Multiplex Image Projection using Multi-Band Projectors

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Abstract

In this paper, we propose a novel image representation method by using multi-band projectors. In this image representation method, each observer, such as human, camera and other sensors, can perceive different images from each other, even if the image projected from the projector is identical. For this objective, we encode multiple images into a single image by using the difference of spectral sensitivity of each observer, and project it by using the multi-band projector. The projected image is decoded by observers, such as human retina and CCD sensor, as different images based on their spectral sensitivity. The experimental results show the effectiveness of the new image representation method.

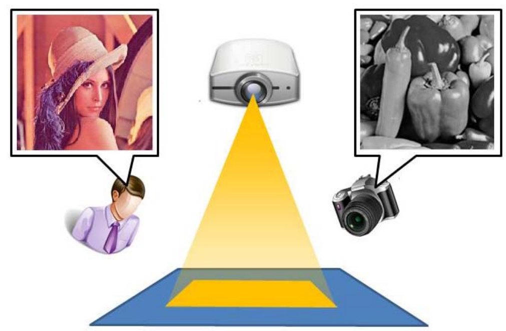


Figure 1. Multiplex image projection: Observers observe different images based on their spectral sensitivities.

1. INTRODUCTION

The color information is important for object recognition and representation, and is widely studied in the field of computer vision. In particular, the multi-band imaging gets more attention in recent years[3, 9, 4, 2, 7, 6, 5]. The 3-band cameras, such as RGB cameras, are widely used for obtaining color information of objects. However, the 3-band cameras compress various components, such as spectrum of light source, spectral reflectance of object and spectral sensitivity of cameras, into just 3 values, and the derived images are often not sufficient for obtaining the spectral properties of objects and light sources. To cope with this problem, multi-band cameras were considered in recent years [9, 6, 10, 4]. Since the multi-band cameras have more than 3 sensors, they can obtain much more information on color spectrum. Park et al. [6] proposed a method for obtaining spectral reflectance of objects by using multiple spectral light sources and multispectral cameras. Yasuma et al. [10] proposed a method for capturing multispectral images by using assorted filters.

On the other hand, multi-band displaying is not so widely studied as multi-band imaging. This is because displaying devices exist for human retina, and the number of bands in human retina is limited, i.e. 3 bands. However, if we can control the whole light spectrum of displaying by using multi-band displaying devices, we have various possibilities of embedding information into the light spectrum. In this paper, we build a multi-band projector, and propose a method for embedding information into the light spectrum. In particular, we propose *multiplex image projection* based on multi-band projectors. The multiplex image projection enables us to embed multiple different images into a single multi-band image by using the multi-band projector. The image is observed as different images by different sensors, such as human retinas and cameras, as shown in Fig.1. Similar techniques, such as INFITEC[1], are used for 3D-cinema. Although they can represent different images for right and left eyes, we need to wear special glasses in order to observe different images. In contrast, our method directly uses the difference of spectral sensitivities of sensors such as camera CCD and human retina. Thus, we do not need to use any glasses to observe multiplex images.

By using our method, we can present different information to different people and cameras. This is similar to the existing image encoding and decoding techniques, but the big difference is that our method does not require any computation for decoding images. This is because the sensors themselves, e.g. human retina, become the decoder. We in this paper show how to synthesize a multi-band image from multiple images for the multiplex image projection.

2. METAMERISM

2.1. Metameric colors

We first consider the relationship among light spectrum, observed signals and spectral sensitivity of observers. In general, ordinary sensors, such as human retina and CCD, cannot observe the whole spectrum of light. The sensors just observe a limited number of signals by using a limited number of receivers. The combinations of the observed signals are recognized as colors. For example, a human retina has 3 kinds of receiver, $\bar{x}(\lambda)$, $\bar{y}(\lambda)$ and $\bar{z}(\lambda)$, and each receiver encodes the spectrum of light $E(\lambda)$ into X, Y and Z as follows:

$$X = K \int_{400}^{700} E(\lambda)\bar{x}(\lambda)d\lambda \quad (1)$$

$$Y = K \int_{400}^{700} E(\lambda)\bar{y}(\lambda)d\lambda \quad (2)$$

$$Z = K \int_{400}^{700} E(\lambda)\bar{z}(\lambda)d\lambda \quad (3)$$

where K is a constant for normalization. As a result, we recognize lights, which have the same encoded values X, Y and Z, as the same color, even if their spectra $E(\lambda)$ are different to each other. This is because the degree of freedom (DoF) of observed signals is much lower than the DoF of light spectrum. This property is called as *metamerism* and such colors are called as *metameric colors*.

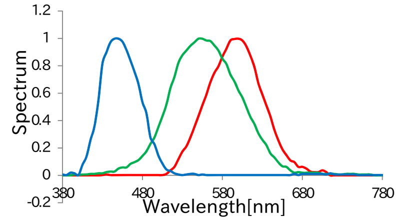
2.2. Multiplex image embedding

Equations from (1) to (3) indicate that there are a lot of metameric colors for each color because the DoF of light spectrum is much higher than the DoF of receivers. As a result, a pair of metameric colors for a certain observer may not be metameric for different observers. Thus, we can embed various information into the light, if we can control the whole spectrum of light. For example, we can emit a special light which is recognized as red by an observer, while it is recognized as blue by the other observer. Thus, we can represent different images to different observers.

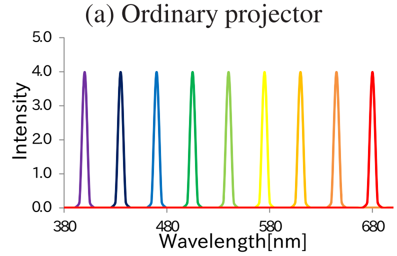
However, the existing displaying devices, such as projectors, cannot control the whole spectrum of light, since they represent colors by combining few kinds of colors, such as red, green and blue. In this research, we build a multi-band projector in order to achieve information embedding. By using the multi-band projector, we achieve the projection of image, which is observed as different images by different observers. We call it as *multiplex image projection*.

3. MULTI-BAND PROJECTORS

In order to achieve multiplex image projection, we construct a prototype of multi-band projector. By using the multi-band projector, we can control light spectrum more flexibly, because it has much more color channels to represent colors, and thus, its DoF of light spectrum is higher than that of the ordinary projectors.



(a) Ordinary projector



(b) Multi-band projector

Figure 2. Light spectrum of ordinary and multi-band projectors

Figure 2 shows the example of light spectrum of an ordinary projector and a multi-band projector. Each projector represents colors by the combination of each band lights. In Fig.2, the ordinary projector can emit three wide-band lights, while the multi-band projector can emit nine narrow-band lights. Therefore, the DoF of light spectrum emitted from the multi-band projector is much higher than that of the ordinary projector.

4. MULTIPLEX IMAGE ENCODING/DECODING

By using the multi-band projector, we encode multiple images into a single multi-band image. In this section, we first explain decoding of multi-band images, and then explain encoding of multiple images.

4.1. Image decoding

Image decoding can be done just by observing images by sensors, which have different spectral sensitivities. Now let us consider the projection from an N-band projector. Let $E_i(\lambda)$ and b_i $(i = 1, 2, \cdots, N)$ be the light spectrum and the intensity of i-th band respectively. Suppose the projected light is observed by M different sensors. When $x_j(\lambda)$ represents spectral sensitivity of j-th sensor $(j = 1, \cdots, M)$, the observed signal X_j of the j-th sensor can be described as follows:

$$X_j = \sum_{i=1}^{N} \int b_i E_i(\lambda) x_i(\lambda) d\lambda. \quad (4)$$

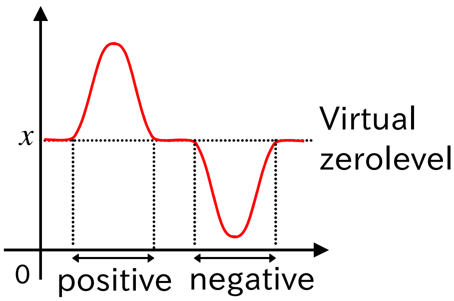


Figure 3. Virtual negative intensities.

Let C_{ji} be an observed signal when $b_i = 1$ in Eq.(4) as follows:

$$C_{ji} = \int E_i(\lambda)x_i(\lambda)d\lambda. \tag{5}$$

Then, Eq.(4) is rewritten by using C_{ji} as follows:

$$X_j = \sum_{i=1}^{N} C_{ji}b_i \tag{6}$$

From these equations, the relationship between the intensity b_i of each band and the observed signal X_j of each sensor can be described as follows:

$$\begin{bmatrix} X_1 \\ X_2 \\ \vdots \\ X_M \end{bmatrix} = \begin{bmatrix} C_{11} & C_{12} & \cdots & C_{1N} \\ C_{21} & C_{22} & \cdots & C_{2N} \\ \vdots & \vdots & \ddots & \vdots \\ C_{M1} & C_{M2} & \cdots & C_{MN} \end{bmatrix} \begin{bmatrix} b_1 \\ b_2 \\ \vdots \\ b_N \end{bmatrix} \tag{7}$$

In this equation, the matrix in the right term is called as spectral sensitivity matrix in this paper. The equation (7) indicates that we can control observed signals X_j by changing the projection intensities b_i of the N-band projector.

4.2. Multiplex image encoding

We next consider the encoding of multiple images into a single multi-band image. In order to achieve multiplex image encoding, we solve Eq.(7) and obtain projection intensities b_i from objective (observed) signals X_j and the spectral sensitivity matrix C_{ji}. The equation (7) has one or more than one solutions, if $N \geq M$. However, the solution b_i includes negative values in general. Unfortunately, we cannot project negative intensities from projectors, and thus, we have to avoid this problem. For this objective, we use virtual negative intensities, where the values lower than a virtual zero level x are regarded as negative intensities as shown in Fig.3.

Although we can avoid negative intensity problem by using the virtual negative projection, this virtual projection reduces image contrast, since real lowest (zero level) intensity becomes higher than usual. In order to relax the effect, we next derive optimum virtual zero level.

Let us consider the case, where there exist a 6-band projector and two sets of sensors, each of which consists of three sensors. Let $\mathbf{b} = [b_1, b_2, \cdots, b_6]^\top$ denote projection intensity and $\mathbf{C}_1$ and $\mathbf{C}_2$ denote spectral sensitivity matrices of each sensor set. Then, observed signals $\mathbf{X}$ and $\mathbf{Y}$ of each sensor set can be described as follows:

$$\mathbf{X} = \mathbf{C}_1\mathbf{b} \qquad \mathbf{Y} = \mathbf{C}_2\mathbf{b} \tag{8}$$

In virtual negative projection, we consider the following observed signals $\mathbf{X}'$ and $\mathbf{Y}'$ instead of the original observed signals $\mathbf{X}$ and $\mathbf{Y}$:

$$\mathbf{X}' = \alpha\mathbf{X} + m\mathbf{1} \qquad \mathbf{Y}' = \beta\mathbf{Y} + n\mathbf{1}, \tag{9}$$

where α and β are scaling coefficients, m and n are virtual zero levels and $\mathbf{1}$ is a vector whose components are equal to 1. Then, the relationship between a projection intensity $\mathbf{b}'$ based on the virtual negative projection and the original observed signals $\mathbf{X}$ and $\mathbf{Y}$ can be described as follows:

$$\begin{bmatrix} \alpha\mathbf{X} + m\mathbf{1} \\ \beta\mathbf{Y} + n\mathbf{1} \end{bmatrix} = \begin{bmatrix} \mathbf{C_1} \\ \mathbf{C_2} \end{bmatrix} \mathbf{b}' \tag{10}$$

Therefore, the projection intensity $\mathbf{b}'$ can be estimated by solving Eq.(10) linearly, if α, β, m and m are fixed. Thus, we next estimate the optimal α, β, m and m.

In order to project positive intensities, $\mathbf{b}'$ must not include negative values. Thus, we define penalty N_{all} for negative values. Let $\mathbf{b}'_j$ denotes projection intensity to j-th pixel, and let b'_{ji} be i-th component of $\mathbf{b}'_j$. Then, the sum of negative values for j-th pixel can be described as follows:

$$N_j = \sum_{i=1} b'_{ji}\zeta(b'_{ji}) \tag{11}$$

where $\zeta(x)$ is a function, which takes 0 if $x \geq 0$ and takes 1 if $x < 0$. Then, the penalty for all pixels N_{all} is defined as follows:

$$N_{all} = \sum_j N_j \tag{12}$$

In order to achieve positive intensity projection, we should suppress the penalty N_{all}.

We next maximize the contrast of projected images. The image contrast R_1 and R_2 of the observed image signals $\mathbf{X}'$ and $\mathbf{Y}'$ are computed as follows:

$$R_1 = \frac{\alpha I_{max} + m}{m} \qquad R_2 = \frac{\beta I_{max} + n}{n} \tag{13}$$

where I_{max} is the maximum projected value. In order to increase the visibility of projected images, we should raise the contrasts, R_1 and R_2.

In the end, we define a cost E from the negative penalty N_{all} and the contrasts R_1, R_2 as follows:

$$E = w_1(R_1 + R_2) - w_2 N_{all} \tag{14}$$

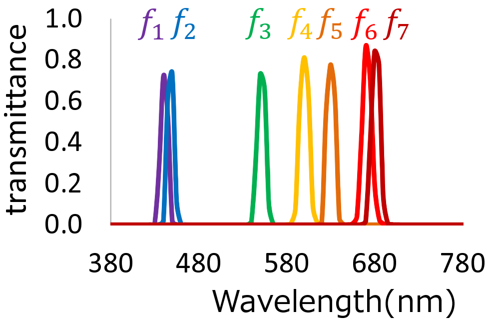
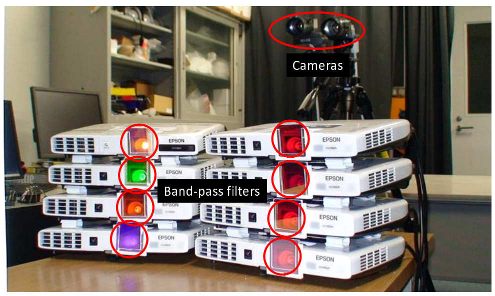
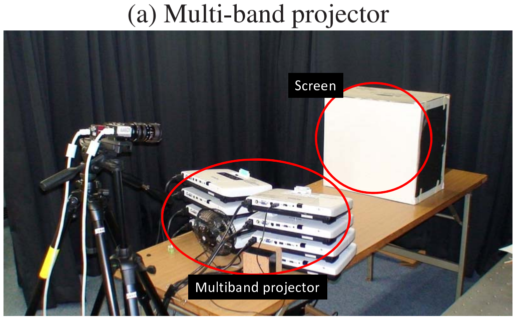


Figure 4. Light spectrum of a multi-band projector.



(a) Multi-band projector



(b) Experimental environment

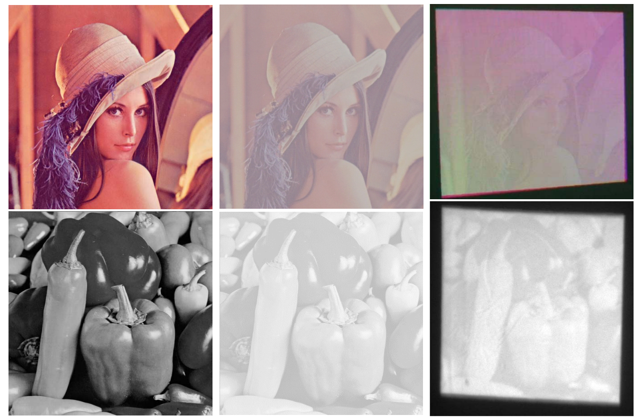
Figure 5. Multi-band projector constructed from 7 projectors and 7 band-pass filters, and experimental environment.

where w_i is weight for each term. The values α, β, m and n which maximize E provide us better image correction, and they can be estimated by non-linear optimization. By using the image correction, we can project multiplex images without negative projection from multi-band projectors.

5. EXPERIMENTAL RESULTS

5.1. Prototype of multi-band projector

In this section, we show the results of multiplex image projection proposed in this paper. In these experiments, we built and used a five-band projector. In order to compose a five-band projector, we used 7 projectors as shown in Fig.5 (a). The original color filters of these projectors were removed, and 7 different band-pass filters were equipped to these projectors as shown in Fig.5 (a). The light spectra of these five bands, f_i $(i = 1, \cdots, 7)$, are shown in Fig.4. These projectors were calibrated geometrically by using homography, so that the 7 projected images overlap properly on the screen as shown in Fig.5 (b). By using the set of these projectors, we project multiplex images as multi-band images.



(a) Objective images (b) Corrected images (c) Observed images

Figure 6. Result of multiplex projections: (a) Objective images, (b) corrected images and (c) observed images for human (upper row) and gray-scale camera (lower row).

(a) f_1 (b) f_3 (c) f_5 (d) f_7

Figure 7. Multi-band images for multiplex projection.

5.2. Multiplex image projection for human and gray-scale camera

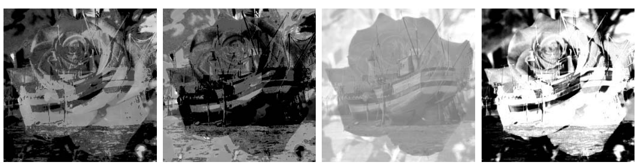
We first project multiplex images for a human retina and a gray-scale camera. In this experiment, a three-band (color) image for the human retina and a single band image for the gray-scale camera were encoded into a multi-band image. Thus, we used 4 bands, f_1, f_3, f_5 and f_7, in the multi-band projector. The spectral sensitivity of the human retina is modeled by the CIE standard observer color matching functions [8]. We used Allied Vision Tech Guppy-146 B Firewire Camera as a gray-scale camera, and its spectral sensitivity is obtained from the specification data of this camera.

The upper and the lower images in Fig.6 (a) show the objective images for human and gray-scale camera respectively, and Fig.6 (b) show objective images corrected by Eq.(14). The cost function Eq.(14) was minimized by simulated annealing algorithm.

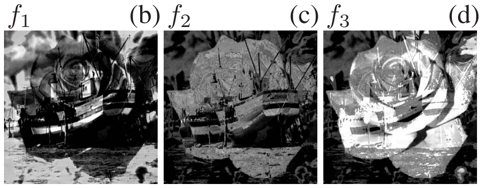
From these objective image signals, we computed multi-band images, i.e. projection intensities, for the multi-band

(a) Objective images (b) Corrected images (c) Observed images

Figure 8. Result of multiplex projections: (a) Objective images, (b) corrected images and (c) observed images for a color camera (upper row) and a gray-scale camera (lower row).

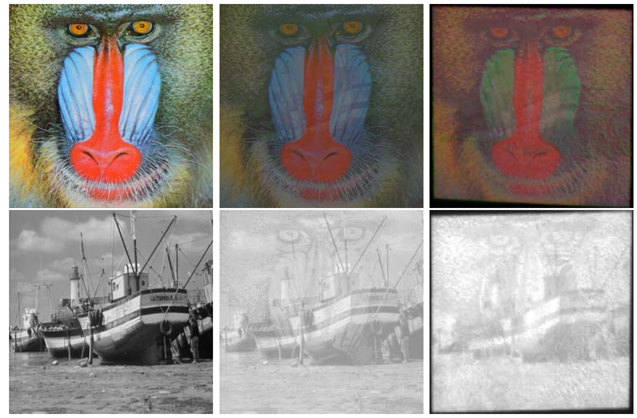


(a) f_1 (b) f_2 (c) f_3 (d) f_4



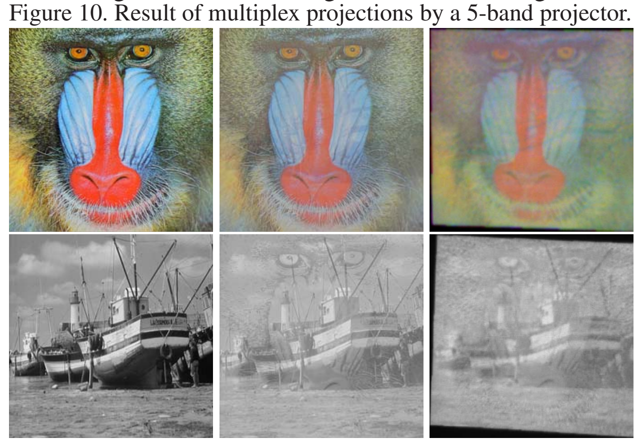
(e) f_5 (e) f_6 (e) f_7

Figure 9. Multi-band images for multiplex projection.



(a) Objective images (b) Corrected images (c) Observed images

Figure 10. Result of multiplex projections by a 5-band projector.



(a) Objective images (b) Corrected images (c) Observed images

Figure 11. Result of multiplex projections by a 7-band projector.

projector. The derived multi-band images are shown in Fig. 7. Then, these images were projected by the multi-band projector and observed by human and a gray-scale camera. Fig.6 (c) show images observed by human and a gray-scale camera. Note, since we cannot represent images observed by human, the human observed image in upper row was taken by a color camera, whose spectral sensitivity is close to human. The actual image observed by human was very close to this image. From these results, we find that the image observed by human and the image observed by a gray-scale camera are completely different. Furthermore, observed images are close to the objective images. These results indicates that the proposed method can achieve multiplex image projection by using multi-band projectors.

Figure 7 shows projected multi-band image of f_1, f_3, f_5 and f_7 bands. The image of f_7 is particularly interesting. We find that it includes the negative image for human and the positive image for camera. The spectral sensitivity of human is very low in this band, and that of the gray-scale camera is not low. Thus, this band is used for removing the human observed image by virtual negative intensity and adding the camera observed image for camera observation.

5.3. Multiplex image projection for color and gray-scale cameras

We next show results for a color (3 band) camera and a gray-scale camera. In this experiment, we used all the 7 bands in multi-band projector. We used FireDragon CSFX36CC3-B of Toshiba Teli as a color camera. The gray-scale camera is the same as before. Figure 8 shows the result of multiplex projection, and Fig. 9 shows projected multi-band images. As shown in Fig.8 (c), the observed images of these cameras are completely different from each other.

Figure 10 and 11 show difference between results from a 5-band projector and results from a 7-band projector. As shown in Fig.10(c), colors of observed images are rather different from those of objective images because representing ability of the 5-band projector is not sufficient for multiplex image projection. In contrast, results from 7-band projector become better than the results of the 5-band projector

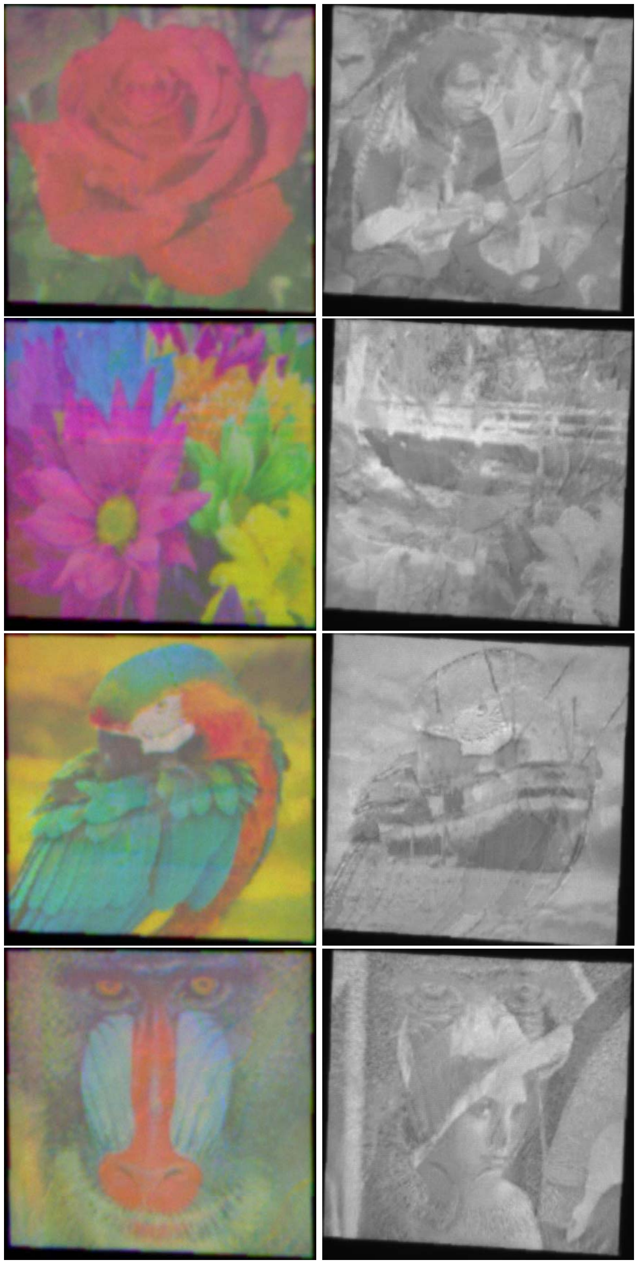


Figure 12. Examples of multiplex projection for a color camera (left) and a gray-scale camera (right).

as shown in Fig.11(c). The fact indicates that we can improve the ability of multiplex image projection by increasing the number of bands in the multi-band projector.

Figure 12 shows some other examples of multiplex projection. In all these results, color and gray-scale cameras observed completely different images. These results indicates that our multiplex projection can represent arbitrary images to arbitrary sensors if the spectral sensitivities are known.

6. CONCLUSIONS

In this paper, we proposed multiplex image projection by using multi-band projectors. The proposed method can represent different images to different observers, such as human and CCD cameras, simultaneously. We explained an encoding method from multiple images to a multi-band image for multiplex projection. The experimental results show that different sensors observe different images by the multiplex image projection. In this paper, we discussed basic theory of multiplex projection. Future works include analysis of detail properties, such as limitation of sensors, optimization of band pass filters and possible applications of multiplex projection. The multiplex image projection can be applied to not only human and camera but also human and human, e.g. left eye and right eye, and any other sensor sets. It opens the possibility of various new applications.

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