Characterization a single-lens based stereoscopic camera

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By:
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1. **Abstract:**

Traditional stereoscopic vision (3D) is achieved through use of two cameras arranged to emulate human eyes. While this method works on large scale projects, it becomes impractical to use on small scale designs, such as surgical endoscopes, in which the operational area doesn’t allow the immensity of dual camera systems. This project is focused on developing a stereoscopic endoscope using a single camera and Conjugated Multiple-Bandpass Filters (CMBF) to create 3D images. Each filter is designed to allow only a distinct spectrum of light to pass through. The stereoscopic image can be obtained by using filters that reflect and reject wavelengths, complementary to one another.

A major concern in all stereovision is crosstalk, defined as the light from one eye image that is present in the other eye image. This incomplete isolation causes deterioration of the 3D image. In our system, the crosstalk comes from imperfect filters. The filter spectrums overlap at certain wavelengths, causing a dim outline of the right eye image to leak into the left eye image and vice versa, a phenomenon known as ghosting. Knowledge of the extent of this phenomenon is critical to creating sustainable, effective stereovision.

2. **Background:**

The Jet Propulsion Laboratory is developing the world’s smallest optical system capable of creating stereoscopic images and video. The primary motivation behind this project is implementing the system into surgical endoscopes to provide brain surgeons with 3D images of the area under observation. Our work is currently being sponsored by Skull Base Institute.

2.1 **Stereovision:**

Traditional stereovision is achieved through use of two cameras capturing the same image from different vantage points, similar to human eyes. This method has been successfully implemented in stereoscopes designed to perform torso-based surgeries. Because these endoscopes use two cameras, they tend to be bulky consisting of an outer diameter of around 10 mm. This is much too large for application in brain surgeries where there is little room for large instruments. Thus, our method for creating stereopsis uses a single detector array, a lens system, and Conjugated Multiband Bandpass Filters (CMBF) to achieve the left and right perspective images.

Each CMBF is designed to allow only a certain light spectrum to pass through and reflect the rest. The two filters we use are complementary to each other, meaning what one blocks, the other allows. Figure 1 shows a simple view of how the system works. By illuminating the object under observation with light that projects the same spectrum as the filters, we can achieve relative left and right perspectives. When the two images are...
viewed through a 3D viewing station, a stereo image is created. With this method, we are able to capture 3D images using a single camera. Consequently, the endoscope will have a diameter of around 4 mm, making them practical in brain surgeries.

2.2 CMBF

Anytime filtering is used, there will be a loss of total light, due to some wavelengths being blocked. Anaglyph (red and blue) 3D demonstrates this as one eye receives an image heavily saturated in red, the other blue. The drastic color difference causes a phenomenon known as color rivalry. When each eye sees the object under different illumination, instead of the two images being superimposed, they flicker back and forth. This generally causes eye strain and makes the image difficult to look at for extended periods of time.

Instead of allowing only the red or blue spectrum through, CMBFs distribute the wavelengths through use of multiple bandpasses. Each bandpass allows a certain spectrum of light through. When multiple bandpasses are applied to a single filter, the result is a filter that can represent a wider visible spectrum. Figure 2 shows a triple-bandpass filter and its complementary filter.

Each filter in the figure contains some red, blue, and green wavelengths. This reduces color rivalry significantly, making the stereo image much easier to view. While having greater numbers of bandpasses result in less color rivalry, it also becomes increasingly expensive. For our research, we use dual-bandpass filters.

One other limiting characteristic of filters is the acceptance angle. The filters are built of dielectric films that have a limit on the angle of light that can be accepted. When the light strikes the dielectric film perfectly orthogonal, the passable light goes through and the blocked light reflects perfectly. When the light is traveling at an angle greater than the acceptance angle, the transmission band widens, allowing part of the ray to be seen as a wavelength that is acceptable [2]. This causes some of the light to leak through. Figure 3 compares the two cases.

3. Objectives:

My primary objective was to characterize the crosstalk of the optical system and determine if the custom designed lenses contribute to the crosstalk. Crosstalk is defined as the incomplete isolation
of the left and right eye image channels so that one image leaks into the other [3]. In polarized displays, if the images aren’t perfectly or near perfectly polarized, a faint outline of the left eye image will appear in the right eye image, and vice versa. This process deteriorates the stereopsis. Every stereoscopic system experiences this to some extent. In our system, the primary source of crosstalk comes from imperfect filters. While Figure 2 shows the spectrum for ideal filters, actual filters will have areas on the edges that overlap in which light can pass through both filters, resulting in crosstalk.

One other area of possible crosstalk lies in the optics system. Figure 4 below shows a schematic of the optics system and the paths the light rays travel. The area of concern for increased crosstalk lies in the filter section and the lenses directing the light through them. Near the edge of the filter apertures, the light may be coming in at an angle greater than the dielectric’s acceptance angle. This will contribute to the crosstalk and my task is to quantify the extent of that.

![Optics system and ray trace simulation](image)

**Figure 4: Optics system and ray trace simulation [1]**

4. **Approach:**

The first step was to characterize the transmission spectrum of each CMBF and calculate the crosstalk. These values were used as a reference to determine the crosstalk caused by the optics. Next, two optical systems were characterized. The first was a lens train built using commercially available lenses, which will be referred to as COTS (Commercial Off The Shelf). The second is a custom designed optics system which was specially fabricated to our design specs.

4.1 **Characterizing CMBF**

To characterize the filters, a monochromator and an optical power meter were used. A monochromator is an instrument used to find the wavelength spectrum of a light source. Figure 5 illustrates how a monochromator works. Light entering

![Monochromator illustration](image)

**Figure 5: Monochromator illustration**
is reflected onto a grating that divides the light into its full spectrum, similar to a prism. The position of this grating allows a specific wavelength to be chosen. The selected wavelength is directed through the exit slit, into the optical power meter. The optical power meter measures light intensity and returns a value in Watts. Each filter was tested by placing the filter in the path of the exit slit to the power meter. Just outside of the slit, the light was collimated to ensure that the light passing through the filters fell within the filter’s acceptance angle. Measurements were taken at each wavelength along the visible spectrum (400nm – 740nm) at increments of 5 nm. Each filter spectrum was measured, along with the light source to normalize the filter curves. The results of these tests are seen below in Figure 6.

![Figure 6: Measured CMBF spectrum compared to designed spectrum](image)

Figure 6 compares the filter spectrum measured and the ideal spectrum that the filters were designed to be. The dotted lines show the ideal design for the filters, while the bold lines show the empirical results. These results will be used as a reference to the camera measurement results.

### 4.2 Characterizing Optical System

The next step was to determine the optics system spectrum. The test to find each filter spectrum within the optics system was more difficult. The entire system, shown in Figure 4, is a total of 3 mm in diameter and approximately 9 mm in length. It is contained in a closed system so it is impossible to block one filter to test the other. A method had to be developed to determine the intensity of each filter simultaneously. In addition, the optical power meter could not be used. Instead, an image at each wavelength had to be taken and analyzed.

To accomplish this, a lithograph was used along with the monochromator. The monochromator again selected the wavelength, but projected the light onto the lithograph, which had a very narrow slit. The optics system, along with the camera, was lined up behind the

![Figure 7: Slit focused(a) and out of focus(b)](image)
slit to take an image at each wavelength. If the camera is perfectly in focus, the resulting image sees a single slit, as shown in Figure 7a. If the camera is brought slightly out of focus, the image begins to see some disparity and two slits appear, as seen in Figure 7b. Each band represents the slit that is observed by one of the filters. An image was taken at each wavelength interval as before, both in focus and out of focus. The in focus images were taken to normalize the curve. These tests were performed on both the COTS optics and the Custom optics.

To determine the transmission spectrum, the images were first converted into grayscale. Once background noise was removed, a mean value was found for each pixel column. Figure 8 shows the grayscale image and a plot of the mean pixel intensity value. Two distinct peaks are seen. By taking the maximum values of these peaks at each wavelength, a spectrum can be assembled. Figure 9 shows the normalized plot of the Custom Optics spectrum.
4.3 Calculating Crosstalk

Once all the filter spectrums were measured, the final step was to calculate the crosstalk of the CMBFs, COTS, and custom optics. The crosstalk at each wavelength was defined as the amount of invading light divided by the total light transmitted by both filters. Figure 10 shows a portion of the spectrum plot of the CMBFs with the crosstalk shown in solid color. These calculations were performed on the CMBFs, COTS, and custom optics.

![Figure 10: Crosstalk shown as filled in area under the filter curves.](image)

5. Results and Discussion:

The results of the crosstalk analysis are shown in Table 1. The CMBFs as a reference had a total crosstalk of about 11.5%. The COTS optics similarly had a crosstalk of 11.5%, while the custom optics showed about 11% crosstalk. Filter B tended to leak into Filter A’s spectrum more than Filter A onto Filter B for all the tests.

These results show that the optics system doesn’t contribute to the overall crosstalk of the stereoscopic system. In fact, the custom optics showed less. While the differences in crosstalk are small, one reason for the reduced crosstalk lies in the custom optics design. The optics system in Figure 4 was designed to direct the light into each filter aperture, and in the process, collimates the light better than the COTS optics.

<table>
<thead>
<tr>
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<th>Crosstalk B onto A</th>
<th>Crosstalk A onto B</th>
<th>Crosstalk Total</th>
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<td>Filters</td>
<td>12.82</td>
<td>10.22</td>
<td>11.43</td>
</tr>
<tr>
<td>COTS</td>
<td>12.19</td>
<td>11.01</td>
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<tr>
<td>Custom</td>
<td>13.06</td>
<td>9.61</td>
<td>10.95</td>
</tr>
</tbody>
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6. Conclusions:

The only significant source of crosstalk comes from the filters. The current measurement of 11% crosstalk is pretty high. To reduce the amount of crosstalk, block filters can be added to the CMBFs. These filters are narrow bandpass filters that allow small portions of wavelengths to be blocked. By applying these filters at areas of high crosstalk, the overall crosstalk of the system will be reduced dramatically.

One issue noticed throughout the measurements was the large amount of crosstalk in the low wavelength spectrum (blue range). This can be seen in Figures 6 and 9. This was caused by the monochromator grating. The grating that was available was designed to transmit the red and infrared spectrum. It was able to transmit the low wavelengths, but at a reduced intensity and with some significant bleeding of white light. Therefore, the raw measurement of crosstalk doesn’t accurately describe the actual crosstalk of the system. Additional tests should be performed using a grating designed for the visible spectrum to calculate the crosstalk.
The error in the grating does not affect the conclusion about the custom optics. Since all tests were performed using the same grating, each test contains the error. The custom optics crosstalk still matched the crosstalk of the COTS optics and the CMBFs, meaning the optics system contributes nothing significant to the overall crosstalk.

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References:

