DESIGN AND FABRICATION OF HIGH QUALITY IMAGING OBJECTIVE WORKING IN THE NEAR-INFRARED SPECTRAL REGION FOR VEIN FINDER DEVICES

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Abstract

This work demonstrates a new design of an imaging objective operating in the near-infrared spectral region for vein finder devices. The objective has a simple structure, consisting of 6 elements divided into 2 groups and a long-pass optical filter that allows a near-infrared spectrum to pass through. Due to the filter, the objective only creates images in the 850-940 nm spectral region produced by the infrared illuminator and therefore it can eliminate optical noise in the visible region. The objective image quality is very high, suitable for vein imaging: large aperture, *f*/2.0, allows creating clear vein images from weak signal reflected from the human skin surface; modulation transfer function (MTF) of 0.5 at a frequency of 72.5 lines/mm; field curvature and image distortion less than 50 µm and 0.1%, respectively. The experimental result indicates that the objective can provide clear vein images when combining with a Sony IMX287 CMOS image sensor.

Keywords: *Objective; vein imaging; optical design; near-infrared.*

1. Introduction

Intravenous injection and blood collection from intravenous lines are common procedures performed in health care, however, its success depends mainly on the perception and experience of the physician. The rate of unsuccessful venipuncture is relatively high in some cases such as small vein size in children, dark skin or veins covered by subcutaneous fat [1]. Taking the wrong vein causes pain, discomfort that harms both the mental and physical health of the patient [2]. To increase the rate of successful venipuncture and the speed of operation, vein finder devices have been developed and demonstrated effectively in helping physicians and doctors to make accurate venipuncture [3]. These devices are now available on the market and the most advanced ones were designed and manufactured by developed countries including the VeinViewer Vision from Christie Medical Holdings - USA, Vein Finder VF30, VeinSight VS400... These high technological equipment are high cost thus they are currently not available in our domestic medical hospitals and clinics. Moreover, the maintenance, repair and replacement parts are almost impossible when these devices are

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supplied in domestic market. As a result, it is significant to investigate on design and manufacturing technology of some main components of a vein finder device. This is the most important approach to make complete low-cost vein finders that can be provided for domestic uses.

In a vein finder device, the image acquisition module plays a very important role because it captures the image of venous lines. This module has to provide high-quality images and satisfy other special requirements compared to conventional imaging systems such as large aperture and negligible image distortion. In addition, the imaging objective must create images in the wavelength range from 850-940 nm of the infrared illumination system, and not in the visible light region to eliminate optical noises from the environment. Currently, there are no specialized objectives on the market that meet the above requirements for use in vein finder systems. Therefore, we propose a new design of the imaging objective that can fulfil the above requirements by integrating a long-pass optical filter at 850 nm into the objective. Our objective has unique properties including high image quality and simple structure. It is also easy to process, manufacture and assemble in a domestic factory which is highly promising for the development of made-in-Vietnam vein finder devices.

2. Methodology

2.1. Image acquisition module in a vein finder system

The image acquisition module is an essential component of a vein finder device as shown in Fig. 1. Near-infrared light from a light-emitting diode (LED) (1) is illuminated onto the skin where vein lines located. This radiation passes through the skin to the veins and surrounding tissues. Part of the radiation is reflected to the image acquisition module where the signal will be collected by the objective (2) to form an image on the light-sensitive layer of the image sensor (4). The optical filter (3), allowing only 850-940 nm radiation to pass through thus it, removes interfering light with wavelengths outside the region of interest. The image sensor converts the optical image into electronic signals and then sends it to the image processing unit (5) where the image is processed before display. Because deoxygenated haemoglobin in the veins absorbs infrared radiation more strongly than surrounding tissues, a vein image is obtained as dark lines against light skin [4]. Generally, the contrast between the vein images and surrounding tissues is not high thus image processing is often required for contrast enhancement. After processing, the vein images can be projected back to the patient’s skin surface or display on a monitor to help the physician determine the exact location of vein lines which is helpful for medical diagnostics, study and treatment.

In this work, we use 850 nm LED as a near-infrared light source because this LED is very popular, cheap, and highly efficient. In addition, the 850 nm radiation has a good ability to penetrate skin and tissue but it is well absorbed by the veins thus the 850 LED is often used in vein finder devices [5-7]. In the case of using LEDs with wavelengths between 850-940 nm, the obtained result will be similar. Materials used for making lenses can use common optical glasses, with a transmittance spectral region of 400-2500 nm.

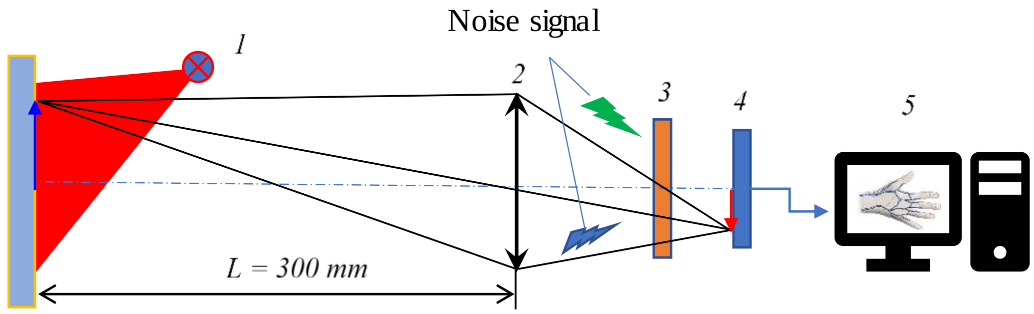

Fig. 1. Schematic diagram of a vein imaging system. 1- Near-infrared 850 nm LED; 2- Objective; 3- Optical filter; 4- Image sensor; 5- Image processing and display system.

2.2. Design of the imaging objective

The design of the imaging objective is the first and important step to make the image acquisition system. Generally, this task begins with the selection of an image sensor. After reviewing several types of image sensors of different brands, we chose Sony's IMX287. This is a CMOS sensor series with Pregius full-frame shutter technology that provides high frame rates, high sensitivity and low noise [8]. The specifications of the IMX287 are as follows:

- Resolution: 720 × 540 (0.37 Mpx);
- Sensor size: 1/2.9″ (4.97 mm × 3.73 mm);
- Pixel size: 6.9 µm × 6.9 µm;
- Working region: 400-1000 nm.

From the specifications of the image sensor, it is possible to calculate the basic parameters of the objective based on technical requirements such as the size of sample area to be observed, working distance, the minimum size of the vein line. We obtain the following results:

- Focal length of the objective: f' = 20 mm;
- F-number: 2.0;
- Field of view (size of observation area): 80 mm × 60 mm;
- Working distance: L = 300 mm; Working spectrum: 850-940 nm.

2.3. Design of optical aberrations of the imaging objective

The imaging objective is designed based on a double Gauss system and optimized on Zemax software. The original double Gauss system is a photographic objective consisting of two components, almost symmetrically constructed with a diaphragm in the middle. To transform this fundamental objective to our new one with the required specifications, we implement an ingenious strategy consisting of several steps as follows:

Step 1. Modifying the optical characteristics of the lens: Calculating and adjusting the parameters of elements such as radius, thickness to obtain the focal value; Inserting the optical filter after the last element of the objective; Changing the working spectrum to the 850-950 nm region. Then performing the first optimization with the spot radius is introduced into the merit function; the focal length and peak focal length are fixed.

Step 2. Improving the image quality: Performing the second optimization with the wave aberration and distortion are introduced into the merit function. After running the optimization algorithm, it is found that the modulation transfer function (MTF) of the system is not uniform, the MTF value at the edge of the image is much lower than that in the centre. This result indicates that the axial aberration of the system is still large, which is caused by the inappropriate position of the aperture stop. As a result, we added a variable that is the position of the aperture stop so that the software can adjust itself optimally. After this step, the desired image quality is obtained.

Step 3. Adjusting the structure: The structure of some lenses are modified for simple fabrication and inspection. Constraints are added to the Merit function to ensure that R-number > 0.8 for all surfaces. Finally, we perform the last optimization and get the final system.

3. Results and discussion

3.1. Optical layouts and parameters of the objective

After optimization, the obtained near-infrared objective structure consists of six elements without any aspherical surface (Fig. 2). The surface of the elements is not too curved to facilitate fabrication and enable achieving the required precision. The utilized evaluation wavelengths are 850 nm, 900 nm and 950 nm. The light beam produce images with heights of 0, 2 and 3.2 mm, respectively. Detailed design data of the imaging objective is presented in Table 1.

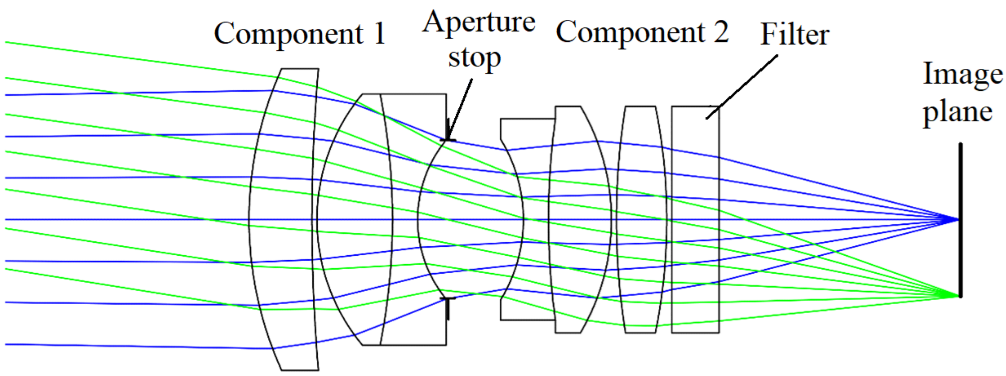

Fig. 2. Optical layout of the objective.

Table 1. Design data of the objective

Surface number	**Radius of curvature (mm)**	**Thickness (mm)**	**Glass**	**Semi-diameter (mm)**
OBJ	Infinite	300.000		46.000
1	Infinite	9.997		7.570
2	14.534	2.500	STK12	6.000
3	70.018	0.200		6.000
4	7.822	3.000	STK12	5.000
5	-25.643	1.000	TF2	5.000
6	4.978	1.200		3.171
STO	Infinite	3.000		3.145
8	-6.095	1.000	TF2	3.200
9	29.240	2.500	STK12	4.000
10	-8.854	0.200		4.500
11	28.344	2.000	STK12	4.500
12	-22.697	0.200		4.500
13	Infinite	1.876	K8	4.500
14	Infinite	9.584		4.298
IMAGE	Infinite	-		3.056

3.2. Quality evaluation of the objective

Distortion represents a deviation of the shape between the image and the object. For a vein finder device, the vein image must be accurate so that there is almost no distortion in vein position when projected the vein image back to the skin surface. As a result, strict control of various types of optical aberrations is required. According to some previous studies, if the image distortion is less than 3%, it will not cause significant deviations [9]. Our objective meets this requirement very well because it has a field curvature of less than 50 µm and distortion of less than 0.1% (Fig. 3a).

The MTF reflects the imaging capabilities of an objective and how well it matches the sensor or imaging device it serves which is in the IMX187 sensor in this work. One of the criteria for considering an objective that can work well with which image sensor is its Nyquist frequency. It is determined by the formula: $f_n = 1000/2p_x$, where f_n is the Nyquist frequency with units of cycles per millimetre and p_x is the pixel size with units of µm. The IMX187 sensor has a pixel of 6.9 µm, which corresponds to the maximum Nyquist frequency of $f_n = 72.5$. From Fig. 3b, it can be seen that at this frequency, the MTF value of the objective is above 0.5 in all 3 fields of view. As a result, the imaging objective can be combined with the IMX187 sensor to produce good image quality.

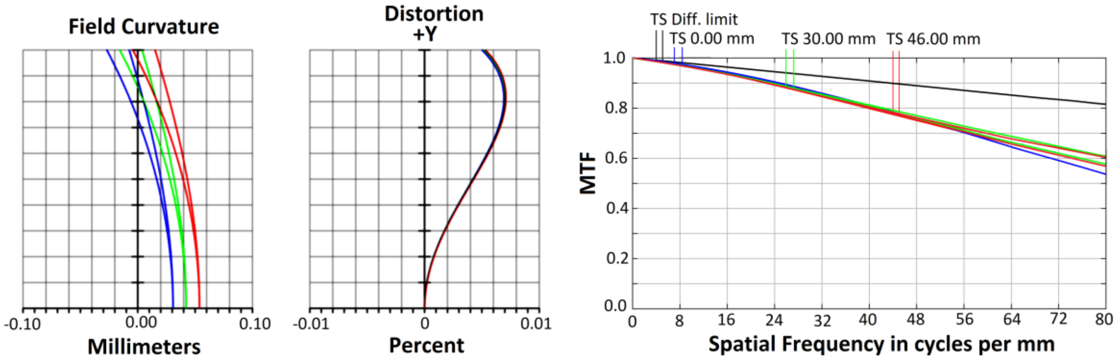

Fig. 3. (a) Field curvature and distortion of the objective. The wavelengths used are 850, 900, 950 nm; (b) MTF diagram of the objective.

3.3. Fabrication of the imaging objective

From the design data shown in Table 1, we have made detailed mechanical drawings and sent them to a domestic factory for fabrication. After fabrication, the surface of the optical parts was checked on the Verifire XP/D interferometer (Zygo) to ensure that the PV error is less than $\lambda/2$ (Fig. 4a). The lens after assembly was tested on the Image Master HR system (Trioptics). The measured MTF is plotted in Fig. 4b. Compared with the designed MTF curve (Fig. 3b), it can be seen that these two curves are lower which indicates the objective has an eccentric error, but the difference is not too much. The average MTF value at Nyquist frequency of 72.5 lines/mm reaches 0.5, indicating that this objective is completely suitable for the sensor's requirements.

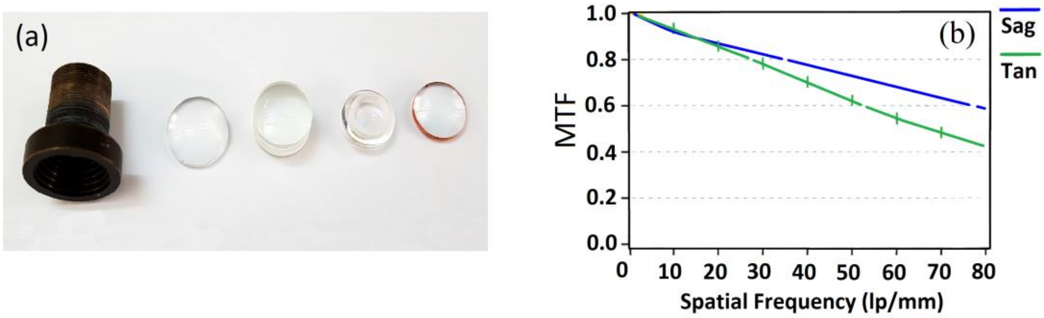

Fig. 4. (a) Objective's components; (b) Measured MTF of the objective.

3.4. Demonstration of vein imaging

To demonstrate the effectiveness of our near-infrared objective for vein imaging applications, we have built an experimental setup as shown in Fig. 5a. Two cameras with the same image sensor were placed on the same platform (1). One of them was equipped with the near-infrared imaging objective (2), the other uses a normal one (3) with equivalent optical parameters. The near-infrared LEDs (4) was placed between the two cameras to illuminate the radiation into the skin area. Figure 5b shows that the raw image (without any image processing) captured by the camera with the near-infrared imaging objective shows the veins in the wrist relatively clearly while the fingerprints and wrinkles on the skin are very faint. In contrast, the camera with a typical objective often shows very clear skin surface contours while venous lines are very faint (Fig. 5c).

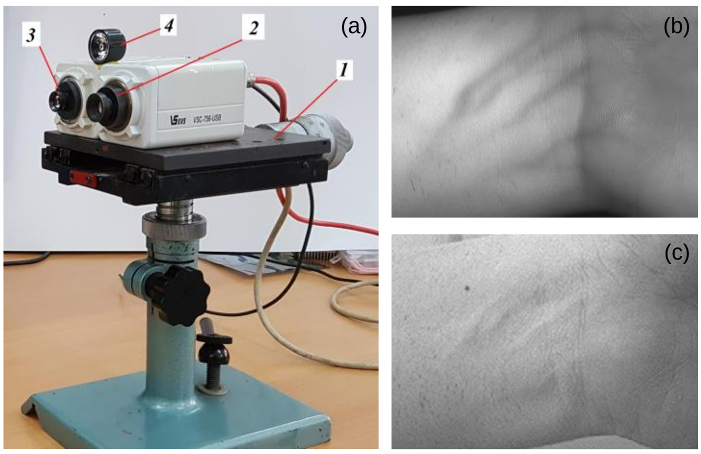

Fig. 5. (a) Experimental setup for capturing vein image: 1- Platform; 2- The camera is equipped with the near-infrared objective; 3- The camera is equipped with a typical objective; 4- Near-infrared LEDs. (b) and (c) Wrist images from cameras equipped with the near-infrared and typical objective, respectively.

4. Conclusion

In this paper, we have successfully designed and fabricated a specialized imaging objective operating in the near-infrared spectral region for a vein finder device. The objective has a simple structure, can be completely manufactured in a domestic factory, but still ensures good image quality. The average measured MTF value of the fabricated objective at Nyquist frequency of 72.5 lines/mm is 0.5, which is close to that of the design one and it meets the requirements of the sensor used in a vein finder device. Especially, the objective only creates images in the 850-940 nm region which is the spectrum of common near-infrared LEDs used for illumination. The experimental result shows that the objective can capture a clear vein image when integrated with a Sony IMX287 CMOS image sensor while it is impossible for an ordinary objective. Our work should be important for the development of made-in-Vietnam vein finder devices.

Acknowledgement

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THIẾT KẾ VÀ CHẾ TẠO VẬT KÍNH CHẤT LƯỢNG CAO HOẠT ĐỘNG TRONG VÙNG PHỔ HỒNG NGOẠI GẦN CHO THIẾT BỊ CHỤP ẢNH TĨNH MẠCH

Lê Duy Tuấn, Lê Hoàng Hải, Dương Chí Dũng, Tạ Văn Dương,
Đào Nguyên Thuận, Lê Anh Tú

Tóm tắt: *Bài báo này đưa ra một thiết kế mới của vật kính chụp ảnh hoạt động trong vùng phổ hồng ngoại gần, dùng cho thiết bị soi tĩnh mạch. Vật kính có kết cấu đơn giản, gồm 6 thấu kính được chia thành 2 cụm và một màng lọc cho phổ hồng ngoại gần truyền qua. Do có màng lọc, vật kính chỉ tạo ảnh trong vùng phát xạ 850-940 nm của hệ chiếu sáng hồng ngoại, giúp loại bỏ tạp quang trong vùng ánh sáng nhìn thấy. Các thông số hiệu năng của vật kính đạt được rất cao, phù hợp với mục đích chụp ảnh tĩnh mạch: khẩu độ lớn f/2,0 cho phép tạo ảnh rõ nét từ nguồn tín hiệu yếu phản xạ từ bề mặt da của bệnh nhân; hàm truyền MTF đạt 0,5 tại tần số ν = 72,5 cặp vạch/mm; cong trường nhỏ hơn 50 µm; méo ảnh nhỏ hơn 0,1%. Kết quả thử nghiệm cho thấy vật kính khi được kết hợp với cảm biến ảnh CMOS Sony IMX287 đã chụp được hình ảnh tĩnh mạch rõ nét.*

Từ khóa: Vật kính; chụp ảnh tĩnh mạch; thiết kế quang học; hồng ngoại.

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