Published in final edited form as:

Appl Opt. 2016 April 10; 55(11): 3058–3068.

Optical design and system engineering of a multiresolution foveated laparoscope

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Abstract

The trade-off between the spatial resolution and field of view is one major limitation of state-of-the-art laparoscopes. In order to address this limitation, we demonstrated a multiresolution foveated laparoscope (MRFL) which is capable of simultaneously capturing both a wide-angle overview for situational awareness and a high-resolution zoomed-in view for accurate surgical operation. In this paper, we focus on presenting the optical design and system engineering process for developing the MRFL prototype. More specifically, the first-order specifications and properties of the optical system are discussed, followed by a detailed discussion on the optical design strategy and procedures of each subsystem. The optical performance of the final system, including diffraction efficiency, tolerance analysis, stray light and ghost image, is fully analyzed. Finally, the prototype assembly process and the final prototype are demonstrated.

1. INTRODUCTION

Laparoscopes, which provide surgeons with the vision of the surgical field inside a human body, have been playing important roles in modern minimally invasive surgeries. The performance and quality of the laparoscope directly affect the surgical outcome. The state-of-the-art laparoscope suffers a number of major limitations, one of which is the trade-off of the limited instantaneous field of view (FOV) for high spatial resolution versus the wide FOV but diminished resolution [1]. It is unable to acquire both the high-resolution and the wide-angle images simultaneously. This limitation raises a series of problems, such as situational awareness issue, ergonomic conflict, and instruments collision [2,3]. Although the zoom camera head [www.stryker.com] and other new laparoscope technologies [4,5] have been developed to improve the laparoscopic surgery by changing the optical magnification or viewing directions, they still cannot capture both a wide-angle view and a high-resolution view simultaneously.

Aiming to address those limitations, we proposed a multi-resolution foveated laparoscope (MRFL), which is able to capture a wide-angle overview as well as a high-magnification zoomed-in view simultaneously [6]. The characterization and *in vivo* evaluation of the

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OCIS codes: (080.2740) Geometric optical design; (170.2150) Endoscopic imaging; (170.3880) Medical and biological imaging; (220.1000) Aberration compensation; (220.0220) Optical design and fabrication.

MRFL prototype has been demonstrated [7]. In summary, an MRFL has two imaging probes, a high-magnification probe and a wide-angle probe, integrated in a compact system. Figure 1 shows the optical layout of an MRFL prototype with a short length profile. In the front end, the two imaging probes share the objective lens, multiple relay lens groups, and the scanning lenses. The objective lens captures an 80° FOV at a nominal 120 mm working distance (WD); then the intermediate image is relayed by multiple identical rod relay lens groups to enable flexible length profile (e.g., two groups of relay lenses create a low-profile scope with an insertion length about 150 mm). The scanning lens group works like an eyepiece and collimates the intermediate image for further imaging. At the far end next to the scanning lens group, a polarizing beam splitter (PBS) splits the optical path into two polarization states: the reflected s-polarized light for the wide-angle probe and the transmitted p-polarized light for the high-magnification probe. In the transmission path, a two-axis scanning mirror is placed at the pupil conjugate position to steer the imaging field of the high-magnification probe toward a region of interest. A quarter-wave plate (QWP) is inserted in front of the scanning mirror with its axis at 45° with respect to the tangential plane. The transmitted p-polarized light becomes s-polarized light after double passing the QWP and reflected by the mirror, and is directed toward the high-magnification probe.

The insertion length of the MRFL is proportional to the number of relay groups. Two prototypes with different insertion lengths were designed and built. The standard length profile MRFL has about 300 mm insertion length, which is similar to that of a standard laparoscope, with four rod relay groups for a standard multiport laparoscopic procedure. The short length profile MRFL has an insertion length of 150 mm, which can help reduce the conflicts with other surgical instruments and the need for additional incisions, with two rod relay groups.

Compared with a standard laparoscope, the dual-view MRFL has a larger working distance (~120 mm) than a standard one (~50 mm), which enables the wide-angle probe to capture an 8× larger surgical area. In addition, by designing an optical system with a much larger throughput, the high-magnification probe captures a similar surgical area to a standard laparoscope but with 3× better spatial resolution. Therefore the MRFL can afford the surgeon with a clear vision from the high-magnification probe with finer details and an overview from the wide-angle probe for situational awareness.

While our previous work [6,7] focused on demonstration of the MRFL system capabilities and its potential clinical applications, this paper will concentrate on the detailed optical design procedure and system engineering challenges, from developing the first-order system specifications and analysis to the optical design strategies and optical system tolerance analysis. The rest of the paper is organized as follows. Section 2 will detail the process of developing the first-order system specifications and properties primarily driven by the clinical applications and choices of key components. Based on these system requirements, Section 3 will present the detailed design strategy and optimization procedure for each suboptical system including the objective lens group, the relay lens group, the scanning lens group, the wide-angle probe, and the high-magnification probe. Section 4 will analyze the key performances of the resulted optical system, including the diffraction analysis of a diffractive optical element used in the design, the tolerance analysis, the stray light and ghost

image analysis. The last section will demonstrate the mechanical design and the prototype of the MRFL system.

2. FIRST-ORDER SYSTEM PROPERTIES AND SPECIFICATIONS

Most of the MRFL system specifications were driven by the clinical objectives and requirements to be met through this research development and this section will focus on articulating how the critical system specifications, including FOV, resolution, magnification, light throughput, as well as the optical allocations, were developed through analytical understanding of the clinical requirements.

A standard laparoscope usually has a FOV of 70° and an optimized WD of 50 mm. At its optimized WD, the visible surgical area is approximately 56 mm × 42 mm, with a spatial resolution of 2.1 line pairs per millimeter (lp/mm) [8]. The ultimate goal of the MRFL development is to provide the ability to survey a large surgical field for improved situational awareness and to visualize a targeted area in high spatial resolvability for surgical treatment, without having to maneuver the instrument in and out as with a standard laparoscope. More specifically, compared to a standard laparoscope, the wide-angle probe of the MRFL aims to achieve a similar spatial resolution but covers an 8×–9× larger surgical area; and the high-magnification probe aims to provide a 3× better spatial resolution and a similar surgical area. Based on these clinical requirements, the overall system is specified to have a working distance of 120 mm, an angular FOV of 80° for the wide-angle probe, and a 26° FOV for the high-magnification probe, which is about 1/3 of the wide-angle FOV. As a result, the wide-angle probe captures a surgical area of 160 mm × 120 mm, while the high-magnification probe captures a surgical area of 53 mm × 40 mm, which is similar to a standard laparoscope.

The spatial resolution of a laparoscope is determined by two factors: one is the numerical aperture (NA) of the system, which sets the diffraction limit, and the other is the pixel size of the imaging sensor. For a laparoscope, it is convenient to characterize its spatial resolution in the object space. The NA of a laparoscope in the object space can be approximated by the ratio between the entrance pupil diameter (EPD) and the WD of the objective lens. In order to achieve a 3× better spatial resolution (at least 6 lp/mm in the object space) for the high-magnification probe than a standard laparoscope, the EPD of the objective lens was set to be 0.8 mm. The cutoff frequency in the object space can be calculated by Eq. (1):

$$f_{\text{cutoff}}|_{\text{obj}} = \frac{2NA}{\lambda} \approx \frac{EPD}{\lambda \times WD} = \frac{0.8 \text{ mm}}{0.55 \mu\text{m} \times 120 \text{ mm}} = 12.12 \text{ lp/mm}. \quad (1)$$

With the cutoff frequency of 12 lp/mm in the object space, we anticipate high image contrast at the desired resolution of 6 lp/mm. It is worth noting that the EPD of a standard laparoscope is less than 0.3 mm, which suggests that the MRFL with a 0.8 mm EPD has 7× more light collection capability than a standard laparoscope. Such a large throughput will make the optical system design quite challenging.

In the prototype, two 1/3 in. imaging sensors (Pointgrey DragonFly II 1280 × 960 pixels) are used for both imaging probes. The diagonal size of the sensor is 6 mm with a pixel size of 3.75 μm, which yields a sampling frequency of 133.3 lp/mm in the image space. Based on the combination of system and sensor specifications, the transverse magnification, the image-space working $F/\#_w$, and the image-space cutoff frequency of the high-magnification probe are calculated according to Eqs. (2)–(4). The resulting image-space cutoff frequency of 114.9 lp/mm is slightly lower than that of the sensor actual sampling frequency, which suggests that the high-magnification probe is limited by the optical system rather than sampling. In order to achieve the desired 6 lp/mm resolution in object space, the optical system will be optimized and evaluated for the performance of 60 lp/mm in the image space for the rest of sections:

$$|m_{\text{high-mag}}| = \frac{h_{\text{sensor}}}{WD \times \tan(HFOV/3)} = \frac{6/2}{120 \times (\tan 40^\circ/3)} = 0.1055, \quad (2)$$

$$F/\#_w = WD/EPD \times |m_{\text{high-mag}}| = 120/0.8 \times 0.1055 = F/15.82, \quad (3)$$

$$f_{\text{cutoff}}|_{\text{img}} = \frac{1}{\lambda F/\#_w} = 114.9 \text{ lp/mm}. \quad (4)$$

The focal length and NA of the objective lens is another important parameter to determine at the early design stage. In the MRFL system design, these parameters are strictly constrained by the maximally allowable lens diameter in order to meet the requirement for a standard 10 mm diameter package for housing the objective and relay lens groups as well as the illumination fibers. We adopted a standard laparoscope packaging from Precision Optical Cooperation, which dictates the maximum lens diameter to be 5.6 mm. In addition, the objective lens is required to be telecentric in the image space, thus the image quality will not degrade after multiple relay groups. By considering all these constraints, the focal length of the objective lens is specified to be 2 mm, resulting in an image-space NA of 0.2. Using first-order optics, the diameter of the objective lens group is 4.16 mm, which meets the lens diameter requirement and will fit into the laparoscope tube.

The objective lens group is followed by multiple sets of identical relay lens groups. Most patented relay lenses for a laparoscope have an NA of 0.1 and a total length less than 45 mm [9,10]. In the MRFL system design, in order to reduce the total cost as well assembly challenges, we aimed to push the length of each relay group to be larger than 80 mm so that only two sets of relays are needed for the low-profile MRFL and four sets of relays for the standard-profile MRFL. Since the relay lens is used to relay the intermediate image formed by the objective lens, its object height should match the image height of the objective lens; its entrance pupil should match the exit pupil of the objective lens, and its NA should also match the 0.2 NA of the objective lens. Such a substantially larger NA and longer profile

length than relays used in standard laparoscopes add another level of challenge to the overall optical system design.

Following the relay lenses is the scanning lens group, which not only serves the function of a common eyepiece used in the standard laparoscope but also relays the pupil onto the 2D scanning mirror for the high-magnification imaging probe. Due to the insertion of a PBS between the scanning lens and the mirror, a large pupil clearance is required. After a preliminary trade study to balance the requirements for space, performance, and overall compactness, a 14 mm focal length was selected for the scanning lens group.

Finally, the focal lengths of the wide-angle and high-magnification imaging lenses are determined according to the specifications of the overall system as well as the objective, relay, and scanning lens groups. As a result, the focal length of the wide-angle probe is set to be 30 mm, while the focal length of the high-magnification probe is set to be 90 mm to achieve $3\times$ magnification over the wide-angle probe. Table 1 summarizes the first-order properties and the specifications of the MRFL.

3. DESIGN STRATEGY AND OPTIMIZATION PROCEDURE

As discussed in the previous sections, the optical design of the MRFL system consists of five mutually dependent subsystems, including the objective lens group, the telecentric rod relay lens groups, scanning lens groups, the high-resolution imaging probe, and the wide-angle imaging probe. A successful optical design of such a complex optical system requires taking into account a wide range of system design constraints and performance requirements. In this section, we mainly focus on our optical design and optimization strategies and the key design procedures.

A. Design Strategy

Although the optical design of each suboptical system is well known, the optical design of the MRFL system is a challenging task due to its large throughput, limited lens diameter, and the complex interaction among the subsystems.

Overall, we adopted a “divide and conquer” design strategy, illustrated in Fig. 2. This strategy enabled us to carry out the optimization of the key lens groups in the MRFL system, including the objective, relay and scanning lenses, in parallel before they were ready to be integrated. At the initial design phase, the shared objective lens, relay lens, and the scanning lens were designed and optimized separately, which allowed us to find best solutions to the subsystems by applying our knowledge and experiences with these well-known lens forms, rather than directly venturing into a complex system. Once good designs were found for these subsystems, the objective lens and the multiple groups of relay lenses were combined for further optimization. Meanwhile, a well-corrected scanning lens was combined and optimized together with the imaging lens group for the high-magnification probe. Following a good design for a combined objective-relay group, the objective lens, multiple groups of relay lenses, scanning lens, and high-magnification probe were integrated and optimized all together. In the last step, by fixing the designs of the objective, relay and scanning lenses, the imaging lens for the wide-angle probe was optimized.

In the process of optimizing the individual subsystems, aside from accounting for the various performance requirements, we identified the key constraints that must be satisfied in order to meet the optical and mechanical requirements of the integrated system. For instance, strict telecentricity requirement was enforced for the designs of the objective lens as well as the relay lens, which helps to ensure minimum amount of image quality degradation when the objective and multiple groups of relay lenses were combined. Choosing a proper starting point for each subsystem is a critical consideration. It can not only achieve better performance, but also reduce the optimization cycles. The objective lens group requires a large FOV and large entrance pupil, therefore we selected an inverse telephoto lens type.

For the relay lens group, we chose a symmetric configuration, with each half being a Petzval lens type. Since the magnification of each relay group is -1 , a symmetric lens can naturally correct odd-order aberrations, such as coma and distortion. In addition, Petzval lens type can achieve a good performance for a large numerical aperture and also correct field curvature [10]. The field curvature should be correct at each intermediate image, because the field curvature accumulates as the number of relays increases.

The scanning lens is similar to an eyepiece but with a much larger pupil clearance for the insertion of a PBS and other components. In order to correct the higher-order aberrations and axial chromatic aberration accumulated from the multiple relay lenses, an aspheric refractive-diffractive plastic lens is applied in the scanning lens group.

The high-magnification imaging probe and the wide-angle imaging probe are relatively simple compared to the other lens groups. Although the high-magnification probe needs a diffraction-limited performance, it only captures 1/9 of the entire surgical area. The wide-angle probe, capturing the entire surgical field, does not require a diffraction-limited performance as the sampling frequency of the sensor is much lower than the cutoff frequency of the optical system.

B. Optimization Procedure

1. Objective Lens—The objective lens captures an 80° FOV and is shared by the wide-angle probe as well as the high-magnification probe. As stated in Section 2, it requires a diffraction-limited performance. A U.S. patent by Murayama [US 7,379,252 B2] was selected as the starting point, because it is a typical inverse telephoto lens. The $F\#$ of this patent lens is larger than $F\#6.9$, with a FOV of 140° . The throughput of the patent lens is calculated by Eq. (5):

$$A\Omega = (WD \times \tan(HFOV))^2 \times \pi \left(\tan^{-1} \left(\frac{EPD}{2WD} \right) \right)^2. \quad (5)$$

Our goal is to design an objective lens of $F\#2.5$, with a FOV of 80° . The patent lens has throughput of 0.0347, which is less than the required throughput of 0.3539 of our objective lens. After several initial optimization trials, it was found the lens form was inadequate in correcting spherical aberration and chromatic aberrations. Therefore we decided to add a

lens before the stop and a doublet behind the stop. After further optimization, with the constraints on the effective focal length (EFL), telecentricity in image space, lens diameter and image clearance, the performance was improved significantly. The lens layout and the polychromatic modulation transfer function (MTF) plots were shown in Fig. 3.

One key problem of this objective design, however, is the large image distortion, which is about -24% . Distortion is a field-dependent magnification error, and our MRFL system needs to provide a high-resolution image of the entire FOV, we constrained the distortion to be less than -17% . Another limitation of this design is the large incident angle on the last lens, which could potentially increase the difficulty of assembling. Therefore, another lens was added to split the power of the last lens. The optimized objective lens is shown in Fig. 4. All the fields have good performance and the chief ray angle of each field on the image plane is less than 0.1° , which indicates the objective lens has great telecentricity in image space.

2. Relay Lens—As described in the design strategy, we chose the Petzval lens type for the half of the relay lens group. In order to increase the length of the relay lens, the doublets were optimized to a rod lens type. Optimization constraints were added on the lens diameter and telecentricity in image space. Figure 5 shows an initial design of half of one relay group. The optical path difference (OPD) plot indicates the main residual aberrations are coma and lateral colors, which will be naturally corrected in a symmetric system.

The optimized relay group achieved a diffraction-limited performance, as shown in Fig. 6. The total length of the relay is 80 mm, with outstanding telecentricity in image space. The angles of incidence of the chief rays of all five sampled fields are constrained to be less than 0.01° , which enables the flexibility of concatenating several groups of the same relay lens to create MRFL systems of different length profile. As shown in Fig. 7, there is no distortion due to the symmetry of the lens structure. The residual high-order field curvature will be corrected when optimized together with the objective lens group [10].

One thing to be noted is that due to the long length of the relay group, the refractive indices of all the lenses are larger than 1.58. The relay length can be increased by a factor of n , where n is the index of the rod lens [10,11]. The flint meniscus lenses at both ends are used to correct the field curvature and astigmatism. The indices of the first doublet are close to each other, thus the middle surface can correct the higher-order spherical aberrations. The other doublet is a conventional doublet, which is composed of a crown and a flint lenses to correct the axial chromatic aberration.

3. Integration of the Objective and Relay Lenses—Following the separate design of the objective lens and relay lens with good performance, as suggested in Fig. 2, the objective lens together with the multiple relay lenses are integrated together for further optimization. When integrating the designs of the objective and relay lenses in Figs. 3 and 6, one major problem was that the accumulated axial chromatic aberration and spherical aberration degraded the performance significantly. As shown in Fig. 8, the MTF performance drops a significant amount, as the number of relays increases. By interpreting the OPD fans shown

in Fig. 9, we identify the main residual aberrations are the axial color and spherochromatism.

Due to the low $F\#$ and large FOV, it was difficult to compensate these accumulated aberrations from the multiple relay groups by overcorrecting the objective lens. Therefore, we planned to correct them by overcorrecting the scanning lens.

4. Scanning Lens—Two doublets were selected as the starting point for the scanning lens design. A perfect lens model with a focal length of 90 mm was used to simulate the high-magnification probe. The initial result is shown in Fig. 10. The second doublet has an air gap which can effectively correct the higher-order aberrations. During the optimization, constraints were added on the angle of incidence of the marginal rays to make the light beams well collimated at the stop location. The pupil clearance was also constrained so that a polarization beam splitter can be fit in. The MTF curve indicates its performance is nearly diffraction limited and this design form was chosen as the starting point for further design of the high-magnification probe.

5. High-Magnification Probe—A triplet was selected for the high-magnification probe, as shown in Fig. 11. It was optimized with the scanning lens. The MTF curves of the central FOV and the peripheral FOV show that the high-magnification probe has near-diffraction-limited performance over the scan range.

Although the performance of the high-magnification probe is near-diffraction-limited, when the objective lens and relay lens groups were added to the system, the performance dropped significantly. The MTF performances of the high-magnification probe with four sets of relay are shown in Fig. 12. It was difficult to compensate those residual aberrations by the scanning lens group, so we decided to use a plastic refractive-diffractive hybrid lens to correct them. The diffractive optical element (DOE) has opposite dispersion, which is effective for chromatic aberration correction. In addition, a plastic lens can be manufactured by a diamond turning machine, thus we can take the advantage of aspheric surface to correct the residual aberrations [12].

The optimized high-magnification probe of the MRFL with four sets of relay groups is shown in Fig. 13. The MTF curves demonstrate the system has near-diffraction-limited performance and the image contrast at the spatial frequency of 60 lp/mm is greater than 0.2 for the central FOV and 0.1 when the scanning mirror is steered toward the peripheral FOV.

6. Wide-Angle Probe—The design of the wide-angle probe is straightforward compared to the high-magnification probe, because the magnification of the wide-angle probe is smaller and it does not require a diffraction-limited performance. As shown in Fig. 14, a doublet and a field lens can make the performance good enough. The MTF shows the contrast is greater than 0.3 at the frequency of 60 lp/mm.

4. PERFORMANCE ANALYSIS

The previous section shows the optimized design of the MRFL system can meet the performance requirements as stated in Section 2. In this section, a detailed analysis of the

MRFL is carried out to demonstrate the MRFL prototype would have the required as-built performance accounting for fabrication and assembly errors. First of all, the diffraction efficiency of the DOE versus the lens radius and wavelengths is shown. Second, the tolerance analysis is demonstrated. Finally, the stray light and ghost image analysis are performed by nonsequential ray tracing in LightTools.

A. DOE Analysis

The diffractive lens has great advantage in correcting chromatic aberrations but the diffraction efficiency varies with the lens radius and the wavelength. A properly working DOE needs to have a good diffraction efficiency across the lens surface and the working spectral range.

In a kinoform diffractive optical element, the physical features become finer toward the lens edge, and the diffraction efficiency at the lens edge is typically lower than that of the lens center. Figure 15 shows the diffraction efficiency as a function of the radius of the diffractive surface at the designed wavelength 550 nm. The overall efficiency varies from 98.7% to 98.5% when the physical feature reaches the maximum diffractive surface radius of 2.5 mm.

On the other hand, the diffraction efficiency is also a function of wavelength as well as profile accuracy. Figure 16 shows that the diffraction efficiency of the DOE varies from 80% to nearly 100% across the visible range and the DOE profile is approximated by a 16-level binary mask, which yields a good approximation of the kinoform DOE manufactured by a diamond turning machine.

B. Tolerance Analysis

The tolerance analysis of the MRFL is complicated, since a standard length profile MRFL has more than 90 optical surfaces and a short length profile MRFL has more than 70 optical surfaces. Even when each surface has a small amount of error, these errors are accumulated through all the lenses and can degrade the final image quality significantly. Therefore the compensator strategy is very critical to achieve the required performance.

The manufacturing errors were set as shown in Table 2. These tolerances are based on the precision-level fabrication process by Optimax, which fabricated all the lenses for the MRFL prototypes except the plastic DOE lens. In order to compensate the errors in glass materials, lens radii and center thicknesses, all intermediate image and the final image positions along the optical axis were set as the compensators. To compensate those nonsymmetrical errors, such as lens wedge and barrel tilt, the first meniscus lens of each relay lens group and the final image plane are allowed to tilt some amount. These meniscus lenses are close to the intermediate images, therefore it is more sensitive to those tilting errors. In the assembly procedure, we first assembled the objective lens, adjusted the compensators of the objective lens group to make the image quality meet the requirement. Then we added the first relay group, only adjusted the compensators of that relay group to fine tune the image quality. We repeated the same procedures for the other relay groups and the two imaging groups. In this way, each compensator was independent and the system has more degrees of freedom to get better quality.

The MTF performance was used as the merit function in the tolerance process [13]. Figures 17(a) and 17(b) demonstrate the cumulative probability plots of the MTF of 60 lp/mm of the central FOV and the peripheral FOV, respectively. Figures 17(c) and 17(d) show the tolerance result of the MTF of 30 lp/mm of the central and peripheral FOV. The MTF degradation of all the sampled fields is less than 0.05 at 99.7% (± 3 sigma) probability for both frequencies of 30 lp/mm and 60 lp/mm. Therefore by properly adjusting those compensators, the assembled MRFL is expected to achieve the required as-built performance.

C. Stray Light and Ghost Image Analysis

Stray light and ghost image analysis is necessary for building an optical system, since these issues can degrade the performance of the real optical system. A nonsequential model of the MRFL with a standard length profile is built using LightTools. Stray light may come from the total internal reflection at the lens edge surface. Thus in the prototype, we blackened the edge surface of all the rod lenses which may cause stray light. Ghost image always comes from the double reflection between lens surfaces. In the prototype, all the lens surfaces were coated with broadband antireflection (BBAR) coating with a transmission of 99.5% over the visible range.

In the LightTools model, all the lens surfaces were set with BBAR coating; the rod lens edge surfaces were set as absorber. Several point sources representing 0° , 13° , 26° , and 40° are placed on the object plane in front of the MRFL. Ten thousand nonsequential rays were traced for each point source; the ray path analyzer was used to filter the imaging light, stray light, and the ghost light [14,15]. Figures 18 and 19 are the nonsequential ray tracing result for the MRFL aiming at the center FOV. Figure 18 is the light distribution on the image plane with a point source at 0° . The simulation result does not show the stray light or ghost image problem. By using the ray path filter analysis of LightTools and deselecting the imaging path, a ghost image point is shown. The ghost image is formed from the double reflection from the rod lens surface. Since the object point is on axis, the ghost image does not shift. However, Fig. 19 shows a ghost image path of the 13° field, which is not coincident with the imaging path. Nevertheless, the relative power of the ghost image is less than 0.5% of the real image. Therefore we can conclude that the central FOV of the MRFL is free from stray light and ghost image. Figures 20 and 21 demonstrate the light distribution on the image plane with a light source at 26° and 40° , respectively. In these two situations, the scanning mirror is tilted so that the image of the 26° field is at the center of the image sensor and that of the 40° is at the edge of the image sensor. Similar to the central FOV, the ghost paths exist, but the relative power of the ghost paths and stray light is less than 0.5% of the real image. Consequently, it can be concluded that the MRFL system is free of stray light and ghost image over the entire FOV.

5. MRFL PROTOTYPE

The MRFL prototypes with a normal length profile and a short length profile were assembled. The objective lens and the multiple sets of relay lenses were aligned and assembled on a v-groove, as shown in Fig. 22. All the tube lenses are blacked on the side

surfaces to prevent stray light. A complete 3D model of the mechanical mounting is shown in Fig. 23. The laparoscope tube contains the objective lens and the relay lenses. The scanning lens and two imaging probes are mounted together with the 2D scanner in a mechanical housing. The laparoscope tube is secured in position by threads on the scanning lens mount. The mechanical housing has a volume of 73.5 mm (W) $\times$ 80 mm (H) $\times$ 100 mm (L). The prototypes were demonstrated to have the required as-built performance. The detailed system characterization and *in vivo* evaluation are described in the previous paper [7].

6. SUMMARY AND FUTURE WORK

In summary, this paper discusses the detailed design strategies and procedure of the multiresolution foveated laparoscope. The system performances including the MTF performance, the diffraction efficiency of the DOE, tolerance analysis, stray light and ghost image analysis are demonstrated. In the end, the MRFL mechanical model and prototypes are shown.

In the future, we will test the MRFL in the laparoscopy training section and develop different display and control modes for this dual-view system to improve the performance and outcome of the laparoscopic surgery.

Acknowledgments

The authors would like to acknowledge Dr. Xinda Hu for the help on the mechanical design and fabrication. Dr. Hong Hua has a disclosed financial interest in Magic Leap Inc. This relationship has been properly disclosed to The University of Arizona and reviewed by the Institutional Review Committee in accordance with its conflict of interest policies.

Funding. National Institutes of Health (NIH) (R01EB18921, R21EB013370).

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Fig. 1.
System layout of a MRFL with low length profile.

Fig. 2.
Illustration of MRFL design process and strategy.

Fig. 3.
Intermediate design: (a) layout and (b) MTF performance.

Fig. 4.
Improved objective lens: (a) layout and (b) MTF performance.

Fig. 5. Starting relay lens: (a) layout and (b) OPD plot.

Fig. 6.
Optimized relay lens: (a) layout and (b) MTF performance.

Fig. 7.
Field curvature and distortion of the optimized relay lens.

Fig. 8. Objective multiple sets of relays: (a) layout, (b) MTF performance two relay groups, and (c) MTF performance four relay groups.

Fig. 9.
OPD fan of objective lens with four sets of relays.

Fig. 10.
Initial scanning lens: (a) layout and (b) MTF performance.

Fig. 11.

(a) Layout and MTF performance of central FOV and (b) layout and MTF performance of peripheral FOV.

Fig. 12.

MTF performance of high-magnification probe with four sets of relays: (a) central FOV and (b) peripheral FOV.

Fig. 13. High-magnification probe of MRFL with the hybrid lens: (a) central FOV and (b) peripheral FOV.

Fig. 14. Wide-angle probe of MRFL: (a) layout and (b) MTF performance.

Fig. 15.
Diffraction efficiency versus lens radius.

Fig. 16.
Diffraction efficiency versus wavelengths.

Fig. 17.

Tolerance analysis results: (a) and (b) cumulative probability plot for MTF tolerance of 60 lp/mm; (c) and (d) cumulative probability plot for MTF tolerance of 30 lp/mm.

Fig. 18. Light distribution of the 0° point source: (a) all ray paths and (b) stray light and ghost image ray path.

Fig. 19. Light distribution of the 13° point source: (a) all ray paths and (b) stray light and ghost image ray path.

Fig. 20.
Light distribution of the 26° point source: (a) all ray paths and (b) stray light and ghost image ray path.

Fig. 21. Light distribution of the 40° point source: (a) all ray paths and (b) stray light and ghost image ray path.

Fig. 22.
MRFL assembly.

Fig. 23.
MRFL 3D mechanical model.

Table 1

Specifications of the MRFL

MRFL	
FOV	80°
Working Distance	120 mm
Wide-Angle Probe	
Field coverage	160 mm × 120 mm
Spatial resolution	2 lp/mm
Working $F\#$	$F5.3$
High-Magnification Probe	
Field coverage	53 mm × 40 mm
Spatial resolution	6 lp/mm
Working $F\#$	$F15.8$

Table 2

Tolerance Chart

Glass material (nd, vd)	$\pm 0.0005, \pm 0.5\%$
Diameter (mm)	$+0.000/-0.025$
Center thickness (mm)	± 0.05
Radius	3 fringes
Irregularity	0.5 fringes
Wedge (ETD, mm)	0.01