Spectral encoding enhances visual flexibility of surgical endoscopes

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Spectral encoding enhances visual flexibility of surgical endoscopes
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ABSTRACT

Endoscope cameras play an important and growing role as a diagnostic and surgical tool. The endoscope camera is usually used to provide a view of the scene straight ahead of the instrument to the operator. As is common in many remotely operated systems, the limited field of view and the inability to pan the camera make it challenging to gain a situational awareness comparable to an operator with direct access to the scene. We present a spectral multiplexing technique for endoscopes that allows for overlay of the existing forward view with additional views at different angles to increase the effective field of view of the device. Our goal is to provide peripheral vision while minimally affecting the design and forward image quality of existing systems.

Keywords: robotic surgery, endoscopy, spectral multiplexing, image reconstruction

1. INTRODUCTION

1.1 Introduction

Endoscopic imaging systems are essential tools in medical diagnostics and minimally invasive and robotic surgery. While providing many advantages over traditional open surgery techniques, endoscopes provide the surgeon with challenges that often arise from the well-known trade-off between restricted field of view and image resolution and quality. Although modern tubular endoscopes provide a forward image at an acceptable resolution approaching the resolution of the human eye, they provide no peripheral vision or ability to pan and tilt the camera view to obtain a better situational awareness of the scene. Moving components can be used to extend the field of view, but they present the risk of potential damage to bodily tissue.

Figure 1. Schematic of spectrally-encoded increase in field of view. Two spectrally sensitive mirrors are used to separate spatially the frontal and side views of an object through a rigid boroscope.

Even though peripheral vision is desirable, however, it cannot come at the cost of imaging resolution in the main forward direction. Even a low-resolution peripheral view can offer the surgeon knowledge of his surroundings, i.e., detailed knowledge about the surroundings is not as crucial. Commercial optical tube endoscope systems are designed to optimize the point spread function, illumination strength, tube diameter, and the tube length. We present an endoscope
system that uses spectral multiplexing to use the tube and imaging system of the endoscope for two simultaneous video feeds, one forward feed and one peripheral feed. The method relies on utilizing the spectrum of the illumination by inserting wavelength-selective filters in the beam path, at both the entrance and exit pupils of the device. A schematic of this contribution is shown in Figure 1. The filters send one spectral band to the front and another spectral band to the side. On the detection side, each band is send to a different spatial location.

1.2 Related Work

Robotic surgical methods are useful for improving minimally invasive surgeries [1,2]. It has been demonstrated that wide-field methods can improve movement times and are prone to fewer errors for surgical tasks such as knot-tying and suturing [3,4]. Therefore, much research is done to increase the field-of-view to generate panoramic images of human cavities [5,6]. Moving wedge prisms can be used to direct the light path to various peripheral locations [7]. Scanning fibers have been shown to have high-resolution in catheterscopes [8,9]. Polarization-based methods multiplex light based on its vector nature [10,11]. Many commercial devices exist [12-14].

However, spectral information is also important for, e.g., cancer detection [15], imaging fluorescent markers [16], and imaging sub-surface features [17], so the spectral coding must be efficient. Some methods exist for mitigating overlapping spectra (in fluorescence imaging) [18]. Wavelength (spectral) coding has been used for topography (shape) [19]. Some work has studied various wavelength coding under solid state lighting [20].

In computational imaging, much work has been done in spectral coding in other fields. Spectroscopy using coded apertures has a long history [21], with much recent progress in light of compressive sensing techniques [22-24]. Super-resolution effects have been demonstrated by spectral dilation [25].

2. EXPERIMENTAL DEMONSTRATION

2.1 Method and Setup

Spectral multiplexing employs passive multiband filters to separate an image into different channels by subdividing the red, green, and blue color channels, so that wavelengths $R$, $G$, and $B$ correspond to, e.g., the frontal view, and wavelengths $R + \delta R$, $G + \delta G$, and $B + \delta B$ correspond to the peripheral view. Because this subdivision is finer than the spectral resolution of the human eye, these channels still carry full color information and can address the complete color space perceivable by a human observer. An example of this technique used for left and right image separation is the Dolby 3D cinema standard [26].

Although the ideal case would multiplex red, green, blue channels to both the front and side views, for our current proof-of-concept example, we use standard dichroic filters designed as a low pass filter at 45 degrees. As a result, our system is monochrome, producing red and green images for the front and side views, respectively. Using custom designed multiband filters similar to the ones used for separation of images in the Dolby 3d cinema standard will allow us to provide full true color images of high quality.

Figure 2. Photograph of the setup. The light source (foreground) is fiber-coupled to a rigid borescope (Olympus). Light at the exit pupil is split by a dichroic mirror (right) to illuminate front and peripheral objects. Light is collected by the scope and is separated on the detection side by an identical dichroic mirror (left). A camera records the front and side views in two different locations.
A photograph of the experimental setup is shown in Figure 2. A rigid boroscope is illuminated via fiber coupling with a light source (Olympus ILK-7 white light source). On either side of the boroscope (5 Series, R060-032-000-50) is placed a multiplexing filter, here a pair of dichroic mirrors with long-pass edge at 567 nm (Thorlabs DMLP567). Both are oriented at approximately 45° relative to the boroscope axis. The object is placed after the mirror at the exit pupil. The object here is a sheet of paper with measuring lines printed on it. Part of the paper is directly in front of the mirror, and part is folded to the side (periphery). Light that is reflected from the object is recorded by an Olympus SLR camera (Olympus E-PL2). The camera has a front and peripheral position, and it is moved to record two images. Thus, the multiplexing dichroic filters route one set of frequencies (green) to the “side” view and another set (red) to the “frontal” view. Images of the object are recorded with and without the filters.

Results are shown in Figure 3. Fig. 3a is an image recorded with only the exit-side mirror in place. As expected, both will overlap onto the image plane, but it is clear that there is spectral separation, with the green channel containing the side-view information, and the red channel containing the frontal-view information. With this single image alone, the two channels can be separated simply by separating numerically the channels in the RGB bitmap. An image recorded with both mirrors in place is shown in Fig. 3b. Now, we see that the peripheral view has been completely filtered out of the “front-view” camera position. This would be the same image with both mirrors removed. Note that there is significant vignetting effects in all images. This is due to the physical separation between the scope and the camera, which is optimized to be in contact. This is necessary here for inserting the image-side mirror. Integrating the mirrors within the scope would eliminate this artifact.

Figure 3. a) Image with a single dichroic mirror placed on the object side of the boroscope. b) Same view, but with both mirrors in place. Only the frontal view is recorded at this camera position. The peripheral view is directed to a different image plane (c.f., Fig. 1).

Figure 4. a) Object under study. Dichroic mirror and boroscope are visible in the foreground. b,c) Images with the dichroic mirror in place. d,e) Images without the dichroic mirror.
We show both front and peripheral views in Figure 4. Fig. 4a shows a photograph of the scene with the exit-side mirror in place. We see clear spectral separation of the (white light) illumination into two colors. Figures 4b,c are the front image and side image, respectively. Each component is routed successfully to the appropriate location. Figures 4d,e show the images without the exit-pupil mirror in place. In this setup, there is no illumination directed to the side, and the frontal view receives the entire spectrum. The frontal image is therefore routed to both output channels. (There is an extra horizontal inversion in the side-view channel because of the lack of one mirror.)

2.2 Discussion

The central insight in this communication is that endoscopic images are enhanced by utilizing the wavelength parameter, which allows for increased information throughput. A possible trade-off, however, is that the recorded images could become noisier, as optical power is split between different channels. To begin to address this noise issue, we analyze the central portion of the images in Figures 3b and 4b,c. A region of 60 × 400 pixels is selected. The intensity values of the red, blue, and green channels, and the composite (sum) are plotted in Figure 4. We see that, for our specific configuration, the pixel value does not exhibit an appreciable change in standard deviation (Table 1). In general, a more detailed analysis, via calculation of Cramér-Rao bounds is necessary. The strength of the illumination light is limited by heat generation in the tube. By filtering the illumination light with the same filters, it is still possible to tune illumination strength for the forward and sideways channels independently or to disable the side view and send all illumination through the forward channel. This would yeald nearly the same illumination power and the same signal to noise ratio in the forward channel as in a system not using wavelength multiplexing.

![Figure 4. Plot of pixel values for the central region of Figs. 3b and 4b,c, respectively. A region of 60 x 400 pixels is plotted. Left: intensity values for Figure 3a. Center: intensity values for Fig. 4b. Right: Intensity values for Fig 4c. Red, green, and blue curves represent the values of the respective color channels. The cyan curves are the sum of the R, G, and B channels.](image)

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<td>Baseline Ch (G) Ch (R)</td>
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<tr>
<td>Ch (R)</td>
<td>88.3</td>
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<td>Ch (G)</td>
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<td>Ch (B)</td>
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<td>Composite</td>
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Table 1. Average and standard deviations of curves in Figure 5. Note that the standard deviations are all relatively low compared to the average, indicating high SNR.

Similarly, the design of the mirror should provide a continuous panorama view of the front and side views. Currently, because the components here are discrete, the filter thickness prevents illumination of the corner of the object (see, e.g., Figure 4a). To calculate the gap, we replace the ruled object with a tilted line. If the entire field were illuminated, stitching the frontal and peripheral views together would reconstruct a continuous line. Here, however, the non-illuminated corner precludes perfect reconstruction, and a gap is revealed (Figure 6). We measure the height of this gap,
using the known object size, and we calculate a gap angle of approximately 40°. However, for a commercial device, the mirrors must be integrated with the boroscope, making the gap far smaller via, e.g., thin film fabrication.

Figure 6. Panoramic stitching of frontal and peripheral views. The gap in the sloped line indicates a missing “wedge” of illumination in the corner of the object. The wedge angle, caused by the finite thickness of the mirror, is ~ 40°.

3. CONCLUSIONS

In conclusion, we have demonstrated a spectral coding method to enhance the field of view of endoscopes for use in robotic-assisted surgery. The method is straightforward and involves spectral separation of frontal and peripheral views using a spectrally selective pair of beamsplitters. Our proof-of-principle demonstrated can be improved by designing a non-planar mirror to acquire a full 360° field-of-view after computational panoramic stitching. In other implementations, this device can include an actuator for the filter at the endoscope tip to provide a full-field view. In addition, the illumination strength can be tuned independently for both channels. Furthermore, multiband channeling can enable additional flexibility for surgical endoscope systems. It can be added to existing designs at little additional cost. We envision that this new degree of freedom will help improve mobility and time performance in robotic-assisted surgeries.

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REFERENCES