Construction of Autostereograms Taking into Account Object Colors and its Applications for Steganography

Yusuke Tsuda Yonghao Yue Tomoyuki Nishita
The University of Tokyo
{*tsuday,yonghao,nis*}*@nis-lab.is.s.u-tokyo.ac.jp*

Abstract

Information on appearances of three-dimensional objects are transmitted via the Internet, and displaying objects plays an important role in a lot of areas such as movies and video games.

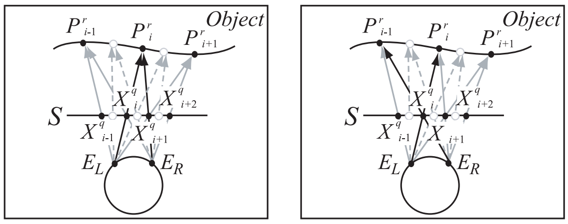
An autostereogram is one of the ways to represent three-dimensional objects taking advantage of binocular parallax, by which depths of objects are perceived. In previous methods, the colors of objects were ignored when constructing autostereogram images. In this paper, we propose a method to construct autostereogram images taking into account color variation of objects, such as shading.

We also propose a technique to embed color information in autostereogram images. Using our technique, autostereogram images shown on a display change, and viewers can enjoy perceiving three-dimensional object and its colors in two stages. Color information is embedded in a monochrome autostereogram image, and colors appear when the correct color table is used. Our technique can also be used for steganography to hide color information. Moreover, file size gets smaller than that of an original autostereogram image because indexed colors are used. Therefore, the 3D images constructed using our method are useful for tranmission through the cyberworld.

1. Introduction

Three-dimensional objects are displayed for many purposes such as research about human vision and representation of virtual objects in movies, and there are a lot of ways to display objects. Depth information is important for three-dimensional impression, and is usually represented by displaying the objects on the screen using perspcetive projection. An autostereogram is one of the ways to represent three-dimensional objects by ordinary display devices taking advantage of binocular parallax which plays an important role in depth perception.

In the previous methods, color autostereogram images have not taken into account the objects' colors. Therefore, we propose an approach to take into account color variation of objects, such as shading. Our approach assign slightly different colors to a pair of points on the screen, which are seen as the same point on the object when performing stereopsis. The images constructed using our method can be used for amusement.



(a) SS-relation (b) OS-relation

Figure 1. Relations on an autostereogram. E_L and E_R indicate left and right eyes, respectively. (a): A pair of points on the screen and a single point on the object correspond with each other. (b): A pair of points on the object and a single point on the screen correspond with each other.

In an autostereogram, a virtual screen S is placed between viewer and the object, and an autostereogram image is constructed by placing points on S. There are two relations to be considered in constructing autostereogram images. Firstly, in performing stereopsis, since viewer sees a pair of points on S with left and right eyes, and perceive them as a single point on the object, these three points correspond with each other (Figure 1(a)). We define the relationship between these three points as a relationship in screen space (*SS-relation*). Secondly, since a single point on S is not only seen by just one eye, but by two eyes, so a single point on S and a pair of points on the object correspond with each other (Figure 1(b)). We define the relationship between such three points as relationship in object space (*OS-relation*). Autostereogram images are constructed taking into account these relations alternately. Because of OS-relation, the color of a single point on S is related to colors of two corresponding points on the object, however is assigned irrelevant to the colors of the points on the object in previous methods.

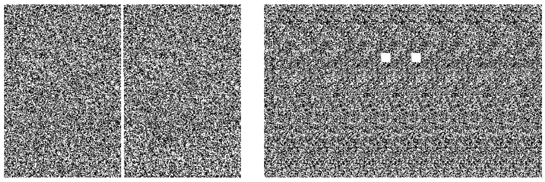
In this paper, we propose a method to determine the color of points on S. Although a pair of points on S has an SS-relation with a point on the object, such points on S also have OS-relations with other points on the object. Therefore, in our method, slightly different colors are assigned to a pair of points on S which have SS-relation. The allowable differences of colors are determined by an user test. We also consider the limitation of representation of colors because it is expected that object colors with wide variety are difficult to be represented in autostereogram images.

We also propose a method to apply color autostereogram images to the amusement of color emergence. Two-stage perceptions of three-dimensional object and its colors are amusing. In the first stage, a sand storm like autostereogram image is displayed. This image has color information in color index, but colors are not displayed because a dummy color table is embedded in. In the second stage, color autostereogram image is displayed by using correct color table. It is amusing that monochrome object and color object can be perceived in two stages. In addition, our technique is a kind of steganography in the sense that the existence of information about object colors are hidden. Color information can be transmitted only to those who should receive color information by taking advantage of our method. Moreover, since indexed colors are used to encode the autostereogram images, file size is reduced from original file size.

The rest of this paper is composed as follows. Related work is described in Section 2. Section 3 reviews previous methods constructing monochrome autostereograms. We describe the algorithm to determine colors of autostereogram images in Section 4. An algorithm to embed color information in autostereogram images, and to construct color tables used as encryption keys is described in Section 5. We show the results in Section 6, and describe conclusion and future work in Section 7.

2. Related work

Wheatstone [14] invented stereoscopes, by which two images drawn or taken from slightly different angles are respectively projected to each eye. David Brewster [1] built stereo cameras, by which two pictures of scenes can be taken. Stereogram images, which consist of a pair of photographs or images are called stereo pair, and view angles of the images can not be wide because it becomes difficult to perform stereopsis when two points on the image, which are to be seen as the same point on the object, are too separated. Gabor [5] invented holography taking advantage of the interference between beams. Holography is a technique to produce a hologram, which is a kind of pho-



(a) (b)

Figure 2. Random Dot Stereograms showing a teapot: (a) a stereo pair, and (b) an autostereogram. Methods to perform stereopsis are explained in Section 3.2.

tograph with three-dimensional information recorded in. Holograms were first created by Denisyuk [4] in 1962, and later by Leith and Upatnieks [8] in 1962. Except for stereo pairs, all the methods discussed above need special devices to record information or to view three-dimensional objects.

Julesz [6] invented Random Dot Stereogram (RDS), which is a technique to construct a pair of images consisting of random dots (Figure 2(a)). Tyler et al. [13] combined a pair of random dot images into a single image, and created Single Image Random Dot Stereogram (SIRDS) (Figure 2(b)). SIRDS is a form of autostereogram or single-image stereogram (SIS), and view angles of autostereogram images can be wide. Kinsman [7] showed a method to create colored autostereograms from a depth map and a pattern image. His method was based on orthogonal projection. In his method, pattern images are distorted according to depth maps and are tiled horizontally, and colors of the objects are out of consideration. In the previous autostereograms, exactly the same color is assigned to a correlated pair of points on the image. This is because, in autostereograms, two or more horizontal points on the image tend to have correlation with each other due to the SS-relation and the OS-relation, and two of the correlated points on the image are thought to be seen as the same point on the object only when they share the same color. Our method improves autostereograms to take into account color variation of objects.

Recently, a lot of methods are researched to improve the performance in the construction of SIRDS. Thimbleby et al. [12] showed an algorithm based on the perspective projection. Yu et al. [15] created a fast and memory saving algorithm based on ray-tracing. Petz et al. [11] introduced an algorithm which is suited for hardware-acceleration and succeeded in constructing SIRDS images at real time.

Applications of stereograms are also searched. Omori et al. [10] analyzed the recognition of stereoscopic images among elderly people using stereogram images on liquid crystal display and papers. Dadson [3] described the tools for evaluation of stereoscopic camera systems using RDS built with ray tracing. Liu et al. [9] developed a system to display trajectories of particles on stereogram images. Stereograms also appear on books for amusement [2].

3. Constructing and viewing autotereograms

In this section, we first review the methods to construct autostereogram images, and then review the viewing method to perform stereopsis.

3.1. Construction of autostereograms

Figure 1(a) is an illustration where a human is looking at an object. In this figure, E_L and E_R indicate human's left and right eyes, respectively, and S is a virtual screen between the human and the object. Information about the object is recorded on S by placing points on S.

Generally, in constructing autostereogram images, calculation is done in each scanline, sequentially. A single scanline is composed of many sequences of points X_i^q (q is the sequence number, and i is the point number in the sequence q). A sequence of points X_i^q is determined as follows. Firstly, the initial point X_0^q on the scanline is selected. X_0^q is normally the first pixel on the left of the scanline. Secondly, the location of P_0^r, where the line of sight from E_L to X_0^q intersects with the object, is calculated. Then X_1^q, which is the intersection point of S and the line of sight from E_R to P_0^r, is calculated. Here, X_0^q and X_1^q correspond to the point P_0^r on the object, and the depth of P_0^r is converted into the distance between X_0^q and X_1^q. We call the relation established between such three points, the *SS-relation*. In the same way, P_1^r, which is the intersection point of the object and the line of sight from E_L to X_1^q is determined, and X_2^q, which is the intersection point of S and the line of sight from E_R to P_1^r is also determined. Here again, X_1^q and X_2^q also have an SS-relation with the point on the object P_1^r. The sequence of points X_i^q is then determined by repeating the same calculation.

In this way, a sequence of points is determined from one initial point, and another sequence of points $X_i^{q'}$ is determined using another initial point $X_0^{q'}$. Note that when a sufficient number of sequences of points are determined, all pixels on the scanline belong to either sequence. By randomly selecting a certain number of initial points and by skipping the process starting from those points, some points on the screen remain blank. At a glance the resulting image looks like random dots (Figure 2(b)), but the depth of the object can be perceived by performing stereopsis. Note that in previous methods, the object colors are not taking into account when plotting the points on the screen.

3.2. Viewing images stereoscopically

In this paper, we indicate a single pair of points on the image by two white squares to help stereopsis (Figures 2, 6, 8, 9 and 10).

For stereopsis, the viewer has his eyes unfocused by gazing blankly at the image or by crossing his eyes. Two squares are seen to be four squares, the two of which are seen from the left eye, and the others are seen from the right eye. By adjusting eyes so that the center two of these four squares are seen at the same position, the eyes are focused on the object in the autostreogram image, and three-dimensional impressions can be perceived. It will be difficult to perform stereopsis for the first time, but it is said that once succeeded, it becomes easy to perform stereopsis.

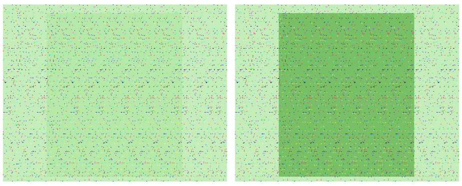
The method by gazing blankly at the image is called *parallel-viewing method*, and the method by having eyes crossed is called *cross-viewing method*. The perceived depth of the objects are reversed depending on the method, because lines of sight from two eyes cross in front of the image in the former method, and cross behind the image in the latter method. In this paper, all of the autostereogram images are constructed for parallel-viewing method.

4. Calculation of colors on autostereograms

In our method, we determine the colors of the points in each sequence q on the screen, taking the OS-relation into account. Due to the OS-relation, a single point on the screen corresponds to two points on the object, which means that the color of the point on the screen should take into account the colors of the two points on the object. On the other hand, due to the SS-relation, a single point on the object corresponds to two points on the screen. Our idea is to assign slightly different colors to such two points on the screen to take into account the OS-Relation, although they correspond to a single point on the object. Since we assign different colors, if they differ too much, then it is likely that the stereopsis becomes difficult because the left eye and the right eye would observe different colors for a single point. Therefore, we conducted an user test to know the allowed maximum difference in colors as described in Section 4.1. The solution to determine the colors of the points on the screen is described in Section 4.2. In our method, colors are calculated in L*u*v* color space, which is explained in Appendix. We use this color space because difference of colors human perceives can be measured more correctly when the differences of colors are small. A technique that facilitates the stereopsis is described in Section 4.3.

4.1. User test for restriction of colors

When two colors of a pair of SS-related points on the screen are similar, it is easy to perform stereopsis. On the other hand, if the two colors differ too much, it becomes difficult. Amounts of color differences seem to vary depending on luminance values. Therefore, we performed an user test to determine the allowable color difference of a pair of points on the screen which are perceived to be the same point on the object when performing stereopsis. As



(a) (b)

Figure 3. Autostereogram images used in the user test: Color difference between square plane and background is small in (a), and is large in (b).

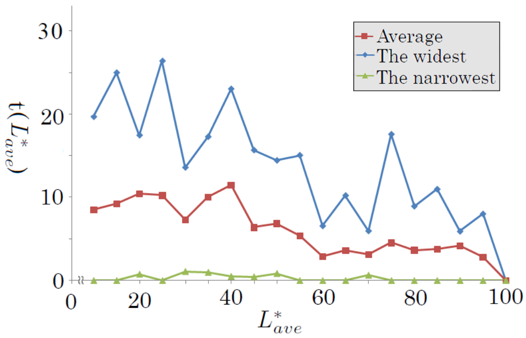


Figure 4. The amounts of allowable distances in L*u*v* color space: Blue and green dots indicate the data of the widest ranges of allowable differences and the data of the narrowest. Red dots indicate the average data. Data obtained from two-thirds of all users are around the average data. L^*_{ave} is the mean amount of L^* values of two colors of the square and the background.

expected, we obtained data of the allowable amounts of color differences which differ with luminance values. We take into account the personal difference when creating an autostereogram, by using the obtained data from the target user. To construct autostereogram images in this paper, we used the average of values obtained from all users.

In the user test, users view an autostereogram image shown in Figure 3 stereoscopically. A square plane and a background can be perceived in the autostereogram image. Either of the square plane or the background is displayed in one color, respectively, and dots with various colors are placed on the square and background so that sterepsis can be performed. The set of dots indicates the SS-related points on the screen. (Note that because of the resolution, the dots shown in Figure 3 may be inconspicuous.)

In the left and right sides of the square, it happens that one eye is seeing a point on the square while the other eye is seeing a point from the background. If colors of the square plane and the background are similar enough, then it is easy to perform stereopsis, otherwise, it becomes difficult.

The color values of the background in L*u*v* color space and L* value of the square plane are randomly chosen from about 1000 sets of colors prepared beforehand, and the u* and v* values of the square plane are determined by users. Users search the crude boundary value between an allowable and not allowable state, and report us the value. Depending on the set of color values, it may be difficult to perform stereopsis for all the u* and v* values of the square plane. In such a case, users report us that it is impossible to perform stereopsis for the values. After the user finished for one set of colors, the colors are changed to the next set.

From the user test, we obtain a set of pairs of two colors (the color of the square, and the color of the background) in the L*u*v* space. We calculate the Euclidean distance between the two colors in each pair, and gather the distances for each L* value (the L* value is discretized and ranges from 0 to 100). Note that a single distance is gathered twice for both the L* values of the two colors. Finally, we average the distances for each L* value, and obtain a relationship between the L* value and the allowed color difference for that value. In the above process, we have assumed that the L*u*v* is locally uniform, that is, if a color is reported to be sufficiently close to another color in the context of performing stereopsis, then the colors that are closer to the former one measured in the Euclidean space are all assumed to be close enough for performing stereopsis. We could remove this assumption by testing larger number of sets of colors, but such an user test would be a very hard task for the user, thus we gave up such an approach.

As expected, the value of allowable color difference depends on colors. Most of users remark that it becomes difficult to allow the difference or to perform stereopsis if the luminance is high. This is because, in L*u*v* color space, it gets difficult to distinguish one color from another when luminance is low. Figure 4 shows the relationship between luminance and the allowable distance. The horizontal axis shows the average luminance of the colors of the square and the background $\frac{1}{2}(L_1^* + L_2^*)$, where (L_1^*, u_1^*, v_1^*) and (L_2^*, u_2^*, v_2^*) are three-dimensional values of the two points in L*u*v* color space. The vertical axis shows the allowable distance, $t((L_1^* + L_2^*)/2)$. It turns out that differences among individuals can not be ignored and that large amount of difference tend to be allowed if the L* value is low.

4.2. Equations of color calculation

According to the algorithm to construct autostereogram shown in Section 3.1, we determine the sequences of points on a scanline, and each pair of adjacent two points has SS-relation. In the proposed method, slightly different colors are assigned to such points taking into account the colors of corresponding points on the object.

Figure 1(a) shows the relationship between points on the object and points on the autostereogram image. In this figure, P_i^r indicates a point on the object and X_i^q indicates a point on the autostereogram image.

Two conditions are taken into account when calculating colors on autostereogram images.

The first condition is that the color of X_i^q on the object is sufficiently similar to the colors of the corresponding points P_{i-1}^r and P_i^r, such that,

$$\begin{cases} \left|c(X_i^q) - c(P_{i-1}^r)\right| \le t\Big(l(P_{i-1}^r)\Big)/2, & and \\ \left|c(X_i^q) - c(P_i^r)\right| \le t\Big(l(P_i^r)\Big)/2, \end{cases} \tag{1}$$

where c is a function which returns the color of the point and t is an arbitrary function to return allowable color difference. l is a function to return L* value of the point, and $t(c(P_i^r))$ seems to be more accurate than $t(l(P_i^r))$, but we employ $t(l(P_i^r))$ to use the result of the user test. From equation (1),

$$\begin{cases} \left|c(X_i^q) - c(X_{i+1}^q)\right| \\ \le \left|c(X_i^q) - c(P_i^r)\right| + \left|c(X_{i+1}^q) - c(P_i^r)\right| \\ \le t\Big(l(P_i^r)\Big)/2 + t\Big(l(P_i^r)\Big)/2 = t\Big(l(P_i^r)\Big), \end{cases} \tag{2}$$

is concluded thus the function obtained from the user test can be used for the function t.

The second condition is that differences between the colors of the object and the colors expected to be perceived when performing stereopsis should be as small as possible, as shown below,

$$min \sum_{i=1}^{n-1} |\boldsymbol{D_i}|^2, \tag{3}$$

where n is the number of points in the point sequence q, and variable $\boldsymbol{D_i}$ is the difference between the mixed color $\frac{1}{2}\big(c(X_i^q), c(X_{i+1}^q)\big)$ and its corresponding object color $c(P_i^r)$, and is shown below,

$$\boldsymbol{D_i} = \frac{1}{2}\Big(c(X_i^q) + c(X_{i+1}^q)\Big) - c(P_i^r). \tag{4}$$

We assume that the color perceived in performing stereopsis is the mean color of the two points' color because a mixed color of two colors is approximately on the straight line between these two colors in L*u*v* color space. The absolute value of $\boldsymbol{D_i}$ should be small, in order that colors similar to the object can be perceived when stereopsis is performed.

We determine colors of pixels on autostereogram images by solving optimization problem taking into account equations (1), (2) and (3). There are some methods to solve the optimization problem, such as the quadratic programming. However, for fast calculation, we employed the least square method, and weakened the conditions as shown below,

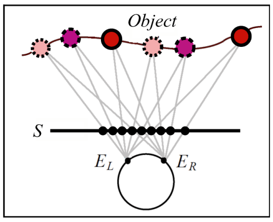
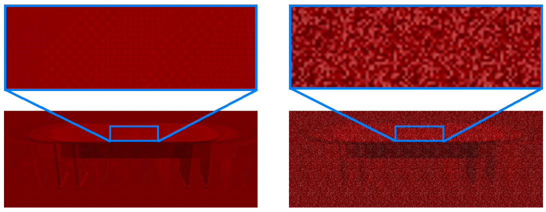


Figure 5. Changing L* values: The L* values of points on the object corresponding to the points in a sequence q, which is defined in Section 3, are changed to the same extent.



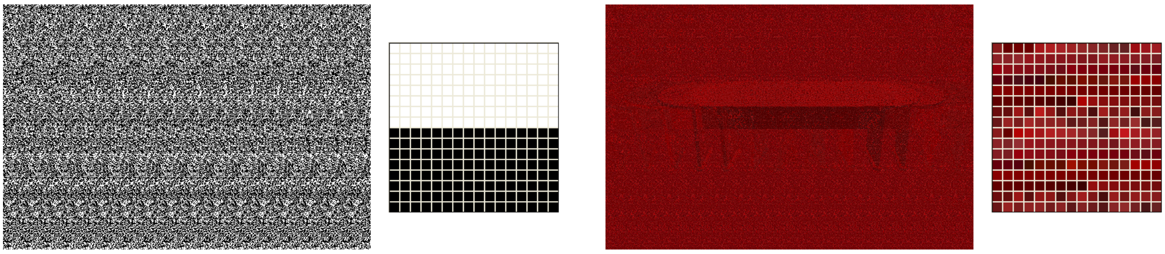
(a) (b)

Figure 6. Facilitating stereopsis: Both of the autostereogram images (a) and (b) show a table, and each center of the image is enlarged. (b) is easier to be viewed stereoscopically than (a).

$$\begin{cases} B_i = \dfrac{|c(X_i^q) - c(P_{i-1}^r)|}{t(l(P_{i-1}^r))}, \\ C_i = \dfrac{|c(X_i^q) - c(P_i^r)|}{t(l(P_i^r))}, \qquad and \\ min\Big(\sum_{i=1}^{n} \alpha(B_i^2 + C_i^2) + \sum_{i=1}^{n-1}(1-\alpha)\dfrac{\left|\boldsymbol{D_i}\right|^2}{\bar{t}}\Big), \end{cases} \tag{5}$$

where $\bar{t}$ is the mean value of the function obtained from the user test. The constant α indicates the ratio between the influences of two conditions discussed above, and runs from 0 to 1. If α is close to 0, the second condition gets influential and more accurate colors are perceived when stereopsis is performed. However, the first condition is less influential and it becomes difficult to perform stereopsis. On the other hand, if α is close to 1, it becomes easy to perform stereopsis, but less accurate colors are perceived when stereopsis is performed.

The value of α should be as small as possible in the range that streopsis is easy to perform. We determined the value of α by comparing autostereogram images constructed using various α values. It seems that stereopsis is easy to perform and colors are well represented when α is about 0.4. We



(a) (b)

Figure 7. The autostereogram images (left) and the corresponding color tables (right): (a) is an autostereogram image displayed with a dummy color table. (b) with correct color table.

constructed all color autostereogram images in this paper using the α value of 0.4 except as otherwise noted.

4.3. Facilitating stereopsis

Since colors of neighboring points on autostereogram images tend to be similar, it is difficult to perceive each point individually, thus making the stereopsis hard. Figure 6 (a) shows the results of color calculation, and is difficult to be viewed stereoscopically. Therefore, we changed the L* values of the points on the object to inform the positions of the points to be seen as the same (Figure 6 (b)).

The L* values are changed as stated below. As shown in Section 3.1, the positions of the points in the sequences on the autostereogram image are calculated. The L* values of the points on the object, which correspond to the points in a sequences on the image, are chaged to the same extent (Figure 5). These values are changed randomly so that the average of the L* values of all points on the object is maintained constant, and the amounts of the change in L* values are below certain threshold. We changed the L* values in the range of $\pm$ 16 from the original values, except as otherwise noted. After changing the L* values of points on the object, colors on the autostereogram image are calculated as shown in Section 4.2.

5. Color embedding and its applications

In this section, we propose a technique to embed color information in autostereogram images, and propose applications of this technique. Using our technique, monochrome object and color object can be perceived in two stages. As applications, our technique can be used for amusement and steganography. An autostereogram image has dummy color table, so monochrome image like the autostereogram of Figure 7(a) is displayed. By replacing dummy color table with correct one, color image like the autostereogram of Figure 7(b) is displayed.

The process of embedding color information and constructing color tables is performed as a post-process to the creation of color autostereogram described in Section 4.2. The colors of the images are indexed and the images are saved in a common file format that allows indexed colors, such as BMP or GIF. Note that the maximum number of indexed colors in those file formats are usually 256.

We randomly classify the sequences of points on the image into two sets. If we let the points in one set to be all black and the points in the other set to be all white, then the resulting image would be a monochrome autostereogram (Figure 8(a)). On the other hand, by assigning 128 colors to both the sets, we obtain the color autostereogram (Figure 8(b)). Therefore, we first reduce the colors used in both sets to 128, and then assign a color index to each point in the sets. The dummy color table is created by assigning black color to the points belonging to one set and white color to the points belonging to the other set.

5.1. Application for amusement

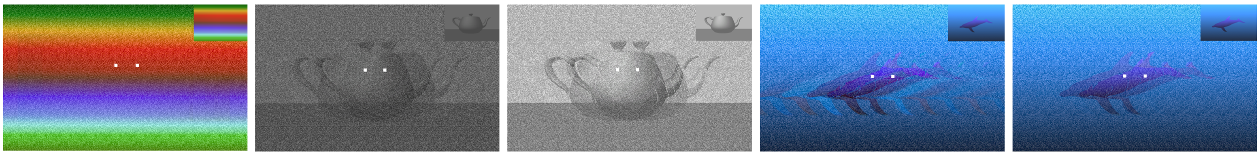
By using autostereogram images with the color information embedded in, two stage perception can be enjoyed and thus is applicable to amusement. Users have both of an autostereogram image and the correct color table. Firstly, users view the image stereoscopically, and perceive a monochrome object. Secondly, users replace the dummy color table with the correct one, and object colors appear. In this way, viewers can enjoy perceiving monochrome object and its color in two stages.

5.2. Application for steganography

Autostereogram images created using our technique are a kind of steganography in the sense that the existence of the color information itself is hidden. By utilizing the correct color table as the encryption key, our technique can also be applied to steganography. An autostereogram image is sent to intended recipient through the Web. Only those who have the correct color table can view color autostereogram images and perceive color variation of objects.

6. Results

We show some color autostereogram images constructed using our method. Color objects to be perceived in autostereogram images are shown in upper right of the images,



(a) (b) $L^*_{ave} = 40$ (c) $L^*_{ave} = 60$ (d) $\alpha = 0.10$ (e) $\alpha = 0.90$

Figure 8. Experiments on color autostereograms: (a) a square, (b) and (c) a teapot, (d) and (e) a dolphin. In (a), even if vertical color differences are large, ghosts do not get conspicuous. The average of L^* value of all pixels in (b) is 40 and that in (c) is 60, and (b) is easier to view stereoscopically than (c). (d) and (e) are constructed using different values of α.

and two white squares exist near the center of each image to help stereopsis in Figures 8, 9 and 10.

Since allowable color differences of two points on the image to be seen as the same point on the object are not wide, there is a limitation of horizontal color variation of autostereogram images. If colors of dots on the same scanline vary much, wispy colors of the objects are seen around the object, and false objects are perceived. We call these false objects *ghosts* in this paper. On the other hand, even if vertical color differences are large, it does not become difficult to perform stereopsis and ghosts do not get conspicuous (Figure 8 (a)).

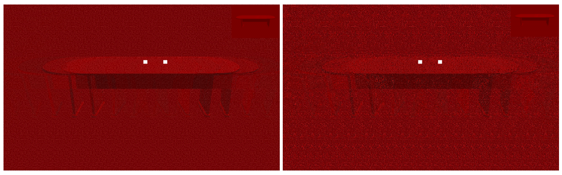
As stated in Section 4.2, the allowable differences of colors are large if the L* value is low. In Figure 8 (c), ghosts seen around the teapot is more conspicuous and it is more difficult to perform stereopsis than in Figure 8 (b) because of the allowable color difference.

Figures 8 (d) and (e) are constructed using different values of α. Figure 8 (d) is constructed using the α value of 0.1, and is difficult to view stereoscopically. (e) is constructed using the α value of 0.9, and is easy to view stereoscopically, but less accurate colors are perceived.

In Figure 9, we show autostereogram images constructed under condition that L* value is low and colors are calculated using the α value of 0.4. This condition seems to be better to construct autostereogram images, which are easy to be viewed stereoscopically, and color variation is well represented. Color variation of objects, especially shading, can be perceived in these images.

We also created an animation of autostereogram. It is much more fun to perceive moving objects than still objects. It takes about 0.7 seconds to create a single 1000×600 pixel autostereogram image using a machine with Intel Core 2 Extreme 3.0 GHz CPU and 8 GB memory.

We also succeeded in steganography. When the image file is opened without an encryption key, monochrome autostereogram image as shown in Figure 7 (a) is displayed. Only those who know that these images are not corrupted but are autostereogram images can perceive the shapes of the objects, and only those who have the true color table can perceive the object colors as shown in Figure 8(b).



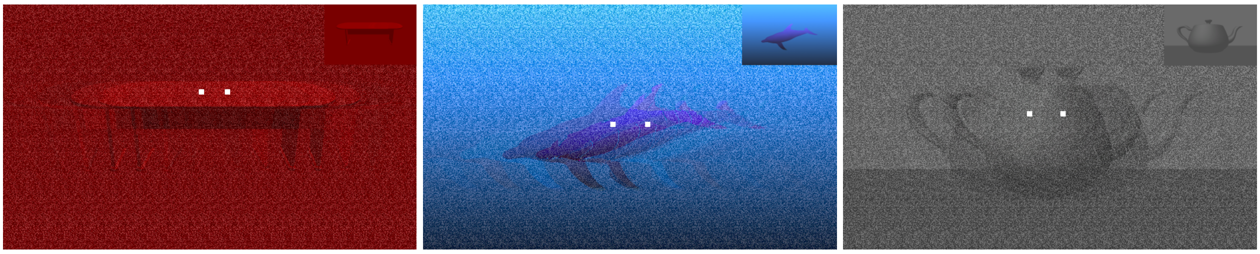
(a) (b)

Figure 10. The autostereogram images showing a table: (a) with 24 bits colors and (b) with 256 indexed colors. Color variation is lost only a little.

Figure 10 (a) is a color autostereogram image with 24 bits colors, and Figure 10 (b) with 256 indexed colors. Because of the limitation of color variation in autostereogram image, loss of color variation is little. An 8-bits color table is used to construct Figure 10 (b), and can be viewed stereoscopically. In addition, the size of file is reduced from that of original file because the colors are indexed.

7. Conclusions and future work

We have proposed a method to construct autostereogram images taking into account object colors, which have not been constructed previously. To assign colors, we considered following two conditions. First, the differences between the colors of the object and the colors perceived when performing stereopsis are as small as possible. Second, the color differences between any two points on the image, which have an SS-relation, are small enough to perform the stereopsis. The second condition are considered also by using the data from the user test. Ratio between the influences of these two conditions are determined by experiments. Using our method, color variation, especially shading of objects, can be represented in autostereogram images. A limitation is that the objects whose colors vary much horizontally, are difficult to be represented. On the other hand, we have found characteristics of color objects, which are easy to be represented in autostereogram images. Objects whose L* values are low tend to be comparatively naturally perceived in autostereogram images. We have also created an animation composed of autostereogram images in which



(a) table (b) dolphin (c) teapot

Figure 9. The autostereogram images constructed under the conditions of low L* value, and α value of 0.4: (a) shows a table, (b) shows a dolphin and (c) shows a teapot.

colored objects' movements can be perceived.

We also succeeded in embedding color information in autostereogram images. It is amusing that monochrome autostereogram images become color ones when the true color table is used. Moreover, autostereogram images can be applied for steganography to hide color information by using color table as an encryption key.

As future work, autostereogram images showing objects with wider ranges of color variation are considered to be constructed by taking advantage of the fact that colors of neighboring points are seen to be mixed. Moreover, colors printed on paper are a little different from those shown on displays. Such difference should be taken into account when printing color autostereogram images created using our method.

References

[1] `http://www.stereoscopy.com/library/waack-ch-2.html`.

[2] Andrews and McKeel. *Magic Eye: A New Way of Looking at the World*. A Universal Press Syndicate Company, Kansas City, USA, 1993.

[3] C. F. Dadson. Random dot stereograms generated with ray tracing as a visualization tool for evaluating stereoscopic camera systems. *SPIE Stereoscopic Displays and Virtual Reality Systems X*, 5006:10–18, 2003.

[4] Y. N. Denisyuk. On the reflection of optical properties of an object in a wave field of light scattered by it. *Doklady Akademii Nauk SSSR*, 114:1275–1278, 1962.

[5] D. Gabor. A new microscopic principle. *Nature*, 161:777–778, 1948.

[6] B. Julesz. *Foundation of Cyclopean Perception*. University of Chicago Press, 1971.

[7] A. A. Kinsman. *Random Dot Stereograms.* Kinsman Physics, 1992.

[8] E. N. Leith and J. Upatnieks. Reconstructed wavefronts and communication theory. *Journal of the Optical Society of America*, 52:1123–1130, 1962.

[9] H.-T. Liu, M. A. Weissman, G. B. White, G. E. Miner, and W. T. Gustafson. Stereoscopic system for measuring particle trajectories past an underwater model. *SPIE Stereoscopic Displays and Virtual Reality*, 2177:232–242, 1994.

[10] M. Omori, T. Watanabe, M. Miyao, Y. Sato, and S. Ishihara. Recognition of stereogcopic images among elderly people. *SPIE Human Vision and Electronic Imaging VII*, 4662:465–473, 2002.

[11] C. Petz, B. Goldlucke, and M. Magnor. Hardware-accelerated autostereogram rendering for interactive 3d visualization. *SPIE Stereoscopic Displays and Virtual Reality Systems X*, 5006:359–366, 2003.

[12] H. Thimbleby, S. Inglis, and I. Witten. Displaying 3d images: Algorithms for single-image random-dot stereograms. *IEEE Computer*, 27(10):38–48, 1994.

[13] C. W. Tyler and M. B. Clarke. The autostereogram. *SPIE Stereoscopic Displays and Applications*, 1258:182–196, 1990.

[14] C. Wheatstone. Contributions to the physiology of vision.-part the first. on some remarkable, and hitherto unobserved, phenomena of binocular vision. *Philosophical Transactions of the Royal Society of London*, 128:371–394, 1838.

[15] B. T. Yu and W. W. Yu. Single-image random-dot stereogram by crosstalk. *SPIE Vision Geometry IV*, 3168:115–122, 1997.

Appendix. L*u*v* color space

L*u*v* color space consists of three axes, L*, u* and v*. The L* axis indicates the luminance, and the u* and v* axes indicate red-green color and yellow-blue color, respectively.

We calculated the values of the colors in this color space because it is constructed so that the distance of two points in this color space approximates the difference of colors the human perceives very well.

The color difference $d(C_i, C_j)$ between the colors C_i and C_j in this space is calculated by the Euclidean distance,

$$d(C_i, C_j) = \sqrt{\Delta L^{*2} + \Delta u^{*2} + \Delta v^{*2}}, \tag{6}$$

where each variable is defined as follows,

$$\begin{gathered} C_i = (L_i^*, u_i^*, v_i^*), C_j = (L_j^*, u_j^*, v_j^*), \\ \Delta L^* = |L_i^* - L_j^*|, \Delta u^* = |u_i^* - u_j^*|, \quad and \\ \Delta v^* = |v_i^* - v_j^*|. \end{gathered} \tag{7}$$