Single lens dual-aperture 3D imaging system: color modeling

Sam Y. Bae[1,2], Ronald Korniski[1], Allen Ream[3], Eric Fritz[4], Michael Shearn[1]

[1]Jet Propulsion Laboratory, Pasadena, California
[2]University of California at Los Angeles, Los Angeles, California
[3]Montana State University, Bozeman, Montana
[4]University of Nebraska, Lincoln, Nebraska

ABSTRACT

In an effort to miniaturize a 3D imaging system, we created two viewpoints in a single objective lens camera. This was accomplished by placing a pair of Complementary Multi-band Bandpass Filters (CMBFs) in the aperture area. Two key characteristics about the CMBFs are that the passbands are staggered so only one viewpoint is opened at a time when a light band matched to that passband is illuminated, and the passbands are positioned throughout the visible spectrum, so each viewpoint can render color by taking RGB spectral images. Each viewpoint takes a different spectral image from the other viewpoint hence yielding a different color image relative to the other. This color mismatch in the two viewpoints could lead to color rivalry, where the human vision system fails to resolve two different colors. The difference will be closer if the number of passbands in a CMBF increases. (However, the number of passbands is constrained by cost and fabrication technique.) In this paper, simulation predicting the color mismatch is reported.

Keywords: 3D imaging system, dual aperture, bipartite filter, complementary multi-band bandpass filters, color rivalry, Bradford, chromatic adaptation transformation

1. INTRODUCTION

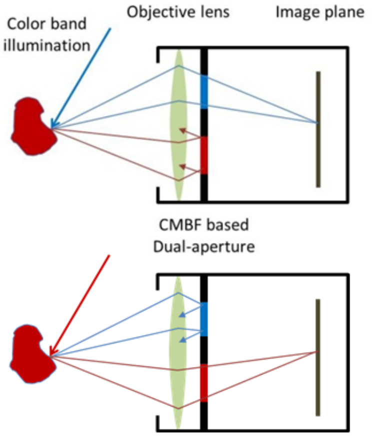
Advanced fabrication techniques in optics and imaging chips have allowed cameras to shrink incredibly small. Some of these cameras are small enough to be mounted on a stick, *aka* distal camera borescope, and inserted and image the interior of small cavities. Also, some of these small cameras are arranged side-by-side, like the arrangement of human binocular vision, to provide 3D sensation or record depth information when working. However, the camera can be scaled down so much before compromising its optics and imager's resolution. In effort to miniaturize the volume of a 3D imaging system without compromising the resolution, the following work was undertaken.

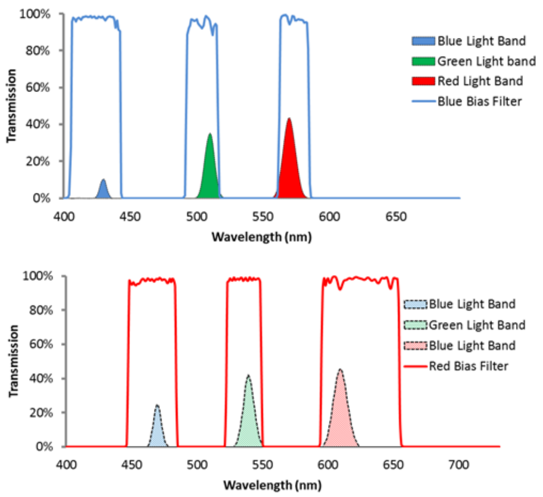
Some patents in the past have claimed to overcome this volume restriction by creating two viewpoints in a single objective lens of the camera.[1-5] The claim works by dividing the limiting aperture area into two regions and open the two alternately; hence each region becomes one viewpoint. One advantage lies in that the use of a single lens allows the viewpoints to converge to a point of infinity like the "vergence" of human vision, a simultaneous inward movement toward each eye in an effort to maintain single binocular vision. When such viewpoints are displayed, the 3D viewing becomes more natural. [6,7] Advantages regarding to the footprint and the resolution are that (1) the total footprint of the single lens is smaller than that of two lenses. More specifically, lens elements and packaging for building a single objective lens would take up a less space than for two objective lenses with an associated cost savings and; (2) only one imaging chip is required for imaging both viewpoints. A single chip operating in a confined space puts limitation on the pixel density, a number of pixels per a given area, with the current technology. The use of the single lens allows the same pixel density used for imaging a single viewpoint for imaging the dual-viewpoint. However, these benefits can be only be attained when the two aperture regions are opened alternately to present each viewpoint to the single imaging chip.

In efforts to develop a mechanism to open/block the dual-aperture alternately, a few patents have been claimed in the past. Two key goals are (1) to open/block the apertures completely so that the two optical paths would not talk to each other and (2) to build a mechanism small enough to be incorporated in a scale of a distal camera borescope. One patent puts into place a physical shutter and displaces it to one half and the other half of the dual-aperture. One concern in this mechanism is that, because the shutter's movement would not be instantaneous, it could smear the image. Another patent claims placing electro-optical liquid crystal blocks at one at each half side of the dual-aperture and electrically making the liquid crystals opaque and transparent alternately. Although the bi-state would be instantaneous, the liquid crystal does not block the light completely. Thus, crosstalk is expected. Another patent claims placing a pair of orthogonal polarizers at each aperture and illuminating the scene alternately with corresponding lights. However, the polarization would be randomized when it interacts with surfaces. Again, crosstalk is expected.

The technique we are developing takes the concept of the next patent to the next level. The patent claims placing a pair of complementary optical bandpass filters in a single imaging lens and illuminating the scene with the corresponding light bands. (Figure 1a) The filters were then single-band bandpasses similar to the spectral characteristic of a pair anaglyph 3D glasses. Therefore, each viewpoint could only image one spectral light band, which leads to render black and white images. Our method goes one step further by putting a pair of Complementary Multi-band Bandpass Filters (CMBFs). [9] Each CMBF has many passbands over the visible spectrum, hence each viewpoint can image RGB (Red, Green, Blue)-spectral images. The spectral transmission curves of the passbands in the CMBFs are nearly a top hat in shape; so the passbands of one multi-band bandpass filter can take places at the stopbands of the other multi-band bandpass filter without overlapping. This way, the pair of CMBFs is staggered or interdigitated and complementary to each other over the visible spectral band. (Figure 2b)

However, the staggering makes the CMBFs to skip some regions in the color band. For example, when a passband of one CMBF takes a place in the red band, a passband of the other CMBF will have to skip that red band. As a result, each viewpoint takes a different set of spectral images hence has a different gamut for producing a color image from the other CMBF. In 3D imaging, when each human eye sees extremely mismatched color, color rivalry can result, in which the brain cannot resolve the two different colors into one blended color but sees the two alternately. [10-13] Ultimately, the color rivalry gives viewers strain and fatigue. However, the mismatched colors can be minimized through digitally correcting colors and choosing a right set of CMBFs. In this paper, we report simulation work to choose an optimal pair of CMBFs.





(a) (b)

Figure 1. (a) A pair of complementary bandpass filters placed at the dual-aperture single objective lens. The scheme describes the two viewpoints made by the complementary bandpass filters. (b) An actual spectral plot of a pair of complementary triple-band bandpass filters purchased commercially off-the-shelf. The bell curves are light bands selected by a tunable filter from a broadband light.

2. SINGLE LENS 3D IMAGING SYSTEM DEMONSTRATIONS

The concept of the single lens 3D imaging system was first validated with a 25-mm lens system. Then, it was validated with 3-mm lens system to demonstrate the feasibility in miniaturization. Multi-band bandpass filters are designed to operate with the light at normal incidence to the surface. The passbands are shifted and distorted as the light incidence departs from normal incidence. To date, a test objective lens designed from Commercial Off-The-Shelf (COTS) lenses have been configured to provide a space and the normal incidence for the CMBFs.

For the first 25-mm lens system, a pair of COTS CMBFs having a shape of 25-mm circular disk was acquired. They were cut in half-moons and put next to each to make the CMBFs a round disk (Figure 2a) so that they could fit along with other 25-mm lens elements. (Figure 2b) However, for the 3-mm lens system, this fabrication method was too crude to be placed in the optical path because the cut-edge was too big gap to be in the 2.4-mm aperture area. So, custom CMBFs were developed for the 3-mm lens system. The needed passbands were determined from modeling. The CMBFs were micro-lithographed in an alternating strip pattern on a substrate and cored out in a 3-mm circular disks. (Figure 3a)

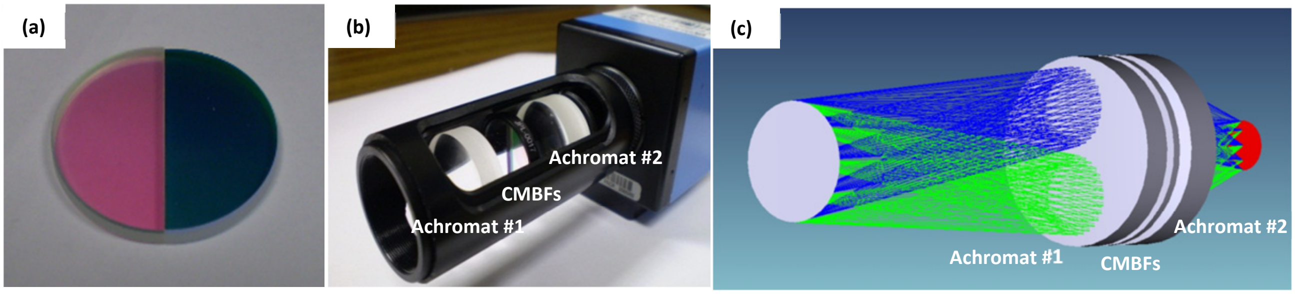


Figure 2. (a) Two half-moon CMBFs put next to the other to be in a shape of a circular disk. (b) Two achromatic lenses sandwiching the CMBF. (c) Ray traces of the objective lens containing the CMBFs. Note the viewpoints are distinctly separated yet the image form at the same optical axis.

2.1 Instrumentation to work with the 25-mm CMBFs

The 25-mm objective lens worked with a handheld monochromatic camera. The system required taking 6 or more spectral images, the half of which rendered RGB-image of one viewpoint and the rest rendered RGB-image of the other viewpoint. Figure 1b shows a spectral plot of a CMBF-pair used in the actual system. Two achromats were chosen to sandwich the CMBF pair. The first achromat (achromat #1 in Figure 2) collimated the light from the subject so that the light enters the CMBFs from the subject are normal or minimal angles (<15 degrees) from the normal to the surface. The second achromat (achromat #2 in Figure 2) focused the light exited from the CMBF-pair onto the imaging system. These were put in a lens tube. Then, the tube was mounted at the camera's C-mount, which aligns the optical axis with the center of the imaging chip. A tunable filter was used to select light bands matching to the passbands from a Xe-lamp. The spectral transmissions of the tunable filter were in a shape of bell-curves. (Figure 1b, superimposed in the CMBF plots)

2.2 Instrumentation to work with the 3-mm CMBFs

The 3-mm objective lens worked with a color imager instead of the monochromatic imager. The system required taking only 2 images each from one viewpoint because the color imager contains a color filter array on the chip for taking simultaneous multispectral images. The 3-mm COTS lens elements were assembled to work with the 3-mm CMBFs. They were held and spaced by custom fabricated plastic lens mounts and were stacked in a brass tube. (Figure 3b)

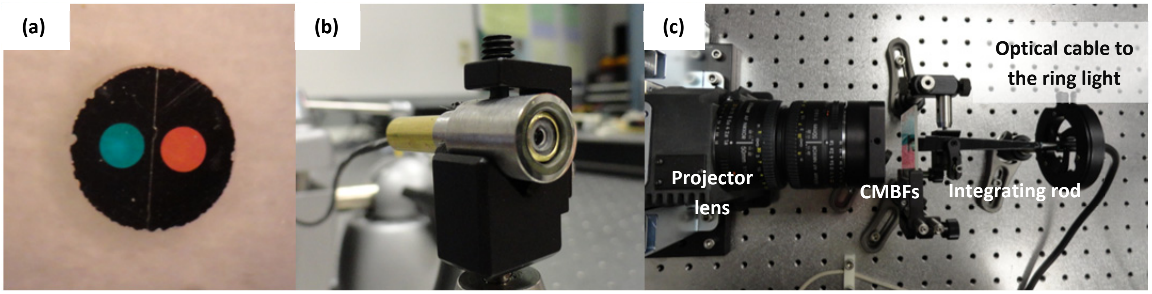


Figure 3. (a) A pair of CMBFs lithographed in a 3-mm circular disk. (b) The objective lens housed in a brass (yellow) metal tube. A ring light having a total diameter of 9.2 mm encasing the objective lens. (c) Digital Mirror Array (DMA) based multispectral light source.

Instead of using the tunable filter, a projector containing a Digital Mirror Array (DMA) was adapted to select the light bands. Bands of light are selected by projecting a broadband light onto one or the other CMBF. (Figure 3c) The reason for the replacement is that the tunable filter was not suitable for building a real-time imaging system. More specifically, 1) the tunable filter lengthened the exposure time because it filtered through only one hundredth of the broadband light, and 2) the tunable filter took a minimum of 50 msec to switch the light bands from one to a next. Another reason for the replacement is that the transmission band of the tunable filter was shifted and distorted as the liquid crystal inside the tunable filter became disoriented when it was applied with the heated Xe-lamp. However, the DMA illumination system made the real-time imaging more realizable because it shortened the exposure time by transmitting exactly matched light bands as the passbands of the CMBFs and switched the light bands fast in the order of micro-seconds. [14] Lastly, it eliminated the shift and distortion problems seen in the tunable filter.

3. OPTIMIZING CMBF-PAIR

Each CMBF should transmit as much RGB-spectral information as possible for rendering a good color image. However, the staggered passbands makes each viewpoint to skip some regions in the RGB band. As a result, the two viewpoints take different spectral images thus render two different color images relative to each other. The raw color image from each viewpoint showed that the color tones are red or blue. The difference in the color tone comes from the illuminations filtered by CMBFs. The difference would be narrowed if the CMBF contains more passbands and narrowed further by applying Chromatic Adaptation Transform (CAT). However, the cost and technique to fabricate the passbands increases significantly with a number of passbands.

3.1 Basic algorithm

CAT maps colors illuminated by one illuminant to another; it can make the colors illuminated by the CMBF-illumination appear as if they were under daylight, D65 illumination. A simulation was applied to find a pair that yields the tolerable difference with the least number of passbands. It ran the scenario of having CMBF-pairs with dual-, triple-, and quadruple-band bandpasses. The CAT calculates the white point of the light source and the daylight illuminants, divides the two in a device independent color space, and multiplies the ratio to other colors. We used Bradford matrix to perform the CAT. The differences were quantified in CIE Lab space in terms of ΔE. Papers have suggested that the ΔE should be less than 10. [10-13]

3.2 Results

We used known RGB values of Macbeth Color Chart in the simulation. The simulation mapped the colors under the D65 illumination and mapped the colors under red biased and blue biased CMBF illuminations. Average differences between the two, ΔE, are tabulated in the first row of the table below. Then, the CAT was applied to map the colors illuminated by the CMBF-illuminations to colors that would appear under the D65 illumination. The difference was observed as the CAT could not map the colors close to the D65. Average differences between the CAT applied colors and D65 illuminated colors are tabulated in the bottom two rows in the table below.

Table. Results of the simulation in CIE Lab values

		Dual-bandpasses	**Triple-bandpasses**	**Quadruple-bandpasses**	**Actual dual-bandpass**
Before the CAT applied	**Avg. ΔE, red biased CMBF and D65**	36	85	20	59
	Avg. ΔE, blue biased CMBF and D65	57	79	40	65
	Avg. ΔE, red and blue biased CMBFs	82	163	57	123
After the CAT applied	**Avg. ΔE, red biased applied with CAT and D65**	26	24	12	19
	Avg. ΔE, Blue biased applied with CAT and D65	24	21	6	11
	Avg. ΔE, red and blue biased applied with CAT	48	43	19	27

As expected a pair of complementary quadruple-bandpass filters yields the least color differences, 20 and 40 before the CAT had been applied, 12 and 6 after the CAT has been applied. The color difference after the CAT was 19. The trend is that, as the number of passbands increases, the color difference is narrowed. This is because a CMBF containing more passbands takes more spectral samples in the RGB band thus render more complete color.

3.3 Evaluation

A pair of complementary dual-band bandpass filters (CDBFs) was chosen for our imaging system. The passbands of the actual CDBFs overlapped at some regions in the RGB-band. (Figure 4) The simulation accounted the spectral power density plot, *i.e.* the Xe light filtered through the CDBFs, and tabulated the simulation result in the last column of the table above. The overlap made the difference to be even narrower.

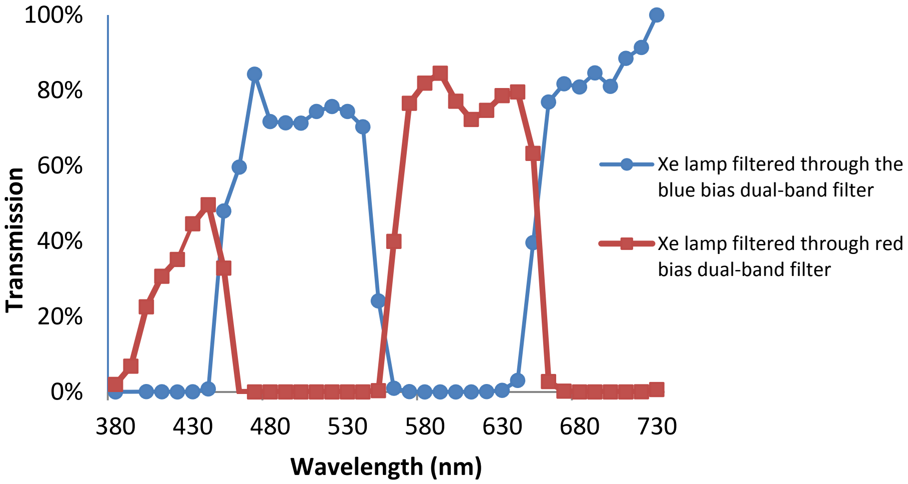


Figure 4. Spectral power density plot of the CMBF illumination *i.e.* Xe light filtered through a pair of complementary dual-band bandpass filters

4. CONCLUSION

A single lens capable to take two viewpoints in color was demonstrated with 25-mm and 3-mm lens systems. Each used a pair of CMBFs to image the viewpoints alternately. However, color images from the two viewpoints could not be the same because the CMBFs take different spectral images due to the staggered arrangement of the passbands. So, CAT was applied to map the colors under the CMBF-illumination to appear as if they are under the daylight. The simulation showed that the more the passbands in the CMBF the less the color difference between the two viewpoints as well as having a better mapping. What we are developing next is the ability of applying the CAT as the color images are recorded to compare them with images without CAT application.

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6. REFERENCES

[1] Greening, A., B. and Mitchell T., N., “Stereoscopic viewing system using a two dimensional lens system,” US Patent 5828487, October 27, (1998).

[2] Shipp, J. I., “Single lens stereoscopic video camera,” US Patent 5471237, November 28, (1995).

[3] Weissman, M., David, C., Anhalt, T.J. and Mattsson-Boze, D., “Single-axis stereoscopic video imaging system withcentering capapility,” US Patent 6624935B2, September 23, (2003).

[4] Lia, R. A., “Endoscope or borescope stereo viewing system,” US Patent 5222477, June 29, (1993).

[5] Sekiya, T. and Eguchi, M., “Stereoscopic endoscope,” US Patent 6517479, February 11, (2003).

[6] Yang, S. N., Sheedy, J. E., “Effect of vergence and accomodative response on viewer’s comfort in viewing 3D stimuli,” Proceedings of SPIE—IS&T 7863, 78630Q (2011)

[7] Lambooij, M., Ijsselsteijn, W., “Visual discomfort and visual fatique of stereoscopic display: A review,” *J. of Imaging science and technology*, 53(3):030201 (2009)

[8] Korniski, R., Bae, S. Y., Shearn, M., Manohara, H., Shahinia, H., “3D imaging with a single-aperture 3-mm objective lens: concept, fabrication, and test,” Proceedings of SPIE 8129, 812904 (2011)

[9] Bae, S. Y., Korniski, R., Ream, A., Shahinian, H., Manohara, H., “A new technique of 3D imaging through a 3-mm single lens camera,” *Optical Engineering*, 51(2), to be published in Feb. 2012
single chip and conjugated multi-bandpass filters,” New Tech Report 47420, Jet Propulsion Laboratory, (2009).

[10] Hovis, J. K., “Review of Dichoptic Color Mixing,” *Optometry and Vision Science*, 66(3): 181-190 (1998).

[11]] Jung, Y. J., Sohn, H., Lee, S., Ro, Y. M., and Park, H. W., “Quantitative measurement of binocular color fusion limit for non-spectral colors.,” *Optics express,* 19(8): 7325-38 (2011)

[12] Ikeda, M., Sagawa, K., “Binocular color fusion limit,” *J. of the Optical Society of America,* 69(2):316-320 (1979)

[13] Qin, D., Takamatsu, M., Nakashima, Y., Qin, X., “Change of wavelength difference limit for binocular color fusion with wavelength and brightness of stimuli,” *J. of Light and Visual Environment,* 30(1):43-45 (2005)

[14] Dudley, D., Duncan, W. M., Slaughter, J., “Emerging digital miromirror device (DMD) applications,” Proceedings of SPIE 4985, 14-25 (2003)