Continuously zoom imaging probe for the multi-resolution foveated laparoscope

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Abstract: In modern minimally invasive surgeries (MIS), standard laparoscopes suffer from the tradeoff between the spatial resolution and field of view (FOV). The inability of simultaneously acquiring high-resolution images for accurate operation and wide-angle overviews for situational awareness limits the efficiency and outcome of the MIS. A dual view multi-resolution foveated laparoscope (MRFL) which can simultaneously provide the surgeon with a high-resolution view as well as a wide-angle overview was proposed and demonstrated to have great potential for improving the MIS. Although experiment results demonstrated the high-magnification probe has an adequate magnification for viewing surgical details, the dual-view MRFL is limited to two fixed levels of magnifications. A fine adjustment of the magnification is highly desired for obtaining high resolution images with desired field coverage. In this paper, a high magnification probe with continuous zooming capability without any mechanical moving parts is demonstrated. By taking the advantages of two electrically tunable lenses, one for optical zoom and the other for image focus compensation, the optical magnification of the high-magnification probe varies from 2 × to 3 × compared with that of the wide-angle probe, while the focused object position stays the same as the wide-angle probe. The optical design and the tunable lens analysis are presented, followed by prototype demonstration.

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1. Introduction

Laparoscope accelerates the development of modern medical surgeries. It has become a standard instrument to perform a wide range of minimally invasive surgeries (MIS), such as cholecystectomy, appendectomy and hysterectomy [1]. The standard single-view laparoscope, however, suffers several limitations. One of the major limitations is the tradeoff between the limited field of view (FOV) for high spatial resolution versus the wide FOV for situational awareness but with diminished resolution [2]. Standard laparoscopes lack the ability to acquire both wide-angle and high-resolution images simultaneously through a single scope. This limitation introduces challenges when used in scenarios requiring both close-up views for details and wide-angle overviews for orientation and situational awareness during surgical maneuvers. Moreover, in the single port access (SPA) procedure, this limitation is more aggravated, since all the instruments are inserted through one shared trocar. The instruments conflict and tunnel vision make the SPA procedures quite challenging. It has been suggested that varying the optical magnification and making the laparoscope low profile can improve the efficiency and outcome of the SPA surgery [3].

In the MIS, it is highly desired for laparoscopes to provide surgeons a high resolution image of the operation field as well as a large peripheral field for situational awareness simultaneously. Because one major complication of the current laparoscopic surgery is the accidental damage on the unintended organs, and these damage is always unnoticeable to the surgeon due to the FOV-resolution tradeoff of the current laparoscope [3].

In recent years, several advanced laparoscopic or endoscopic technologies have been developed to address these limitations. For example, the compact ultra-high-definition endoscope [4] can reduce the instrument conflict while remaining high resolution, the zoom laparoscope [5,6] or zoom camera head [Stryker 1488 HD] can effectively change the optical magnification, thus change the field coverage and resolution; variable viewing direction laparoscopes [7,8] can change their view by varying its viewing direction optically or mechanically. None of these existing solutions, however, are able to simultaneously acquire both wide-angle images and high-resolution images. Therefore, in the current laparoscopic surgery, a camera assistant is still required to move the laparoscope forward for zoomed-in views and to move backward for situational awareness.

We proposed a multi-resolution foveated laparoscope (MRFL), which is capable of providing the surgeon with both a wide-angle view and a high-resolution view simultaneously though an integrated system [9]. The MRFL consists of two fully integrated imaging probes, a wide-angle probe and a high-magnification probe (foveated probe), and the two probes share the same objective lens group, multiple rod lens relay groups and a scanning lens group. Compared with a standard laparoscope, the wide-angle probe, at a working distance about 120mm, captures about 8 × surgical area with a similar spatial resolution; and the foveated probe acquires a similar field coverage but 3 × spatial resolution. The dual-view capability of the MRFL effectively solves the FOV-resolution tradeoff of a standard laparoscope, which promises great potentials in improving the efficiency and safety of MIS.

Although the foveated probe was demonstrated to offer an adequate magnification for viewing surgical details through an in-vivo evaluation with a porcine model [10], the existing MRFL prototype is limited to two fixed levels of magnifications. The fixed level of magnification limits the flexibility of obtaining a foveated view at an adequate magnification without turning to a manual maneuver of the instrument. A fine adjustment of the optical magnification is highly desired for the foveated probe to obtain views with a desired size of field coverage and spatial detail resolvability. For instance, since the optical magnification of the foveated probe of the existing MRFL prototype is 3 × as a standard laparoscope, it is...
sufficient to perform MIS procedures such as cholecystectomy and appendectomy. However, for surgeries like liver section and colon resection, larger field coverage may help the surgeon to perform the operation more efficiently.

In this paper, we present the design and prototype of a high-magnification probe with continuous zooming (2 × ~3 ×) capability, while the wide-angle probe of the MRFL remains the same as the existing prototype. The foveated zoom probe is able to adjust its optical magnification and keep focused on the same object without any mechanically moving part by applying two electrically tunable lenses. Thus no camera assistant is required to manipulate the entire laparoscope, and the ergonomic conflict between the surgeon and the camera assistant can be eliminated. To our best knowledge, this is the first time demonstration of an optical zoom laparoscope using two commercially available tunable lenses. This new imaging probe has great potential in improving the laparoscopic surgery.

The optical approach and the design challenges of the high-magnification zoom probe are presented in detail in Section 2, followed by the optical design and prototype demonstration in Section 3 and a preliminary evaluation of the optical performance and zooming capability in Section 4.

2. Optical approach

The key requirement of the zoomable MRFL is the ability to continuously vary the optical magnification and spatial resolution of the foveated probe without affecting the wide-angle view and to maintain the same focusing distance in the object space for different zoom positions. It is anticipated that the focusing distance of the wide-angle and foveated probes will remain the same and fixed once the scope is positioned at its desired working distance. This requirement imposes a major challenge because varying the optical power for zoom inevitably causes a change of object-image conjugate planes, which results in a change of focusing distance in the object space or a change of the detector plane position in the image space. If not appropriately compensated, varying the optical power of the foveated probe alone may cause severe mismatch of focused object between the wide-angle and foveated probes and cause image blurry during zooming.

The schematic layout of the foveated probe with continuous optical zooming and autofocus capabilities is shown in Fig. 1, in which both the focusing distance in the object space and the detector plane maintain fixed with no mechanically moving parts. It consists of two electrically-controlled tunable lens groups and an imaging lens. The two tunable lens groups form a Keplerian telescope. By properly adjusting the focal lengths of these two tunable lens groups, making the sum of the focal lengths equal to a constant, the optical magnification can be tuned without changing the object distance or imaging distance. The rays in solid lines in Fig. 1 illustrate a lower optical magnification than those rays in dashed lines.

![Fig. 1. Schematic layout of the zoom probe design in MRFL system.](image)

The equivalent focal length of the zoom probe is calculated by Eq. (1), where $f_{TL1}$ and $f_{TL2}$ are the focal lengths of the first and second tunable lens group, respectively; and $f_{img}$ is the focal length of the imaging lens.

$$f_{eq} = f_{TL1} + f_{TL2} + f_{img}$$
The overall zoom ratio of the foveated probe is defined by the ratio between the focal length of the zoom probe and that of the wide-angle probe. Given that the desired zoom ratio is $2 \times \sim 3 \times$ and the focal length of the wide-angle probe is 30mm in our existing MRFL prototype [9], the focal length of the zoom probe varies from 60mm to 90mm, corresponding to the $2 \times$ and $3 \times$ zoom ratio, respectively. In order to make the probe compact, the focal length of the imaging lens is specified to be 15mm. Therefore the magnification of the Keplerian telescope, which can be simply calculated by $m = -f_{TL2}/f_{TL1}$, should vary from $-1/4$ to $-1/6$.

$$f_{zoom} = \frac{f_{TL1}}{f_{TL2}} \times f_{img}$$  \hspace{1cm} (1)$$

Fig. 2. Field coverage of zoomable foveated probe at two different zoom ratios in comparison to the field coverage of the wide-angle probe.

The corresponding field coverage of the two extreme magnifications, i.e. $2 \times$ and $3 \times$, is shown in Fig. 2. The blue rectangle shows a field coverage of $160 \times 120$mm$^2$, which is field coverage of the wide-angle probe at a 120mm working distance. The red rectangle and the green rectangle indicate the field coverage of the zoom probe of $2 \times$ and $3 \times$ zoom ratio, respectively. At the $2 \times$ zoom ratio, the field coverage is about $80 \times 60$mm$^2$, which is about 1/4 of the wide-angle probe. At $3 \times$ zoom ratio, the field coverage is about $53.7 \times 40$mm$^2$, which is about 1/9 of the wide-angle probe.

The tunable lenses used are Optotune EL-10-30-LD., which has a focal range of 40mm to 120mm. In order to achieve the magnification from $-1/6$ to $-1/4$, offset lenses are added to each tunable lens, therefore the focal range of each tunable lens group can be adjust based on the focal lengths of the offset lenses. Figure 3(a) and 3(b) show the focal range of the tunable lens groups as a function of the focal length of the offset lenses. The calculation is based on Gaussian optics and assuming the offset lens is assumed to be in contact with the tunable lens.
As indicated in Fig. 3, the shorter the focal length of the tunable lens group, the smaller the focal range is. Since the spacing between the tunable lens groups is a constant, the change of focal length of each tunable lens group is the same but with different signs. In addition, since the magnification of the telescope varies from $-1/6$ to $-1/4$, the second tunable group requires a smaller focal length. We first specified the focal length of the second tunable lens group to be 15mm for the zoom ratio of $2 \times$, and then determined the focal length of the first tunable lens group to be 60mm. As a result, the spacing between the two tunable lens groups is 75mm. For the zoom ratio of $3 \times$, the focal lengths of the first and second tunable lens groups should be 81.43mm and 13.57mm, respectively. As shown in Fig. 3, an offset lens with a focal length of 20mm can be used in the second tunable group to achieve the required focal range. For the first tunable group, the offset lens choice is quite flexible, because it does not make use of the full focal range of the tunable lens.

3. Optical design and system prototype

The most challenging aspect of the zoom probe design is the aberration correction across the zoom range while fixing the object or image distance. In addition, since the zoom probe can be scanned and registered within the wide-angle view, it needs to correct the aberrations of those peripheral fields as well. In order to cut the budget and reduce the delivery time, we decided to design the zoom probe by using off-the-shelf lenses, which raised another challenge. Although lens vendors such as Edmund Optics, Ross Optical and Thorlabs have plenty choices for off-the-shelf lenses, the lens shapes are limited to plano-convex, plano-concave, double convex and double concave. Additionally, the glass choices are quite narrow. Most singlets are made from BK7, and some lenses with large optical power are made from flint glasses such as SF4 or SF5. Moreover, the doublet choices are limited. Therefore it is quite challenging to achieve design with a near-diffraction limited performance.

The foveated imaging probe of the MRFL system with the optimized zoom probe is shown in Fig. 4. As discussed in the previous section, the two tunable lens groups form a Keplerian telescope which is capable of continuous zooming and autofocusing. Besides the tunable lenses, all other lenses in the zoom probe are off-the-shelf lenses from Edmund Optics and Ross Optical. In the first tunable group, a plano-convex lens is inserted between the tunable lens and the beam splitter to reduce the beam diameter such that the converging beam diameter is smaller than the 10-mm clear aperture of the tunable lens. The plano-concave lens behind the tunable lens adds the adequate optical power to the first tunable group and corrects the spherical aberration to some extent. In the second tunable group, a doublet with a strongly curved middle surface is placed near the relayed pupil location, in
order to correct the chromatic aberration and sphero-chromatism. In the imaging lens group, a plano-concave lens and a plano-convex lens were used to correct the field curvature and astigmatism.

The MTF performance of the zoom probe is demonstrated in Fig. 5. Figure 5(a) shows the polychromatic MTF at the 3 × zoom ratio for sampled fields of 0°, 4.4°, 6.3°, 9.3°, 13°, when the foveated probe is aimed at the central 26° FOV, corresponding to a 0° scanning angle [9]. Figure 5(b) summarizes the MTF performance across the zoom range (2 × ~ 3 ×) for both the 0° and the maximum 26.6° scanning angle. Each curve is the average MTF of a specific zoom ratio and scan angle and is averaged across the 5 sampled field angles in both tangential and sagittal directions. For instance, the curve for the 3 × peripheral FOV corresponds to the average MTF within a 26° FOV with the scanner steered toward the 26° and the tunable lenses set for 3 × optical zoom. As indicated by the figure, all the fields and zooms have a similar near-diffraction limited performance.

The 3D model of the zoom MRFL is shown in Fig. 6. The zoom probe is mounted by the cage system from Edmund Optics, and all the lens mounts are 3D printed by QuickParts using the stereolithography. The lenses are UV cured with the 3D printed lens mounts. The total cost of the zoom probe alone is less than $1500, because all the components including the optics are off-the-shelf-components. For comparison, we quoted another design with all
customized lenses, and it costed about $10,000 and the delivery time was more than 1 month. In the next section, the performance of the zoom probe will be demonstrated. Moreover it also demonstrates the capability of off-the-shelf lenses to build high quality optical system.

Fig. 6. 3D model of the zoom MRFL.

4. Performance evaluation

A US1951 resolution target was used to test the resolution of the zoom probe. The resolution target is located at optimized 120mm working distance. Figures 7(a) to 7(d) demonstrate the resolution of the zoom probe of four different zoom ratios from $2 \times$ to $3 \times$. As shown in the figures, the best resolvable bar images vary from element 3 group 2 (5.04lp/mm) for the $2 \times$ zoom to element 6 group 2 (7.13lp/mm) for the $3 \times$ zoom ratio. The corresponding image contrast of resolution target at different zoom ratio is summarized in Table 1, Table 2, Table 3, and Table 4.

Figures 8(a) to 8(d) demonstrate the field of view coverage corresponding to four different zoom ratios from $2 \times$ to $3 \times$. A bladder model was used as the object, and was placed at 120mm working distance. To be noted, as the field coverage changes due to the action of varying the optical magnification of the zoom probe, the bladder model is always in focus which demonstrates the auto-focus capability of the probe.

Fig. 7. USAF 1951 resolution target images at different zoom ratios: (a) $2 \times$ zoom; (b) $2.33 \times$ zoom; (c) $2.67 \times$ zoom (d) $3 \times$ zoom.
Table 1. Image Contrast of the Zoom Probe at 3 × Zoom Ratio

| Contrast | G2 E6 (7.13lp/mm) | G2 E5 (6.35lp/mm) | G2 E4 (5.66lp/mm) | G2 E3 (5.04lp/mm) | G2 E2 (4.49lp/mm) |
|----------|------------------|------------------|------------------|------------------|------------------|
| Vertical | 0.2000           | 0.2174           | 0.2308           | 0.3103           | 0.3421           |
| Horizontal | 0.2281       | 0.2800           | 0.2958           | 0.3287           | 0.4286           |

Table 2. Image Contrast of the Zoom Probe at 2.67 × Zoom Ratio

| Contrast | G2 E6 (7.13lp/mm) | G2 E5 (6.35lp/mm) | G2 E4 (5.66lp/mm) | G2 E3 (5.04lp/mm) | G2 E2 (4.49lp/mm) |
|----------|------------------|------------------|------------------|------------------|------------------|
| Vertical | 0.1807           | 0.1923           | 0.2174           | 0.2683           | 0.3115           |
| Horizontal | 0.1892      | 0.2157           | 0.2364           | 0.3010           | 0.3462           |

Table 3. Image Contrast of the Zoom Probe at 2.33 × Zoom Ratio

| Contrast | G2 E3 (5.04lp/mm) | G2 E2 (4.49lp/mm) | G1 E6 (3.56lp/mm) | G1 E5 (3.17lp/mm) | G1 E4 (2.83lp/mm) |
|----------|------------------|------------------|------------------|------------------|------------------|
| Vertical | 0.1005           | 0.1592           | 0.3281           | 0.3521           | 0.3846           |
| Horizontal | 0.1519      | 0.1837           | 0.3617           | 0.4118           | 0.4379           |

Table 4. Image Contrast of the Zoom Probe at 2 × Zoom Ratio

| Contrast | G2 E3 (5.04lp/mm) | G2 E2 (4.49lp/mm) | G1 E6 (3.56lp/mm) | G1 E5 (3.17lp/mm) | G1 E4 (2.83lp/mm) |
|----------|------------------|------------------|------------------|------------------|------------------|
| Vertical | 0.0469           | 0.1667           | 0.3000           | 0.3500           | 0.3725           |
| Horizontal | 0.1379      | 0.1667           | 0.3277           | 0.3481           | 0.4091           |

Fig. 8. Images of a bladder model of at different zoom ratios: (a) (a) 2 × zoom; (b) 2.33 × zoom; (c) 2.67 × zoom (d) 3 × zoom.

5. Conclusion

In conclusion, we have developed a high-magnification zoom probe for the multi-resolution foveated laparoscope, which can effectively change the optical magnification and field coverage of the high-resolution view, while maintaining a fixed imaging distance. Two commercially available tunable lenses were implemented in the design, so that no mechanical moving parts are needed to achieve the zooming and auto-focusing functions. The zoom ratio of this probe varies from 2 × to 3 × . The corresponding field coverage varies from 80 × 60mm² to 53.7 × 40mm², and the maximum resolution varies between 5.04lp/mm and 8.98lp/mm in object space at a 120mm working distance. The zoom and auto-focusing capabilities will further improve the maneuverability of the dual-view multi-resolution foveated laparoscope, and make it adaptable to more types of minimally invasive surgeries.

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