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Decoupling structural artifacts in fiber optic imaging by applying compressive sensing

Jae-Ho Han [a,*], Sang Min Yoon [b], Gang-Joon Yoon [c]

[a] Department of Brain and Cognitive Engineering, Korea University, 145 Anam-ro, Seongbuk-gu, Seoul, 136-701, Korea
[b] School of Computer Science, Kookmin University, 77 Jeongneung-ro, Seongbuk-gu, Seoul, 136-702, Korea
[c] Institute of Mathematical Science, Ewha Womans University, 52 Ewhayeodae-gil, Seodaemun-gu, Seoul, 120-750, Korea

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ABSTRACT

Endoscopic optical coherence tomography (OCT) is an emerging method for noninvasive microscopic probing in biomedicine. In this paper, the feasibility of alleviating the pixelated structural artifacts created by a fiber bundle-based OCT imaging method is investigated using a novel statistical analysis. We demonstrate an efficient nonparametric iterative compressive sensing (CS) technique that is efficient in reconstructing the original pattern shape from a pixelated image of a reference US Air Force resolution chart. An efficient implementation scheme for the shape recovery is presented along with the results of experiments that demonstrate a peak signal-to-noise ratio of 18 dB and a noise variation of less than 0.3 dB with no honeycomb effect in the image is obtained after 40 iterations which is significantly efficient than the previous iterative method of learning image priors.

1. Introduction

Compressive sensing (CS) or sampling is an emerging approach whereby an exact image reconstruction can be obtained from a sufficient number of measurements of a sparse signal, i.e., images sampled at a rate significantly below the Nyquist/Shannon limit. This approach has generated considerable excitement in the signal (one dimension) and image (two dimensions) processing community and enables a potentially large reduction in the sampling and computational costs [1]. Recently, various techniques for denoising or inpainting a distorted image have exploited the fact that the image may be compressible using a prescribed basis. In other words, it is possible for an image to be reconstructed accurately (or even exactly) from a small number of measurements such as samples and projections. This approach stems from the data-acquisition technique of CS [2].

The emerging powerful microendoscopy method of optical coherence tomography (OCT) has been developed in recent biomedicine applications for producing noninvasive cross-sectional images with a high resolution in the z or depth-projection direction [3]. By utilizing OCT, it is possible to observe and visualize not only surface images but also subsurface area images and en face images at different depths. Interesting applications of OCT have appeared in ophthalmology, dermatology, gastroenterology, and cardiology, all of which use a microendoscopy technique. To create effective, miniaturized imagers or probes, a coherent fiber-bundle imaging system has been introduced [4]. This imaging probe removes the lateral scanning mechanism from the endoscopic probe so that the probe can be simply packaged or integrated with other medical devices or catheters currently used in biomedicine and easily modified for other novel medical designs.

Although there are advantages to using a fiber bundle, the resulting lateral image is not a continuous image but contains a pixelated artifact resembling a honeycomb. This phenomenon originates from the array structure of the individual fiber cores in the bundle and the background from the shared cladding region; light is guided only through the narrow core region by total internal reflection in a single optical fiber. Several attempts to overcome this discrete image artifact, or image pixelation, have been made [5], but previously reported methods have utilized simple image processing techniques (in either the spatial or frequency domain) for the acquired image. The structure of the imaging system itself was not considered in attempting to alleviate the pixelated effect. A more recent study in [6] demonstrated an iterative artifact removal method using a combination of linear filters and mirrored image for obtaining the reference. However, the reference image should be obtained before measuring the specimen to facilitate pattern learning which requires heavy iterations. In the work of Ford et al. [7], an out-of-focus background rejection method was applied using an algorithm that requires three calibration images prior to the image

* Corresponding author. Tel.: +82 2 3290 5927.
E-mail addresses: hanjaeho@korea.ac.kr, jhhan16@gmail.com (J.-H. Han).

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data acquisition, including measurement of the camera bias, output source power, and core transmission efficiencies. This method may be cumbersome because the calibration has to be performed each time the fiber bundle probe is connected and aligned with the imaging system.

Here, to alleviate the pixelation caused by the fiber-bundle imaging system, we propose a novel non-parametric formulation for reconstructing the original shape or pattern of an observed image using a CS technique by recovering the missing data in the input image. This method is shown to be efficient in comparison to previous reconstruction techniques as the reconstruction uses only a few intensity values. Even though the image under test is acquired using a specific two-dimensional (2D) scanning microscopy technique, the method can be applied to other similar fiber-based scanning optical microscopy techniques that produce the same pixelation artifacts.

2. Optical image data acquisition

2.1. Experimental setup for optical coherence tomography

A schematic of the data acquisition setup of the OCT-based fiber-bundle imaging system is shown in Fig. 1. The setup is based on spectral-domain OCT and employs a spectrometer to collect the spectral modulation (interferogram); different wavelengths are recorded by different pixels of a linear charge-coupled device (CCD) array. To convert the spectral information to raw image data, the spectral data are simply converted from wavelength space to wavevector space ($k=2\pi\lambda^{-1}$) for their interpolation and Fourier transform. The modulated spectrum contains different frequency components that correspond to reflections from different depths in the sample, and the axial or depth information can be directly extracted from a Fourier transform of the frequency terms modulated by the interference of the reference and sample beams. A reference distance was obtained at the distal end of the imaging probe from Fresnel reflection at the glass-air interface, which forms a novel common path configuration [8]. A directional optical coupler for wide-bandwidth operation matched to the source was used for the fiber optic interferometry. The low-coherence source (coherence length ~7 μm) was a superluminescence diode (SLD) that had a center wavelength of 0.8 μm (bandwidth: 40 nm) and an emitting power of approximately 2 mW.

The output beam was coupled effectively through the core of the fiber bundle by a focusing element. To avoid unnecessary reflections in the system, all the connectorized fibers had angled terminations. A rigid fiber bundle with a length of 76 mm and a 50-μm core spacing was employed to prevent fiber bending from altering the optical polarization. The overall imaging fiber size was 3.2 mm (diameter), and image scanning was performed using the center of the bundle to avoid scanning with the edge region. The fibers had a numerical aperture of 0.53, and the refractive indices of the core and cladding were 1.58 and 1.49, respectively. The initial volumetric (three-dimensional) image was obtained by laterally scanning the proximal entrance of the fiber bundle imager rather than the distal end of the probe in front of the specimen. In these experiments, a high-resolution linear translational stage (step size: 5 μm) was used as the practical scanner for both the x- and y-directions. Other experimental details can be found in [9].

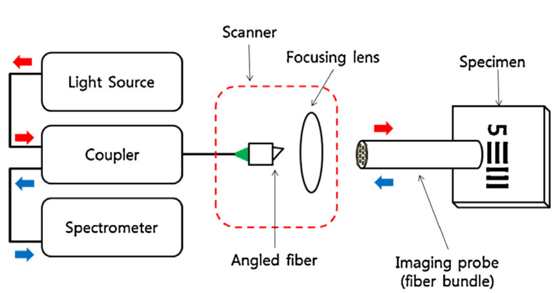

Fig. 1. Schematic optical setup of the scanning microendoscopy based on OCT (red arrow: direction of illumination; blue arrow: direction of returning light) (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.).

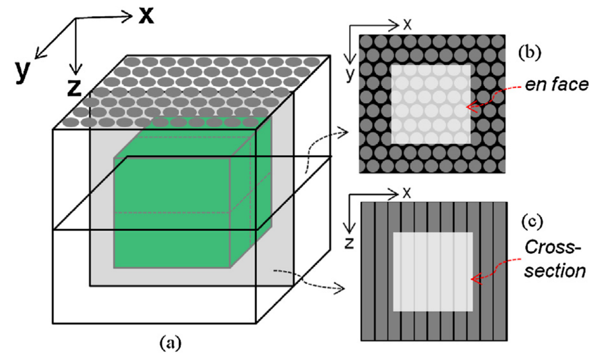

Fig. 2. Example images constructed by OCT: (a) original volumetric data (left); (b) en face image (x–y horizontal plane); and (c) subsurface cross-sectional image (x–z vertical plane; z is the axial direction of the imaging probe). A honeycomb-like structural artifact is observed in the en face or top surface images.

2.2. Image acquisition using optical fiber bundle

By removing 2D slices from the original volumetric image data (in a rectangular cuboid matrix) as in Fig. 2(a), we can construct various images of the specimen using OCT (the fiber cores extend from the top to bottom). We have used a 2D microendoscopic image obtained from an en face OCT image to clearly observe the effects of pixelation (shown by the darker regions between the circular cores); Fig. 2(b) was obtained with the fiber-bundle imager in the horizontal x–y image plane. There is no honeycomb-like effect along the z-direction (i.e., in the x–z and y–z planes), but a discontinuity due to the cladding region (marked as the darker vertical lines) between the cores can be seen in Fig. 2(c). One of the merits of OCT is that any lateral x–y image at any depth z can be chosen; thus, if the pixelation is corrected in the 2D en face image, then the observed structural artifact can be automatically suppressed in every z-axis-projected cross-sectional image (x–z and y–z images) [10]. (In the case of cross-sectional images in the z-direction, the discretized image can be corrected by a simple interpolation or smoothing, and so this has not been a problem unlike the honeycomb effect in the en face image [11,12].)

A US Air Force resolution chart with well-defined metallic bar patterns on a glass surface was prepared as the specimen (Fig. 3(a)),

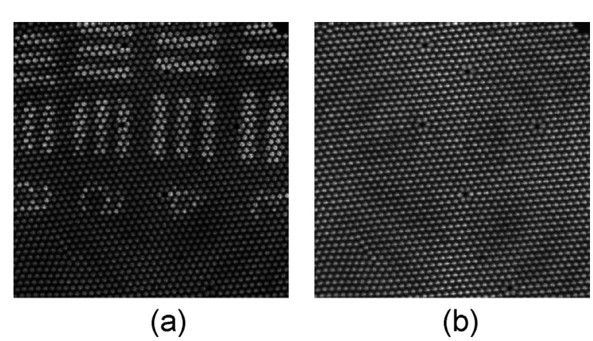

Fig. 3. Original images from OCT (en face images): (a) US Air Force Test chart image obtained using the fiber bundle imager [9] and (b) fiber bundle image without a sample (2 mm × 2 mm; resolution: 400 × 400).