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Synthetically generated fiber pixelated image database

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ABSTRACT

Visual access to physically inaccessible parts has become the forefront of research and development in medical diagnostics tools and procedures. Flexible and thin endoscopes with fiber bundle as an image conduit serves this purpose. However, when the light passes through the core of the fiberlet, it is blocked by the inter fiberlet gap. This structural limitation creates special honeycomb like pattern overlaying the image captured with the image fiber assisted probes, known as the comb structure or fiber pixelation. It obstructs the perception of the original image sacrificing resolution and contrast and inhibits the use of object recognition and tracking algorithms. Generally, comb structure removal or depixelation methods are employed to remove honeycomb pattern from an image. In the recent past, several depixelation techniques have been proposed albeit using different set of pixelated images by different researchers. It is quite difficult to make a comparison of their performances based on such images, as they adopt different images for different particular framework of their study. In this context, a basic database of such images is the need of the hour to meet the growing diagnostic needs in the medical and industrial arena. This paper in this context proposes and details a Comb Structure Affected Image database (CSAI) to meet the objective. Images are generated considering the image fiber specifications and the characteristics at different targeted optical imaging modalities delineated by resolution scales. The proposed database is designed to have a set of synthetically generated pixelated images of test patterns of different scales, sizes and shapes.

Keywords: Pixelation, Comb structure noise, depixelation, fiber bundle

INTRODUCTION

Minimally invasive surgery (MIS), non invasive surgery and combined diagnostic procedures are the future methods in medical diagnostics and therapeutics¹⁻³. These methods require visual access to physically inaccessible area/s of the body⁴. Visual access is achieved with the keyhole endoscopy by taking small incisions in to the body. MIS due to its advantages like reduction in the operation time, faster recovery time and cost effectiveness, is gaining popularity in doctors and patients⁵. Endoscope has to pass through small and complex cavities or hollows. Inaccessibility to the small cavities, complexity of scene and need for depth information prevent the use of rod lens endoscopes or tip chip videoscopes. This leaves surgeons with the only option of flexible, fiber optic endoscopes or fiberscopes. Fiberscopes feature a coherent fiber optic imaging bundle. In spite of its widespread usage it has a prominent problem of comb structure or pixelation noise^{6, 7}. Several methods discussed in literature are capable of removing comb structure noise⁸⁻¹⁷. They are called as depixelation methods can be grouped as different methodologies such as spatial averaging, spectral filtering, spatial interpolation, super resolution with temporal images etc. Recently our group has reviewed depixelation methods with parametric and non parametric performance measures¹⁸. Unfortunately, researchers have used their own pixelated images to perform the depixelation algorithms^{8, 9, 19, 20}. Different depixelation methods perform differently but as they are demonstrated with the help of different images in reported literature, it is difficult to compare them directly based on depixelated images. Another limitation of the observed data from literature is that only pixelated image and depixelated image are available but the sample from which the pixelated image is generated is not available^{12, 13, 19-21}. The sample image or the image at the distal end of the fiber bundle along with the depixelated image can be used for the calculation of statistical parameters such as variance and standard deviation. In this context, the need for the database of pixelated images is observed which will serve as the test image database for researchers working on novel depixelation algorithms^{22, 23}. The above explained limitation is also the prime limitation of image fiber based probe imaging methodologies

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reported in literature or practiced in proven equipment. Pixelation noise removal of images captured using coherent imaging fiber bundle is a major research problem to be solved completely and has become one of the thrust research areas in the recent past. In this context, a pixelated image database of synthetic images is proposed in this paper. This database consists of different test images with their pixelated counterparts generated with the help of configuration of fiber bundle. Availability of such database will help researchers to compare their work with other reported literature. Moreover, the database provides an image at the distal end of the fiber bundle as well as at the proximal end of the fiber bundle, which can be used to calculate first and second order error (mean, standard deviation, variance, standard error) parameters.

IMAGE ACQUISITION

Pixelation is observed in images captured with the Fiber Optic Imaging Bundle (FOIB). There are several possible optical setups for capturing an image through FOIB. Figure 1 shows an optical configuration for FOIB imaging in widefield reflection mode which we have used in our probe configurations reported earlier²⁴⁻²⁶. Inset in Figure 1 shows the flow of information in the fiber bundle. Information in fiber bundle transfers from the distal end of the fiber to the proximal end of the fiber. Image captured through FOIB can be described as follows. Image of a sample is formed at the distal end of the fiber bundle. Formation of this image depends on optical components between the fiber and sample and depends on optical parameters such as effective Numerical Aperture (NA) of the FOIB. This image when observed at the other end of the fiber (proximal end) comb structure noise is observed, the image is pixelated.

Figure 1. Optical configuration for imaging with FOIB.

If images of the end facets of fiber bundle are captured, one of those images is mirror image of the other. In other words, position of particular fiberlet with respect to some other fiberlets inside the FOIB is same at both the ends. Coherent nature of fiberlets allows images to be transferred through FOIB. Fiber bundle has thousands of fiberlets in very small cross sectional area. Specifically, FOIBs available today have fiberlets ranging from 3000 to 100000 and in diameters of 0.6 to 2 mm. Packing fraction defines the number of fibers per unit area and it depends on the size of fiber core, fiber cladding thickness, inter fiber gap distance and image circle diameter. Fiberlets in fiber bundle are single mode fibers and usually drawn in circular shape. Core and cladding are two parts of fiberlets; some fiberlets also come with the sheathing over a cladding. Core of the fiberlet cannot carry the entire information incident on it. At any given time instant, cross section of the fiberlet core has single intensity information. Intensity inside the core of the fiberlet follows a two dimensional Gaussian distribution²⁷. Amplitude of the Gaussian distribution corresponds to the intensity value carried by the fiberlet.

Figure 2. Pixelated Image showing uniformly lit white surface captured through FOIB.

Image in Figure 2 shows the pixelation effect. Pixelation in these images can be analyzed in three steps. In first step, part of an image which incidents on the distal end of the fiber bundle is blocked. Cladding and inter fiber gap restricts the inflow of reflected light from the sample. 2D Gaussian distribution of an intensity value is observed at cross section of the fiberlet.

FIBER BUNDLE CONFIGURATION

Image passing through distal end of the fiber bundle to the proximal end of the fiber bundle gets converted from undistorted, non pixelated to the pixelated image. In order to generate a pixelated image from non pixelated image synthetically, a configuration of fiber bundle is required. In this section, the configuration of fiber bundle is developed in bottom up approach. Configuration of single mode single fiberlet is designed which is used for the development of whole image fiber bundle configuration.

As discussed previously, fiberlet carries only one intensity value despite receiving large information content. This intensity refers to the amplitude of the 2D Gaussian distribution of signal inside the fiberlet. It becomes necessary to compute the amplitude of the Gaussian distribution. Let us assume that the amplitude of the Gaussian distribution is an average of the intensities falling on to the core of the fiberlet,

$$A = \frac{1}{2\pi r^2} \int_0^L \int_0^{2\pi} I(r, \theta) \times C(r, \theta) dr d\theta \quad (1)$$

Where,

I – Intensity of light falling on to the distal end of fiberlet

C – Light coupling factor for fiberlet

L – Radius of fiberlet.

r, θ – Radial co-ordinates.

Intensity Distribution of the signal in fiberlet²⁷,

$$I(x, y) = A e^{-\left(\frac{(x-x_0)^2}{2\sigma_x^2} + \frac{(y-y_0)^2}{2\sigma_y^2}\right)} \quad (2)$$

Where,

(x_0, y_0) – Center of the end facet of fiberlet

σ_x – Standard deviation controlling Gaussian spread in direction of 'x'. σ_x is Gaussian spread in the direction of x and

σ_y represent Gaussian spread in y direction.

If core of fiberlet corresponds to distal end pixel set P with k pixels and coupling factor 1 then amplitude of intensity pattern inside the fiberlet is given by,

$$A_D = \frac{1}{k} \sum_{p \in P} I(p) \quad (3)$$

Where,

P – set of pixels p corresponding to the distal end of the core of fiberlet.

I(p) – Intensity at pixel p.

K – number of pixels in set P.

Fiberlet at the proximal end is imaged using a charge coupled device (CCD) camera giving digital signal with center at point $p(m_0, n_0)$,

$$I(m, n) = A_p e^{-(\frac{(m-m_0)^2}{2\sigma_m^2} + \frac{(n-n_0)^2}{2\sigma_n^2})} \text{ for } \sqrt{(m - m_0)^2 + (n - n_0)^2} \leq r \quad (4)$$

In pixelation, the observed pattern is that of a hexagonal pattern. In ideal case the fiberlets are placed equidistantly. In this context, configuration of fiber bundle asks for the placement of fiberlets at equidistant points. If fiberlet is considered to be at the center of a hexagon then equidistant fiberlets are placed such that center of the fiberlets coincides with the vertices of the hexagon. Figure 3 shows the fiberlets arrangement in the fiber bundle configuration.

Figure 3. Arrangement of fiberlets inside the fiber bundle. White areas of image correspond to fiberlet. cores.

SIMULATED TEST IMAGES

The image fiber configuration for FOIB is described in the previous section. This configuration is overlaid over synthetically designed test images to generate the pixelated images. The behavior of the fiber bundle imaging and relevant possible scenario are to be investigated. Simulations involve design of test samples or images which correspond to different possible conditions.

Table 1. Grating pattern frequencies for which pixelated images are simulated.

	Vertically oriented grating pattern (frequency)	Grating pattern slanted by 5° (frequency)
1	1	1
2	2	2
3	4	4
4	8	8
5	16	16
6	32	32
7	64	-

Capability of reconstruction with depixelation method has to be examined for these conditions, mainly involving effect of sharp edges; line spread function, aliasing effect and resolution limit. Consider a line with width of 'N' pixels in simulated test image; the test image is pixelated with a configuration of fiber bundle. When this image is depixelated, the same line width is represented by 'N+L' pixels. This increase in the width of the line from original image to reconstructed image is called line spread.

Figure 4. Original grating patterns with increasing frequencies in the first two rows and their pixelated counterparts represented in the lower rows. First row [Grating period: a- 512, b- 256, c- 128 and d- 64] and second row [Grating period: e- 32, f- 16, g- 8 and h- 4] shows grating pattern with decreasing period. Third [i, j, k and l] and fourth row [m, n, o and p] show the pixelated images corresponding to the grating patterns in row one and row two respectively.

Investigating an edge response by any imaging system involves test images with binary transformations or abrupt variation from bright to dark intensity values. Area covered by slanted edge gratings varies in number of fiberlets covered where as areas covered in vertical grating are the same. Square wave grating patterns with 50 percent duty cycle are used for investigating the above mentioned conditions. Slanted patterns with angle of orientation changed by 5° are also used. Table 1 shows the frequencies of the simulated grating patterns used in pixelated database. It is evident that faithful reconstruction is difficult with reduction in the grating period by observing pixelated images for increasing frequencies of grating pattern. Edge spread in slanted pattern is wider as compared to the vertically oriented grating.

Figure 5. Inclined grating patterns with increasing frequencies in first two rows and their pixelated counterparts in lower rows. First row[grating period: a- 256, b- 128 and c- 64] and second row [d- 32, e- 16 and f- 8] shows inclined grating pattern with decreasing period. Third row [g, h and i] and forth row [j, k and l] show the pixelated images corresponding to the grating patterns in row one and row two respectively.

Fiberlets in an image fiber behave as sampler; to examine the effect of aliasing interlacing pattern of bright and dark lines is pixelated. If line spread of two lines superimposes over one another it becomes difficult to separate two lines; the effect is known as aliasing. This is also related to the resolution, which is defined as the minimum feature size that can be identified from depixelated image. According to Nyquist sampling theorem²⁸, faithful reconstruction of a periodic signal X having frequency f_x is possible only if the sampling frequency is greater than or equal to $2f_x$. Figure 4 and Figure 5 shows the effect of aliasing with pixelation using square wave grating pattern and with inclined square wave grating pattern respectively. From the two figures it is evident that resolving a pair of lines from a grating pattern is impossible for grating frequencies more than particular threshold frequency. On subjective evaluation of Figure 5 it is observed that reconstruction of grating pattern from Figure 5j is impossible.

Prior to evaluation of grating patterns, a response of a system to the minimum and maximum intensity values has to be checked. Reconstruction of smoothly varying intensity values or part of a pattern with constant intensity values is evaluated with constant intensity value test images such as bright pixelated image and dark pixelated image. Figure 6 shows the bright and dark test pattern images and their corresponding pixelated images. Fiber bundle may have some discrepancies such as dust over some fiberlets or damaged group of fiberlets also the coupling factor may not be uniform for all the fiberlets; these factors contribute to possible aberrations in the pixelated image. In ideal scenario, every fiberlet should provide same output if illuminated with same input pattern. Studying pixelated images of uniform intensity pattern shown in Figure 6, helps in characterizing the fiber bundle. This in turn helps in better reconstruction of pixelated images. Reconstruction of an image which has pixelated dark test pattern provides the value of dark noise. On the other hand, pixelated image of uniform bright surface provides maximum intensity value that can be detected. Two images in turn provide the possible detection range of an optical system.

Figure 6. Pixelation pattern of uniform intensity patterns a- Uniform dark pattern with no light illuminating distal end of the fiber bundle. b- Uniform bright pattern, illuminating distal end of the fiber with maximum light intensity. c and d represent the pixelated images of a and b respectively

Siemens star as proposed in ISO 12233 is generally used for the calculation of Modulation Transfer Function (MTF). In this study, reconstruction with several other patterns like Siemens star is also investigated. Siemens star is an intensity varying pattern with intensity variations along the circumference of a circle. Width of the intensity variation is controlled by arc angle. Section of a circle covered by particular arc angle has bright intensity values. Adjacent section with same arc angle has dark intensity values. These arc sections coming together form a Siemens star. For any given radius, cycle length for Siemens star pattern in pixels is given by,

$$L = \frac{2 \pi r_{pixel}}{S_{cycles}} \quad (5)$$

Where,

r_{pixel} - Distance from center pixel where cycle length is calculated.

S_{cycles} -Number of cycles in Siemens star.

Cycle length increases with increase in radius and decreases with increase in number of cycles. Figure 7 shows original and pixelated Siemens stars with increasing number of cycles. Reconstructed image which is able to discriminate all the cycles for largest number of cycles should be used for parameter calculations. Subjective

evaluation suggests that with increase in cycle frequency, it becomes difficult to distinguish between patterns near center of Siemens star. Using the intensity profiles along the circumference at radius r , the MTF can be calculated⁸.

$$MTF = \frac{I_{max} - I_{min}}{I_{max} + I_{min}} \frac{I_{white} + I_{black}}{I_{white} - I_{black}} \quad (6)$$

Where,

I_{white} -Average intensity of part of reconstructed image corresponding to the white portion of sample.

I_{black} -Average intensity of part of reconstructed image corresponding to the black portion of sample.

I_{max} -Maximum intensity value from depixelated image.

I_{min} -Minimum intensity value from depixelated image.

Figure 7. Original Siemens star with increasing cycle frequency [Number of cycles: a- 2, b- 4, c- 8 and d- 16] and their corresponding pixelated images [e, f, g and h].

Performance analysis of any system is incomplete without specifying the linear response of the same. This is specified by a graph depicting response of output signal verses input signal. If image captured is an 8 bit image, number of possible gray levels are 256. Ideally, reconstruction method should be examined for all the possible input intensity values. It consumes a lot of time in testing phase; to reduce this time depixelation is examined for only a set of intensity values increasing in predefined steps. These set of intensity values form a ramp signal from minimum to maximum intensity. To analyze these increasing intensity values, single line of pixels cannot be used as it won't even cover a single fiberlet. Samples containing blocks of different intensity values are simulated. Each block corresponds to one intensity level. Two samples are generated containing blocks of 32 gray levels; one for intensities increasing from minimum to half of the maximum intensity and second sample for intensities beyond half of the maximum. Figure 8 shows two sample images and their corresponding pixelated images.

As discussed in section 1, if sample image is provided with pixelated image; researchers implementing depixelation algorithms can compare depixelated image with original sample image. This database provides original image or image at the distal end of FOIB and pixelated image. Figure 4-8 show the original and pixelated images of different patterns. Expected output image of depixelation algorithm is original image or sample image at the distal end of the fiber bundle. Difference between expected image and reconstructed image is error²³,

$$E(x, y) = D(x, y) - O(x, y) \quad (7)$$

Where,

D - Depixelated image.

O - Original image.

x and y – pixel co-ordinates.

Variance between two images is given by²³,

$$V = \frac{1}{M.N} \sum_{x=1}^M \sum_{y=1}^N (D(x,y) - O(x,y))^2 \quad (8)$$

Where,

M- Number of rows.

N- Number of columns. Standard deviation can be computed as²³,

$$S = \sqrt{\sum_1^M \sum_1^N \frac{(D(x,y) - O(x,y))^2}{M.N}} \quad (8)$$

Figure 8. Sample image with varying intensity values: a- zero to half of the maximum detectable intensity value and b- half of the maximum to maximum detectable intensities. c and d are pixelated images of a and b respectively.

CONCLUSION

Minimally invasive surgery and diagnostics are the latest thrust research areas and thin flexible diagnostic imaging systems like fiberscopes are prominent probes to facilitate such diagnostic or therapeutic procedures. However, flexible probes based on image fiber bundle suffer from poor spatial resolution and contrast by inherent pixelation noise as detailed in this manuscript. This paper in this context was devoted to developing a database of pixelated images with different test patterns. This database expected to serve as a reference test image database for researchers working on depixelation algorithms. Both original image and image with comb structures are provided in this database. As original image is available, the reconstructed image can be compared objectively with different parameters. Several different shapes with variations in frequency and angle are given in this proposed database. It is to be emphasized that the images analyzed in this database are synthetic pixelated images. Hence future works in this area should be aimed at capturing experimental images with proper correlation in order to complete experimental image database.

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