Dynamic Band Imaging: Image Enhancement for Endoscopic Diagnosis

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Abstract

In this study we propose a new image enhancement technique named Dynamic Band Imaging (DBI) which changes its parameters in time. DBI is the technology based on multi-spectral estimation to enhance the endoscopic color images in order to distinguish the slight color difference more clearly. From some results of fundamental analysis by subjective evaluations, DBI represents the effectiveness for image enhancement in comparison with the typical still image evaluation. Furthermore we developed the user interface to determine many parameters easily and then some practical appropriate parameters for endoscopic diagnosis are obtained. DBI is found as the effective method to enhance medical images.

Introduction

A color image taken by electronic endoscopes gives important information for diagnosis of various kinds of rectal and stomach diseases, it is important to observe the fine structure of the mucous membrane surface in detail. Color reproduction of electronic endoscopes, however, is not enough to diagnose the early stage of the diagnosis. Therefore, to improve color reproduction of electronic endoscopes has been required.

In 2002, Gono et al. have proposed the Narrow Band Imaging (NBI) technique [1], [2] to improve the image quality with regard to such the fine structure by adjusting the spectrum feature in consideration of the wavelength dependence of the light penetration depth into the tissue. This method is quite significant and is remarkably focused on by medical doctors. Because the NBI system requires dedicated hardware with fixed narrow-band filters, it costs very high and has no freedom of designing arbitrary spectral bands. To overcome such problems, Miyake et al. have proposed the image enhancement technique using the multi-spectral images in 2005 [3], which is based on the spectral analysis as follows. In 1988, they have developed the endoscope spectrophotometer [4] to measure the spectral reflectance of gastric mucous membrane. Many measured spectra of the gastric and rectal mucous membrane have been analyzed by principal component analysis and they showed that the reflectance spectra can adequately be described by only three principal components. Based on the above experimental result, it was shown that the reflectance spectra of gastric and rectal mucous membrane can be estimated from the R, G, and B signals of the conventional electronic endoscopes. Then three of estimated single band images are chosen form estimated multi-band images and are assigned to RGB channels again. Although some endoscopic images are improved effectively by using this method, since it is essentially only a simple color transformation by using 3x3 matrices, it has the limitation of enhancement. Therefore we propose in this study a new image enhancement technique based on multi-spectral imaging named Dynamic Band Imaging (DBI).

Human perception has more sensitivity against the changing stimulus than the still stimulus. In order to distinguish the slight color difference, it can be thought that color-enhanced movies are more effective than still images. The DBI is an extension of Miyake's synthesizing method and changes its parameters in time. Since the DBI is also the software post-processing method, it's very easy to implement into conventional endoscopes additionally. In this study, we first analyze the fundamental effectiveness of the DBI by evaluating the distinguishable rate between two slightly different colors. Since the DBI has a lot of parameters and its change can be designed freely, we prepared six example cases to confirm the basic effectiveness one by one. We also implement the DBI for the practical medical application for the endoscope diagnosis. Because the DBI has many parameters which need to change simultaneously, it's very hard to find the best changing way of parameters by using conventional user interface. Therefore we develop an interface which can adjust six parameters in real-time. Then the effectiveness of the DBI for the medical application is evaluated by medical doctors who are specialized for endoscopic diagnosis.

Image enhancement by spectral processing

Spectral estimation from RGB values

The color reproduction characteristics of electronic endoscopes depends on many optical factors such as spectral radiant distribution of illuminant $E(\lambda)$, spectral sensitivity of CCD $S(\lambda)$, spectral transmittance of filters $f_i(\lambda), i=\{r,g,b\}$, and spectral transmittance of imaging lenses $L(\lambda)$. Then the output signal $v_i(x,y)$ can be calculated as,

$$v_i(x,y)=\int_{vis} E(\lambda)S(\lambda)f_i(\lambda)L(\lambda)r(\lambda,x,y)d\lambda \quad i=\{r,g,b\} \qquad ,(1)$$

where $r(\lambda,x,y)$ is a spectral reflectance of the mucous membrane and (x,y) is coordinate of the object. From the principal component analysis and the Wiener estimation, reflection spectra of the recta $r(\lambda,x,y)$ can be estimated from three Eigen vectors and principal components of spectral reflectance. Then it's possible to estimate the reflection spectra of the object with high accuracy by using RGB three-band cameras.

In the Wiener estimation, at first, we measure digital values $v_{i,j}, j = \{1, \cdots, 24\}$ of the Macbeth Color Checker taken by electronic endoscopes which has RGB, three-band CCD. Secondly, we measure the precise reflectance spectra of each color patch $r_j(\lambda)$ with a spectrophotometer. Using these two data sets, we can calculate a system matrix to estimate spectral reflectance of the object by the Wiener estimation method.

Image enhancement by estimated spectral information

In 2005, Miyake et al. proposed the image enhancement method [3] by assigning three single band images of arbitrary wavelength to R, G, B image planes. For example, by choosing 500nm for R plane, 450nm for G plane, 410nm for B plane from estimated 61-band spectral images, a synthesized image is shown in Figure 1. The edge of the tumor area is clearly emphasized by using this method. This color transformation is just multiplying 3 by 3 matrix to the pixel values of CCD output $v_i(x, y)$ as follows,

$$\mathbf{p}(x, y) = \mathbf{M} \cdot \mathbf{v}(x, y),$$

$$\begin{bmatrix} p_r(x,y) \\ p_g(x,y) \\ p_b(x,y) \end{bmatrix} = \begin{bmatrix} -0.00119 & 0.002346 & 0.0016 \\ 0.00402 & 0.000068 & -0.00097 \\ 0.005152 & -0.00192 & 0.000088 \end{bmatrix} \begin{bmatrix} v_r(x,y) \\ v_g(x,y) \\ v_b(x,y) \end{bmatrix} . \quad (2)$$

Since this operation is very simple, it's easy to implement it to the conventional endoscope system additionally as a software post process in real-time.

In the practical diagnosis, medical doctors have to diagnose the hundreds kinds of tumors on the mucous membrane which has different spectral properties. When a tumor has particular reflectance spectra which is clearly different from reflectance spectra of mucous membrane, the conventional method is effective to emphasize the edge. There are, however, many tumors which has quite similar reflectance spectra to the membrane. To enhance such slight difference of spectral properties, we propose a new method named Dynamic Band Imaging.

Dynamic Band Imaging (DBI)

As typified by small involuntary eye movement, human perception has more sensitivity against the changing stimulus than the still stimulus. In order to distinguish the slight color difference, it can be thought that color-enhanced movies are more effective than still images. Since endoscopic diagnoses are conventionally performed by evaluating the still images, in this study we generate the color-enhanced movie from the spectral estimated still image.

In this method, we define three time-varying parameters for a color plane such as center wavelength $c_i(t)$ (nm), band width $w_i(t)$ and intensity coefficient $n_i(t)$, where t is the time and $i = (r, g, b)$. This method is namely equivalent to change the transformation matrix $\mathbf{M}$ dynamically, and then we call it Dynamic Band Imaging (DBI).

By using estimated reflectance spectra $\tilde{r}(\lambda, x, y)$ and these parameters, output digital values can be generated based on Gaussian distribution as follows,

$$p_i(x,y) = n_i(t) k_i \int_{vis} \frac{1}{\sqrt{2\pi} w_i(t)} \exp\left(-\frac{(\lambda - c_i(t))^2}{2 w_i(t)^2} \right) \cdot \tilde{r}(\lambda, x, y) \cdot E(\lambda) d\lambda \cdot (3)$$
$$i = \{r, g, b\}$$

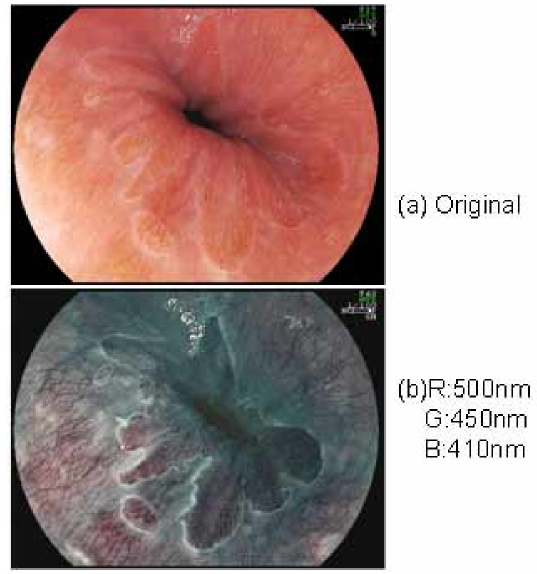

Figure 1 *(a) Usual endoscopic image, (b) Synthesized image by spectral images at 500nm, 450nm and 410nm.*

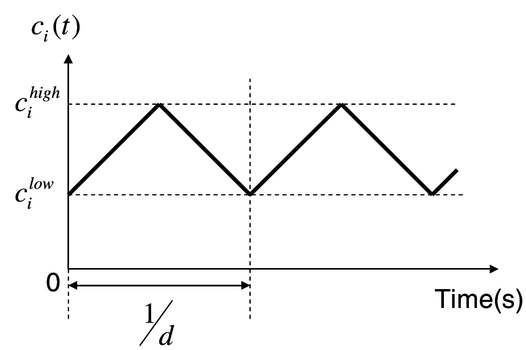

Figure 2 *Triangular waveform of* $c_i(t)$

Table 1 Color difference of each combination of skins.

Combination	ΔE_{94}
SC1	0.2659
SC2	0.4356
SC3	0.6231
SC4	0.7981
SC5	0.9266
SC6	0.9334
SC7	1.5048
SC8	2.0547

Coefficient k_i is determined to give $\mathbf{p} = (p_r, p_g, p_b) = (255, 255, 255)$ when the system takes the perfect reflecting diffuser as follows,

$$k_i \int_{vis} \frac{1}{\sqrt{2\pi} w_i(t)} \exp\left(-\frac{(\lambda - c_i(t))^2}{2 w_i(t)^2} \right) \cdot E(\lambda) d\lambda = 255 \quad .(4)$$
$$i = \{r, g, b\}$$

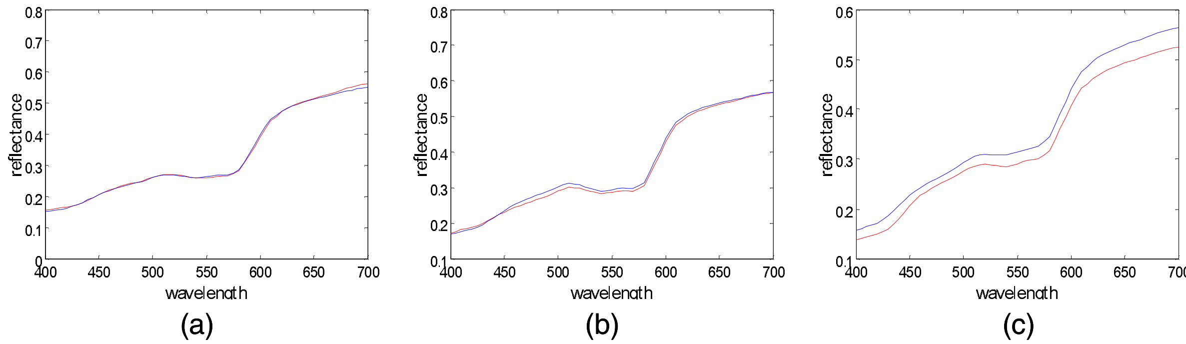

Figure 3 *Example reflectance spectra (a) SC1 (b) SC4 (c) SC8*

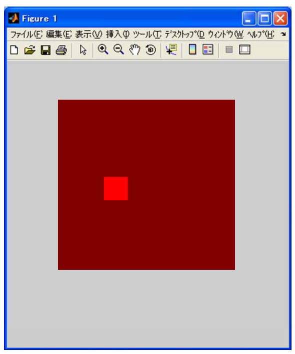

Figure 4 *Display image of the evaluation experiment. A small color patch is placed on the large color patch.*

Table 2 DBI parameters of test case B to F

Case	Wave	Freq.	c_R^{low}	c_R^{high}	c_G^{low}	c_G^{high}	c_B^{low}	c_B^{high}
B	**Triangular**	**2 (Hz)**	**600**	**680**	**500**	**580**	**420**	**500**
C	Triangular	**1 (Hz)**	600	680	500	580	420	500
D	Triangular	2 (Hz)	**620**	**660**	**520**	**560**	**440**	**480**
E	**Square**	2 (Hz)	600	680	500	580	420	500
F	Triangular	2 (Hz)	600	680	500	580	420	500

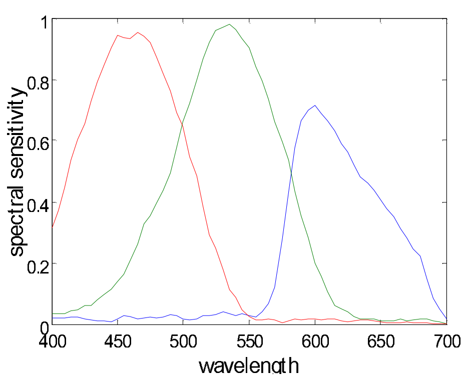

Figure 5 *Spectral sensitivity* $Q_i(\lambda)$ *of the camera*

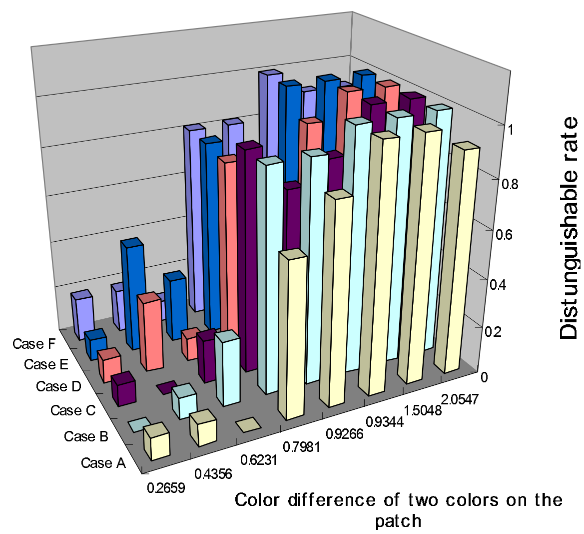

Figure 6 *Results of subjective evaluation. Distinguishable rates of each case are shown.*

In this method, we have infinite degrees of freedom to define these time-varying functions. In order to analyze the fundamental effectiveness of the DBI, we give following simple functions.

$$c_i(t) = \begin{cases} c_i^{low} + 2dt(c_i^{high} - c_i^{low}) & \text{if } 0 \le t < \dfrac{1}{2d}, \\ c_i^{low} + 2(1-dt)(c_i^{high} - c_i^{low}) & \text{if } \dfrac{1}{2d} \le t < \dfrac{1}{d}, \end{cases}$$
$$w_i(t) = 10,$$
$$n_i(t) = 1, \tag{5}$$

where c_i^{low}, c_i^{high} (nm) are the lower and higher boundary of the oscillation of the center wavelength respectively and d (Hz) represents the frequency of the oscillation. Then $c_i(t)$ is the triangular wave function as shown in Figure 2. Furthermore another waveform is prepared for the evaluation as follows,

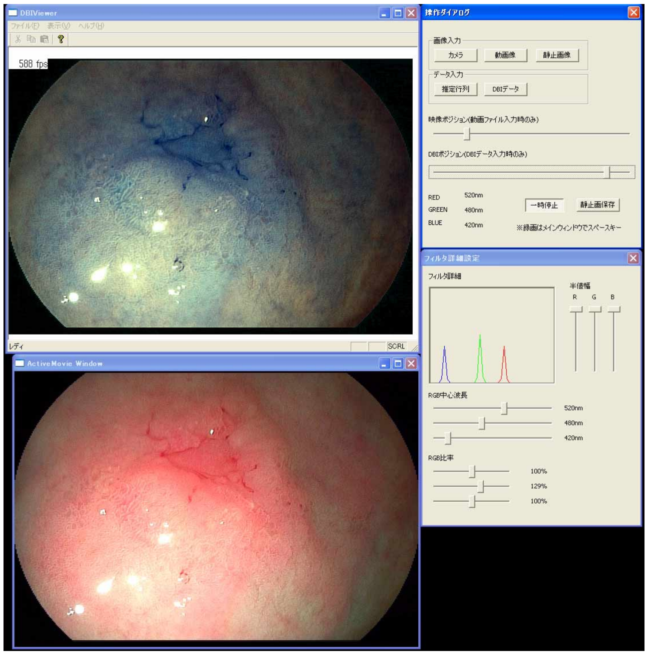

Figure 7 *DBI application for endoscopic diagnosis*

$$c_i(t) = \begin{cases} c_i^{low} & \text{if } 0 \le t < \dfrac{1}{2d}, \\ c_i^{high} & \text{if } \dfrac{1}{2d} \le t < \dfrac{1}{d}, \end{cases}$$
$$w_i(t) = 10, \tag{6}$$
$$n_i(t) = 1,$$

This shapes simple square wave. Using these ways, the effectiveness of dynamic band imaging can be evaluated in comparison with the still image evaluation.

Experimentation

In this study, in order to evaluate the fundamental effectiveness of the DBI, we have performed the subjective evaluations. In this experiment, we have prepared eight example combinations of similar reflectance spectra of human skin. Each combination consists of two kinds of reflectance spectra of human skin. The color differences ΔE_{94} under D65 illumination between them are shown in Table 1 and reflectance spectra of SC1, SC4 and SC8 are shown in Figure 3. A small square patch which is colored by the first reflectance spectra is placed on the large square patch colored by the second reflectance spectra as shown in Figure 4. The effectiveness of the image enhancement is evaluated by judging whether the small patch can be found or not.

These color patches are taken by a camera simulator which has the spectral sensitivity $Q_i(\lambda) = S(\lambda) \cdot f_i(\lambda) \cdot L(\lambda)$ as shown in Figure 5. By using this camera simulator, we can calculate the pixel values of the camera output $v_i(x, y)$, and obtain the estimation matrix which gives $\tilde{r}(\lambda, x, y)$ from $v_i(x, y)$ by Wiener estimation method with Macbeth Color Checker. Dynamic Band Imaging described in Eq.3 is performed with the triangular wave (Eq. 5) and the square wave (Eq.6). For the subjective evaluation, we prepare six kinds of imaging scheme as follows

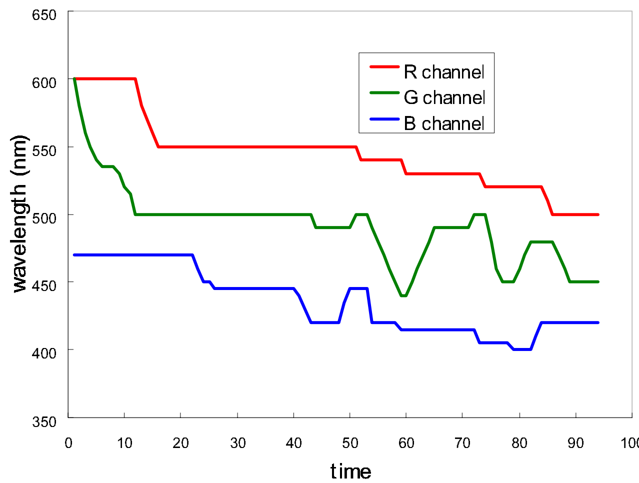

Figure 8 *An example change of $c_i(t)$ determined by a medical doctor using PHANTOM.*

Case A) Color patches are displayed as is taken by the camera simulator (Figure 5)

Case B to E) DBI from estimated reflectance spectra $\tilde{r}(\lambda, x, y)$

Case F) DBI from original reflectance spectra $r(\lambda, x, y)$

DBI parameters of case B to F are shown in Table 2. At the subjective evaluation, 54 patches (nine combinations of skins × six cases) are displayed on the LCD monitor for five seconds each. Subjects answer whether they could find the small square patch inside the large square patch or not (Figure 4). The distinguishable rates of six cases evaluated by eleven subjects (21-30 years old) are shown in Figure 6. From these results, we could find that every cases of DBI tend to improve the distinguishable rate in comparison with the still image (case A). Though case C is the slower version of DBI than case B, they don't have significant difference explicitly and we couldn't obtain the effectiveness of changing speed of DBI. On the other hand, cases D and E show significant difference from case B at the range of $\Delta E_{94} < 0.5$ and they represent advantages totally in comparison with the case A. Namely square wave DBI and small oscillation range of triangular wave DBI are quite effective to enhance the colored edge of the image. In case F, because original reflectance spectra not estimated one is used for DBI, we predicted in advance that case F shows the best performance among DBI results, however it doesn't. We need to consider the appropriateness of the evaluation scheme and more effective parameters of DBI.

Endoscopic diagnosis

As the practical application of DBI, we implement the real-time DBI system for endoscopic diagnosis as shown in Figure 7. Because the DBI has many parameters which need to change simultaneously, it's very hard to determine the best change of parameters by using conventional man-machine interface. Therefore we propose that the best parameters of DBI are determined by using PHANTOM[R] (SensAble technologies) which has six degrees of freedom as the input interface. Six parameters of DBI ($c_i(t), w_i(t) : i = (R, G, B)$) are assigned to the X,Y,Z coordinate and roll, yaw, pitch angles of PHANTOM's stylus. The medical doctor can seek the best changing way of the six parameters in real-time with displaying the endoscopic image. An example change determined by a medical doctor who is the young specialist for the endoscopic diagnosis for the slight cancer on the mucous membrane of the stomach is shown in Figure 8 and an example endoscopic image used for this evaluation is shown in Figure 7. After the evaluation of the DBI by the medical doctor, he told that the DBI is an effective method to enhance the image for medical diagnosis and the interface is very useful to determine many parameters at the same time.

Conclusions

In this study, we propose a new image enhancement technique named Dynamic Band Imaging (DBI) for the endoscopic diagnosis. In order to analyze the fundamental effectiveness of the DBI, we performed some subjective experimentation with various cases of parameters of the DBI. From these results, we found that DBI presents the tendency to improve for distinguishing two skin colors which have slight difference of reflectance spectra, in comparison with the still image evaluation. Particularly square wave change of DBI and small changing range of the DBI show significant effectiveness among some cases of the DBI.

Because the parameters variation of DBI can be designed freely, we need to analyze the effectiveness by accumulating the fundamental experimentations and need to find more significant parameters by evaluating many practical medical images.

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