3D imaging with a single-aperture 3-mm objective lens: concept, fabrication and test

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ABSTRACT

There are many advantages to minimally invasive surgery (MIS). An endoscope is the optical system of choice by the surgeon for MIS. The smaller the incision or opening made to perform the surgery, the smaller the optical system needed. For minimally invasive neurological and skull base surgeries the openings are typically 10-mm in diameter (dime sized) or less. The largest outside diameter (OD) endoscope used is 4mm. A significant drawback to endoscopic MIS is that it only provides a monocular view of the surgical site thereby lacking depth information for the surgeon. A stereo view would provide the surgeon instantaneous depth information of the surroundings within the field of view, a significant advantage especially during brain surgery.

Providing 3D imaging in an endoscopic objective lens system presents significant challenges because of the tight packaging constraints. This paper presents a promising new technique for endoscopic 3D imaging that uses a single lens system with complementary multi-bandpass filters (CMBFs), and describes the proof-of-concept demonstrations performed to date validating the technique. These demonstrations of the technique have utilized many commercial off-the-shelf (COTS) components including the ones used in the endoscope objective.

Keywords: Stereoscopic, 3D, stereopsis, endoscope, endoscopy, surgery

1. INTRODUCTION

A stereo view would provide a surgeon the much needed depth information during critical aspects of surgery[1-5]. The 4-mm endoscopes currently used in MIS brain surgery require moving the endoscope to get depth information, which then has to be recalled by the surgeon when needed. Providing stereoscopic imagery for MIS of the brain is a challenge because of the confined spaces and the restrictive skull opening, which is about the size of a dime or less. The endoscope and other instruments are inserted through this opening at the same time; the size of the 3D-imaging instrument cannot be any larger than 4-mm in outer diameter (OD). Such a small space poses a significant challenge to implement conventional stereo-imaging techniques that use two-lens systems.

A technique for imaging full-color 3D images using a single camera is presented. Unlike a typical 3D-imaging system comprised of two independent cameras, each camera contributing one viewpoint, the presented technique creates two viewpoints in a single-lens camera by placing a bipartite-filter at the limiting aperture. The bipartite-filter has the transmission characteristic of a pair of complementary multiple bandpass filters, and one or the other viewpoint transmits when the area illuminated matches the bandpasses of one or the other filter. A color image is rendered for each viewpoint when individual exposures are combined. This technique has been incorporated into a single-objective lens camera configured from 3-mm OD COTS optical components. This paper will describe the stereoscopic technique and the COTS optics used in a series of demonstrations validating it even when incorporated in a single-objective lens using 3-mm OD COTS optical components.

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2. PROPOSED STEREOSCOPIC TECHNIQUE

Humans interpret depth from observing the differences, disparity, in the left and right views presented to the brain by each eye. For 3D imaging, the disparity is captured typically by a two-camera system. The ability of recording two-viewpoints is also a requirement for the design of a 3D endoscope. However, the optical configuration of an endoscope differs from that of a typical camera lens objective. An endoscope also has a relay-lens system that is typically coupled with an eyepiece for viewing. Combining two 4-mm cameras for 3D imaging enlarges the probe diameter by about a factor of two. Such a dual system for surgery has been incorporated into the robotic *da Vinci*® Surgical System, which has a 12-mm diameter stereo endoscope. This larger size is a significant disadvantage for a 3D endoscope for use in confined spaces.

In general, a rigid endoscope is preferred over a flexible endoscope because it provides better optical resolution between endoscopes of the same diameter because of dead space between fibers in the bundle. The diameter is an important consideration in endoscopy because the optical resolution of any imaging system is dependent on the diameter of the imaging optics. However, a small diameter endoscope not only keeps the incision small but also makes some MIS possible, such as neurological, skull base, and joints surgeries.

Many approaches for 3D imaging have been proposed besides dual optical systems[6-16]. Some objective lens designs employ mechanically switching apertures or use liquid crystal switching or use bipartite filters, polarized or not, to capture the two viewpoints of the subject needed to create 3D imagery to view. However none of these methods easily adapt to the packaging needed for skull base MIS.

In this paper we present a new method that uses bipartite filters to produce 3D imagery is presented. The bipartite-filter is composed of a pair of complementary multiple bandpass filters (CMBFs). By complementary, we mean that each filter's transmission characteristic of optical bandpasses does not overlap with other. Thus, a given wavelength of monochromatic light passes through only one of the two filters. The optical bandpasses are interdigitated over the visible spectrum in Figure 1. The bipartite filter is placed at the limiting aperture (stop) of an objective lens, dividing the single pupil into two halves (dual-pupil) and is coupled with an adapted illumination system. The illumination spectral band is matched with the bandpasses of the CMBF pair. By illuminating within the bands of a single CMBF, light passes through only one of the two pupil, effectively shuttering the other pupil[17]. The dual-pupil makes the single camera into a 3D camera. A color image is rendered from one viewpoint when three or more multispectral images through the CMBFs

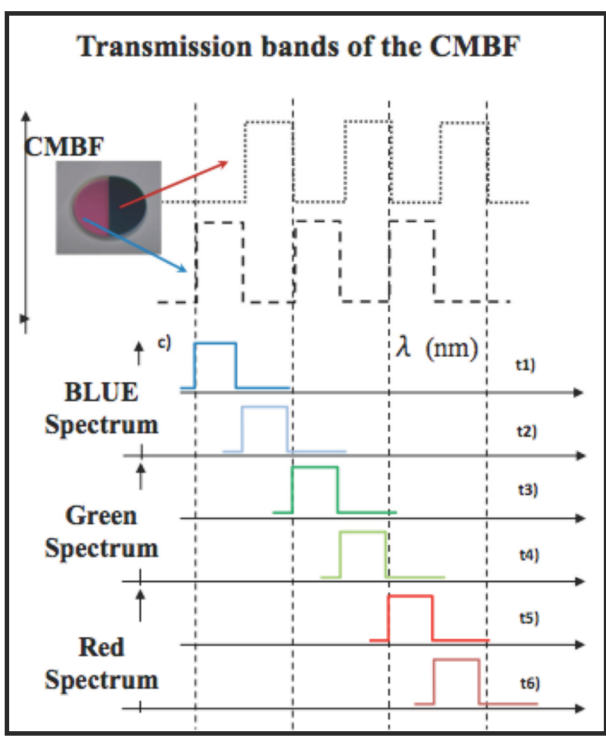

Figure 1: Idealized interdigitated CMBF transmission bands

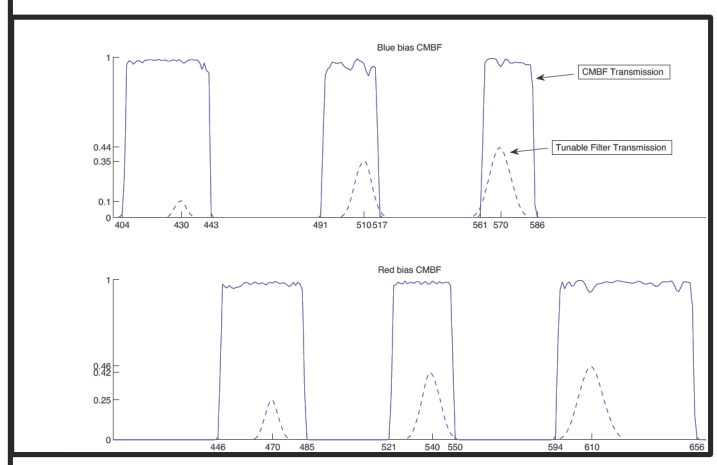

Figure 2: COTS CMBF transmission bands and spectral illumination bands (SIBs)

are recorded. The SIBs in relation to the transmission bands of the bipartite-filter are illustrated in Figure 2. This use enabled each viewpoint to render colors, and the dual-pupil uses the entire image plane for each viewpoint, which maximizes the utilization of each pixel for each viewpoint, see Figure 3. We believe this 3D technique is especially advantageous in miniaturizing 3D optical systems for use in applications in limited space environments such as borescopes and endoscopes.

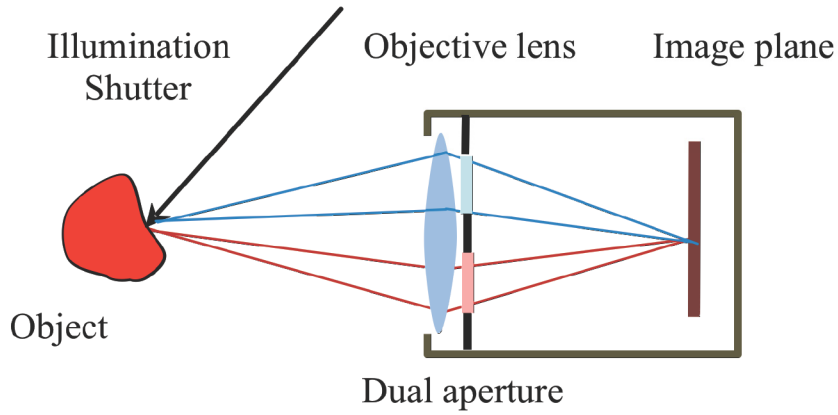

Figure 3: Illustration of CMBF technique

3. VALIDATING CMBF PERFORMANCE IN 3 -MM OPTICS FOR A 4 -MM DEVICE

The CMBF imaging technique was validated in two stages. The first stage verified the effectiveness of the CMBFs blocking or transmitting SIBs with normal-scale equipment. The second stage verified the effectiveness of bipartite filter working for 3D imaging through a series of demonstrations that led to 3-mm objective lens design suitable for a 4-mm OD endoscope. A short review is presented below on the stereoscopic technique and endoscope optics used in the proof-of-concept demonstrations that utilized COTS optical components. The description and performance of the objective lens designs used to demonstrate the technique are presented.

3.1 Demonstrating the CMBF technique at large scale

Demonstrating the CMBF technique at large-scale portion was divided into two steps. The first one is to verify the CMBF technique. The latter one is to show that 3D imagery can be obtained utilizing it when imaging through a single lens system.

3.1.1 Two-camera demonstration of the CMBF technique

For the initial evaluation of the CMBF technique, two full-scale cameras were positioned to look at a target. A CMBF was placed in front of the lens of each camera, see Figure 4. In theory, only one of the two cameras should see each of the SIBs. What the cameras were seeing was recorded in terms of intensity pixel values. A xenon lamp was used to illuminate the subject through a tunable filter to generate SIBs, of the specific bands. The CMBFs are designed to operate with the light incident at normal incidence. The camera setup had the targets distant enough to provide near normal incidence. The recorded images showed a 1000:1 contrast for each of the two cameras. This verified that the filter was blocking or transmitting the SIBs nearly completely. These results validated the CMBF interdigitation of the spectral band concept at a larger scale.

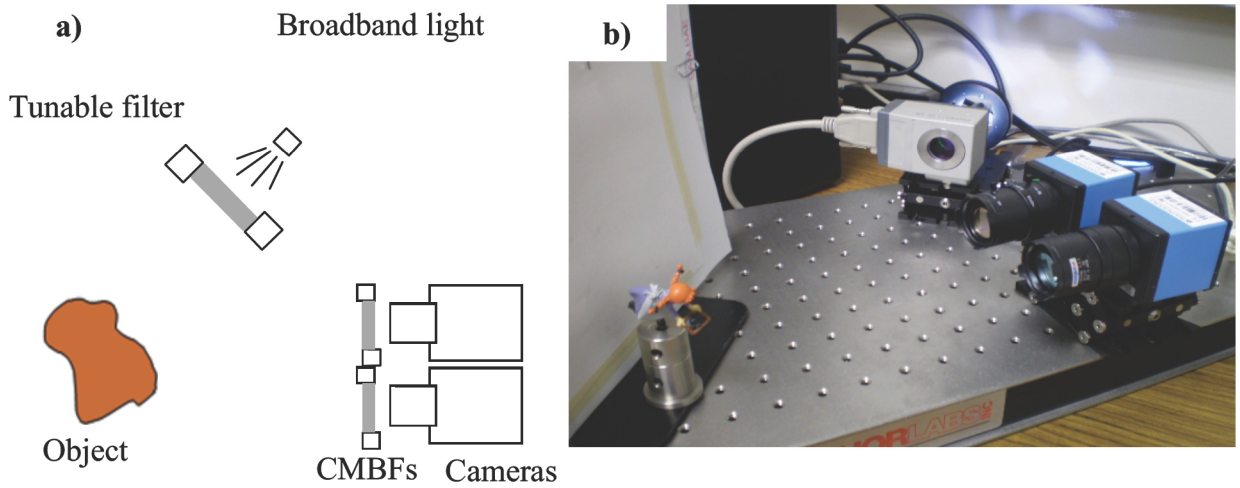

Figure 4 (Left) Illustration of two cameras with CMBFs; (Right) Actual lab set up

3.1.2 Demonstrating 3D imaging using CMBFs and a single imaging lens system

The next step was to show that this technique would work through a single objective and create a stereo view of a subject. The test set up contained a pair of COTS achromatic lenses with the CMBF situated between the achromatic lenses, Figure 5 (Left). But the achromatic lenses only operate well over a limited field of view, see Figure 5 (Right). The acquired COTS lens set allowed lens pairings to simulate various stereo baseline situations. This arrangement also allowed obtaining empirical information of visual impact of the 3D image based on quantified stereo baselines.

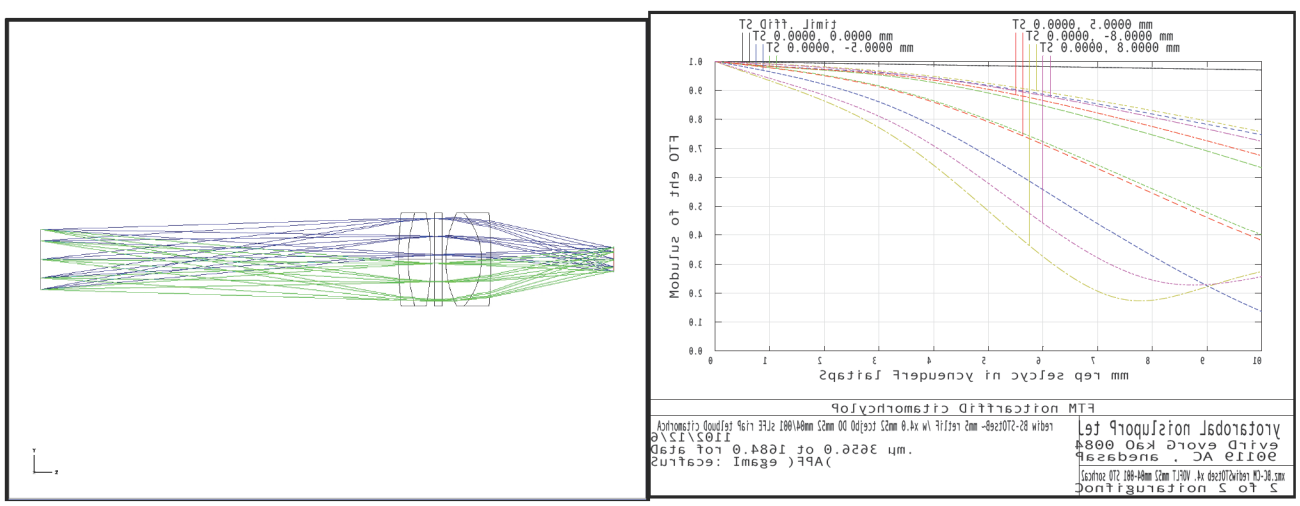

Figure 5 (Left) Cross-sectional view of the paired achromatic lens configuration; (Right) MTF performance at 10 c/mm for a 16-mm diameter object

The lenses and the CMBF were mounted in COTS prototype housing that was attached to a camera, see Figure 6. With easy access to the CMBFs between the two lenses, a variety of CMBF apertures were used. Plus, a variety of experiments were run on this set up where full half-moon CMBF apertures were used, as well as, separated circular apertures. The results from this test set up showed that the technique was adaptable to a single optical system and the 3D performance was comparable to what was obtained in the initial evaluation with the two cameras.

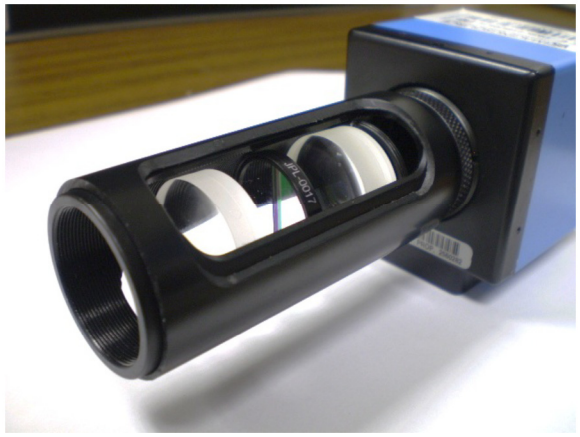

Figure 6 Paired achromatic lenses demonstration setup

3.2 CMBF technique demonstration at endoscope scale

Having shown the feasibility of the CMBF concept to produce 3D images using larger optics and a tunable filter illumination, the next step was to demonstrate the viability of this technique at smaller endoscopic dimensions. Before developing custom optics system, the first iteration implementation as reported in this paper used COTS lenses in COTS prototype housing. A second iteration used micro-machined CMBFs arranged inside a square cross-section, rapid prototyped plastic housing. Details of these efforts are given below

3.2.1 Optical considerations with COTS micro optics

The inspiration for the demonstration lens configuration using the micro optics (Figure 7) came from a eondoscope objective design for a fiber relay design by Laikin[18]. With the realization that the fiber feed endoscopic objective design could be essentially configured with common COTS component shapes; its configuration was pursued for adaption to our miniature stereo endoscope demonstration. The lens design configuration is made up of components that are, or nearly so: a plano-concave lens, an equi-convex singlet, and an achromatic doublet. Possibly similar lenses, in some incarnation, are available COTS. The appropriate focal lengths of these three components were acquired from a scaled model from the Laikin design. Though the glass types were limited, a search through COTS vendor's lists yielded a potential set of lenses.

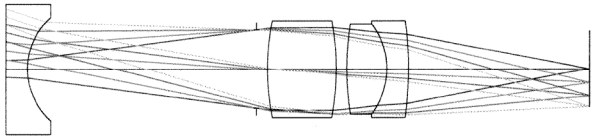

Figure 7 Laikin design cross-section layout from published tabulated data

Thanks to the boom in micro optics for cameras in cell phones and other mobile devices, COTS micro-optics lenses have not only been making an appearance in optical vendor catalogs, but they have been growing in numbers and variety. Remarkably a set of micro-optic lenses of the corresponding shape and relative focal lengths were found after an extensive search through vendor catalogs. This good fortune was achieved not once, but surprisingly twice.

The lenses found were LINOS 314-001-000 (6-mm OD), Edmund 45-131 (3-mm OD), and Edmund 63-692 (4-mm OD). These promising micro-optics lenses were appropriately orientated along with a COTS CMBF, positioned 10 mm from the surgical site, and the airspaces between these components were optimized to provide the best possible performance within the required constraints. The resulting endoscope objective design had a front lens-to-back lens length of 20 mm and a surgical site-to-detector distance of about 36 mm. The design total field of view (TFOV) was 52° and, when operating at f/4.5, had an entrance pupil diameter of 0.61 mm. The MTF performance of this configuration was greater than 0.3 over most of the TFOV at a spatial frequency of 100 c/mm. The optical system and the full-aperture optical

performance is shown in (Figure 8). Notice that this lens design configuration has a section where the axial field point is nearly collimated which is an appropriate place for the CMBF filter to be placed for near optimum performance.

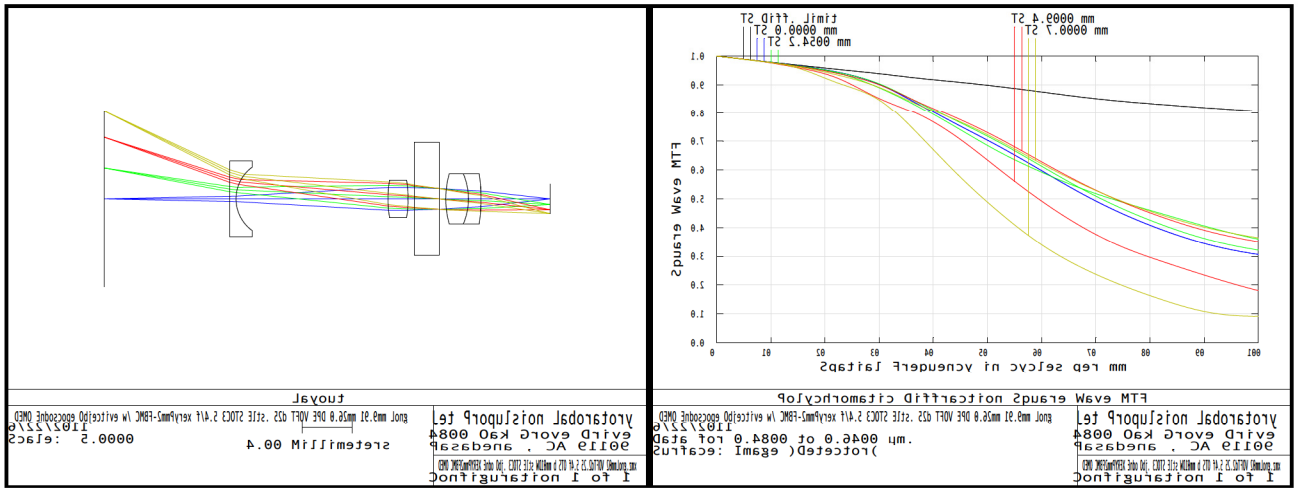

Figure 8 (Left) Cross-sectional view of the 52 degree "6-mm" lens configuration from COTS components, except filter was supplied at specified 9-mm size; (Right) MTF performance to 100 c/mm for a 14-mm diameter object

3.2.2 CMBF 3D imaging technique demonstration with micro optics

Our second demonstration of the 3D imaging technique using a single objective utilized this COTS objective lens design occurred in August 2010. The lens elements were held in 13-mm COTS prototype housing. A pair of COTS CMBF substrates was obtained with reduced diameters (9 mm) to fit this housing Figure 9 (Left). The lenses and CMBFs were set to separations as close as possible to the optimized COTS design. Using an adapter, the assembly was mated to an on-hand Sony camera Figure 9 (Right). Because of the tight space and the size of the on-hand ring light from the achromatic lens demonstration, it was adapted to provide indirect illumination of the target. Though the demonstration was a success, the objective, made up of COTS components, utilized a 6-mm OD plano-convex element, the 3D-imaging technique still had to be demonstrated with an objective lens that could be housed in a 4-mm OD endoscope.

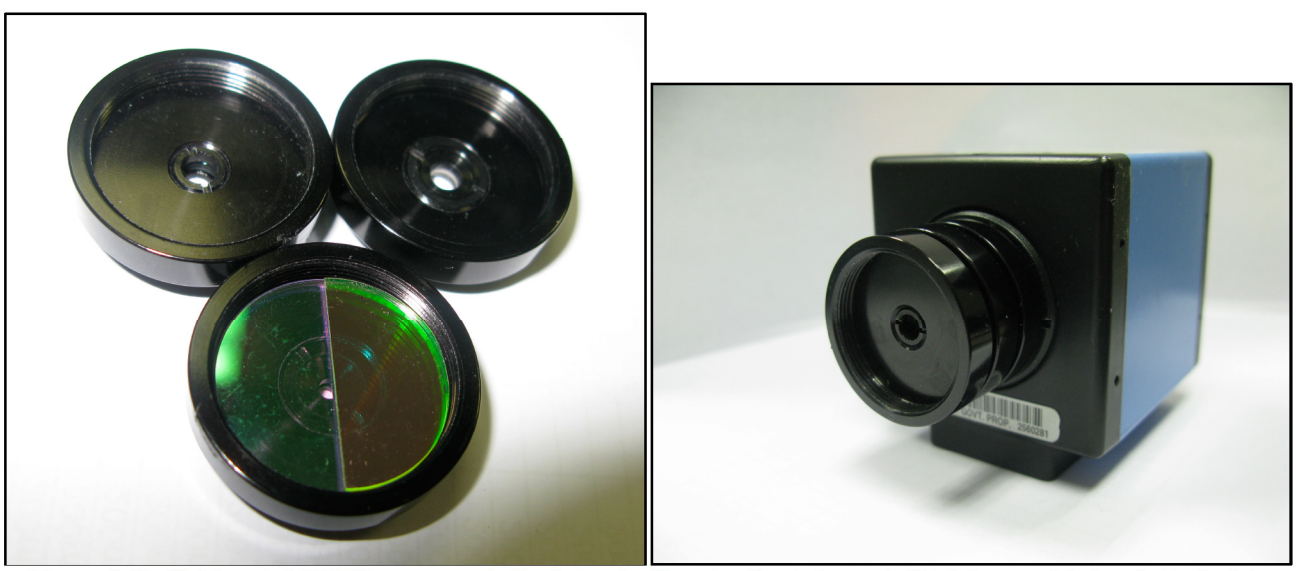

Figure 9 (Left) Mounted COTS components for 6-mm in diameter front element; (Right) assembled and attached to Sony camera

3.2.3 Building a 3-mm micro optical system

Edging down the 6-mm element to 3 mm would sacrifice a significant amount of the field of view and, besides, there still was a 4-mm element in the objective design. Reviewing the slim, but increasing, selection of COTS 3-mm elements yielded another objective lens design. However, though its performance was not as good as the design using the 6-mm lens but adequate to demonstrate the CMBF 3D technique.

The lenses found were LINOS 314-000-000 (3-mm OD), Edmund 32-953 (3-mm OD), and Edmund 45-089 (3-mm OD). These promising 3-mm micro-optics lenses were appropriately orientated along with a reduced OD COTS CMBF (3 mm) and the airspaces between these components were optimized like before to provide the best possible performance within the required constraints. The resulting endoscope objective design had a front lens-to-back lens length of 11 mm and a surgical site-to-detector distance of about 25 mm. The design TFOV was again 52° and, when operating at f/3.5, had an entrance pupil diameter of 0.80 mm. This design was pushed to a faster relative aperture than the last time with slightly larger ODs. However the MTF performance at this aperture is lower than the previous design at 100 c/mm, though still about 0.3 in the central part of the field of view. The lens design and the full-aperture optical performance are shown in Figure 10. Notice again that this lens design configuration has a section where the axial field point is nearly collimated which is an appropriate place for the CMBF filter to use near its optimum.

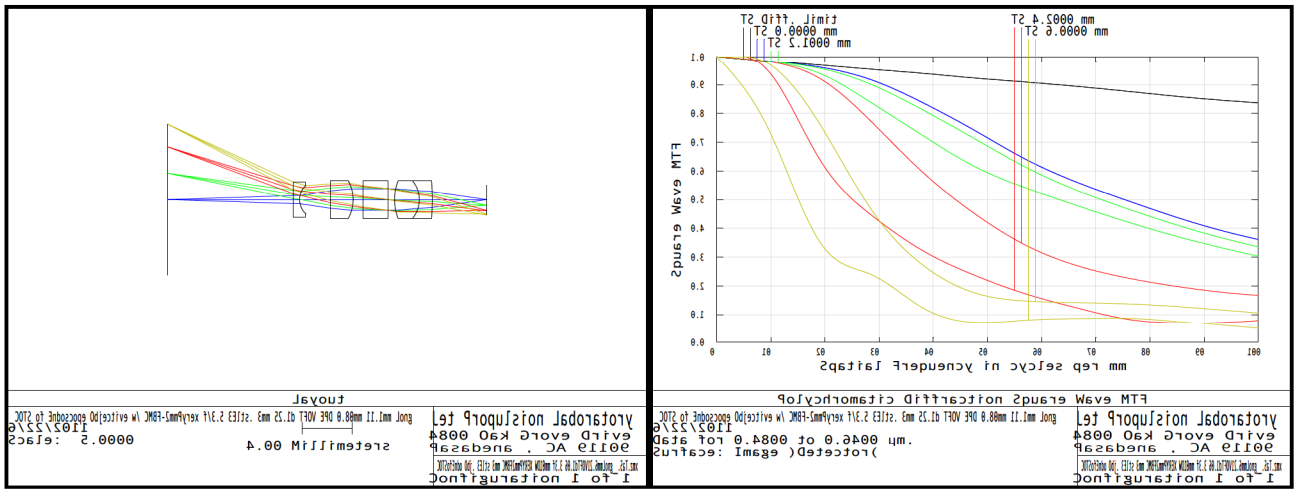

Figure 10 (Left) Cross-sectional view of the 52 degree "3-mm" lens configuration from COTS components, except filter was supplied diced 3-mm square and JPL-modified it with apertures; (Right) MTF performance at 100 c/mm for a 12-mm diameter object

However, new problems emerged. A major one was the realization that COTS prototyping housing could not used to assemble the elements into an objective. Many ideas were considered but the best choice was to have the housing rapid prototyped for this next demonstration. Tolerance analyses showed that the accuracies of the rapid prototyping process were adequate for performance at full aperture to about 30 to 40 c/mm. And the technique would use only smaller portions of this full aperture, which would provide a performance boost over the full-aperture tolerance analysis.

The lens mount exterior was designed rectangular to make it easier to handle on a flat surface and gives slightly more room to house a square set of bipartite filters, see Figure 11 (Left). However, the plastic material used in rapid prototyping is slightly translucent to light, so aluminum foil was wrapped around the lens mount to block out the ambient light after black Magic Marker failed to adhere to the plastic housing, see Figure 11 (Middle).

The round 25-mm COTS bipartite-filter pairs, used earlier, had to be modified to fit into the tubular interior amongst the 3-mm round lens elements. The housing was designed to accommodate this square shape. Each CMBF pair contained a lithographed aperture, diced into 3 x 1.5 mm and was joined with the other pair at the edges side-by-side. This time, a triple-band bandpass filter pair was used instead of the quadruple-band bandpass filters. A COTS triple-band bandpass

filter was selected for this demonstration because most of the outer bandpasses of the COTS quadruple-band bandpass filter were beyond the visible spectrum and had insignificant impact on the color rendition. Figure 11 (Right) shows a close up of a CMBF pair of apertures used with the 3-mm COTS lenses.

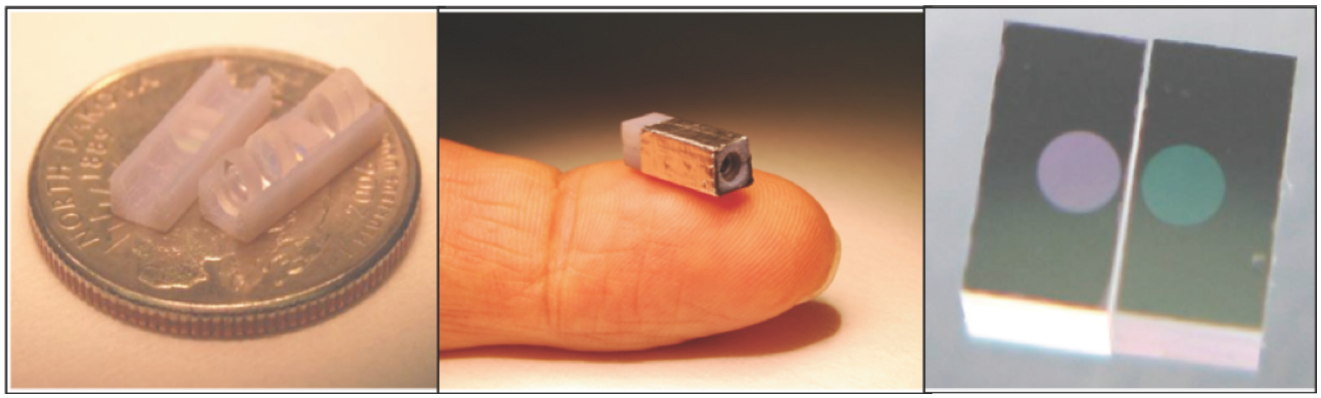

Figure 11: (Left) Shows the relative size of the rectangular half-shell housing with the 3-mm COTS lenses, (Middle) Shows the aluminum wrap housing to block the light coming through the housing, (Right) Shows the dices CMBF incorporated used.

The CMBF apertures used were about 0.8 mm in diameters with a center-to-center distance of 1.2 mm. The separation distance plays a significant role in the recording the stereo disparity, the disparity.

A monochromatic camera having the overall dimensions of 12 x 12 mm was procured. The camera's body had to be kept small because the diameter of the ring light chosen for illuminating the small objects to be imaged. An adapter was fabricated to couple the 3-mm lens assembly to the detector housing. This configuration is similar to an endoscopic system but not quite fully integrated into one compact package, see Figure 12.

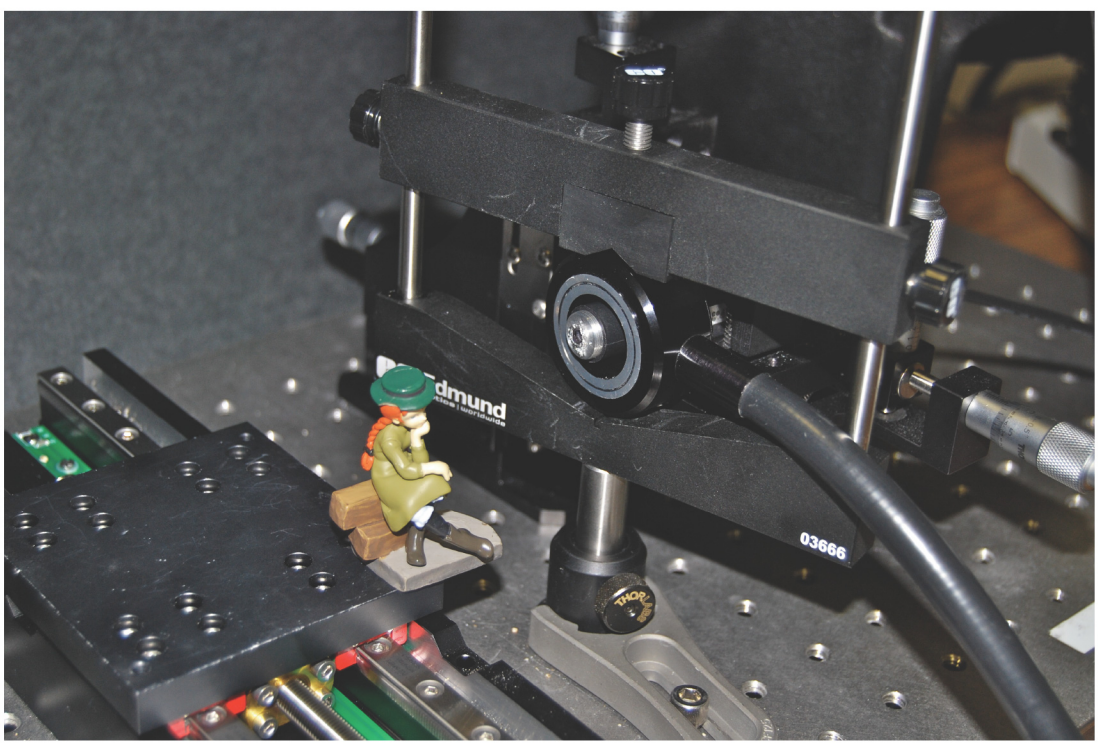

Figure 12: Demonstration setup using a 3-mm OD COTS elements

A program was written to sequence the SIBs coordinated with the multispectral imaging. Also, the program collected and sorted six multispectral images into two sets each according to the viewpoint and had each of the sets render a color image. The program adjusted the exposure times to compensate the for low light illumination generated from the tunable filter. The program repeated this to refresh the 3D display to emulate a real-time imaging. Even so, the fastest frame rate for this demonstration set up was about 1 frame per every 2 seconds, which is far slower than 30 frames per seconds, for displaying a naturally moving scene. A chief reason for the slow frame speed was caused by long exposure times to compensate the low subject illumination because the tunable filter only transmitted about 10% of the visible light.

3.2.4 CMBF technique demonstration with a 3-mm micro optical system

The lenses were acquired, the CMBFs with apertures were made and diced in appropriate sizes, a custom housing was made and conditioned for the optical components, a more appropriately sized imaging camera was acquired, adapter was made to attach the housing to the camera, ring light acquired and mounted around the square housing to provide illumination, software was written to process and display the data. The test setup all came to together for a successful demonstration in December 2010.

The last paragraph oversimplifies the whole process effort to put together a working 3-mm demonstration. In actuality immense effort was devoted to integrating the COTS camera assembly with the optical assembly along with developing the appropriate software to work properly to make this all work together for the demonstration.

4. RESULTS AND DISCUSSION

A 3D display was used to view the recorded color imagery. The 3D display had two displays each projecting one of the 3D images simultaneously on a beam splitter with oppositely polarized light. To view, the observer wore polarized glasses matched to the imagery displayed. The viewers of the displayed 3D imagery recorded with the CMBF technique indicated having favorable stereo experiences.

4.1 Implied disparity calculation

The 4-mm objective lens of 3-mm COTS components could accommodate a 2.4-mm diameter optical limiting aperture on axis. Two 0.8 mm diameter apertures with a center-to-center separation of 1.2 mm were place at the limiting aperture location. The entrance pupil diameter of the objective lens was 1.12 mm for a 2.4-mm diameter stop. This implies that the interpupillary separation at the endoscope objective entrance pupil present to the scene was 0.56 mm. The recorded scene was 15 mm away, though the design goal for the working distance was 10 mm. Using similar triangles, the effective disparity of the scene recorded correlates to an average human, one having a 65-mm interpupillary distance, viewing the scene about 1740 mm away (5.7 feet). Though this distance is greater than arms length, it is still a good range for human perception of depth[19].

The effective interpupillary distance that “views” the surgical site determines the perceived depth. In order to maximize the recorded disparity, the pupil separation needs to be as large as possible. Unfortunately, for limited space situations, the lens diameters are limited to very small sizes.

4.2 System ramifications

The CMFBs 3D technique creates a dual-pupil entrance pupil. At most, the CMBF splits the pupil shape into two half moons. The half-moon dual pupil effectively makes the objective lens operate at a slow relative aperture in one direction. If osculating round apertures are used, each aperture creates a "slower" lens than the original full aperture lens. These slower "left" and "right" lenses require a longer exposure time to record a similarly illuminated scene than the same lens without the dual apertures. Also, the entrance pupil for a fixed limiting aperture size goes down as the field of view goes up, since the negative power in the lens facing the surgery area increases to provide the wider field of view. This trend has an adverse effect on the interpupillary separation for wider field-of-view designs. Therefore, design goals for the custom designs are to maximize the entrance pupil to allow for larger dual-pupil separations and to increase the lens

speed to improve exposure while still providing high quality imagery. These two design goals are being studied to find a best compromise in the custom lens design effort that is underway.

The COTS CMBF spectral bands were not optimum to provide RGB color in each channel (eye). For example, one of the bandpasses of one CMBF omitted large portions of the red band but sufficiently covered the green and blue bands. This omission led the green and blue to dominate over the RGB scheme. The corresponding colors tones between the binocular images were noticeably different when viewed individually; one had a warmer color bias, the other had a cooler color bias.

However, any color domination was less noticeable when the two images were overlapped and simultaneously viewed on the 3D display. Binocular Color Mixture theory[20] (BCM) was formulated out of studies of color perception of individuals when two different colors are presented simultaneously to the observer in 3D format. The results indicate that the color differences will be less noticeable when the brain fuses the two separate images, which was observed in the 3D imagery viewed in the demonstration systems. However, improving the color balance of the individual binocular images is also part of the current phase of developing this technology.

Lastly, in principle the CMBF technique could be configured to work with some existing endoscope and borescope optical assemblies. The practicalities of an effective implementation still have not been investigated to date. However, existing systems are not conditioned to make the most of a dual aperture requirement where, as presented earlier, for best results larger entrance pupils and operational relative apertures are desirable. The best optical performance and stereopsis would be obtained from a custom optical system designed and built to accommodate the needs of the dual aperture usage of the CMBF technique.

5. CONCLUSIONS

A method to create two viewpoints of an object using a single objective lens with a bipartite-filter system has been developed. The method made the shuttering of the viewpoints dependent on spectrally multiplexing the illumination to match one or the other complementary filters in the two apertures capturing the two viewpoints. The complementary multi-bandpass filters (CMBFs) at the apertures were spectrally interdigitated allowing capturing color images of each viewpoint. This method avoids the incorporation of mechanical, optoelectric, and other active equipment into the optical path to switch viewpoints. The dual pupil created in the demonstration single objective lenses utilized the full image plane (no need for doubling the pixel density to maintain the optical resolution) and also used the full pixel density of the monochrome detector (no need for RGB filter quad groupings).

The CMBF technique was validated in two stages. The first stage validated the effectiveness in opening or blocking a particular spectral band of light and creating 3D imagery through a pair of cameras. The technique was also demonstrated through a single 25-mm OD optical that consisted of paired achromatic doublets. The second stage transitioned from large optics to micro optics. The final micro-optics demonstration used a 3-mm objective lens that was configured from off-the-shelf lenses, incorporated CMBFs to effect the bipartite filtration, and was assembled in a custom, rapid-prototyped housing. The 3D color imagery captured was viewed on a stereo display. This final demonstration validated this new method for producing stereo color images. The results of the demonstration set up indicate that the CMBF technique appears to be readily adaptable to miniaturized 3D camera systems that can be used in confined spaces, such as endoscopic minimally invasive brain surgery.

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