluorescence image-guided surgery. (a) High-resolution and stereo imaging based on the features of the human eye vision system, (b) Multispectral imaging and polarization imaging of the mantis shrimp's compound eye, (c) Exploded view of the bio-inspired multimodal 3D endoscope that consists of a binocular optical system like as human eye and a multiband sensor inspired by the mantis shrimp's compound eye. (d) Panoramic view of the bio-inspired multimodal 3D endoscope system.

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3D endoscopic imaging system includes a bio-inspired multimodal 3D endoscope, a host for controlling and image processing, a light source, a 3D monitor, and one or more VR glasses. In this work, a prototype of this multimodal 3D endoscope with simultaneous and real-time 3D imaging of both color and NIR fluorescence under normal illumination was fabricated. This multimodal 3D endoscope which can provide real-time feedback in the operating room will be widely used in image-guided and robotic surgery.

2. Results and discussion

2.1. Prototype of the bio-inspired multimodal 3D endoscope

One prototype of the bio-inspired multimodal 3D endoscope combining the features of human eyes and compound eyes of mantis shrimp is fabricated as shown in Fig. 2. The prototype of the bio-inspired multimodal 3D endoscope consists of a dual-channel optics rigid borescope, an optical relay system, and a bio-inspired multiband sensor. By introducing an intermediate optical relay system, the two sub-images after the dual-channel optics rigid borescope can be projected onto one and the same bio-inspired multiband sensor. The dual-channel optics rigid borescope is composed of a pair of twin rigid borescopes where each of them contains a 30° viewing prism group, an imaging objective lens group, and three pairs of relay cylinder lenses. Figure 2(a) shows the detailed structure and function of each component. The 30° viewing prism group deflects the light path downward by 30° and does not participate in imaging. The imaging objective lens group is the core of this prototype, which is responsible for the main imaging tasks. Then, three pairs of relay cylinder lenses transmit the image to the end of the rigid borescope without any processing. These three components are all juxtaposed in pairs. The internal structure is arranged as shown in Fig. 2(b). An optical relay system was introduced to enable the image to be re-imaging on the bio-inspired multiband sensor. The filters array of this multiband sensor is dichroic and selectively transmits light of a specific wavelength. Finally, four pairs of images from different spectral bands are acquired. Figure 2(c) is prototype pictures that have been made and its main parameters of this prototype are listed as Table 1.

Table 1. Main parameters of this prototype.

Object distance	50mm
Field of view	90°
Viewing angle	30°
Optical total length	300 mm
Diameter of this prototype	12 mm
Spectral response	400nm to 1000nm
Resolution	3296×2472
Spectral bands	4
Frame rate	21fps
Output images	2D color/NIR, 3D color/fusion

Figure 3 shows the schematic diagram of simultaneous and real-time 3D imaging of color and NIR fluorescence using this prototype. Two cuvettes at different locations, filled with pure water and ICG solution, were used as imaging targets. To achieve simultaneous imaging of both color and NIR fluorescence, a white light source whose wavelength band ranges from 400nm to 700nm and a laser source which wavelength is 785nm is used to illuminate the targets at the same time. The white light source provides sufficient light for the dim surgical environment to ensure the acquisition of RGB images with high contrast. While the external 2W 785nm laser source with 10nm spectral width is used to excite NIR fluorescence from ICG. The NIR fluorescence with a

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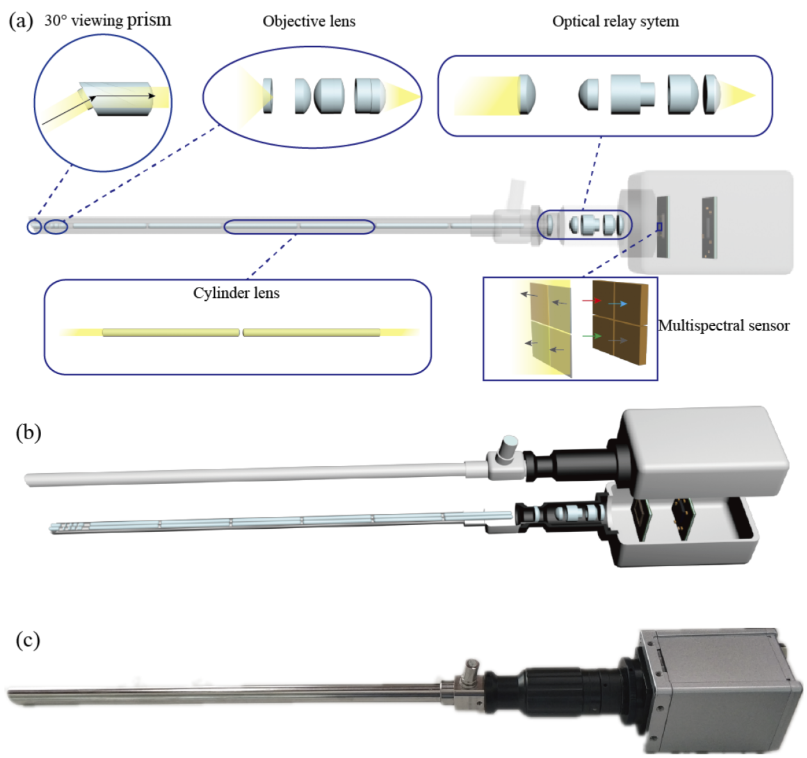

Fig. 2. The prototype of bio-inspired multimodal 3D endoscope (a) The detailed structure and function of each component, (b) Internal arrangement of this prototype, (c) The picture of this prototype.

wavelength of about 830nm will be captured by the NIR channel of the bio-inspired multiband sensor with a working band of 815-1000nm. Although the bio-inspired multiband sensor is not sensitive to the light with a wavelength of 785nm, a notch filter is placed in front of the sensor to further reduce the interference of the laser source. These two cuvettes were imaged on the bio-inspired multiband sensor through the dual-channel optics rigid borescope and the optical relay system, as shown in Fig. 3(a). The bio-inspired multiband sensor has four spectral channels of red, green, blue, and near-infrared. As a result, a pair of images formed by the dual-lens optics rigid borescope was divided into four pairs of sub-images which each sub-image covers about 672×378 pixels as shown in Fig. 3(b). Among them, each pair of sub-images has parallax, providing the possibility for 3D imaging. In order to achieve simultaneous and real-time 3D imaging of both color and NIR fluorescence, a high-resolution color image with 1344×756 pixels will be got by de-mosaicking based on these three sub-images from R, G, B channels [29]. Thereby a pair of color images and a pair of NIR fluorescence images were obtained. Each of them contains a left sub-image and a right sub-image. A left fusion image can be obtained by fusing the left sub-image of color image and the left sub-image of NIR fluorescence image. In the same way, the right fusion image can also be obtained. Apparently, this pair of fusion images have parallax. 3D image can be obtained when an appropriate 3D encoding algorithm is giving. The resolution of the fusion images and the 3D images are is consistent with the color image. Figure 3(c) shows the procedures of these complex image processing. As an example, the Red & Blue format was adopted as the 3D format. One red and blue 3D glass is needed when you watch these 3D images.

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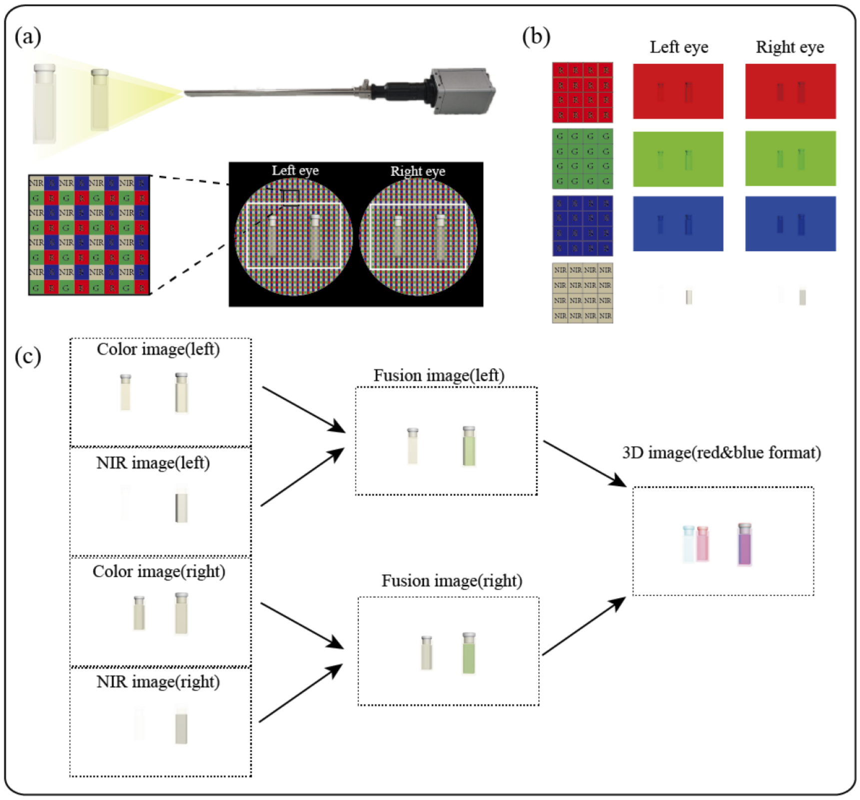

Fig. 3. Conceptual view of image formation by the bio-inspired multimodal 3D endoscope. (a) Two cuvettes at different locations, filled with pure water and ICG solution respectively, were used as imaging targets of this bio-inspired multimodal 3D endoscope. A pair of images captured by the dual-lens optics rigid borescope was outputted. (b) Since the bio-inspired multiband sensor has four channels of R/G/B/NIR, the pair of images was divided into four pairs of sub-images. Among them, a pair of color images will be obtained by fusing the three pair of sub-images of RGB. (c) A pair of fusion images can be obtained by fusing the pair of color images and the pair of near-infrared fluorescence images. Finally, this pair of fusion images with parallax can be encoded into a 3D image.

2.2. Optical performance of the bio-inspired multimodal 3D endoscope

In order to verify the optical performance of the bio-inspired multimodal 3D endoscope, a series of experiments were done. The results of these experiments were shown in Fig. 4. An ISO 12233 chart, a checkerboard picture, and a 24-color test board were used to test the resolution, contrast, and color accuracy of this 3D endoscope system respectively. In Fig. 4, the images of each row are captured by this multimodal 3D endoscope at the same time. The images of each row are the color image of the left eye, the near-infrared fluorescence image of the left eye, the color image of the right eye, and the near-infrared fluorescence image of the right eye from left to right. The color image and the near-infrared fluorescence image are captured by this 3D endoscope system under visible and NIR (830nm) illumination, respectively. The first row in Fig. 4 is the images of the ISO 12233 chart taken by the bio-inspired multimodal 3D endoscope. Partial view of these images shows that the resolution of the multimodal 3D endoscope system can reach 7lp/mm under visible illumination and 4lp/mm under NIR illumination. The small number of pixels that respond to NIR light is the main reason for the low resolution under NIR illumination. Nevertheless, it can still meet the accuracy of fluorescent labeling. The second row in Fig. 4 shows that the images of the checkerboard photographed by this multimodal 3D endoscope system under visible and NIR illumination, respectively. The corresponding intensity profiles along the blue lines clearly indicate that the color images provide higher contrast than the NIR images. The Michelson contrast can be calculated by the formula (1).

$$Contrast = (I_{\max} - I_{\min})/(I_{\max} + I_{\min}) \tag{1}$$

where $I_{\max}$ is the maximum value of the intensity, $I_{\min}$ is the minimum value of the intensity. The calculated Michelson contrast of an image is 0.67 for the color images and 0.45 for the NIR images, respectively.

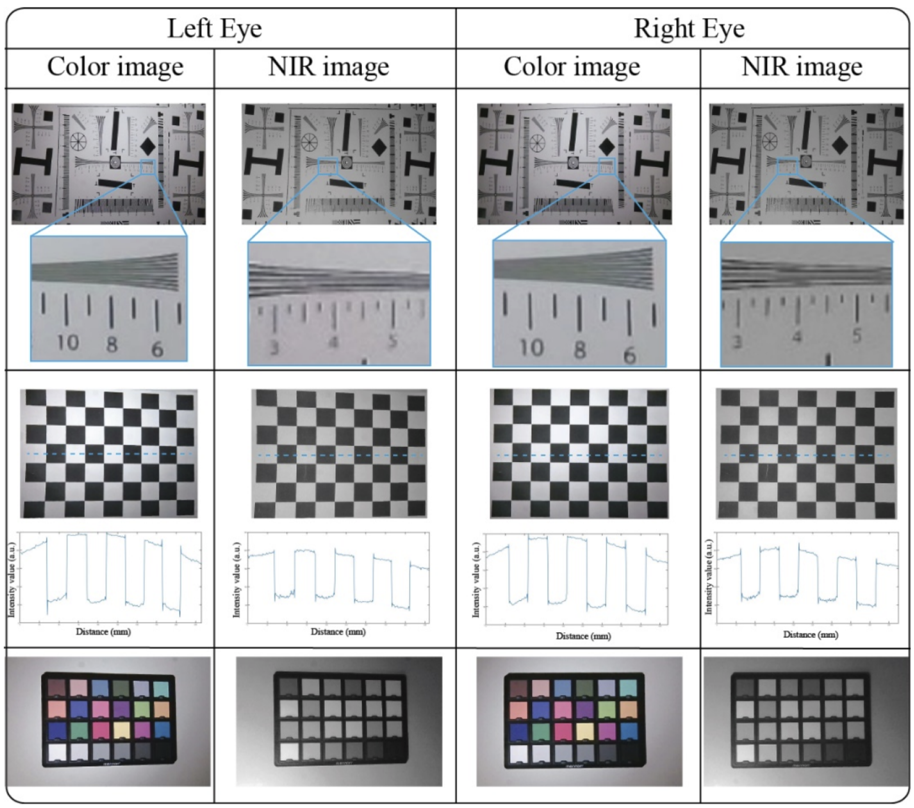

Fig. 4. Optical performance of the bio-inspired multimodal 3D endoscope. An ISO 12233 chart, a checkerboard, and a 24-color test board were used as imaging targets to measure the resolution, contrast, and color accuracy of this 3D endoscope system respectively.

For surgical navigation, the color accuracy of the image is very important. The bottom row in Fig. 4 is the images of the 24-color test board acquired by the bio-inspired multimodal 3D endoscope system, indicating that this prototype has good color accuracy.

2.3. Acquiring NIR fluorescence and color under surgical light illumination

Simultaneous and real-time imaging of both NIR fluorescence and RGB information can enhance cancer treatment by decreasing positive tumor margins, as these enable the surgeon to identify the location of the tumor on the correct anatomical features [30]. However, most fluorescence endoscopic imaging systems need physicians to stop the operation and switch between color imaging and fluorescence imaging. This drawback prevents wide acceptance of this technology in clinical surgery. The bio-inspired multimodal 3D endoscope system overcomes this shortcoming, and further realize simultaneous and real-time 3D imaging of both color and NIR fluorescence. To test the imaging performance of both color and NIR fluorescence, three samples of ICG were prepared. The concentration of ICG from left to right are 0µM, 1µM, and 2µM, respectively.

Figure 5(a) is NIR fluorescence image captured by the left eye of the bio-inspired multimodal 3D endoscope when the NIR excitation laser was on under normal surgical lighting condition. The pure water (0µM) is invisible under the excitation lighting condition. The intensity distribution of the NIR fluorescence image is shown in Fig. 5(b). The corresponding color image under visible illumination is shown in Fig. 5(c). These three samples are indistinguishable under visible illumination. A fusion image shown as Fig. 5(d) can be obtained by fusing the NIR fluorescence image and the corresponding color image. The brightness of the color part in the fusion image is lowered to highlight NIR fluorescence labeling. The fusion image clearly reveals the distribution of the concentration of ICG. Similarly, another fusion image captured by the right eye of the bio-inspired multimodal 3D endoscope can be obtained.

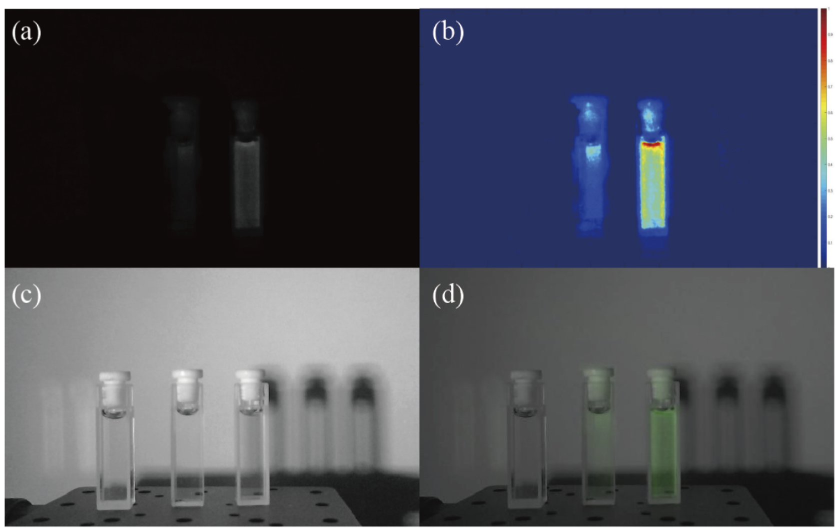

Fig. 5. Simultaneous and real-time imaging of both NIR fluorescence and RGB information captured by the left eye of the bio-inspired multimodal 3D endoscope. (a) NIR fluorescence image of ICG samples under excitation lighting condition. The concentration of ICG from left to right are 0µM, 1µM and 2µM respectively. (b) Intensity distribution of the NIR fluorescence image. (c) Color image of ICG samples under visible illumination. (d) A fusion image by fusing the color image and the NIR fluorescence image.

2.4. Simultaneous and real-time 3D imaging of both NIR and color information under surgical light illumination

As we all know, the physical world around us is three-dimensional. However, the traditional endoscopes are able to acquire only two-dimensional images that lack the depth information [24]. Lack of 3D information has greatly limited the ability of surgeons to use endoscopic instruments for seeing and understanding the complexity of real- world objects. To overcome this problem, the bio-inspired multimodal 3D endoscope provides not only simultaneous and real-time imaging of both color and NIR fluorescence but also three-dimensional stereoscopic imaging to surgeons making them have a comprehensive understanding of the operating environment.

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To verify the 3D imaging performance of the bio-inspired multimodal 3D endoscope, a toy with lots of crisscross parts is employed as an imaging target. Two cuvettes containing ICG resolution and pure water were placed on the front and back of this toy respectively. Multi-modal images (see Figs. S1- S4 of Supplement 1) were captured by the bio-inspired multimodal 3D endoscope under visible and excitation laser (785nm) illumination. Two fusion images with parallax (see Figs. S5 and S6 of Supplement 1) shown in Figs. 6(a) and 6(b) can be obtained after the aforementioned treatment. A 3D image (see Figs. S7 and S8 of Supplement 1) can be got when a proper 3D encoding algorithm is run. In this work, the Red & blue format is adopted since this format does not rely on special monitors. It still maintains 3D characteristics even when printed on paper. Figure 6(c) shows the schematic illustration of 3D encoding process of the Red

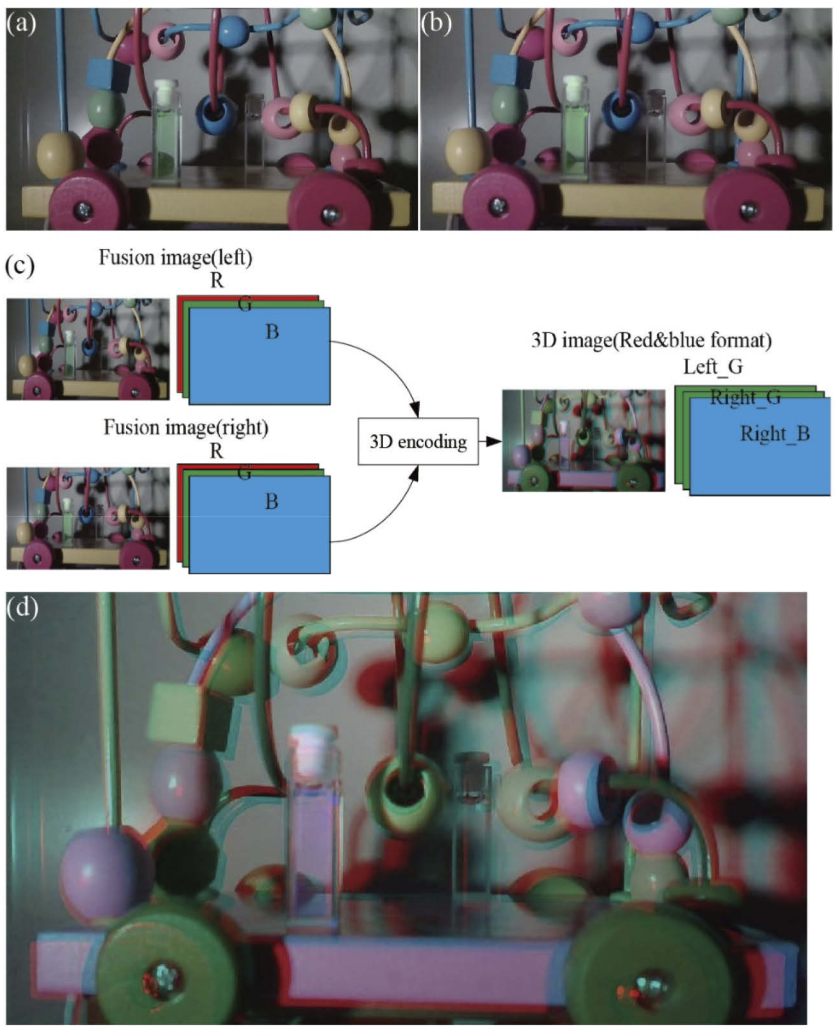

Fig. 6. Simultaneous and real-time 3D imaging of both NIR fluorescence and color information under surgical light illumination. A 3D image will be obtained by encoding (a) the left fusion image and (b) the right fusion image. The two fusion images with parallax are captured by the left eye and the right eye of the bio-inspired multimodal 3D endoscope respectively. (c) The encoding process of the 3D image in red & blue format. (d) A 3D image in red & blue format. See Visualization 1, Visualization 2, Visualization 3.

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& blue format. A 3D image in red & blue format shown in Fig. 6(d) could be got by replacing the red channel of the right fusion image with the green channel of the left fusion image. It is worth mentioning that the polarized 3D display is currently the best 3D display method. A polarized 3D format, such as side by side format (see Fig. S8 of Supplement 1), can be adopted when there is a polarization monitor or a virtual reality (VR) device. Further, the dynamic diffusion process of water droplets and ICG solution on the dust-free cloth under normal illumination was recorded in different modes (see Visualization 1, Visualization 2, Visualization 3 in supporting information). The software of images acquiring and 3D format encoding is completed in C/C++ and OpenCV.

The 3D image containing color and NIR fluorescence information can effectively guide the physicians to smoothly remove the tumor tissue without damaging healthy tissue. As an auxiliary, 2D color images, 2D NIR fluorescence images, and 3D color images could also be provided to doctors at the same time to help them make a better diagnosis.

3. Materials and methods

3.1. Design of the broad-band binocular optical system

The techniques for 3D endoscopic imaging mainly include dual chips at the tip, single-chip dual optical channels, structured light, and uniaxial 3D imaging with a monocular endoscope. To achieve simultaneous and real-time 3D imaging of both color and NIR fluorescence information, a single-chip dual optical channels method with an optical relay system was employed and a broad-band binocular optical system was developed whose ranges from 400nm to 1000nm. One prototype of the bio-inspired multimodal 3D endoscope, consisting of a dual-channel optics rigid borescope, an optical relay system, and a bio-inspired multiband sensor, is fabricated. By introducing an optical relay system, the focal planes after the dual-channel optics rigid borescope can be projected onto the focal plane of the imaging sensor. Only one optics rigid borescope needs to be designed, since the dual-channel optics rigid borescope consists of two identical optics rigid borescope. The distance between the stereoscopic lens, or called baseline, is 4 mm. The working distance of the endoscope is 5mm – 50mm, so a baseline of 4 mm can provide sufficient parallax. This 3D endoscope is an extension of the human eye. Its baseline and working distance are reduced in proportion to the human eye (The distance between the pupils of the eyes is about 16cm, and the distance range with obvious three-dimensional effect is 20cm-50m), in order to make the surgeon comfortable without dizziness.

The optical design parameters of the broad-band optical system are shown in Fig. 7. This broad-band binocular optical system consists of four parts: 30° viewing prism, imaging objective lens, relay cylinder lens group, and an optical relay system. Among them, the 30° viewing prism, the imaging objective lens, and the relay cylinder lens are all paired. The 30° viewing prism is responsible for deflecting the center axis of the field of view 30° downward, which is more conducive to the operation. The imaging objective lens is the core of the broad-band binocular optical system and completes the first imaging of the target. The relay cylinder lens group, which consists of 3 pairs of cylindrical lenses with a total length of 300mm, transmits the image formed by the imaging objective lens to the end of the endoscope. Finally, the optical relay system re-images the image transmitted by the relay cylinder lens on the multiband sensor. The transmittance of the broad-band binocular optical system is about 90% at 800 nm −1000 nm. Its field of view and focal length are 90° and 3.7 mm respectively. Figure 7(b) is the light path of the broad-band binocular optical system. To simplify the design, we only focus on one imaging objective lens and cylinder lens group. Figures 7(c) and 7(d) show the MTF, field curvature, and spot diagram respectively, indicating that the system has good imaging quality.

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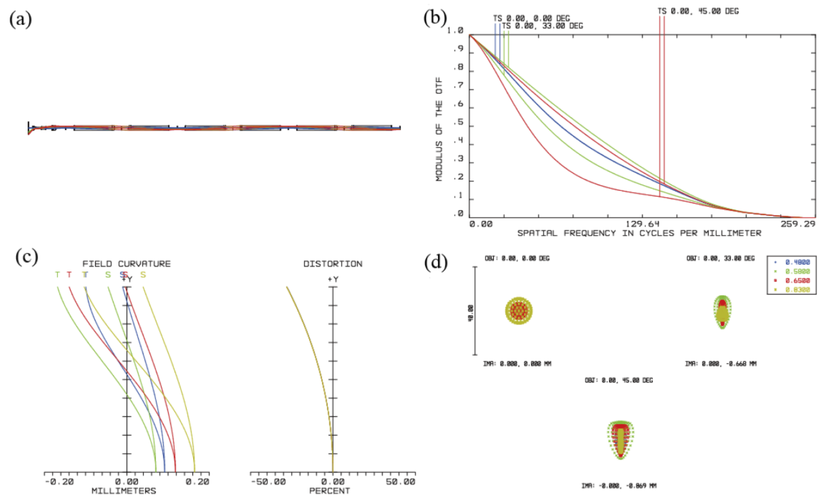

Fig. 7. The optical design parameters of the broad-band optical system. (a) Layout, (b)MTF, (c)Field curvature, (d)Spot diagram.

3.2. Multiband sensor bio-inspired by mantis shrimp's compound eye

The mantis shrimp possesses one of the most advanced and elegant visual systems in nature, capable of high polarization sensitivity and hyperspectral imaging. In the prototype of the bio-inspired multimodal 3D endoscope, a dichroic multiband sensor inspired by the mantis shrimp's compound eye was adopted as the imaging sensor. The schematic diagram of the dichroic multiband sensor is shown as Fig. 8(a). One custom dichroic filter array with four different spectral bands is integrated into the focal plane array at wafer-level to create area sensors that extract high-contrast spectral information at visible and infrared wavelengths. This dichroic filter array is customized and produced by Ocean Optics. It is integrated into a NIR enhancement CCD sensor (KAI-08052, ON SEMI) with pixel size of 5.5μm and a resolution of 3296×2472 to create a dichroic multiband sensor. The spectral sensitivity of the dichroic filter arrays of the bio-inspired multiband sensor is shown in Fig. 8(b). Three visible spectral bands of red, green, and blue are used to collect color information. The near-infrared filter arrays of 815nm long-wave pass are used to collect fluorescence information from ICG. Visible light and near-infrared signals

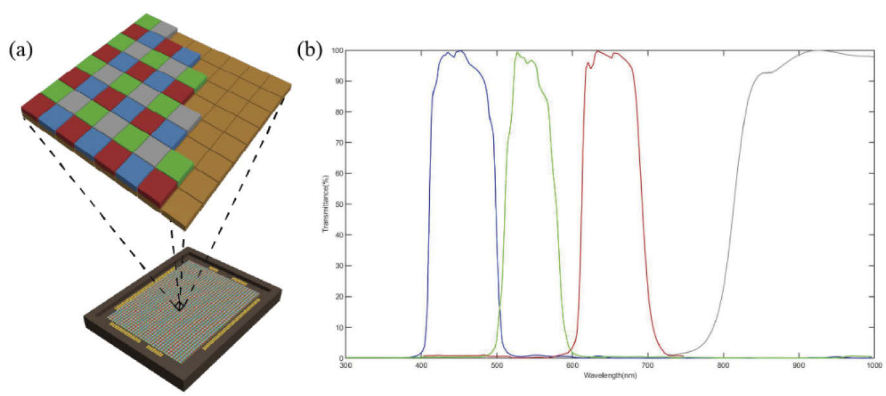

Fig. 8. (a)The dichroic bio-inspired multiband sensor and (b) Spectral sensitivity of the filter arrays of this bio-inspired multiband sensor.

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are detected by different pixels and do not interfere with each other. In particular, it is easy to integrate polarization imaging into this sensor so that it has good scalability.

4. Conclusion

In this study, a bio-inspired multimodal 3D endoscope system combining the features of human eyes and compound eyes of mantis shrimp is proposed. One prototype of the bio-inspired multimodal 3D endoscope has been fabricated and a series of experiments were designed to verify the performance of the prototype system. This prototype of the bio-inspired multimodal 3D endoscope system can achieve simultaneous and real-time overlay of color and NIR fluorescence 3D images. The resolution of this prototype can reach 7lp/mm and 4lp/mm respectively under visible and NIR illumination. This multimodal 3D endoscope can provide real-time feedback in the operating room and therefore can be widely used in image-guided and robotic surgery.

Although most of the work on this bio-inspired multimodal 3D endoscope has been done, it is still challenging for the coupling of white light source and excitation laser. Further, integrating polarization imaging into this bio-inspired multimodal 3D endoscope is another interesting direction. In the following research, a CMOS NIR enhancement sensor (NOIP1SN025KA-ENIR, ON SEMI, Pixel resolution 5120×5120) with higher pixel resolution will be adopted in order to further improve the spatial resolution and integrated polarization imaging. At the same time, pixel multiplexing can also be used to reduce pixel loss. The filter and polarizer can share one pixel, and then the corresponding information will be restored by algorithm.

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Disclosures

The authors declare no conflicts of interest.

See Supplement 1 for supporting content.

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