System for Clinical Photometric Stereo Endoscopy

Nicholas J. Durr[*a,b], Germán González[a,b], Daryl Lim[a,b], Giovanni Traverso[c,d], Norman S. Nishioka[c], Benjamin J. Vakoc[b], Vicente Parot[a,b]

[a]Madrid-MIT M+Visión Consortium, Massachusetts Institute of Technology, 77 Massachusetts Ave, 35-749, Cambridge, MA 02139; [b]Wellman Center for Photomedicine, Harvard Medical School and Massachusetts General Hospital, Boston, MA 02114; [c]Division of Gastroenterology, Harvard Medical School, Massachusetts General Hospital, Boston, MA 02114; [d]Department of Chemical Engineering and Koch Institute for Integrative Cancer Research, Massachusetts Institute of Technology, Cambridge, MA 02139

ABSTRACT

Photometric stereo endoscopy is a technique that captures information about the high-spatial-frequency topography of the field of view simultaneously with a conventional color image. We describe a system here that will enable photometric stereo endoscopy to be clinically evaluated in the large intestine of human patients. The clinical photometric stereo endoscopy system consists of a commercial gastroscope, a video processor, custom synchronization electronics, white light LEDs, a set of four fibers with diffusing tips, and an alignment cap. The custom pieces that come into contact with the patient are composed of biocompatible materials that can be sterilized before use. The components can then be assembled in the endoscopy suite before use. The resulting endoscope has the same outer diameter as a conventional colonoscope (14 mm), plugs in to a commercial video processor, captures topography and color images at 15 Hz, and displays the conventional color image to the gastroenterologist in real-time. We show that this system can capture a color and topographical video in a tubular colon phantom, demonstrating robustness to complex geometries and motion artifact.

Keywords: Topography, stereo, three dimensional imaging, photometric, endoscopy, colonoscopy

INTRODUCTION

In many endoscopic applications, tissue topology is a critical feature for identifying and accurately assessing lesions. In screening colonoscopy, for instance, lesions have characteristic shapes that are correlated with malignant potential [1]. However, conventional endoscopy captures only color and intensity contrast of the field of view, and consequently, the tissue topology can only be inferred through indirect cues. This lack of three-dimensional information may contribute to missed lesions and reduce the effectiveness of screening endoscopy. Techniques that capture tissue topography my improve lesion contrast and ultimate reduce the frequency of missed lesions in screening endoscopy [2]. Chromoendoscopy, for instance, is known to increase adenoma detection rate in colonoscopy, and works by effectively translating topographical contrast to color contrast by spraying a dye on the mucosa. Unfortunately, this technique is too time-consuming to be adopted in routine screening. To improve screening endoscopy there is a need for real-time techniques that capture topography in a wide field-of-view configuration, and can be implemented in the small form-factor of an endoscope.

To address this need, our laboratory is developing Photometric Stereo Endoscopy (PSE). PSE is a technique that enables the high-frequency topography of the entire field of view to be rapidly acquired with only a slight modification to existing commercial endoscopes. It is based on an established concept in computer vision called photometric stereo. By acquiring images that are illuminated from different light sources, s_i, and assuming that the objects in the field exhibit Lambertian remittance, the surface normal of each pixel, $\hat{n}$ can be estimated (Figure **1** a) [3,4]. The traditional photometric stereo approach works in well-controlled geometries, where the positions of the camera and light sources are all known with respect the object. However, these constraints are not compatible with medical endoscopy because the working distance is unknown and constantly changing. To adapt this technique for practical use in endoscopy, we have developed a new algorithm that filters out the errors associated with an unknown working distance, enabling a qualitative estimation of the high-frequency topography [5].

*ndurr@mit.edu, phone: 617-253-2538 http://scholar.harvard.edu/ndurr

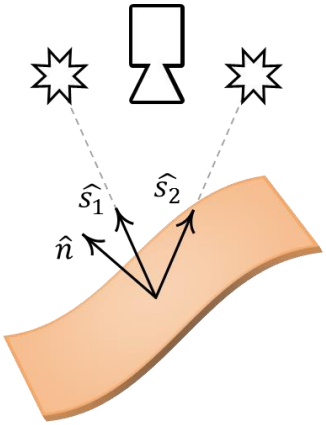


Figure 1: Photometric stereo imaging enables the surface normal of each pixel, $\hat{\boldsymbol{n}}$, to be estimated by comparing pixel intensities taken under different illuminations. Conventionally, the source vectors, $\boldsymbol{s_i}$, must be known to accurately reconstruct the surface normal map. In PSE, a set of constant source vectors are assumed for all pixels, and the resulting reconstruction error is filtered out, resulting in a qualitative map of the high-spatial-frequency surface topography.

We have previously demonstrated PSE using a benchtop system and a modified commercial endoscope [5]. In this paper, we describe our work to create a system that is suitable for clinical testing in human patients. First, we describe the system and reconstruction technique. Second, we validate the system by demonstrating video reconstruction of the topography of a tubular colon phantom.

METHEDOLOGY

1.1 Clinical PSE Endoscope

To expedite the translation to human testing, we built a PSE system that requires minor modifications of a clinically-used gastroscope and video processor. We disabled the light source of the video processor, extracted a timing pulse that is synchronized with the frame rate of the endoscope, and generated alternating white light pulses that are delivered to the distal end of the endoscope via optical fibers. Our endoscope consists of:

1. A Pentax EG-2990k commercial gastroscope with an outer diameter of 9.8 mm.
2. An alignment cap that is 3D printed from polycarbonate ISO. These caps are made to fit snugly around the gastroscope tip and have slits for the fibers to fit into. Polycarbonate ISO is an ISO-1099-3 compliant material that is used by medical device manufacturers.
3. Four plastic optical fibers with diffusing tips made from polymethyl methacrylate (Outer diameter = 1 mm, Core diameter = 0.96 mm, Numerical Aperture = 0.50, Doric Lenses, Quebec, Canada).
4. Surgical tape for wrapping (3M Transpore surgical tape). Surgical tape is currently used in colonoscopy to attach plastic caps in cap-assisted therapy and diagnosis.

Each of these components is made of biocompatible materials. The assembled PSE endoscope has an outer diameter of 14 mm, which is within the range of clinically used colonoscopes. For example, the Olympus CF-H180AL/I has a 13.9 mm outer diameter and the Olympus Q160ZL/I colonoscope has a 15 mm outer diameter. The Pentax gastroscope was cleaned before use following the standard operating procedures of the Massachusetts General Hospital Division of Gastroenterology. The alignment cap and plastic optical fibers were sterilized before using cold gas sterilization (STERRAD, Advanced Sterilization Products, USA). The cleaned endoscope, sterile alignment cap, and sterile optical fibers were assembled using surgical tape to wrap the fibers and cap to the outside of the endoscope. The assembly process takes approximately 5 minutes. After assembly, the distal tip can be articulated by up to 90°.

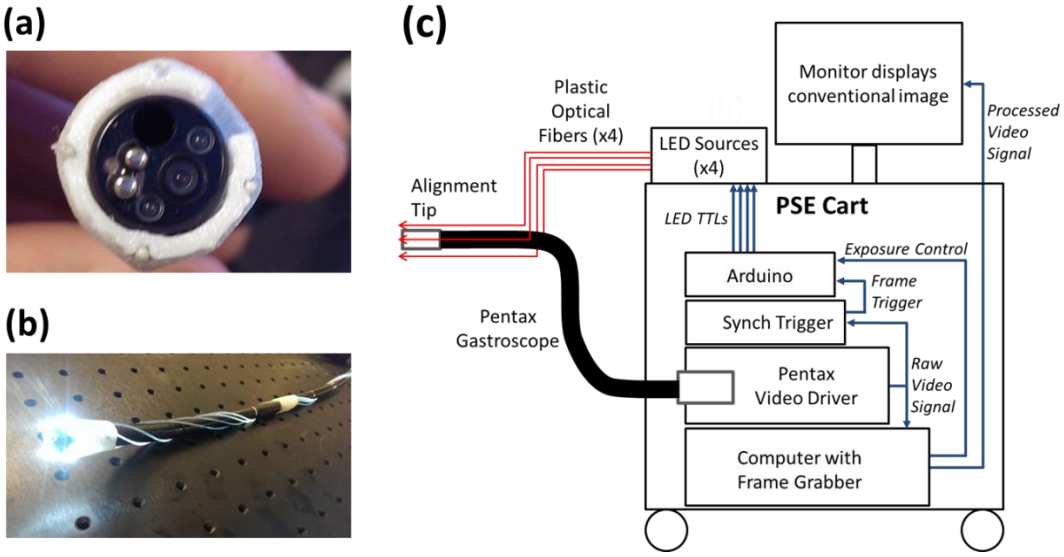


Figure 2: (a) The PSE clinical system is built by incorporating our own white light sources to a commercial gastroscope. The four light sources are aligned at equal angles about the center of the gastroscope with a custom alignment tip. (b) We found that by wrapping the fibers helically around the gastroscope, we could preserve tip flexibility. (c) We use custom electronics to synchronize our light sources with the frame rate of the endoscope sensor. The image displayed to the user is a moving average of the previous two images, which eliminates blinking effects that would be observed in the raw video stream.

1.2 Custom synchronization electronics

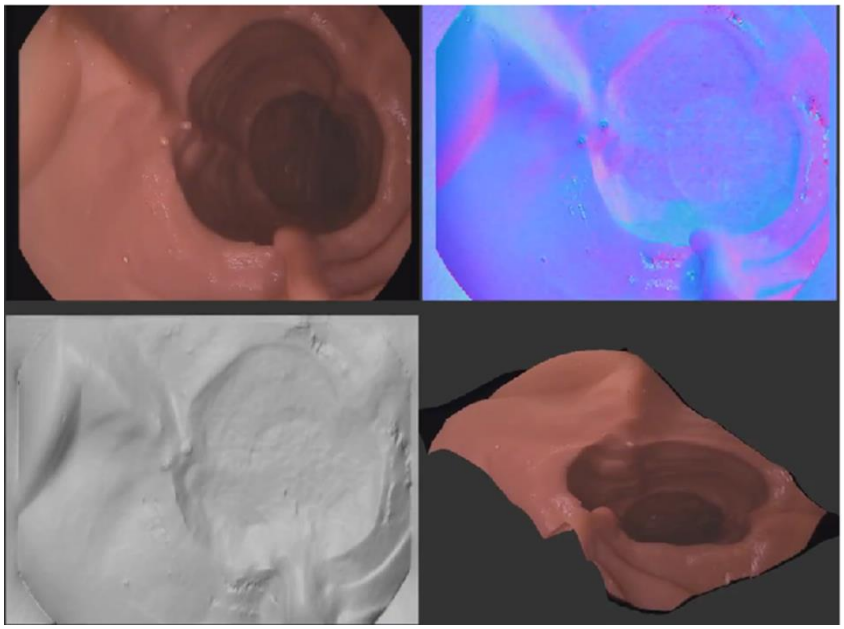
In order to synchronize the external light sources with the frame rate of the endoscope, we created a custom circuit with a video sync separator (LM1881, National Semiconductor). The circuit extracts a vertical sync synchronization signal from the NTSC video signal out of the Pentax video driver. We alternate between two light sources for each interlaced frame, creating four unique images at half the frame rate of the endoscope. The synchronization signal, along with the desired duty cycle of the LED, is sent to a microcontroller (Arduino Leonardo). The microcontroller then outputs four sequential TTL pulses to our LED modules (Mightex FCS-000-000). Our fiber-coupled LED light sources each output a maximum of 20 mW of white light out of the endoscope. This is significantly less light than is capable of being generated by the commercial gastroscopes light source (55 mW). All images are acquired with a video grabber (Matrox Orion HD) and the topography is generated in post-processing using our previous-described algorithm [5]. Since our light sources are pulsed twice for each full interlaced image, the unique images have a resolution of 720 x 243 pixels. The topography can be generated with every four unique image (15 Hz). The image displayed to the user is a moving average of the previous two images, updated at 30 Hz, which eliminates blinking effects that would be observed in the raw video stream. This will enable the endoscopist to navigate by looking at a conventional full-color image.

1.3 Tubular colon phantom

To demonstrate the evaluate the ability of the clinical PSE system to capture surface topography, we imaged the inside of a tubular silicone colon phantom (Colonoscopy Trainer, The Chamberlain Group). This phantom has been used in a previous study to test lesion detection rates and is the approximate size and shape of an adult human colon [6].

RESULTS

We recorded a video with the clinical PSE system moving through the transverse colon section of the colon phantom. Video 1 shows the conventional image computed by averaging images from each of the four sources, the normal map computed from our PSE algorithm, a rendering of the reconstructed topography that is estimated by integrating the normal map [5], and a rendering of the surface topography with a conventional color image overlay. In recording the video, no effort was made to minimize motion artifact. We found that the 15 Hz topography calculation was sufficiently fast to capture subtle topography without being obscured by motion artifact.



Video 1: (Top left) The conventional color image is generated by averaging every two frames (four light cycles). (Top right) The normal map shows that topographical features that can be observed in the conventional video are registered with the PSE technique. (Bottom left) Here, the normal map can be integrated to produce a surface topography. (Bottom right) Here the reconstructed surface rendered obliquely with the conventional color image overlayed on top of the surface. This shows that the locations of calculated bumps and dips are correlated with the color image, and provides an intuitive way to visualize both color and topographical information. http://dx.doi.org/doi.number.goes.here

Figure 3 shows the conventional images and the calculated normal map of two fields of view with small polyps. In the first field of view (Figure 3 (a) and (b)), small polyps can be seen clearly in both the color image and the normal map, demonstrating. In the second field of view (Figure 3 (c) and (d)), a non-polypoid lesion (defined by having a height of less than half of its width) is observable in the color image, but appears with higher contrast in the normal map.

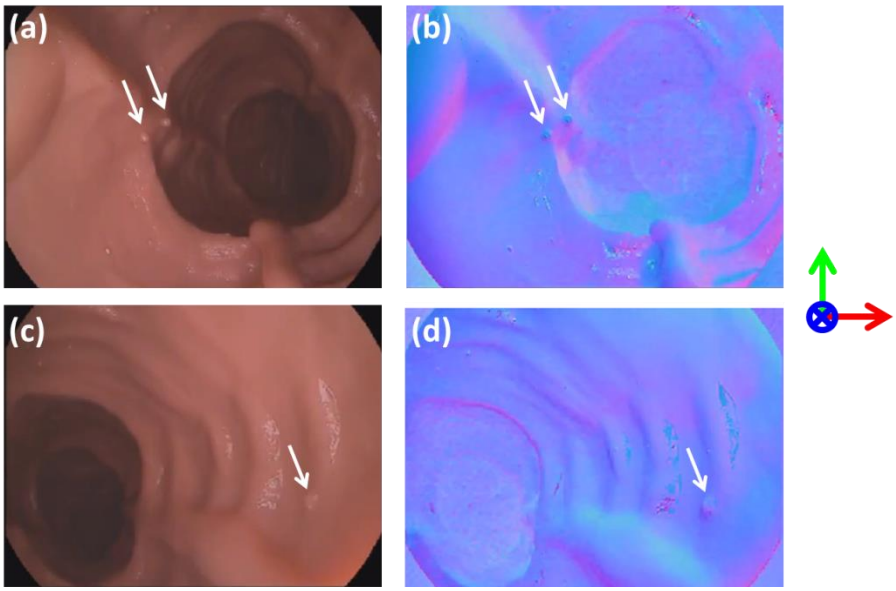


Figure 3: (a) Conventional color image of two small polyps (white arrows) in the transverse colon phantom. (b) The reconstructed normal map of the same field of view as in (a) shows that these small polyps generate

topographical contrast. (c) Conventional color image of one small non-polypoid ("flat") lesion (white arrow). (d) The reconstructed normal map of the same field of view as in (c) shows that even lesions with subtle topology changes are captured with PSE. The colormap for the normal vector map is: red channel represents the right component of the normal vector, green channel represents the up component of the normal vector, and the blue channel represents the component of the normal vector that points out of the page.

DISCUSSION

Some compromises were necessary to adapt a commercial system to perform PSE. The frame rate of the clinical PSE system is half that of the conventional system. Our light sources are also further away from the endoscope objective lens than the conventional light sources, which can lead to the light sources being occluded when the distal tip is pressed against the tissue wall. Our illumination diffuser does not spread out the light as widely as the existing diffusers. Lastly, specular reflections appear to be slightly worse in our modified system than in the original gastroscope. Nevertheless, these tradeoffs do not appreciably affect the usability of the device. The clinical PSE system is able to acquire high-quality conventional color images and detailed topography maps of the field of view at near-video rate. We found that the surface topography of subtle "lesions" in our colon phantom could be captured with our clinical system, even in a challenging tubular and deformable colon model, and in the presence of significant motion noise.

CONCLUSION

This article outlined the progress made towards developing a clinical PSE system. The described system will enable human evaluation of PSE to improve lesion contrast in screening endoscopy.

We developed and validated a clinical PSE system that, pending institutional review board approval, is ready for human testing. This system can be constructed on top of a commercial gastroscope using sterilized, low-cost components. This approach allows for many subjects to be tested consecutively, using the existing gastroscopes in an endoscopy suite. Importantly, our clinical PSE system displays a conventional color image and has a flexible distal tip, which will create a familiar interface for the gastroenterologist.

One area that will require future work is to improve the capability of PSE to reconstruct surface normals in the presence of specular reflections. The current PSE system assumes a Lambertian surface, which is a poor approximation to human tissue, and especially gastrointestinal tissue. In areas with bright specular reflection, there are large artifacts in the surface normal calculations, which are emphasized by our high-spatial-frequency filter. We are currently exploring alternative approaches that have the potential to accurately reconstruct surface normal map of non-Lambertian surfaces using more sophisticated algorithms [7]. An alternative approach is to incorporate cross polarizers between the illumination and collection channels [8].

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