High-Speed Generation of Illumination Spectra for a Stereoscopic Endoscope

August 9, 2011

Prepared for
Dr. Harish Manohara, Dr. Michael Shearn, Student-Faculty Program

By:
Eric Fritz

Abstract:

Traditional stereoscopic vision (3D) is achieved through use of two separate cameras, arranged to emulate human eyes. This method works well on most projects, but becomes impractical on small scale designs, such as surgical endoscopes. This project is focused on developing a stereoscopic endoscope, using a single camera and Conjugated Multiple-Bandpass Filters (CMBF) to produce stereoscopic vision. Each half of filter is built to allow a distinct spectrum to pass through, while blocking the complimentary spectrum. A system with complimentary filters can produce stereoscopic images.

To accomplish this, the light must be filtered at the source to match the filters at the camera. Additionally, the light source and camera must be synchronized in a way that each image will show only one filter spectrum. In this paper, I will describe the design and characterization of the prototype electro-optical system, including optical throughput measurements and video produced using this method.

Background:

Three-dimensional viewing technology, or stereovision, has become increasingly common in industrial applications. Stereovision can increase the viewer's hand eye coordination and visual awareness when using a remote tool. In multiple studies done, monocular vision is either the cause, or part of the cause for error: 97% of surgical error was caused by a visual perceptual illusion [1], 87.5% of surgeons determined that 3D vision either somewhat or greatly helped [2], and motor movements are significantly faster in 3D than 2D endoscopes [3]. Because of this, companies have begun implementing stereovision into minimally invasive surgical endoscopes. Commercially available stereo endoscopes boast a dual camera system to create a 3D environment, which have successfully completed torso-based surgeries since 1999. However, these endoscopes had an outer diameter of 10mm, which prevented their use in skull based surgeries where the incision alone is only 10mm. Because of this, a new approach to stereovision must be taken. Instead of using two cameras, this new system will employ a single imaging chip and a series of lenses and filters. This will ultimately end up producing an endoscope with an outer diameter of only 4mm, making it feasible for brain surgeries.

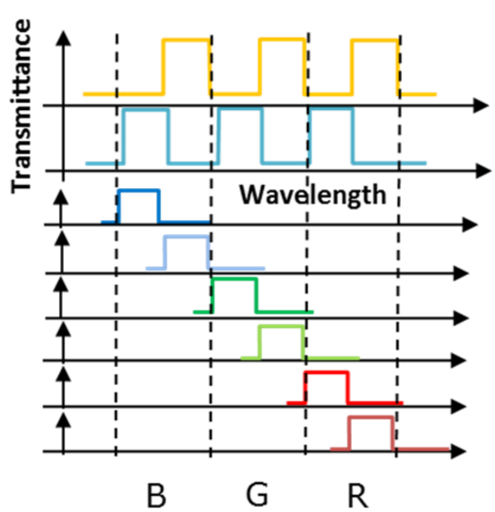

Figure 1: Each CMBF is a combination of certain wavelengths of blue, green, and red. This allows a much broader spectrum to be viewed under these filters [4].

The endoscope that is being designed achieves stereovision by using two optical filters that each allow only select wavelengths of light to pass through [4]. These filters will act as the 'eyes' of the system. This method is similar to the red and blue (anaglyph) glasses that early forms of 3D imaging used. However, the anaglyph filters create a lot of color rivalry because each eye only sees either a red-heavy or blue-heavy view of the object. Color rivalry occurs when each eye sees a different color for the same object and the brain has to choose which color gets priority. This is very uncomfortable to look at for extended periods of time, which is why it was never used in surgeries. Instead of using anaglyph filters, this design will use Conjugated Multiple-Bandpass Filters (CMBF).

These filters are designed to allow multiple colors on the visible spectrum through and blocking others. They are also complimentary to one another, so one filter receives none of the wavelengths that the other receives. Figure 1 shows how the CMBFs work. By choosing the wavelengths of light that each filter allows, a separate red-green-blue (RGB) image can be created for each 'eye' of the camera system. Although this sharply reduces color rivalry, it doesn't eliminate it. Each filter consists of a distinct set of wavelengths used for the RGB illuminants. This means that the palate of reproducible colors differs between the 'left and right' images. Correcting the image data is necessary to reduce the color rivalry to a state that isn't noticeable. Different matrix multiplications can be applied to the images to produce these desired results. While the new images may be false color, the mixed image will be as close to true color as possible.

Once the proper filters were chosen, designs of the endoscope system began. The CMBFs work alongside lenses to give the effect of a 'left and right eye' image. Figure 2 is a representation of the imaging chip, CMBF, and lens system.

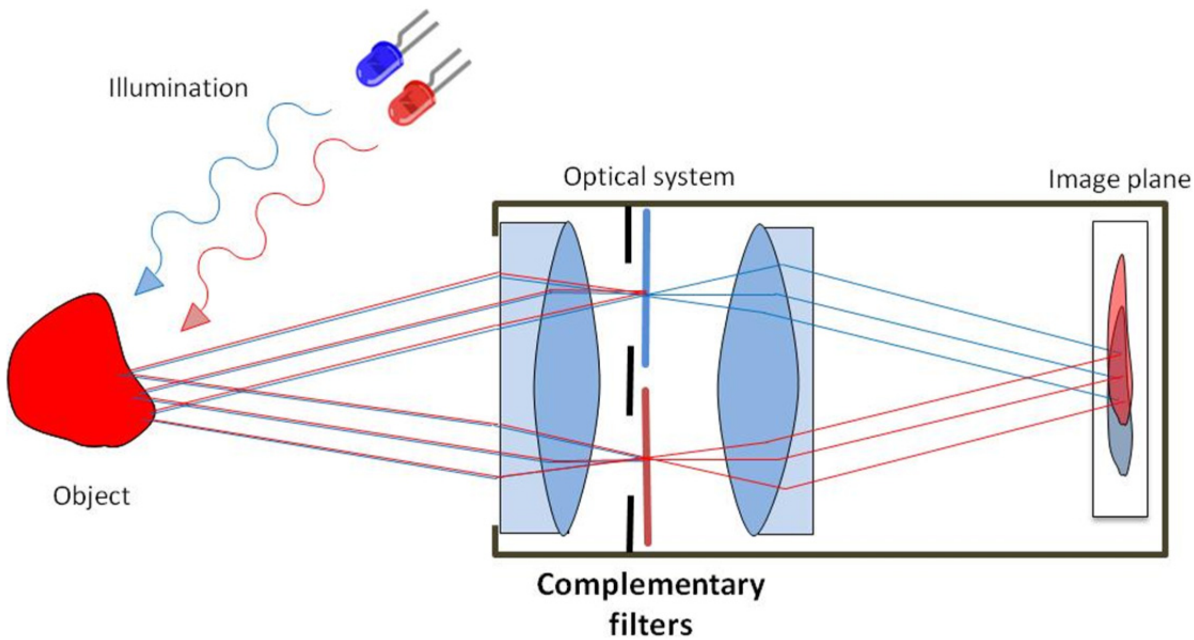

Figure 2: Stereovision using CMBF system

Objectives:

This project is primarily focused on the programming and optical side of the project. The first goal is to find a way to create the spectrums that the CMBFs operate at. Second is to construct an experimental setup for the endoscope that is fully synchronized and capable of capturing images. Finally, efficiency tests are to be performed to determine the loss of light throughout the optical system.

Because the CMBF system is being used, optical filtration at the light source is also necessary. The light shining on the object must switch between the spectrums designed for each filter in order for the imager to capture a frame of just one filter spectrum. Once this is completed, a prototype can be constructed to work towards synchronizing the hardware with itself, as well as with the software.

The final goal is to examine where the greatest amount of power loss is occurring and why. Because this endoscope is designed with the intention of being used in brains surgeries, any heating is a concern. These tests will also examine how different wavelengths of light flow through the optics system and ensure that the light is spectrally uniform throughout.

Approach and Discussion:

In order to achieve stereovision with the CMBF system, there will need to be filtration of the light at the source. Because white light contains all wavelengths of light, flooding the area with it would result in some light passing through both filters. Since the goal is to have separate images for each filter, we must alternate between projecting the correct spectrum for each of the filters. Figure 3 is a simplified view of what this part of the project is trying to achieve. The first task is finding a way to filter at the light source.

The easiest way to do this is to apply a similar CMBF system at the light source; have both filters side by side. To alternate between the filters, a Digital Micromirror Device (DMD) was used. A DMD consists of an array of micromirrors that have two states: on and off. If a mirror is on, then light reflecting off of it will get sent out of the projector. If it is off, the light will get reflected to a light absorber. A TI DLP LightCommander [5] was chosen because it can supply the light, has a programmable DMD, and is capable of operating at up to 5000Hz. The DMD was then programmed to project light through one of the filters. The light that passes through will be the correct spectrum for the appropriate CMBF in front of the camera. The DMD will then switch to illuminating the other half and light will be projected through the other filter, thus allowing the camera to see only one filter spectrum for a certain time interval. Although this is an easy way to split the light, it isn't the most efficient. The filters must be perfectly aligned with the DMD and all lenses must be perfectly focused. This method works well for this stage of the endoscope, but the final product will employ a better method: Hyperspectral Imaging.

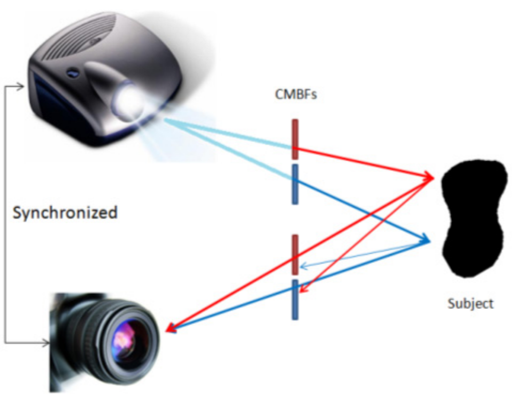

Figure 3: Overview of the optics system

Hyperspectral image projection [6] is another method for creating the spectrum needed. This system also utilizes a DMD, but instead of shining light through filters, the DMD itself creates the spectrum. Figure 4 shows this method. The light will first get projected through a prism that will split white light into all wavelengths of light. Next, the light will reflect off of the DMD, which will have a spectral image uploaded to it. A spectral image is a black and white rendering of spectrum data. If the spectrum data has a greater frequency of a certain wavelength, there will be more white pixels (or 'on' mirrors on the DMD) at that wavelength on the spectral image. A program was designed to take spectrum data and convert it into a spectral image that is compatible with the DMD. Since the spectral data of the CMBFs are known, appropriate spectral images can be produced. The resulting light will then get projected through another prism to condense it into a single beam. The DMD can be programmed to alternate between the two spectral images of the CMBF's spectrum. Although this method is preferred, no work has been done to implement the system beyond writing the program to convert spectral data to the spectral image, due to this being an early stage of the project.

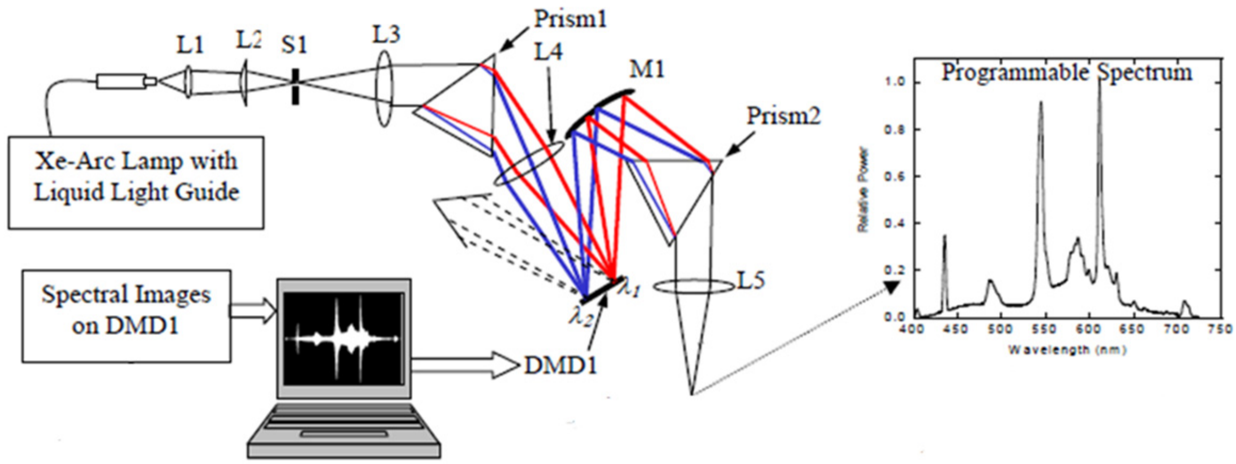

Figure 4: Hyperspectral Imaging method [4]

The next step towards assembling an experimental setup is synchronizing the camera with the light source. The camera being used is an Omnivision OV6930 rolling shutter camera [7]. Most cameras capture an image by exposing all the pixels at once and exporting the data as a single snapshot. Rolling shutter cameras capture the image by scanning across the frame vertically (or in some cameras, horizontally). In other words, pixels on the top row of the frame get exposed, send their data, and end their exposure as the pixels in the next row down begin this process. Once all the pixels have sent their data, a pulse (called Vertical Sync or VSYNC) is sent, signaling the top rows to start again. Because of this, there will always be exposed pixels somewhere on the imager.

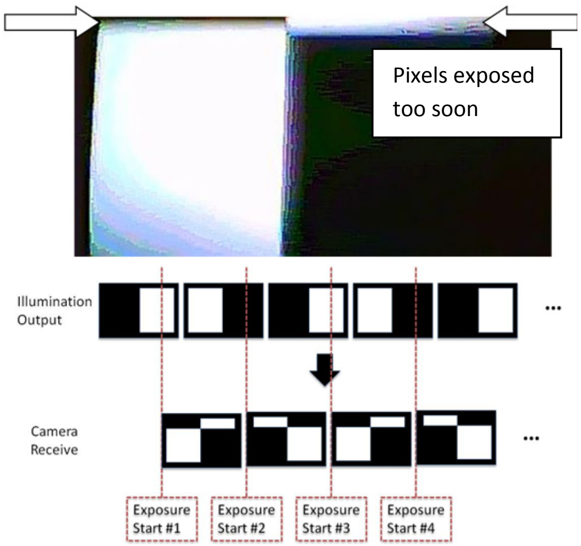

Figure 5: The top row of pixels are being exposed before the DMD can switch

The camera and the light source need to be synchronized in order to ensure each frame gets exposed to only one CMBF spectrum. The DMD software permits an external trigger to control the switching instead of controlling it through its internal clock. This option allows the camera to control the DMD. The DMD was wired to the camera's refresh pulse (VSYNC) and the resulting image was captured, shown in Figure 5.

There is significant lag between the time that the VSYNC is sent and the time that the DMD receives the pulse and switches. Because of this, the first rows of pixels are being exposed to the previous state of the DMD. In order to counter this, a delay was added to the circuit.

After trials with different methods of implementing the delay, the most efficient choice was using a programmable microprocessor, Arduino [8]. The Arduino was chosen because of its versatility, easy programmability, and low price. The new circuit consists of the Arduino receiving the VSYNC pulse, waiting for a predetermined time interval, and sending a pulse to the DMD, signaling the switch. The length of delay was chosen experimentally and was dependent upon the camera's refresh rate. The result was a perfectly synchronized image, shown in figure 6.

Figure 6: The DMD switches at the same time as a new image begins exposing

With the camera and DMD synchronized, the next step was image acquisition and system control. This involves assembling the endoscope system. Three primary elements comprise the endoscope system: Optics, Image Acquisition, and Electronic Control. The Optics system consists of a lens, the CMBF, an integrating rod, and a ring fiber optic cable. The lens refocuses the light from the DMD through the CMBF, and into the integrating rod. The integrating rod accepts light at one end and condenses that light into a smaller area. This rod can focus the light into the fiber cable, which will then project that light onto the object under observation. From there, the camera will capture the image and output it to Matlab.

The Electronic Controls include two of the Arduino microprocessors and Matlab. Two Arduinos are used because Matlab doesn't operate fast enough to read the VSYNC consistently. One Arduino will be uploaded with a program that allows Matlab to control it. The second Arduino will be uploaded with the same program that sets the delay with a slight modification. It will only send the pulse to switch when Matlab sends the command to, via the first Arduino. This allows the user to capture images at any frame rate and do the necessary color correction or other desired modification. This entire system can be seen below in Figure 7.

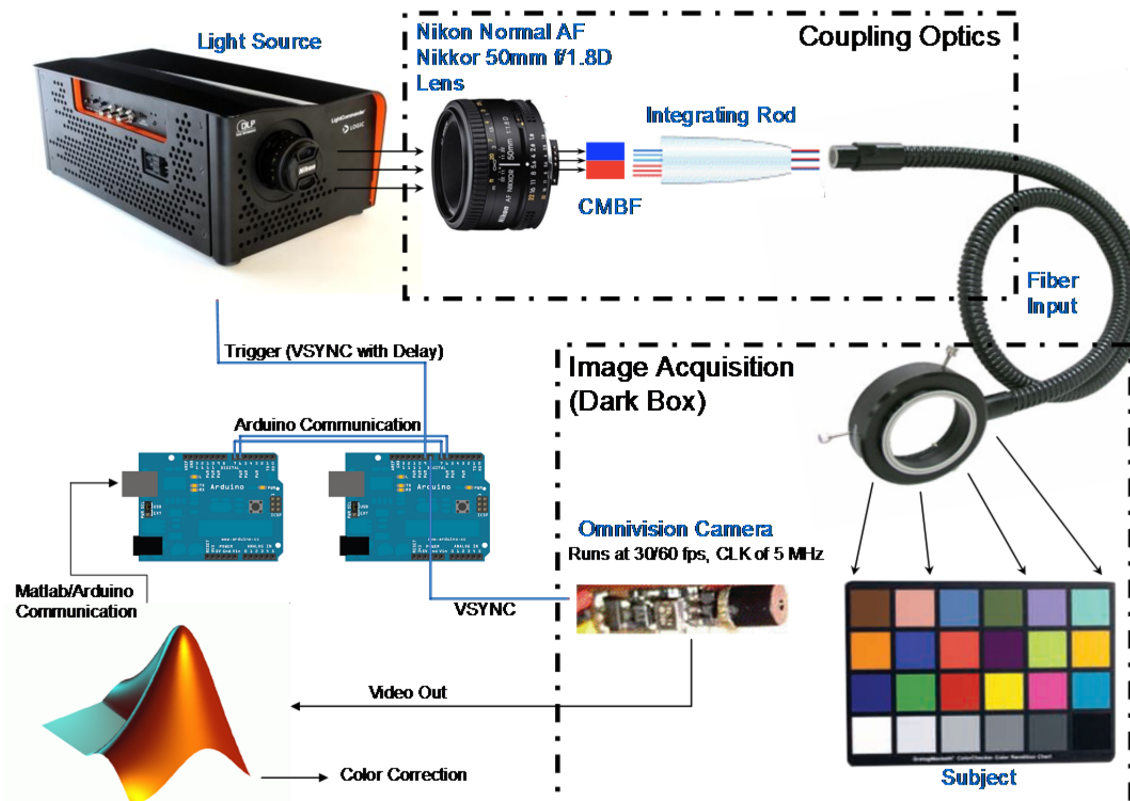

Figure 7: Current Endoscope system

Using this system, we were successfully able to capture separate images from both filters at a frequency of approximately two frames per second. This is still too slow for real time video feed, which will require a processor that is able to perform the calculations much faster than Matlab currently is able to.

The final task is to analyze loss of light throughout the optical system. For every optical component, there will be a certain amount of light lost. This is an inevitable process and it is of great interest to know how much loss is occurring and where the greatest loss takes place.

An optical power meter was used to find the intensity of the light after each optical component. These meters are designed to accept and reflect light coming in from a wide range of angles onto a photovoltaic cell. The overall power of the light can then be recorded. Power readings were taken after each element in the optical system. Because the light source being used utilizes red, green, and blue LEDs, each individual LED was tested. Figure 8 shows the amount of light exiting each component as a percent of light leaving the previous component.

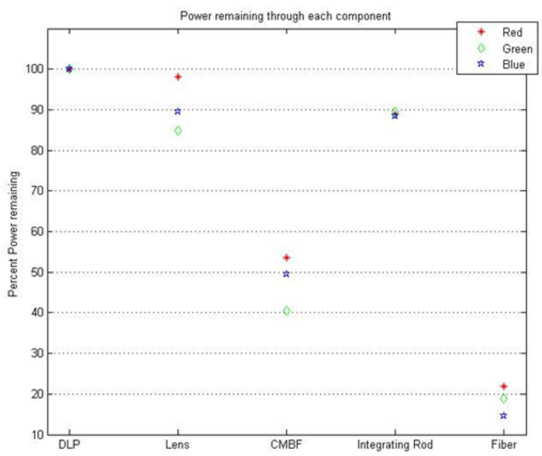

Figure 8: Percent power remaining through each element of the optics system

The lens and integrating rod showed minimal loss, averaging about 90% efficiency. The CMBF showed an expect 50% loss due to the fact that half the wavelengths weren't allowed through. The biggest loss occurred at the fiber cable, where only 20% was transmitted. Upon investigation, it was concluded that the majority of this loss can be attributed to a characteristic of light called etendue, not heat, which would be catastrophic in brain surgery. Etendue is a property that describes how spread out light is in area and angle. There is a relation between the area of the light and its angle. As area decreases, angle increases. Because the integrating rod is reducing the area of the beam, some of the light exits the integrating rod at an angle that is beyond what the optics cable can accept. The final endoscope design should thus use optic cables with greater acceptance than the ones currently employed for this prototype.

Because the CMBFs only allow half of the light though, additional tests were done that excluded the filters from the system. The overall throughput of the two systems was 7.2% with the filters, and 18% without. To get a sense of how this competes with endoscopes already available, power tests were also performed on a commercially available endoscope, which showed a throughput of 20%. One final conclusion that was made from these tests was spectral uniformity. Because the stereoscope relies heavily on color to work, it is critically important that the spectrum doesn't get distorted through the system. While figure 8 shows some inconsistency in the LED transmittance through the system, there was no spectral disruption found.

Conclusion:

The efforts of this project have taken the necessary steps towards a fully functional stereoscopic endoscope. Through experimentation, the results have shown that the proposed endoscope system is able to acquire separate images for each filter, a critical prerequisite for achieving stereovision using the CMBF method. The power tests yielded the loss of light through the system, allowing us to anticipate the required strength of the light source. These tests also confirmed spectral uniformity throughout the system. Because the images are of one filter spectrum, it will not be an accurate representation of the true color of the object. To fix this, additional research is being conducted into color correction. Integrating the image capturing and color correction, as well as acquiring the necessary hardware and software to stream live video is the next step towards a fully functional stereoscopic endoscope.

Acknowledgments:

This research was carried out at the Jet Propulsion Laboratory, California Institute of Technology, and was sponsored by the Space Grant program and the National Aeronautics and Space Administration.

References:

[1] LW Way et. al., Annals of Surgery 2003, 237:4, 460—469

[2] JF Fraser et. al., Minimally Invasive Neurosurgery 2008; 51:1—7

[3] A Blavier et. al., Acta Medical Belgica 2006; 106:6, 662—664

[4] Y. Bae, V. White, K. Scheglov, H. Manohara, and H. Shahinian. “Stereo imaging miniature endoscope with a single chip and conjugated multi-bandpass filters (CMBF).” NTR 47420. 11 November, 2009.

[5] “DLP LightCommander” *Texas Instruments.* Web. 12 Aug 2011 <http://www.ti.com/ww/en/analog/mems/dlplightcommander/index.shtml?DCMP=DLP_Light_CommaComm&HQS=Other+OT+dlplightcommander>

[6] Rice, J. P., & Allen, D. W. (2009). Hyperspectral image compressive projection algorithm. *Proceedings of SPIE*, *7334*, 733414-733414-11. Spie. doi:10.1117/12.818844

[7] “OV6930” *Omnivision.* Web. 12 Aug 2011 <http://www.ovt.com/products/sensor.php?id=49>

[8] “Arduino Uno” *Arduino.* Web. 12 Aug 2011 <http://arduino.cc/en/Main/ArduinoBoardUno>