Chip-on-the-Tip Projection Design with Large Depth of Focus for Structured Light 3D Endoscopic Imaging

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Abstract—Designing a projection lens system for endoscopic 3D structured light system is challenging due to the extreme requirements of large depth of focus and light efficiency. We are proposing a systematic approach for finding out an optimal design that provides large depth of focus using conventional spherical lenses. Our contributions are 1) geometrical study of projection of light cone for depth of focus 2) Computer-aided optical design tool. Our proposed system is designed for a miniature binary-coded 3D structured light system, which makes it possible to apply to endoscope. The designed prototype diameter is only 2.8mm and total length is 13.78mm. Resulting system achieves a 15mm depth of focus in throw distance from 5mm to 20mm, and most of the MTF at 24lp/mm are more than 50% as shown in experimental results.

Index Terms—projection system, depth of field, endoscope, structured light, lens design

I. INTRODUCTION

Endoscopes are indispensable tool in MIS (Minimally Invasive Surgery), but many MIS involved endoscope was a challenge, due to using CT (Computed Tomography) or monocular camera for safe navigation and manipulation lack of depth information. Using a stereo camera [1] for 3D acquisition is not easy for showing the insides in 3D due to lack of light inside and the large volume required for fitting two cameras with enough base line and a light source for 3D capture. 3D structured light is more suitable for such an application. C. Schmalz [2] proposed single shot color ring patter projector, although the size of this projector is small enough, but only one pattern is not flexible for application. Another solution for structured light illumination method is presented by N. T. Clancy [3], the pattern is generate outside then transform by the optical fiber in the tip projected by projection lens, disadvantage is that optical fiber due to length induces pattern

distortion. Commercial projectors even pico-projector, for such application, not only big in size but also they are designed for projecting on an even plane instead of unpredictable plane. The design of the projection system is grounded by extreme constraint on the length of depth of focus, the overall system volume as well as the light efficiency.

In photographic lens system design, one of the common optimization aspects is the depth of field [4] where in projection system, corresponding aspect, known as depth of focus, is commonly ignored assuming projection surface is a perpendicular plane. When designing a projection lens system for a structured light sensor, maximizing depth of focus becomes a design criterion. Structured light system usually consists of a projector and a camera; Imposing a large depth of focus on a projection lens system design while maintaining high contrast and brightness is an unconventional challenge. Depth of focus for a projection system is a range of distance in which an acceptable CoC (Circle of Confusion also call maximum disc) [5] is formed on the screen. For instance, if throw distance of certain projector is T_d in which a perfect focus is formed, there exist a range of distances along optical axis around T_d in which projection system can still form a clear image. In this paper we proposed a method for designing a wide DoF projection lens system in micro-scale size which can be used in limited space applications, such as endoscopic structured lighting system.

There are two main architectures of projection lens design [6] telecentric architectures and non-telecentric architectures, by describing the conditions at the pattern generator, like DMD, LCoS and LCD. Definition of telecentric architectures is the exit pupil location for illumination system which is entrance pupil of the projection system. Advantages of this structure are uniform grey level, saving axially space. Disadvantage, on the other hand, is the relatively low light efficiency. Non-telecentric architectures' exit pupil of illumination path compare with previous architectures is way shorter,

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and the projection system's entrance pupil is exactly in the illumination's exit pupil. This structure reduces the number of lens greatly, making the whole structure more compact. The drawback is the higher distortions caused by illumination angle, thus projection lens design becomes more difficult to design in order to eliminate these distortions. CRT projectors lenses with large exit apertures, as a result, have a quite limited narrow depth of focus. These CRT projectors are required to collect the light projected from the large sized cathode tube. DLP and LCD projection system focuses light from illumination sources smaller compared to CRT projector. DLP and LCD projectors provide high quality of images using lenses with smaller exit apertures, accompany with benefit of relatively wide DoF performance.

Hence, considering the axial space saving and wide DoF required by endoscopic application; we are proposing a telecentric structure with single LCD panel in this work.

II. START TO DESIGN

A. System Development Flow Chart

In this work, we will apply lens system development flow chart as Fig. 1.



Figure 1. Lens system development flow chart.

In the initial phase, we set the basic requirements and specification. In this section we had given a set of requirements (DoF, FoV, pixel size and so on) as the guideline of design for fundamental phase and optimization phase. We will state the specific requirements of our endoscopic application in Section 2.1. Next, we use a top-down approach to find the proper solution to the given requirements. First, we use a paraxial [7] model to find a fundamental design that satisfy the required magnification, depth of focus and resolution while ignoring lower level criterions such as aberration and light efficiency. Second, we convert our paraxial model into a thick lens [8] design in which we address physical challenges. Number of lenses, system volume, lenses materials, location and size of aperture stop, and many other parameters are optimized in this step. Commercial software packages, such as Zemax, provides assistant for auto-optimization in non-linear

high dimensional space using a custom user-defined merit function. Finally, we also use Zemax for evaluation of the resulting system as well as a basis for comparison with other designs.

B. Requirements and Specification

In this section, we are proposing a specific application for our projection design specification by adopting telecentric architecture, which shows a structured light system [9], as show in Fig. 2, composed of a camera and a projector.



Figure 2. Triangulation principle for structured light system.

Structured light is approach for 3D reconstruction of shaped object based on triangulation. Most of structured light system's projector predefines a series of binary pattern projected onto the object and distorted pattern is captured by the camera. As we mentioned, binary pattern we don't need color in this projection system design, so we choose the monochromatic wavelength. The basic idea is demonstrate in Fig. 2. The camera ray CX intersects with PX, to find a 3D coordinates of X is problem. Using the recorded distorted pattern and the precoded pattern; we can reconstruct the object 3D shape as a 3D point cloud [10].

Under the constraint of structured light camera target area, we propose the following projector prototype. We are applying KOPIN's 0.16" inches LCD, with specifications showed in Fig. 3(b). The LCD's resolution is 320×240 and we filter the LCD image by a square mask, instead of 4:3 aspect ratio rectangle, with resolution 240×240 to maximize the area utilization. Using simple triangulation, the pixel size at 5mm throw distance is 41.66μ m, whereas, at 20mm pixel size it will be 166.6666μ m. These criteria will be used for evaluation of the final system.



Figure 3. Structured light 3D endoscopic imaging system specification and requirements.

As we mentioned in section 3, the endoscope's target area should be covered. Thus, the projector's screen should be at least bigger than the camera target area. Hence, the magnification can be computed as follows:

$$M = \frac{15.998}{2.475} = 6.4638 \tag{1}$$

To reach both side of max disc, as shown in Fig. 3(a),

$$\frac{x}{0.04166} = \frac{15 - x}{0.16666} \tag{2}$$

here, x=2.999 mm, the throw distance is 7.999 mm. So, we will use this particular representative throw distance for Zemax optimization.

Since we will be using a binary structured light code, we designed the projection system for a monochromatic wavelength.

The specifications for the projection lens system are as follows:

Design specifications

- Magnification 6.4638
- Depth of Field rang 5~20mm
- Max pixel size 41.66 µm@5mm
- Max pixel size166.666 µm@20mm
- Throw distance T_d 7.999mm
- Wavelength 0.48613 µm (Monochromatic)

III. FUNDAMENTAL PHASE

A. Paraxial Design Based on Requirements

Projecting on a predictable geometrical object [11], we can use warping software like Nthusimto correct the distortion. However, in the application of structured light system, the shape of objects in workspace is unpredictable. So, in this case we define projection range $T_n=5$ mm~ $T_f=20$ mm as the near-to-far through distance respectively. By our analysis, there is a perfect focus point for this projection system. In the focus point neighborhood, this beam is blocked by screen. By our criteria, design method should fit the spot size from range of 5mm to 20mm.

Projector's depth of focus is determined by the lens exit pupil, the distance from the lens to the screen and an acceptable disc size which is demonstrated in *Design Specifications*.



Figure 4. Projecting light cone blocked by distance's disc difference.

As shown in Fig. 4, ray traced from a projection lens to a perfectly focused spot on a screen forms a light cone from the lens surface to the screen point. Assume we shift the screen closer or farther to/from the lens (without adjusting the focus) the spot size grows linearly with the distance. And perfect focus spot becomes "unfocused". These are nearest and farthest planes corresponding to each maximum acceptable disc (D_n and D_f).

Focused and unfocused are defined with respect to predefine constrain. The projection image is out of focus when the circle of confusion size becomes larger than pixel size.



Figure 5. Projection on different distance plane.

Since the maximum acceptably disc limitation for front and rear side are not the same, as shown in Fig. 5, the front and rear DoFs are not equally clear. The front disc size is closer to the camera's viewpoint, thus is smaller while the rear disc is farther away and is larger.

The size of image divided by the number of pixels can estimate the maximum discs for nearest and farthest planes. And x=2.999mm represents the distance from nearest plane in which rays should converge in perfect focus. Thus, we choose to optimize the system at this particular through distance.

$$T_{\rm r} + x = 7.999 \,{\rm mm}$$
 (3)

Since we know the maximum disc is $41.66 \mu m$, and the throw distance is 7.999mm. So the exit pupil of this projection lens system will be D_L =111.11 μm

B. Fundamental Deign and Thick Lens Design

Finding a global optimal thick lens solution to the given set of design criteria shown in Section 3 is extremely difficult as it resembles a high dimensional non-linear optimization problem. While tools, such as Zemax and Code V, can provide optimization modules to assist, they often only search subspaces to find tractable solutions, variables such as number of lenses, aperture of each lens, location of aperture stop, etc., are not explored by such tools and are left for the designer to decide. Usually, designers rely on fixed well-performance templates to accommodate for the missing degrees of freedom. This limits the capabilities of the final solution on the diversity of the templates set available to the designer and his/her experience.

Instead, we have developed an optical lens design tool that hieratically assists a non-experience designer to search the non-linear optimization space for high quality solutions. We used this tool to design the projection lens we discussed in this paper.

First layer of the search is fundamental layer, where we looked for the best set of paraxial lenses that can project the LCD image to the desired depth of focus. The objective of this layer is to find the best set of paraxial lenses, their principle axis location and their focal distance to satisfy the depth of focus, magnification and image resolution criteria.

Using assisted cascaded ratio of magnification to depth of focus, we were able to construct a solution using 3 paraxial lenses as shown in the top part of Fig. 6. The trapezoid's base 40mm and 20mm represent the target area size range from 5mm to 20mm. As showed in Fig. 6(a), the original trapezoid projected by paraxial lens 1, generate a shrunken trapezoid i. Then i project by paraxial lens 2 iterative process. Eventually, trapezoid iii achieve the required CoC 11 µm and LCD size.

The next layer is physical layer where designer is required to construct a set of thick lenses per each paraxial lens such that the equivalent backward principle plane of the set lies exactly at the paraxial principle plane, and the backward effective focal distance of this set is equivalent to the paraxial focal distance. In order to correct the spherical aberration, we applied lens splitting in thick lens 1, 2, 3 [12] and picked up pairs of flint/crown materials to minimize Petzval sum, i.e. field curvature. Because this is monochromatic system, chromatic aberration is ignored. Using this layer, we were able to obtain 7 thick lenses design that satisfies the required criteria as shown in the lower part of Fig. 6.



Figure 6. The fundamental layer by thin lens and physical layer in thick lens.

C. Optimization by Zemax [13]

In order to provide a high-accuracy, high-quality solution, we use the solution we developed by our tool as a polished template and use Zemax to fine tune and optimize overall system performance. Imperfections in image can be formed by optical system aberrations. To overcome such imperfections, optical elements should be well designed to compensate for the aberrations. Zemax provide powerful optimization function. It allows the user to assign variables such as curvatures, thickness, and glass material, etc.; as well as specify an optimization merit function with weighted objectives. Zemax uses the least square method to search the non-linear space for a solution that satisfies the given optimization functions. And since the searching space is often high dimensional and non-linear, it's infested with many local minima which likely leads the least square algorithm to get stuck. However, since we started the search with a near-optimal design developed by our tool, the search has a high likelihood of reaching a good optimal point, with few trials.

After optimization, the YZ cross section 2D Layout of the projection design to the presented particular application is shown in Fig. 7.



Figure 7. Layout projection lens by Zemax.

The LCD on the far left represents the pattern generator for the projection system. We assume the illumination system provides a uniform backlight. Then, this passes through the projection lens designed by our tools from fundamental layer, then optimized by commercial software package by Zemax. Eventually, the pattern is projected on the final screen. Different pixel height is represented by different color in Fig. 7. Blue means field is in the center, green is for -0.7035 mm pixel height and red is for -1.2488mm pixel height. There is a rod lens with length of 2.5mm, which guarantee the light efficiency. This projection dimension's diameter is only 2.8mm and total length is 13.78mm.

IV. EVALUATION AND CONCLUSION

A. Evaluation by Zemax

There are large amount of criterions to evaluate the performance of optical system provided by Zemax.

The Ray Fan plot represents ray aberration as a function of pupil coordinate. Generally, horizontal axis, abscissa shows the entrance pupil scalar of optical system, between -1 to +1. Obviously, 0 corresponds to the optical axis of focus which is center of the entrance pupil. The vertical axis represents the aberration value. Ray Fan plot shows the aberration of an optical ray with respect to the distance of its intersection point from chief rays.

Since we are considering two types of rays in calculation: the meridional surface and the sagittal surface. So in Zemax ray fan plot, there are only two ray fan plots for each corresponding field. And, in a perfect optical system, the ray aberration should be zero across the pupil, with overlapping curve of the abscissa.



Figure 8. Ray fan plot for the lens of Fig. 6.

There are three fields of ray fan plot for projection lens. Since we are proposing a single wavelength projection system, there is only one curve drawn. The fields of 0.0, - 0.7035, and -1.2488, there are spherical aberrations showed by Fig. 8 respectively.

Zemax inbuilt spot diagram chart simulates the actual focusing spot. Without aberrations, Zemax assumes a point object will project to a perfect image point. By default, Zemax plots the spot diagram for each field point. Optimized by Zemax, the final result should be making the lower limit of the real spot size determined by the diffraction pattern (Airy disc).

As we calculated previously, our spot diagram should be smaller than $41.66 \,\mu\text{m}$ at 5mm and $166.66 \,\mu\text{m}$ at 20mm. After the optimization by Zemax, from Fig. 9 which is for $41.66 \,\mu\text{m}$ at 5mm by the entire field.

The dash curve in chart showed in Fig. 9 represents the pixel spot size on the screen distance of 20mm, which is smaller than our limitation of 166.66 μ m. And for 5mm, the spot size is also smaller than our limitation of 41.66 μ m.

The Modulation Transfer Function (MTF) is one more indication of optical system. MTF function estimates the resolution limitation of this optical system performance. MTF demonstrates the contrast in the image of a spatial frequency. Fourier transform is used to characterize the contrast of the image in spatial frequency.

Spatial frequency is related with the pixel size of LCD sensor. CyberDisplay[®]300MLV 0.16" LCD with pixel size is 11 μ m, manufacture by KOPIN, and the corresponding limiting resolution is 241p/mm. As shown in Fig. 9, we can find that most of the MTF at 241p/mm were more than 50%, and most of the MTF at 121p/mm (1/2 Nyquist frequency) were more than 70%, which shows that this projection lens system had quite a good projection quality.

Spot size µm









As we can see from the chart of Fig. 10, meridional and sagittal curves of each field of view are approaching to the diffraction limit. Fig. 10 also shows the contrast ratio for spatial frequency from 0 to maximum frequency of 24lp/mm for this optical system. 24lp/mm means 24 lines per millimeter, corresponding to different field of view.

B. Conclusion

We have developed a new projection lens system with large depth of focus, which is capable to project a clear image from 5mm~20mm. We obtained this fundamental layout of the design from our too land optimized the result by the Zemax. We, then, simulated the lens in Zemax and evaluated the performance as shown above.

Although resulting light efficiency is acceptable for the scope of the desired application, further work is needed to improve the efficiency in open-environment applications, such as smart phones, as well as enhance the overall performance. Utilization of aspherical lenses [14] may also reduce the overall number of lenses and system length.

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