Encrypted Image Display based on Individual Visual Characteristics

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Abstract: In this paper, we propose an encoded image displaying system based on light field decoding by human visual systems. We focus on the difference of individual characteristics of the human visual systems, and we indicate that the difference of the characteristics makes a significant difference in the observation results. Based on the observation difference, we achieve image encoding to a light-field which can be decoded by the human who has a particular visual characteristic. To achieve the image encoding system, we construct a 5D light field display system. This 5D LF display controls the spectral distribution of the light rays as well as position and directions. By using the 5D LF display, we utilize the characteristics of the spectral sensitivity and opticalcharacteristics of the human visual system. Several experimental results show that our proposed method can disturb the observation of the general audience and provide appropriate information to a target person.

1 INTRODUCTION

In modern society, confirmation of secure communication using computers is one of the most critical issues to protect privacy, critical information, etc. In general, data servers and computer networks have already had a secure communication system using data encryption, and encryption techniques are studied widely and extensively. For example, critical data on the server are transferred to client computers through the protected networks by data encryption. The transferred data is decrypted on the client computer and the decoded data, i.e. raw data, is displayed to users through the data displaying devices such as video display. This fact indicates that displayed data is easily stolen when malicious persons peek computer display. This peeping cannot be disturbed even if the most secure data servers and networks are utilized.

To protect the direct attack on the displaying data, we need to encrypt the data not only on the computers but also on the displays. However, if the encrypted data is presented on the displays, the users need to decrypt the data by themselves. This decryption is very hard and requires lots of computation, and thus, the convenience of the system becomes extremely decreased. Therefore, if we want to prevent the decreasing of the convenience of the system, the encrypted data on display should be naturally and involuntarily decrypted by only a particular target user.

In our system, we propose an image encryption system using light field displays. In our system, we focus on the individuality of the human visual systems. It is known that human visual systems have a lot of characteristics such as color sensitivity, response speed, etc (Hori et al., 2017; Muramatsu et al., 2016). The characteristics have a difference in a person by person. The fact indicates that all people observe different images even if they observe the same scene. We focus on the difference of the observation results and propose an image encoding system which can be decoded by only a particular person who has a target visual characteristic.

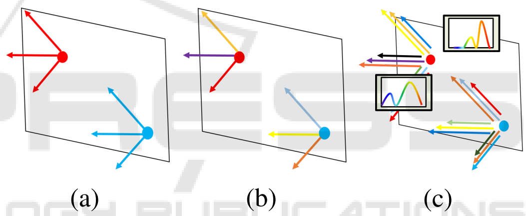

Figure 1: Difference between (a) standard displays, (b) light-field displays and (c) 5D light-field displays.

For this objective, we construct a 5-dimensional light field display that can control not only directions of light rays but also spectral distribution. In general light-field displays can emit different light rays to each direction, as shown in Fig.1(b). By using this property, various systems are proposed(Wetzstein et al., 2011; Hirsch et al., 2014; Hung et al., 2015; Huang et al., 2014), such as 3D display without glasses, vision-correcting displays, and so on. In our system, we also control the spectral distribution of

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each light rays to utilize spectral sensitivities of human visual systems. This display can control the 4-dimensional light field and 1-dimensional spectral distribution, and then we call the display 5D light field display.

By using the display, we propose an image displaying system with encryption by a particular visual characteristic of the human. In this system, special encoded light-field are emitted from the display, and the field is decoded only by a target user. If the other human observes or peeps the display, their visual system cannot decrypt the light field to the original image. Therefore, a secure and involuntary image encoding system can be achieved.

2 RELATED WORKS

Light field display is studied extensively(Wetzstein et al., 2011; Hirsch et al., 2014; Hung et al., 2015; Huang et al., 2014) and utilized for various kinds of image representation. The most representative light field display is an autostereoscopic display. The autostereoscopic display presents different images in the right and left directions. Thus, different images to be observed in the right and left eyes, and it realizes stereoscopic viewing. The light field display has been utilized for visual correcting display without glasses(Huang et al., 2014). In this display, visual characteristics such as myopia and hyperopia are corrected by controlling the light field without using glasses. Furthermore, a method measuring the detailed optical characteristics of human eyes has been proposed(Hori et al., 2017). In this system, observers observe different images according to their characteristics. In this case, the observation results indicate the characteristics of the observer, and thus, we can measure detail characteristics without individual measuring devices.

On the other hand, many methods that focus on the spectral sensitivity of the human visual system have been proposed(Nonoyama et al., 2013; Muramatsu et al., 2016). Nonoyama et al. proposed a technique that presents different images for each observer who has different sensitivities(Nonoyama et al., 2013). In this method, a multiband display which can control spectral distribution pixel by pixel is utilized. Also, a method to measure human spectral sensitivity based on observation results has been proposed(Muramatsu et al., 2016).

Although both of these methods are based on human visual characteristics, both require special image presentation devices and have been independently studied. However, since these multiple factors are included in a human visual system, more various applications can be expected if these characteristics can be used simultaneously. In this paper, we propose an encrypted image presentation system based on optical characteristics as well as spectral sensitivities. Furthermore, we construct a 5D light field display to achieve the abovementioned displaying system. The 5D light field display built for this purpose can be expected to be applied to a broader range of information presentation technologies in addition to the encrypted image presentation proposed in this paper.

3 HUMAN VISUAL SYSTEMS

In this section, we describe the characteristics of human visual systems that are utilized in our system. As described in **1**, human visual systems have several kinds of characteristics, such as color sensitivity, response time, and so on. Besides, these characteristics have individuality, and then, the characteristics are different in person by person. In our system, we focus on the differences of the characteristics. Based on the differences of the characteristics, we propose an image encryption method to a light-field which can be decoded by only a particular user who has a target visual characteristics. Especially, we utilize the individuality of spectral sensitivity and optical aberration of human eyes, and we describe the details of the characteristics in this section.

3.1 Spectral Sensitivities

We first describe the spectral sensitivity of the human visual system. In our eyes, light-rays from the target objects pass through the pupil, and light-sensitive cells, which are called cone cells, receive the light rays. The cells emit stimulus depending on the input light rays.

There are three kinds of cone cells, which are L, M, and S cells. Each cell have different spectral sensitivity $x(\lambda)$, and the cells emit a stimulus which depends on their sensitivity and spectral distribution of the received light as follows:

$$S_a = K \int E(\lambda) x_a(\lambda) d\lambda, \qquad (1)$$

where a indicates a kind of cell, λ is a wavelength of the light, $E(\lambda)$ is the spectral distribution of the input light, and K is a coefficient for the normalization. In this case, the observed color is determined by a combination of these stimulus S_a. Therefore, the observer observes the same color when the combination of S_a is the same even if the light spectral E is different.

Inversely, even if the light rays which have the same spectral distribution E are provided to the observers, they observe different colors if the combination of S_a is different. These observation differences often occur because spectral sensitivity x is different in person by person. Based on these differences of sensitivity, we encrypt the image to the light field.

3.2 Optical Characteristics

We next, consider the optical characteristics of the eyes. We have lenses in our eyes, and these lenses converge the light ray to our retina. If the lens has an ideal shape to converge the light rays, perfect images can be projected to the retina. However, the lenses have various forms. That is, the lens has individuality, and thus, the conversion result of the light rays becomes a different person by person.

The most critical parameter of the lens is the focal length. By using the focal length f, the refractive power D of a lens is represented as follows:

$$D = \frac{1}{f} \tag{2}$$

Although the D represents an essential characteristic of the lens, other several parameters are required to describe the whole characteristics such as optical aberration. As mentioned above, a general lens shape includes distortion, and the distortion causes the optical aberration. The aberration producesinaccurate converging of light rays. The aberration is also included in the lens of eyes. We use the parameters of the aberration as the individuality of the lens. We utilize Zernike polynomials(von F. Zernike, 1934) to represent the aberrations by a few parameters.

Let $W(x,y)$ denote optical aberration at point (x,y) on the lens. The aberration $W(x,y)$ is represented by Zernike bases $Z_n^m(\rho,\theta)$ as follows:

$$W(x,y) = \sum_{n=0}^{k} \sum_{m=-n}^{n} C_n^m Z_n^m(\rho,\theta) \tag{3}$$

where C_n^m denote Zernike coefficients, and they represent the optical aberration of the lens. The parameters (ρ,θ) satisfy $x = \rho\cos\theta, y = \rho\sin(\theta)$. The Zernike bases are computed as follows:

$$Z_n^m(\rho,\theta) = \sum_{s=0}^{\frac{n-m}{2}} \left(\frac{(-1)^s (n-s)! \rho^{n-2s}}{s!(\frac{n+m}{2}-s)!(\frac{n-m}{2}-s)!} \right) \cdot \begin{cases} \cos|m|\theta & (m \geq 0) \\ \sin|m|\theta & (m < 0) \end{cases} \tag{4}$$

The bases are shown in Fig.2. By using the Zernike bases, the individuality of the lens is described by Zernike coefficients C_n^m. In this paper, we describe the set of these coefficients by $\mathbf{W}$.

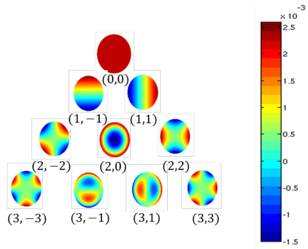

Figure 2: Zernike bases: numbers below each images indicates n and m.

4 OBSERVATION OF THE LIGHT FIELD

4.1 Light Field

We consider the observation of the light field. We first describe a summary of the light field. In the real 3D scene, many and various light rays are flying. The light field represents the status of the light rays in the scene. The 4D light field is a partial representation of the plenoptic function(Adelson and Bergen, 1991), which represents the complete status of the light rays in the scene.

In the light field representation, we attent to a plane in the scene to describe light rays because light rays fly straightforward in the scene. When the light ray passes through the point (x,y) and it directs to (u,v), this light ray is regarded as a point (x,y,u,v) in the 4D light field. Let $L(x,y,u,v)$ denote intensity of a light ray at point (x,y,u,v) in the 4D light field.

Cameras converge the light rays by lens and project to a 2D image. This light ray converging can be regarded as partial integration of the 4D light field. The 4D light field display emits the light field to the scene from displaying a plane.In this section, we consider the observation of the light field.

4.2 Light Field Observation based on Ray Tracing

We consider light field observation based on ray tracing. In this discussion, we consider not 4D light field consisted by (x,y,u,v), but 2D light field consisted by (x,u) to simplify the description.

Let us consider the case when a light ray is emitted from a point x_1 on display direct to u_1 as shown in Fig.3. In this case, the light ray reaches a point x_2 by the transformation of the light field as follows:

$$\begin{bmatrix} x_2 \\ u_2 \end{bmatrix} = \begin{bmatrix} 1 & a \\ 0 & 1 \end{bmatrix} \begin{bmatrix} x_1 \\ u_1 \end{bmatrix} \tag{5}$$

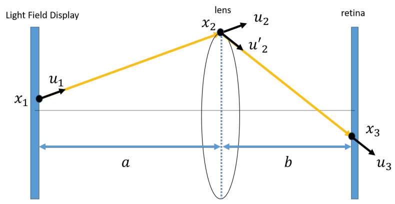

Figure 3: Ray tracing from light field display to observer.

Furthermore, the light ray is refracted by a lens as follows:

$$\begin{bmatrix} x_2 \\ u'_2 \end{bmatrix} = \begin{bmatrix} 1 & 0 \\ -\frac{1}{f} & 1 \end{bmatrix} \begin{bmatrix} x_2 \\ u_2 \end{bmatrix} \tag{6}$$

where f denotes a focal length of the lens. The light ray finally reaches to a point x_3 on a retina as follows:

$$\begin{bmatrix} x_3 \\ u_3 \end{bmatrix} = \begin{bmatrix} 1 & b \\ 0 & 1 \end{bmatrix} \begin{bmatrix} x_2 \\ u'_2 \end{bmatrix} \tag{7}$$

This transformation is integrated as follows:

$$\begin{bmatrix} x_3 \\ u_3 \end{bmatrix} = \begin{bmatrix} 1 & b \\ 0 & 1 \end{bmatrix} \begin{bmatrix} 1 & 0 \\ -\frac{1}{f} & 1 \end{bmatrix} \begin{bmatrix} 1 & a \\ 0 & 1 \end{bmatrix} \begin{bmatrix} x_1 \\ u_1 \end{bmatrix} \tag{8}$$

By using the transformation of the light field, observation of the light field can be described in an ideal case. However, the general lens shape is distorted from the ideal shape, and thus, we need to consider optical aberration caused by the distortion.

4.3 Light Ray Distortion by Optical Aberration

Let us consider the case when the light ray does not reach to ideal point (x,y), but $(x',y') = (x+\Delta x, y+\Delta y)$ by optical aberration through the point (X,Y) on the lens as shown in Fig.4. In this case, the difference $(\Delta x, \Delta y)$ is computed as follows:

$$\begin{bmatrix} \Delta x \\ \Delta y \end{bmatrix} = \begin{bmatrix} \frac{R}{n} \cdot \frac{\partial W(X,Y)}{\partial x} \\ \frac{R}{n} \cdot \frac{\partial W(X,Y)}{\partial y} \end{bmatrix} \tag{9}$$

where n denotes refractive index and R denotes distance from a point (X,Y) to (x,y). Under the assumption optical aberration W is known, $(\Delta x, \Delta y)$ is computed. Thus, we achieve a light ray tracing by computation of ideal point (x, y) from light field transformation and $(\Delta x, \Delta y)$ from optical aberration.

4.4 Light Transport Matrix

As described in the previous section, light rays tracing from a display to the observer is achieved. Based on the ray tracing, we next consider image transformation from a 4D light field to a 2D observed image. Let $L(x,y,u,v)$ denote intensity of a light ray from a pixel (x,y) to a direction (u,v). When an observer who has optical aberration $\mathbf{W}$ receives the light ray at pixel (x_r,y_r), we define the light transport matrix $T(x,y,u,v,x_r,y_r,\mathbf{W})$ as follows:

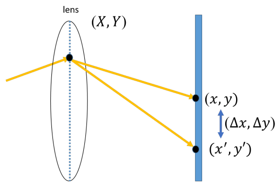

Figure 4: Optical aberration by lens distortion.

$$T(x,y,u,v,x_r,y_r,\mathbf{W}) = \begin{cases} 1 & \text{if } L(x,y,u,v) \text{ reaches to } (x_r,y_r) \\ 0 & \text{otherwise} \end{cases} \tag{10}$$

By using the light transport matrix, observed image I is computed as follows:

$$I(x_r,y_r) = \sum_{x,y,u,v} T(x,y,u,v,x_r,y_r,\mathbf{W}) L(x,y,u,v) \tag{11}$$

By this computation, observation of a light field by an observer can be described linearly.

5 5D LIGHT-FIELD DISPLAY

In order to utilize the visual characteristics mentioned above, we construct a 5-dimensional light-field display which can control the spectral distribution of the light rays. In this section, we show the detail of the construction of the display.

5.1 Multiband Display

We first show the construction of multiband display, which can control light spectral distribution on 2D image pixel by pixel. In this display, we construct a multiband projector and project the multiband image from the backside of the screen, as shown in Fig.5.

In this system, several projectors which equip different optical narrow band-pass filter, as shown in Fig.6, are utilized. By combining each bandwidth images, we construct a multiband projector. By projecting the multiband image from the backside of the screen, the multiband image is scattered by the screen. Thus, we achieve the construction of a 2D multiband display.

5.2 5D Light Field Display

We next describe the construction of the 5D light field display utilizing the multiband display. In standard 4D light field display, lens array or barrier structure is utilized to emit a light ray in a particular direction. In

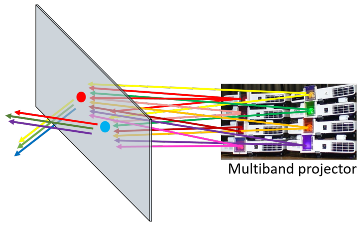

Figure 5: 2D Multiband display by rear projection of a multiband projector.

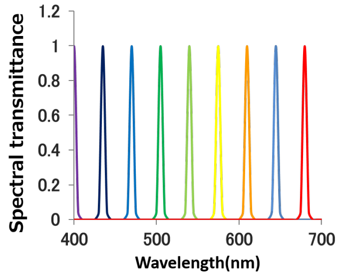

Figure 6: Examples of spectral transmittance of narrow bandpass filters equipped on a multiband projector.

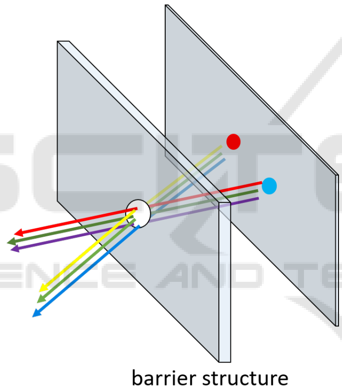

Figure 7: 5D light field display using multiband display and barrier structure.

our system, we use the barrier including a lot of holes is set in front of the multiband display, as shown in Fig.7

In this system, The barrier structure, which has many holes, is set in front of the multiband display, as shown in the figure. In this case, only light rays emitted from a particular pixel to a specific direction pass through the hole, and the other rays are disturbed by the barrier. As a result, the hole virtually emits different light rays in each direction. Besides, the spectral distribution of the rays is controlled since the multiband display emits the rays. Finally, we achieve a 5D light field display that can emit different spectral light rays to each direction from each pixel. By using the constructed 5D light field display, we next consider image encoding to the light field, which can be decoded by only a specific visual characteristic.

6 LIGHT FIELD SYNTHESIS FOR IMAGE ENCRYPTION

6.1 Observation of 5D Light Field

For considering the image encoding method, we define a 5D light field observation model based on visual characteristics.

First, we consider the spectral property of the observation. This observation can be written in linear equations because the light spectral distribution of the light rays in our system is a linear combination of the narrow-band projectors. We consider the case when the light field displays consist of N projectors, and $E_n(\lambda)$ denotes the spectral distribution of each projector. In this case, the stimulus S_a is computed by the spectral sensitivity $x_a(\lambda)$ as follows:

$$\begin{aligned} S_a &= \sum_{n=1}^{N} l_n \int E_n(\lambda) x_a(\lambda) d\lambda \\ &= \sum_{n=1}^{N} l_n c_{na} \end{aligned} \tag{12}$$

where $c_{na} = \int E_n(\lambda)x_a(\lambda)d\lambda$ and l_n is intensity of the emitted light from projector n. As shown in the Eq.(12), stimulation values S_a by multiband display observation are computed by linear equation using sensitivity coefficients c_{na}. We describe the set of sensitivity coefficients by $\mathbf{c}$ in this paper.

Based on the above mentioned linear equation, we consider the observation of a 5D light field. Let $L(x,y,u,v,n)$ denote intensity of a light ray from a pixel (x,y) to a direction (u,v) by a projector n. When the sensitivity of the observer is c_{na}, stimulation values $S_a(x_r,y_r)$ at (x_r,y_r) are computed as follows:

$$S_a(x_r,y_r) = \sum_{x,y,u,v,n} c_{na} T(x,y,u,v,x_r,y_r,\mathbf{W}) L(x,y,u,v,n) \tag{13}$$

where T is a light transport matrix. As indicated in this equation, the observation of the 5D light field emitted by a 5D light field display is represented by linear equations.

6.2 Image Encoding to 5D Light Field by Multiplex Image Displaying

We last consider image encoding to 5D light-field for encrypted image displaying. For this objective, encoded light-field should be satisfied with the following conditions.

- The light-field can be observed as an original image by a target person.

- The light-filed should be decoded to a meanless image when the other audience observes the field.

To satisfy these two conditions, we consider two kinds of image encoding method. In this section, we describe image encoding based on the multiplex image displaying.

In this way, a light-field which are decoded to different two images by a target person and by the other person who has representative visual characteristics are computed. We consider the case when the optical aberration $\mathbf{W}_t$ and sensitivity $\mathbf{c}_t$ for a target person is known, and representative aberration $\mathbf{W}_r$ and sensitivity $\mathbf{c}_r$ is provided. Typically, $\mathbf{W}_r$ represents characteristics of the normal vision and $\mathbf{c}_r$ represents the CIE color space, and we assume that the characteristics are known as similar as the target characteristics.

Let S_t denote observation by the target based on $\mathbf{W}_t$ and $\mathbf{c}_t$, and S_r denote a representative observation based on $\mathbf{W}_r$ and $\mathbf{c}_r$. In this case, we define evaluation value E_m for providing objective image S'_t and S'_r for the target person and representative audience as follows:

$$E_m = \|S'_t - S_t\|^2 + \|S'_r - S_r\|^2 \tag{14}$$

where the light the light-field L composing the observed result S' is limited depending on the property of the projector as follows:

$$0 \leq L \leq L_{max} \tag{15}$$

where L_{max} is the maximum intensity of the display. By minimizing the value E_m in this range, a light-field which provides images S'_t and S'_r to the target and audience is computed. Thus, image encryption, which can be decoded by a target person, is achieved.

In this method, we can easily estimate the light-field by just solving linear equations. However, as mentioned in the introduction, visual characteristics are different in person by person. Therefore, it is not easy to define representative characteristics for this encoding. If a person whose characteristics are far from the defined representative characteristics, observes the light field, we cannot predict what image is observed by this person.

6.3 Image Encoding based on Difference Maximization

We next consider the image encoding method, which uses only the target characteristics. In this method, we focus on the change of observed image when the visual characteristics change. As described in the previous section, observed image change depends on the characteristics of the observer, and then, the observed results change when the characteristics changes. If

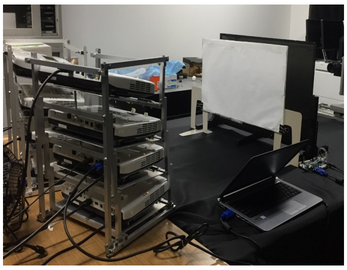

Figure 8: 5D Light field display.

we want to hide the original image by changes in the characteristics, the observed image should be changed drastically by the small change of those characteristics. That is, the derivative of observed image wrt the visual characteristics should be maximized for our image encoding. Therefore, we define an evaluation value E_m for image encoding as follows:

$$E_m = \|S'_t - S_t\|^2 - \|\frac{dS_t}{d\mathbf{W}_t}\|^2 - \|\frac{dS_t}{d\mathbf{c}_t}\|^2 \tag{16}$$

where $\mathbf{c}_t$ is a set of the coefficients for spectral sensitivity. In this minimization, the range of the light-field is also limited by Eq.(15). By minimizing the E_m in this range, the light-field for our image encoding can be estimated. When the target person observes the light-field, the light-field is decoded to the objective image S'_t. In contrast, the result is far from the S'_t when the other audience decodes the light-field.

7 EXPERIMENTAL RESULTS

7.1 Environment

In this section, we show several experimental results in our proposed method. We first describe an experimental environment. In this experiment, we constructed a 5D light field display using four projectors, translucent screen, and an optical barrier, as shown in Fig.8. Each projector equipped a narrow band-pass filter, and thus, each projector project narrow band light. Figure 9 shows spectral distribution of each projector. The projector projected images from the backside of the screen, as shown in Fig.7 and the screen scattered the light in any directions. A transparent LCD was utilized for the barrier structure, and the display showed many holes in a black screen. The barrier set in front of the screen, and it blocked unnecessary light rays.

As an observer, the camera is set in front of the display. To control the optical characteristics of the lens with reproducibility, we observed the light field by the camera. For obtaining the light field by a single

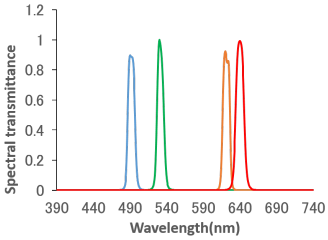

Figure 9: Spectral distribution of each projectors.

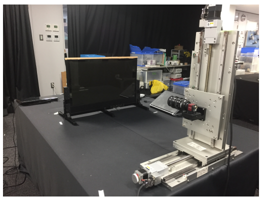

Figure 10: Camera on a moving stage.

camera, the camera was set on the moving stage, as shown in Fig.10, and it observes five images at the center, left, right top and bottom positions.

From the image, two observers who have different visual characteristics are simulated. Observed images by each observer were synthesized by light field rendering technique(Gortler et al., 1986) according to their optical characteristics. They have different focal lengths, and the image synthesis reproduces it. A color temperature conversion filter represents the difference in spectral sensitivity. In observation by a target person (i), the standard image was obtained without the filter. The filter was equipped in a case when the other audience (ii) observed the display.

7.2 Results

Let us show the experimental results by our proposed method. Figure 11 shows observation results by using multiplex image displaying described in **6.2**. In this technique, objective images (a) and (b) are utilized for a target (i) and the other audience (ii). They observed images (c) and (d), respectively. As shown in this figure, (i) and (ii) observed different images that are similar to their objective images. The results indicate that our proposed method can present different images based on their visual characteristics, that is, image encryption based on the characteristics can be achieved.

Figure12 shows image observation results when difference maximization described in **6.3** is utilized. In this figure, (a) shows an objective image, (b) shows an observed result by (i), and (c) shows an observed result by (ii). In this figure, (a) and (b) are similar to each other, and it indicates that a 5D light field display presents the appropriate light field. However, (c)

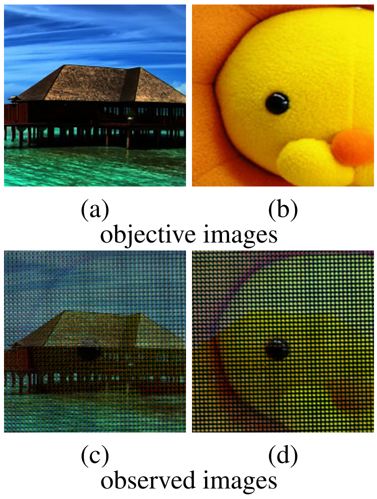

Figure 11: Image encryption based on multiplex image displaying: (a) and (b) shows objective images for a target and the other person, and (c) and (d) shows observed results.

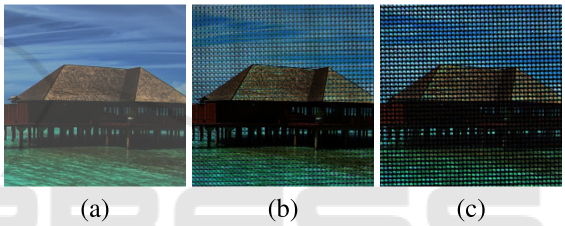

Figure 12: Image encrypting by difference maximization: (a) shows objective image, (b) shows observed result by a target and (c) shows observed result by the other person.

was not different from (b), and the fact indicates that the image encryption is not achieved correctly by difference maximization in this experiment.

We consider that the reason for the results is the resolution of the light field display. In order to achieve image encryption based on difference maximization, it is necessary to project different light for each fine direction. However, resolution for the direction component is rough in our light field display, and then we did not maximize the difference in optical characteristics. In the next section, we show the result using hight resolution light field display in the synthesized environment, and the results will indicate the effectiveness of the difference maximization.

7.3 Evaluation in Synthesized Environment

We next show evaluation results in a synthesized environment for more detailed analysis. In this experiment, the resolution of the light field display was 100 x 100 x 5 x 5, and the display controls the spectral distribution of the light by combining four narrow-

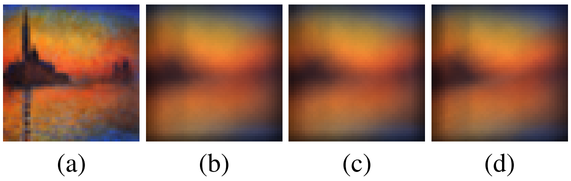

Figure 13: Observation difference by different Zernike coefficients: (a) shows displayed image and (b), (c) and (d) indicates observed result by (i), (ii) and (iii) respectively.

band light. An observed camera set in front of the display observes the light field display. There are three observers, (i) a target, (ii) 2nd target who has representative characteristics and (iii) the other audience whose characteristics are different from both (i) and (ii), and they have different visual characteristics In their optical characteristics, only higher-order four coefficients for Zernike bases are different because low-order characteristics such as focal length will be corrected by using glasses in general. Figure13 shows the observation results of a standard display by their characteristics. As shown in this image, observed images, although the observed images are blurred, the results are similar to each other. These images show higher-order coefficients do not have a significant influence in standard display observation.

We first evaluate the method based on the multiplex image displaying. Figure 14 shows objective images and observed results. In this figure, (a) objective images for a target (i), and (b) image for 2nd target (ii) were utilized for computing the light field. For comparison, results based on only spectral sensitivity and results based on only optical characteristics are shown simultaneously. Three persons observe all light fields, and the results are shown in each column.

As shown in the result (c), (d), and (f), (g), methods utilizing the light field provided different images to the target persons. Besides, the other person observed an entirely different image from both objective images. The results indicate that image encoding using light field is very sensitive to changes in visual characteristics. Therefore, the other audience cannot observe the original image even if their visual characteristics are different from the representative ones. The fact indicates that our proposed method can hide original information when the characteristics of the audience are different from the target.

Figures (i), (j), and (k) show results based on spectral sensitivities. In these results, changes in observed images are not so significant. The reason for the results is the low degree of freedom in controlling spectral distribution. In this experiment, the distribution was controlled by only four combinations of the light. Therefore, they are not enough to change the observed image according to characteristics. The result will

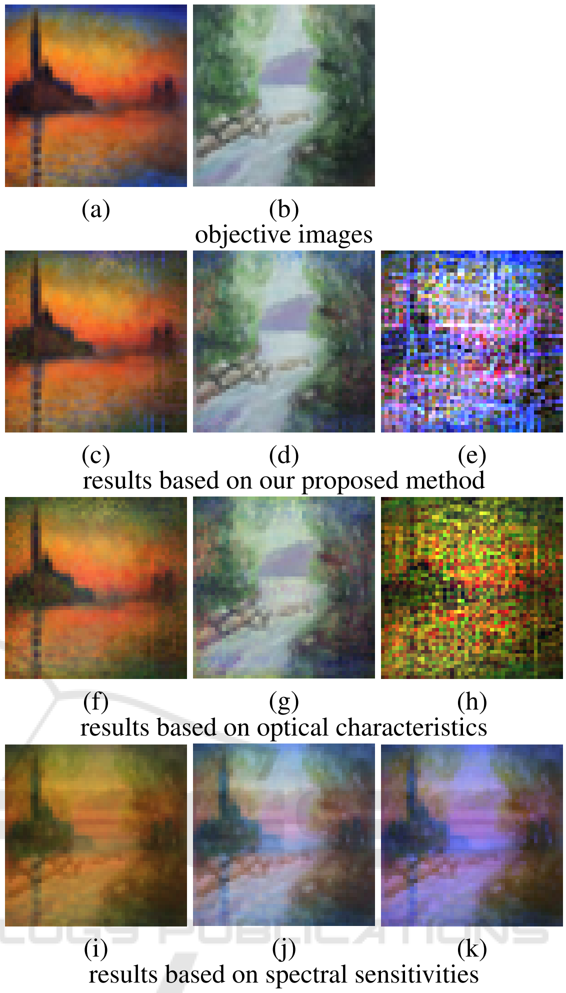

Figure 14: Image encoding results based on the multiplex image displaying: (a), (b) show objective images for a target and the other, (c), (d) (e) show observed result based on the proposed method by a target, 2nd target and the other. Images (f), (g) (h) are based on only optical characteristics, and (i), (j), (k) shows results on only spectral sensitivity.

become better when more detail controlling can be achieved in spectral distribution control.

We next show results based on difference maximization. In this experiment, only a single objective image was used for a target person (i) to synthesis the light field. The light field was observed by three persons, the same as the previous experiment.

Figure15 shows observed results based on different characteristics. In this figure, all methods provide appropriate results for the target person (i) as shown in (c), (f) and (i). However, (ii) and (iii) can read the original information when only spectral sensitivities are utilized as shown in (j) and (k). The fact indicates that the difference of the spectral sensitivities is not enough for hiding the original information. In con-

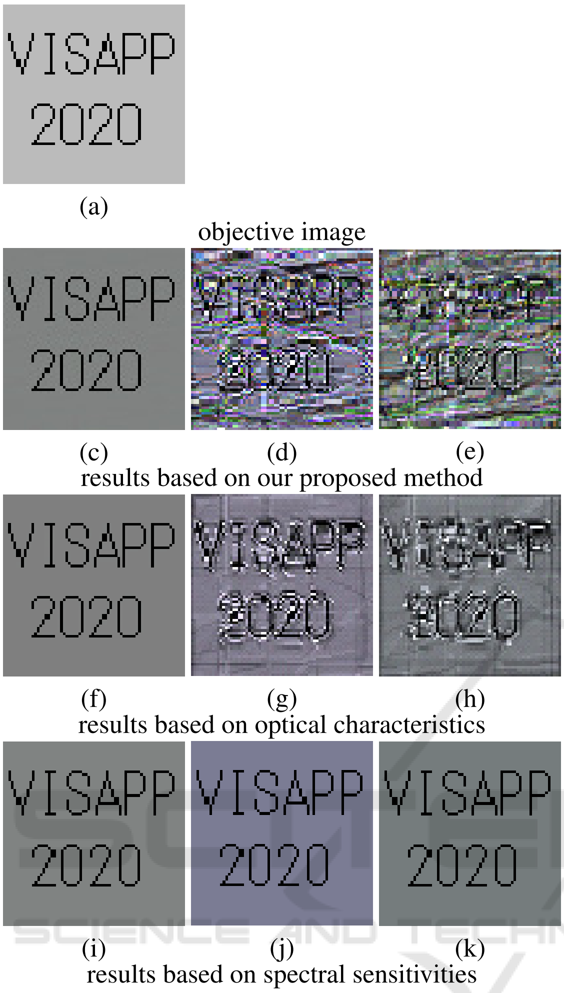

Figure 15: Image encoding results based on the difference maximization: (a) shows objective image for a target, (c), (d) (e) show observed result based on the proposed method by a target, representative and the other. Images (f), (g) (h) are based on only optical characteristics, and (i), (j), (k) shows results on only spectral sensitivity.

trast, the proposed method and the difference in the optical characteristics disturb the reading of the original information by (ii) and (iii). Notably, the proposed method hides the information both (ii) and (iii) sufficiently.

These results indicate that our proposed image encoding method can hide original information from the other observers. Notably, the multiplex image displaying method is much useful to protect the original information.

8 CONCLUSION

In this paper, we propose an image encoding method to the light field for image encryption. In this method, we focus on the difference of the visual characteristics in the human visual system and achieve the image encryption based on the difference. Especially, we focus on optical characteristics on the lens and spectral sensitivities of the human visual system. For utilizing the multiple characteristics effectively, we built a 5D light field display for image encryption. We propose an image encoding method to the 5D light field based on the multiplex image displaying and difference maximization. This image encryption method is more effective since the method requires only individual visual characteristics to decrypt the image.

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