Project Report: Reducing Color Rivalry in Imagery for Conjugated Multiple Bandpass Filter Based Stereo Endoscopy

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Abstract

A pair of conjugated multiple bandpass filters (CMBF) can be used to create spatially separated pupils in a traditional lens and imaging sensor system allowing for the passive capture of stereo video. This method is especially useful for surgical endoscopy where smaller cameras are needed to provide ample room for manipulating tools while also granting improved visualizations of scene depth. The significant issue in this process is that, due to the complimentary nature of the filters, the colors seen through each filter do not match each other, and also differ from colors as seen under a white illumination source. A color correction model was implemented that included optimized filter selection, such that the degree of necessary post-processing correction was minimized, and a chromatic adaptation transformation that attempted to fix the imaged colors tristimulus indices based on the principle of color constancy. Due to fabrication constraints, only dual bandpass filters were feasible. The theoretical average color error after correction between these filters was still above the fusion limit meaning that rivalry conditions are possible during viewing. This error can be minimized further by designing the filters for a subset of colors corresponding to specific working environments.

Background

Three-dimensional viewing technology has been making a huge surge in industrial applications lately due to its ability to increase dexterity and efficiency when controlling devices from remote sites [2]. Medical applications in particular have been creating many more such uses for 3D camera systems with the advent of new, minimally invasive surgery procedures. Intuitive Surgical, a company specializing in minimally invasive surgical systems, has been manufacturing stereoscopic endoscopes based on the traditional two camera design which have been successfully used in torso-based surgeries since 1999 [3]. However, for new ground breaking minimally invasive neurosurgery (MIN) procedures at the Skull Base Institute, the ten millimeter outer diameter of the current endoscopes is far too large. Therefore, a new design for a stereo-endoscope has been proposed that will ultimately be four millimeters in diameter and use only a single lens package and imaging chip. The benefits of using a single lens package to reconstruct stereoscopic imagery are, decreased manufacturing costs by utilizing larger optics with higher dimensional tolerances, fewer imaging planes used which reduces system complexity, and minimization of non-light collecting frontal area which is at a premium in a four millimeter package. This all decreases the diameter of the endoscope to a level small enough to fit into any hole for MIN procedures while allowing room for other tools to be maneuvered alongside.

The endoscope that is being designed creates a stereo-image using the new novel approach of conjugated multiple band-pass filters (CMBF) that each allows only select wavelengths of light to pass through [1]. In wavelength bands where one filter allows light to pass the other filter completely blocks transmission; this is shown in figure 1. As many band-passes as desired can be used to achieve this effect. However, manufacturing limitations place an upper cap of four bands per filter currently, while full color reproduction requires a minimum of two bands per filter since red, green and blue data channels need to be covered by each filter in the pair.

By placing one filter set in front of a broad band light source, such as a xenon lamp, an alternating illumination spectrum corresponding to the band-passes of each CMBF filter is established. A second set of the same filters placed inside the camera optics effectively splits the optical path in two, thus creating the two physically separated 'eyes' of the system. By synchronizing the rate at which the illumination source switches with the rate of frame capture by the camera every set of two images from the camera feed forms a stereoscopic pair which are easily displayed to the viewers corresponding eyes on a 3-D display. This process is depicted in figure 2. The benefit of this process is that the stereoscopic pairs are established through a passive process for the camera, meaning no moving parts or electrically charged filters rapidly changing. This results in fast, crisply defined imagery that is captured through the use of minimal hardware.

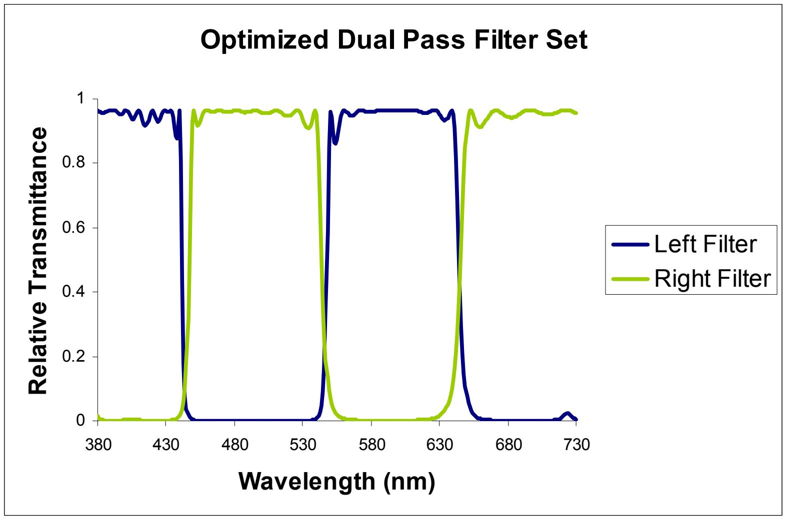

Figure 1: Diagram of simulated dual bandpass filters. Where one filter allows the transmission of light the other blocks it. These filters, in conjunction with an alternating light source, can be used as a shuttering system to capture stereoscopic images.

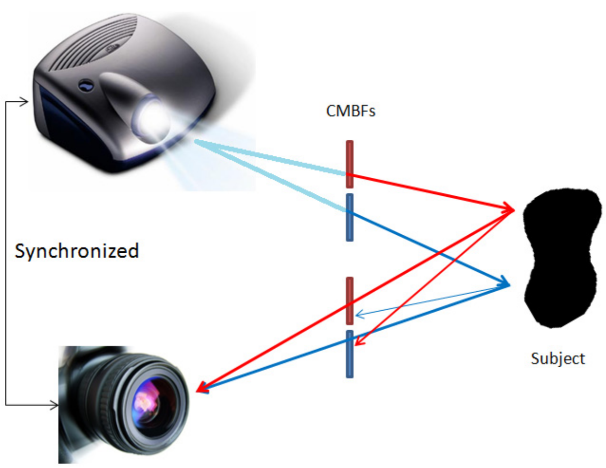

Figure 2: The illumination source alternates between shining through the left or right CMBF limiting the light to wavelengths that will only pass through the corresponding CMBF in the imaging system. By synchronizing the camera and light projector every two images will form a stereoscopic pair.

Through careful selection of the band-passes of each filter, the system is capable of capturing stereoscopic paired color images by through a conventional RGB imaging array. The issue that arises from this process, however, is that the color composition of each of the paired images will differ from each other. If the color stimuli displayed to each eye of the observer differ too much for a given object in the viewing scene, the viewer's brain will have a difficult time determining which color it should interpret as the correct color. In many instances, depending on the dominancy of viewer's eyes, the colors that are being seen and the colors of the surrounding image, the color the brain chooses as correct may change with time. This can create an alternating image perceived by the viewer which can be very uncomfortable to look at. This condition is known as color rivalry [4].

The fusion limit is a boundary that has been studied which seeks to show the limit of dichoptic color stimulus difference where rivalry does not take place [5,6,7]. By knowing the range of fusion, better filters and color correction methods can be employed to eliminate color rivalry from the final imagery. While the exact mechanisms for color rivalry and fusion are still not known, there is at least a general understanding of the limits of fusion that have been determined through experimentation. In the perceptually linear CIE LUV color space a color error in the range of 0.0415 to 0.0640 [5], depending on chromaticity and luminosity, which corresponds to a range of ten to fifteen in the more widely used LAB color space, has been found to give a rough approximation of the fusion limit. Color rivalry can be effectively avoided by designing a system that reduces the error of any color pair to less than this range.

Besides the fact that rivalry causes headaches for the viewer when looked at for too long and degrades the quality of stereopsis, it can also be very distracting which has the potential to be disastrous for a neurosurgeon. Eliminating color rivalry from the resulting imagery of the system, such that it is safely and comfortably useable for surgery procedures, is the motivation for this project.

Objectives

This research seeks to achieve two main goals; finding a color correction method which can be easily incorporated into the imaging and display software allowing for real time viewing, and creating a software package that helps to optimize filter sets for a given set of operating parameters.

Surgeons require a real-time video feed so that every movement they make can be as precise and controlled as possible. This is especially true for neurosurgeons where the smallest of slips can have deadly effects. This requirement means that the video stream needs to be a fast as possible. Therefore, any color correction, or other post processing, needs to be simple enough that it induces no noticeable lag time. This color correction, in addition, must also be robust enough to correct for the highly misrepresented colors that are present when dealing with CMBFs. Determining a suitable color correction method is the first objective dealt with in this report.

There are many hardware parameters that are involved in the selection of the best filters for the application. As this device evolves and changes, many different light sources and cameras, among other pieces of hardware, will be tested to see which combination is best for the job. Through modeling of the spectral characteristics of the light source, transmittance properties of various optics in the system, filters used in the RGB imaging array, sensitivities of the human cone cells, and taking the color correction model into account, a software package will be developed that will aid in optimizing the filter band-passes to reduce color rivalry for the given set of system parameters.

Approach

The method used to pursue the goals of this project began by determining the possible color correction models that have been proven to achieve accurate color reproduction. After a comprehensive search, there were two main candidates that displayed potential. The first was a sophisticated method used in multispectral imaging where the spectra of a point in a scene can be estimated by minimizing the values of positive coefficients of spectral basis functions (these behave much like a Fourier series) [8]. From the estimated spectra, a very close approximation of the RGB coordinates at a point could be calculated for display. The second method considered was a linear approximation to a non-linear, non-invertible transformation called a Bradford matrix [9,11,12]. The Bradford is a linear transformation in XYZ color space where the known spectra of a white light source, after being passed through one of the CMBF filters, is compared to that of the white light source on its own.

The relative merits and downfalls of these are that the basis function approach has the ability to quite accurately calculate the spectra of a color but at the cost of very high computing power. The Bradford is very cheap and easy to program since it only has to be calculated once and is a simple linear transformation. However, the Bradford tends to be less accurate since it is essentially a curve fit to experimental data. Due to the fact that processing power has been an issue in the past, the Bradford transformation was selected as the method of choice. However, for better reproduction value in future iterations, basis functions should be carefully considered.

The next phase of this project was to create an automated MATLAB program to simulate the effects of a Bradford matrix correction on the color rendering capabilities of various filter sets so that an iterative search could determine the best possible filter combination. This program was designed to take filter transmissions over the visible range, illumination source properties, and optical system losses and calculate the colors of a Munsell color checker card as seen through each of the filters. These calculations were carried out following the procedures for color calculations as set forth by the ASTM E308 standard using the CIE 1931 values [10]. The program then takes the filtered colors and calculates the Bradford transformation to map what is seen through the filters, the source, back to what should be seen under a white illuminant, the destination; in most cases a D65 illuminant [9].

Systematic errors were calculated for the color correction technique in LAB color space based on the standard color error $\Delta E=((L_1-L_2)^2+(a_1-a_2)^2+(b_1-b_2)^2)^{1/2}$. Error was calculated between the colors, before and after transformation, with the white source they were being mapped to, and also between the colors of the left and right eyes to show the color rivalry condition. This error was used to compare various filter sets to see which one, in conjunction with the Bradford transformation, produced the most accurate color set.

The final part of the analysis package created simulations of the Munsell color checker card so that a visual representation of the colors at each step in the correction process could be seen. This step provided a human perspective in the color correction process to account for the yet not fully understood nature of the fusion limit. The analysis code output is demonstrated in figure 3.

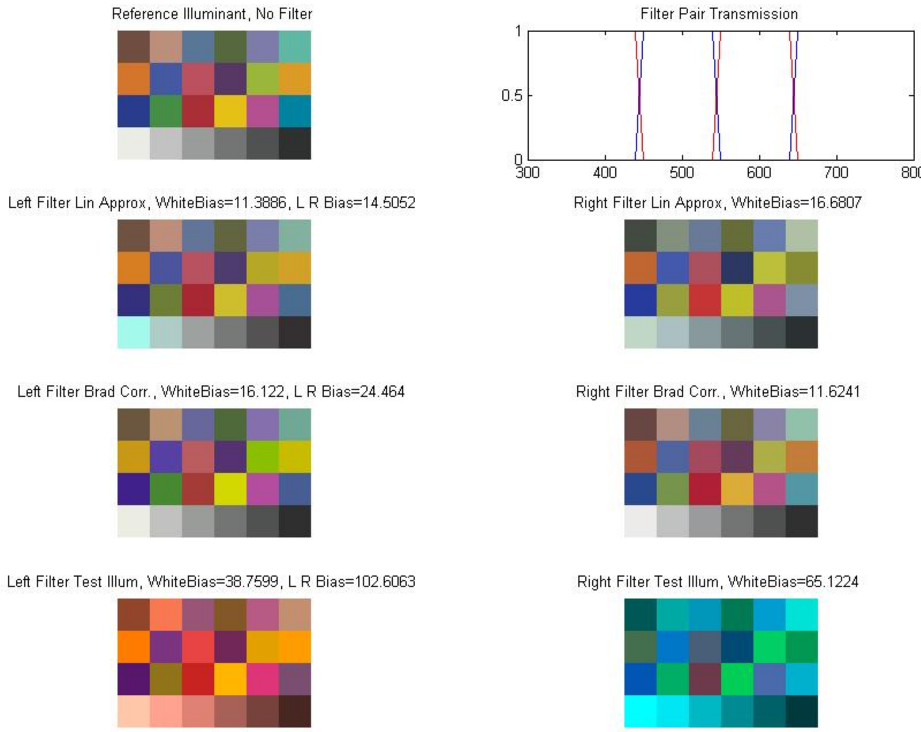

Figure 3: Output of color correction software developed for optimizing filter selection. The top row shows the reference card, to which everything is being corrected, and the filter pair being simulated. The bottom row produces images of the card as seem through the left and right filters, while the middle rows demonstrate the results of color correction schemes.

Using this software, a brute force search was carried out to determine the best filter set that could be manufactured that would exhibit the following properties. First, the filters needed to reduce any rivalry conditions to a level below the fusion limit. Secondly, the final color reproduction needed to be reasonably close to an unfiltered scene, illuminated by a daylight stimulant, such that displayed colors were as accurate as possible. Finally, the filters needed to be simple enough in design that they could be manufactured by current processes. These three conditions were used to judge possible filter designs to determine the optimal filter set for the application.

Results and Discussion

Using the Bradford matrix technique to improve the color quality of images as seen through CMBF filters, there is a correlation between the filters used and how well the color is able to be corrected. This is due to how the coefficient matrices were developed for the Bradford transformation. The Bradford was derived for color corrections that were between primarily broadband spectrum illumination sources and performs exceedingly well in this regime [11,12]. When a CMBF filter is added, especially one that blocks large portions of the visible spectrum, a large amount of color data is lost. Therefore, the Bradford is not able to correct for all of the large missing bands since it cannot fill like other techniques seek to do. The more complete the spectrum, the better the Bradford transformation is able to correct the colors. Due to this relationship, it was observed that as the number of bandpasses increased, with roughly even distribution over the visible range, the quality of the correction was improved.

This phenomenon can be thought of in a similar manner to sampling an audio signal. If the sampling frequency is high enough (lots of bandpasses) it is possible to perfectly reconstruct the input signal. However, as the sampling frequency reaches the Nyquist frequency aliasing starts to occur. If the input signal and sampling rate are relatively well known, then approximations of the input can be made when aliasing is seen. In the same sense, as the number of bandpasses decreases, the bandpasses themselves stay very well known (the sampling frequency), while the spectra of a given color is relatively understood (the input signal), meaning that an approximation of the actual color spectra can be made. However, this is only an approximation, and is also an approximation that gets worse with decreasing number of bandpasses or poorly placed bandpasses.

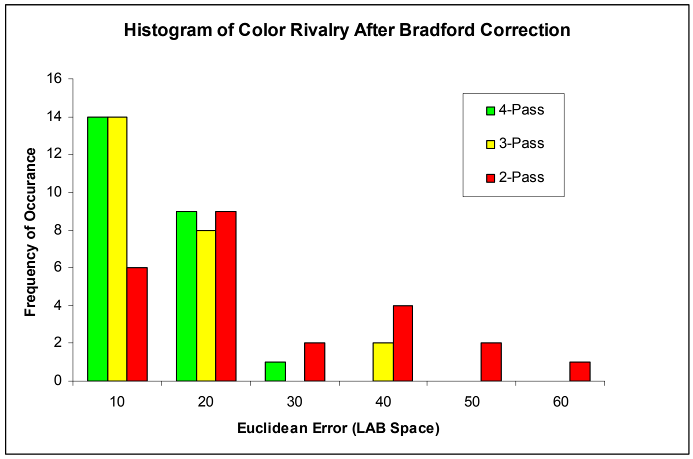

Figure 4: Histogram showing the increase of color rivalry as the number of bandpasses decreases.

Since humans are trichromats, three bandpasses would appear to be the point at which severe color aliasing would occur. Experimentation shows that there is a much greater difference in color rendering between a well designed three-pass filter and a similarly well designed two-pass filter than between a three-pass and a four-pass filter set, see figure 4. By judiciously selecting the locations of the bandpasses for a two-pass filter, however, decent color reproduction can still be achieved due to the fact that one bandpass can sample the wavelength regions of two cone cells in

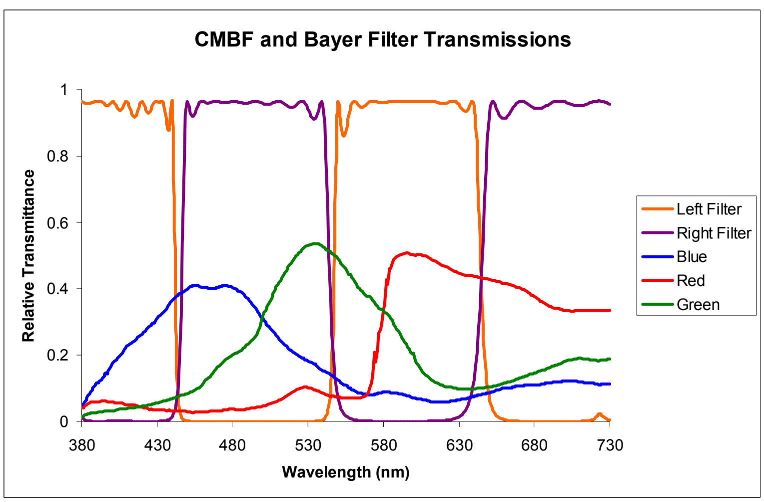

Figure 5: Dual bandpass filters overlaying the transmission of Bayer filters for a typical RGB camera. Notice how the bandpasses can be arranged such that each passes light on intervals where there is high transmission through each of the three channels of the Bayer filters.

the human eye. This can be seen in figure 5.

Manufacturing constraints placed a current limit on filter bandpasses at two with the possibility of three in the future. Therefore, a filter selection search was carried out to determine the optimal filter set of two and three-pass filters for a xenon lamp light source imaging a full spectrum of colors. The three-pass filters, as expected, had the best overall final color composition and the minimum color rivalry error. In fact, the three-pass filter selection was good enough that, when viewed dichopticly on a stereoscopic monitor, there was no noticeable color rivalry in the resulting simulated imagery. A comparison of the two and three-pass filter sets, after correction, can be seen visually in figures 6 and 7, and a comparison of their ΔE errors for white point and color rivalry can be seen in table 1.

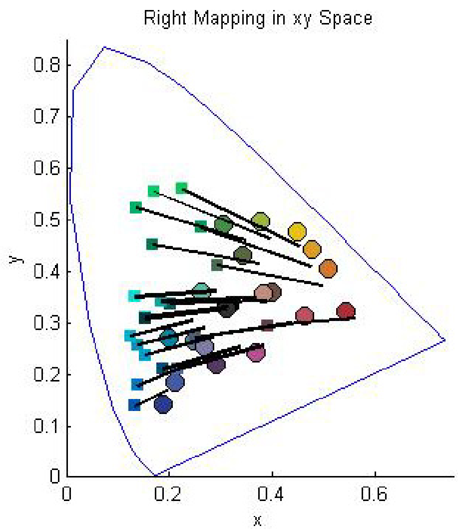

Figure 7: Dual bandpass color mapping for the right filter (circles are unfiltered colors). Since colors are highly misrepresented they must be corrected a large amount. The Bradford is a linear approximation and therefore will not correct accurately over such large distances.

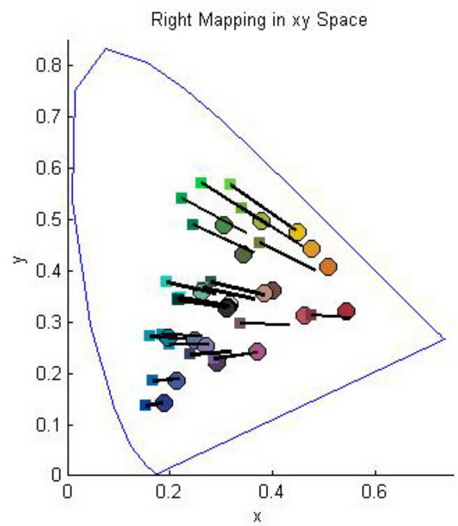

Figure 6: Triple bandpass color mapping for the right filter. Since the colors are more accurate before correction than the dual bandpass colors are, the Bradford correction is able to correct with higher integrity.

Table 1: Error comparison in LAB space for optimized filters of various numbers of bandpasses.

Table 1:Comparison of ΔE Error for Optimized CMBF Sets After Bradford Correction						
	RMS ΔE			Max ΔE		
Filter Set	Left-WP	Right-WP	Left-Right	Left-WP	Right-WP	Left-Right
4-Pass	6.732	7.0588	13.758	16.8533	18.1372	33.3991
3-Pass	7.0423	7.6946	12.1483	18.9563	17.9969	29.8561
2-Pass	16.122	11.6241	24.464	34.0114	24.9599	50.5854

As the results in table 1 indicate, even a four-pass filter set (which cannot even be manufactured currently) has color rivalry biases that fall outside the experimentally determined range of color fusion. However, for a subset of the colors represented by any of the filter choices, the color reproduction falls within an acceptable range. Therefore, due to the fact that manufacturing constraints limit the number of bandpasses in many cases to two, if the range of colors that will be viewed by the endoscope is well known, then a specific two-pass filter set could be optimized to reduce all rivalry for the colors that will be imaged. As manufacturing processes get more sophisticated the number of bandpasses will increase allowing for a greater and greater subset of colors to be reproduced without rivalry. Considering that surgery procedures deal with mostly tissue colors it is not impractical at all to conceive of a set of two-pass filters that will thoroughly eliminate color rivalry for scenes viewed during surgery.

While the Bradford transformation in conjunction with well chosen filters has the ability to produce real-time imagery with minimal rivalry conditions, a more refined color correction method may be possible that could eliminate some of the dependence on filter selection for accurate color rendering. Given that RGB data is typically stored in a relatively small eight bit format, it may be possible to take a more refined color correction method that is too slow for real time imaging and condense it into a look up table style correction method. For example, analyzing basis functions beforehand for any possible color that the camera could detect would eliminate the reliance on minimization techniques that slow the process too much for real-time. While this table would have to be remade for any given filter selection, it could be done before the camera was used so that minimal calculations would have to be carried out during operation. By employing this method, less dependence on filter selection may be possible, easing the burden of fabrication constraints and reducing system cost.

Conclusions and Recommendations

The software package that has been created provides a great platform with which to optimize CMBF selection depending on multiple hardware and environmental factors. The main issues that affect the process of filter selection and color correction are camera speed and color rivalry. The correction technique must be fast enough to be employed in a real-time imaging situation where stereoscopic stimuli are being captured. This sets a high precedence for a simple linear color correction scheme or table lookup. While the Bradford correction method is a simple and fast transformation, the ability to correct color is highly dependent on the filters used. Therefore, employing a more refined correction method would be beneficial if the mathematics could be reduced to a look up table style correction scheme.

The presence of color rivalry in the imagery that is captured with this endoscopic system has the ability to cause headaches and eye strain for the surgeon who will be using it which could lead to mistakes during high stakes procedures. The elimination of all color rivalry has been shown to not be possible through the use Bradford corrections when such a minimal number of CMBF bandpasses is used. Designing the bandpasses of the CMBFs for a certain subset of colors present during MIN procedures is a possible solution to this problem. Through reduced color palates or more refined color correction methods, accurate and rivalry free stereoscopic imagery can be captured in real-time that will aid neurosurgeons in performing highly technical procedures with maximum agility and dexterity.

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