Development of Three-Dimensional Visualization Technique and Its Application to Scientific Arts

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Contents

Chapter 1

Introduction

Nomenclature

d	Parallax displacement
f	Focal length
L	Distance between two cameras

1.1 General background

The flow visualization technique has been developed especially in the field of fluid engineering (Visualization Society of Japan, 1986 and 2002; Fujisawa, 2003). Since 1980's, computers and cameras have been evolved drastically; the visualization technique has been advanced rapidly with the new hardware. In recent years, these visualization techniques have been applied widely (Bruno et al., 2006; Glen, 1985), to the field of science and arts. The study for application to the field of arts is widely called Scientific Arts.

The visualization of the Scientific Arts is a field of research which deals the application and development of the visualization technologies to fine art, culture, education, sports, archaeology, literature, psychology and economics and so on (Fujisawa et al., 2008). Visualization of scientific arts has been a topic of interests in recent years, since the application of flow visualization technique to the archaeology by Nakayama et al. (2004), who explain that the surface pattern on the Jomon pottery comes from the vortex pattern observed behind the river stones and trees. The other example is the interdisciplinary education for both engineering and art students through the images of fluid flow (Hertzberg and Sweetman 2005). Later, Fujisawa et al. (2007) classified the flow visualization techniques into four groups, which are applicable to the generation of fluid art. Burge (2007) shows the flow visualization techniques for application to the fluid art, and presents some examples of visualization. More recently, net-work pattern (Uchida and Shirayama 2007), music (Ohmi et al. 2007) and rhythmical movement of gymnasts (Sakashita et al. 2007) are studied through the application of visualization techniques, which are originally developed in the scientific research field. The object of visualization of the Scientific Arts is to evolve these research areas of general arts dramatically by the use of visualization techniques to the flow of literature. Thus, the visualization technique has the role as a bridge with the arts.

The three-dimensional visualization has been used many years. However, most of them have been developed as qualitative methods with analogue imaging devices. In recent years, digital imaging techniques have been used actively in such area, according to the evolution of computer hardware. With digital imaging techniques, three-dimensional visualization can be used not only qualitative, but also quantitative. Such quantitative information can be used for production and evaluation of arts. Thus, the visualization technique is useful in the field of the Scientific Arts.

In the following section, the previous studies on three-dimensional visualization techniques are reviewed shortly, which is followed by the explanation of experimental techniques, such as the template matching algorithm and related image processing techniques, which has been developed and used in the present study.

1.2 Binocular vision

The binocular vision is one of the three-dimensional rendering techniques for adding depth information to a planar image. Since human (and most animals on this planet) have two separately placed eyes, they can see two different images at the same moment. It can give precise depth perception, which is provided by the two eyes' different positions on the head. It is called stereopsis. **Table 1.1** shows several methods of rendering techniques, which can be classified into two types; one needs special imaging devices and the other doesn't need such kind of special devices. In general, it is easier to see stereo images when such devices are used, because observers have to see two difference images by two different eyes. However, there're cases that sometimes almost impossible to use. For instance, if the images are printed on a journal paper, the polarizing filter method could not be used, because in principle the polarizing filter method requires two LCD projectors for rendering. Thus, choosing suitable method for the application is very important.

Anaglyph is a method which uses color filtered glasses to see (Glen, 1985; Smith et al., 1999; Sakashita et al., 2007). Colors are chosen from two complementary colors such as red-cyan pair. It can be printed on both papers and display monitors, relatively low price and easy to see, and most of color information can be reproduced.

Random dot stereogram is a method just for presenting depth information (Julesz, 1964). Observers can see depth from the stereogram with a certain amount of exercise. The image for left eye is plotted by random dot pattern and the other image is displaced image according to the parallax; random dot stereogram is a composition of these two images. It can be printed on any kind of display devices; however it requires some experience to defocus on the random dot image, and focused out of the printed surface. It is often used for books, because absolutely no devices are required to see.

Side by side stereo pair is a method which can be used for color images (Radvanyi, 1999). Two images are just printed side by side. It is cheap because it requires no additional devices to see; however it's hard to see compared to other methods.

Time delaying is a method which uses the Pulfrich effect (Lit, 1949). It is a phenomenon that a swinging object appears to move in an elliptical orbit when it's observed with a neutral density filter over one eye, since the observer detects darker image slower than brighter image. This method requires updatable displaying devices such as monitors or projectors, and a ND filter for one eye.

Parallax barrier requires special devices for breaking up left and right images. Recently, lenticular lens are used widely especially for 3-D LCD monitors in general market. The lenticular lens can be produced easily by industries, so that this method is becoming very popular. Since the light path is fixed by the parallax divider, observer must stay in a limited area against the monitor. This method gives 100 % color reproducibility and easy to see, but cannot be used for papers.

Stereoscope is a method that shows two images separately for left and right eyes. It requires a special imaging device such as the Head Mount Display (HMD). Since left and right images are broken up for each observer's eye, this method applicable only to one observer with one device.

Spectroscopy system uses prisms for dispersion. It is used to produce the parallax by the spectrum in right and left eyes. It requires one or two prisms.

Polarizing filter usually uses two projectors with two polarizing filters (Matsushita et al., 1998). In every frame, one projector prints an image for the left eye, and the other prints an image for the right eye. The direction of polarization crosses at the right angle for two projectors, and observer put on glasses with polarizing filter, which corresponds to the same direction of polarization attached on the projectors respectively. Thus, any pixels of the right image cannot be seen through the polarizing filter for the left eye, and vice versa. It requires special imaging devices, usually costs high; however, it can reproduce 100 % of color information, and low limitation for the area of observation. Thus, it is used for theaters in general market.

Optical band pass filter method uses two projectors, which have different RGB color spaces. For instance, a product by Daimler Chrysler Germany, which is named "Infitec," uses 629 nm (R), 532 nm (G) and 446 nm (B) for one projector, and 615 nm (R), 518 nm (G) and 432 nm (B) for the other projector. Since the color spectrum is different, it is easy to separate by the use of optical band pass filter. Additionally, the differences of wave-lengths between two projectors are close enough to detect by humans' perception, so that almost 100 % of color information can be reproduced. This method requires such special imaging devices, which is rarely findable in general market.

Anaglyph can be printed on papers and displayed via projectors without any additional special devices. Therefore, author chooses anaglyph method in the present thesis. Although many kinds of binocular vision systems are proposed, the core idea is that they print two different images for left and right eyes. Note that the same

Table 1.1 Binocular vision

Method	Device	Cost	Color reproducibility	Reference
Anaglyph	Paper, Monitor	Low	Middle	Glen, 1985
Random dot stereogram	Paper, Monitor	Low	Low	Julesz, 1964
Side by side stereo pair	Paper, Monitor	Low	High	Radvanyi, 1999
Time delaying	Monitor	Low	High	Lit, 1949
Parallax barrier	Lenticular lens	Middle	High	
Stereoscope	HMD	Middle	High	
Spectroscopy system	Paper, Monitor	Middle	Low	
Polarizing filter	Two projectors	High	High	Matsushita et al., 1998
Optical band pass filter	Two projectors	High	High	

technique described in this thesis can be used for the other binocular vision systems.

1.3 Standard anaglyph

In general, anaglyph can be created by the use of two cameras placed parallel to each other, at the certain distance that is equivalent to the distance between human eyes, which is called the Interpupillary Distance (IPD). Statistically, the IPD is about 60-65 mm for women and 62-67 mm for men of adult age (Dodgson, 2004). Note that cameras are placed at the distance around 64 mm to acquire the depth information.

Two different color filters are attached on each camera to separate the spectrum of the light. This color filter can be chosen from any combination of two complementary colors. Usually, anaglyph uses red-cyan pair for the filters, because:

1) The dominant eye detects much more information compared to the others (Khan and Crawford, 2001), so that it is reasonable to allocate more bandwidth for the eye.
2) In RGB image, it is very easy to separate the color into red and cyan pair, because the cyan is a simple composition of green and blue components.

Both cameras are synchronized when images are recorded.

After images are taken, usually minor modification is curried out, due to the misalignment of two cameras. Standard anaglyph can be produced by simply compositing two images.

1.4 Three-dimensional visualization

The three-dimensional visualization technique has been used widely in the research fields, such as visualization of electron and nuclear densities, crystal structures

(Macrae et al., 2006), air hydrate in ice layer of Antarctic Pole (Bingham and Siegert, 2005), geological condition (Artimo et al., 2003), computational fluid dynamics (Wesche, 1999), and so on. In general, three-dimensional visualization contains two parts of technologies: measurement and rendering. The present thesis focuses on a rendering technique of stereoscopic images of a target object, and measurement technique is also studied to accomplish the rendering technique.

There are several ways for obtaining geometrical information of an object. For instance, the three-dimensional measuring machine or measuring studio for motion capturing can be used. However, they are generally huge and expensive. The three-dimensional measuring machine can only measure very limited size of target, so that human-size object might not be measured. The motion capturing studio can be used for human-size objects, but it is more huge and expensive. Additionally, it is necessary that markers are put on the target surface, to determine the position by the motion capturing system. These markers shall not be moved during measurement. In the present thesis, the geometrical information measured by such devices can be used for generating three-dimensional images; however, it should be preferable to obtain geometrical information easier, by the use of digital cameras found in general market. To accomplish this, two parallel placed cameras are used.

There're several methods to obtain three-dimensional positions from camera images, such as the pin-hole model method (Murai et al., 1981) and the direct mapping method (Soloff et al., 1997). The pin-hole model method is based on the optical analysis of camera positions. The method also considers the lens effects, but it's sometimes hard to determine the camera information from recorded images. On the other hand, direct mapping method uses a matrix to determine the relationship between real and image coordinate system, so that lens distortion information is included in the matrix. The direct mapping method originally developed for the measurement of velocity field of fluid (the time derivative of the position), so that it is not for measurement of positions. In this present thesis, direct mapping method is used for the basement to measure geometrical information. If the two cameras are placed parallel, the depth information can be measured by the displacement with sub-pixel accuracy:

$$z = \frac{fL}{d} \tag{1.1}$$

This equation is relatively easy to solve, so that CPU time can be reduced to measure the depth information. Further description for obtaining geometrical information is shown in Appendix 1.

1.5 Objectives and Structure of Thesis

The purpose of this thesis is to develop the method for rendering the anaglyph quantitatively, for application to the visualization of the Scientific Arts.

In order to understand effectiveness of three-dimensional visualization technique to the application in the field of the Scientific Arts, the flow of rhythmical movement was visualized by standard anaglyph stereo images taken by two color CCD cameras placed side by side, which is described in Chapter 2.

Chapter 3 describes the study of quantitative anaglyph stereo visualization technique by the use of a single image and depth information from other methods. In addition to this, the method to obtain the geometrical information of the target object by the use of two digital cameras is studied. By the use of this technique, the distance of cameras is not constrained in 64 mm, because the whole depth information is obtained and used to generate an anaglyph.

Chapter 4 is the summary of this thesis, which shows three-dimensional visualization and application to the Scientific Arts.

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Chapter 2

Anaglyph Stereo Imaging in Rhythmical Movements

2.1 Introduction

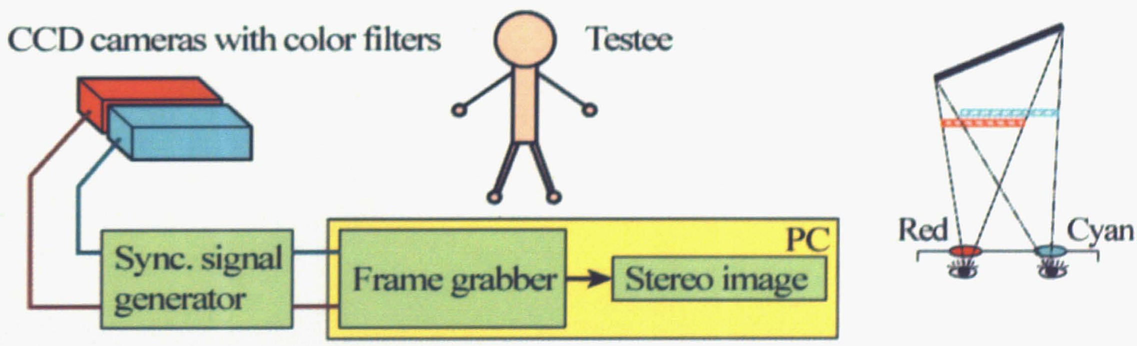
Rhythmical movements by well-trained gymnasts have such characteristics as wholeness, rhythmical flow and harmony. They are also characterized by the central movement theory (Braithwaite, 1976), which states that movements should flow from the center of the body to the peripheral parts of the body. Thus, the performance of gymnast has been evaluated from these points of view. In general, the rhythmical movements are evaluated using analogue video system. This system reproduces the temporal and spatial variations of the flow, but some of the information, such as the dynamics of the movements, reality and artistic impression may be lost due to the planar nature of the images (Takizawa et al., 2005). On the other hand, the visualization of physical phenomenon has often been a topic of interests in engineering field by using stereo images. Three-dimensional (3D) visualization using anaglyph stereo images has evoked interest in imaging science due to the simplicity and low cost (Glen, 1985; Ideses and Yaroslavsky, 2005), and has been widely used for the general 3D visualization purposes including the application to the visualization of art (ex. Hertzberg, 2005; Takizawa et al., 2005; Fujisawa et al., 2007). Such technique is known to be effective in some applications for understanding the 3D information of physical bodies. However, such stereo images have not been introduced into the evaluation of the performance of gymnasts undergoing rhythmical movements, in spite of the potential interests in the application.

Anaglyph is one of the most economical methods for three-dimensional visualization of physical images. It reproduces the 3D visual effect when viewed using color-filtering spectacles, such as red-blue (green) transparent color films, that can be easily found in stationery shops. In general, anaglyph images are generated from two cameras with filters placed parallel with a distance of 64 mm, which is equivalent to that of human eyes. The two captured images are often tuned in position slightly to enhance the 3D effect, which is due to the misalignment of cameras and filters that produce the ghost image appearances. There are some recent advances to enhance the 3D effect of anaglyph, which includes the stereo image registration, defocusing and non-linear operation on the depth maps (Ideses and Yaroslavsky, 2005). Although these methods reduce the ghost image appearance, the generated anaglyph may lose quantitative information on the depth map. Thus, there is still more space for research on improving the anaglyph to make it quantitative in 3D visualization. It should be mentioned that such quantitative anaglyph is useful for evaluating the performance of gymnasts in rhythmical movements, which require not only the visual impact but also the correctness.

The purpose of this chapter is to introduce a stereo view system into the evaluation of rhythmical movements of gymnast and to understand the role of stereo images for evaluating the performance of gymnasts.

2.2 Experimental method

A schematic illustration of experimental system for stereo imaging is shown in **Fig. 2.1 (a)**. It consists of two monochrome CCD cameras (659 x 494 pixels, 8-bit, 60 frames per second) or color CCD cameras (640 x 480 pixels, 8-bit, 30 frames per second), a personal computer with frame grabber and a 3D monitor. They are all placed on a floor of gymnasium for recording and processing of the images. Two CCD cameras are placed side by side with a horizontal distance of 64 mm. The red filter is attached to left CCD camera and the cyan filter is on the right one. Anaglyph stereo images are generated from a pair of captured images sequentially using the software written by C++, which allows for tuning of 3D information of the stereo images. Although this system allows for the observation of stereo images using a 3D monitor, the anaglyph stereo image is chosen in the present study due to the simplicity and the economical reason. The generated anaglyphs can be observed through red-cyan glasses, where the red filter should be on the left eye and the cyan filter is on the right eye, as shown in **Fig. 2.1 (b)**. As the red and cyan images are displaced slightly in the image plane, the 3D information can be reproduced in the anaglyphs (**Fig. 2.1 (b)**).



(a) Experimental setup (b) Stereo viewer

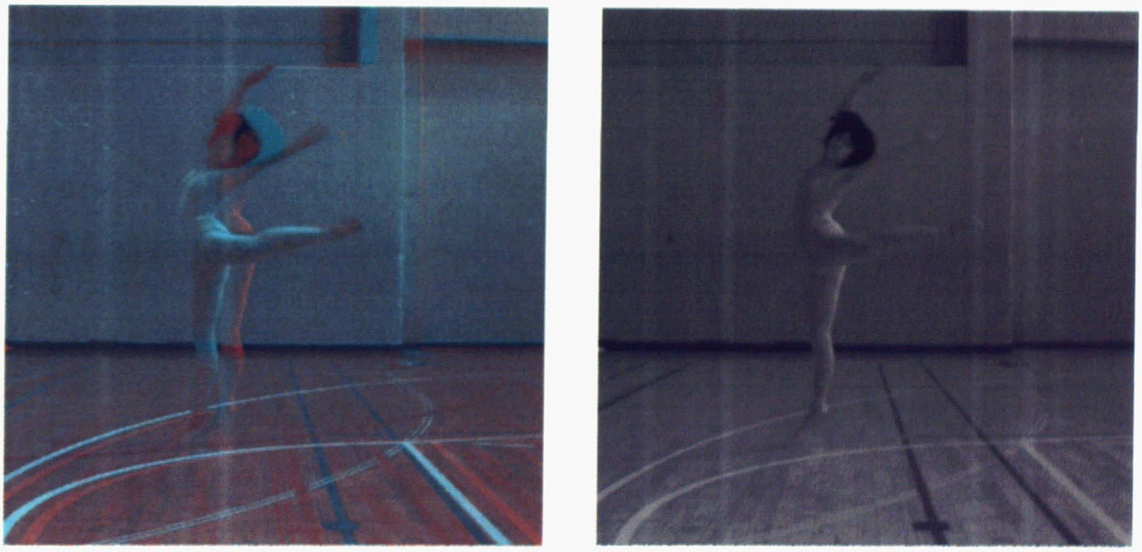
Fig. 2.1 Experimental setup and stereo viewer

It is important to choose appropriate color for the target. The red-cyan pair is used in this article, so that yellow, white or similar bright color is a good choice for the target, because those color pass through red and cyan filters.

2.3 Results and discussion

2.3.1 Comparison of anaglyph and planar images

Figure 2.2 (a) shows a typical example of the anaglyph stereo images generated from the present experiment. A vertical jump turn motion of gymnasts is selected here as a typical example. The liveliness of rhythmical movement can be seen in a series of stereo images, such as wave, wind, water flow and so on. These movements flow from the center of the body to peripheral parts of the body. We can understand a sequence of rhythmical movements from a time series of stereo images of every 0.2 s. In order to understand the difference of the stereo images from the planar images (usual video images), the same motion was displayed in **Fig. 2.2 (b)** in planar images. We can understand the same motion from the planar images but with less dynamics and liveliness. Note that these images are taken by monochrome CCD cameras.



(a) Anaglyph image (b) Planar image

Fig. 2.2 Anaglyph stereo and planar images of gymnastics in vertical jump turn motion.

In order to understand the difference of the stereo and planar images in rhythmical movements, the impression of the image is evaluated by questionnaire how the sequence of motion can be expected from a snapshot. For details of the questionnaire see a paper by Takizawa et al. (2005). Note that the evaluators are composed of 8 advanced level gymnasts (having carrier more than 10 years) and 7 middle level gymnasts (having carrier between 3 and 5 years). It was found that the vertical jump tern motion was well recognized by the evaluators with the stereo image in comparison with the planar image. This result was obtained from both gymnast groups, but it was clearer in the evaluation from the middle level gymnasts. Therefore, the stereo images are considered to be useful for understanding the dynamics of vertical jump turn motion, which is due to the 3D information of the image. However, the vertical growing motion and the horizontal rotating motion are not so well understood even in the stereo images except for the twisted motion in the part of the horizontal rotating motion. From these results, it is found that the stereo images are useful in the evaluation of gymnastics, especially in the exercise of dynamic motion, such as body twist, bounce and postures of the gymnasts. It is also understood that the liveliness of the motion is more clearly observed in the stereo images, which suggests the effectiveness of the stereo images for evaluating the performance of rhythmical movements.

2.3.2 Color anaglyph

Color anaglyph can be generated from color images. **Figure 2.3** shows color version of anaglyph in vertical jump motion. The images are taken in gymnasium with sun light illumination. In general, monochrome cameras have more frame rate and consume less memory compared to color cameras, so that choosing the type of camera to use depends on the target. The present motion includes a jump, which is fast movement of body. Observers may understand colorific information from the color version of anaglyph; however, frame rates of 30 fps is not enough to record detailed information of jump motion, which is the frame rates that can be recorded by the general color video cameras.

Figures 2.4 and **2.5** are the other examples of color anaglyphs. **Figure 2.4** is called turn motion. The turn motion is a slow, turning arm over motion. The motion is slow enough to record with 30 fps, so that color cameras are suitable to be used for recording both detailed motion and colorific information. One of the important points of this motion is making a long arm and seeing the end of the finger. From the anaglyph, they are easily understood compared with the case of planar images. Some rhythmical movements may take place by more than one person at a time. An example of such movement is shown as **Fig. 2.5**. Anaglyph helps understanding physical relationship of gymnasts.

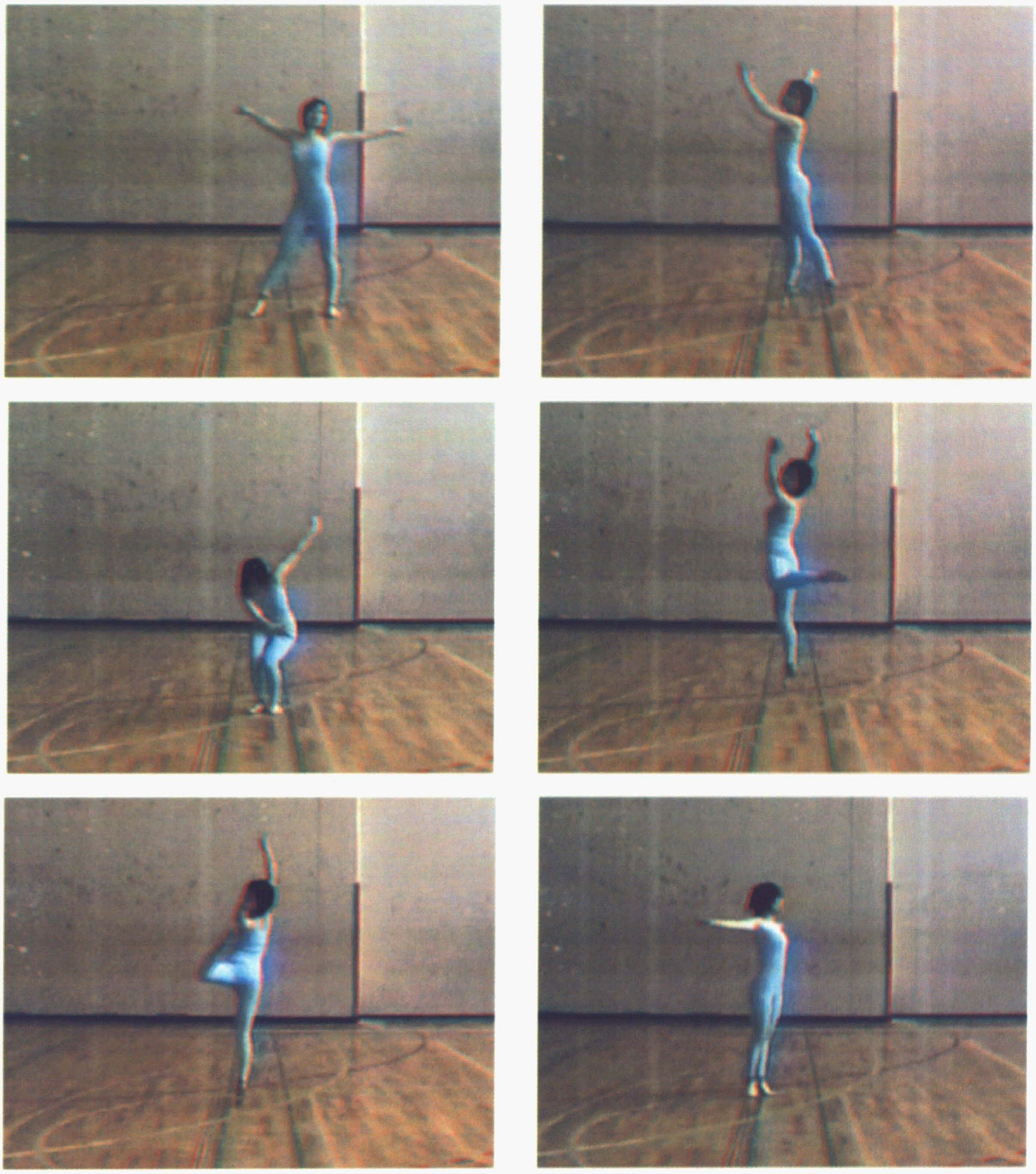


Fig. 2.3 Examples of color anaglyph stereo image in vertical jump motion.

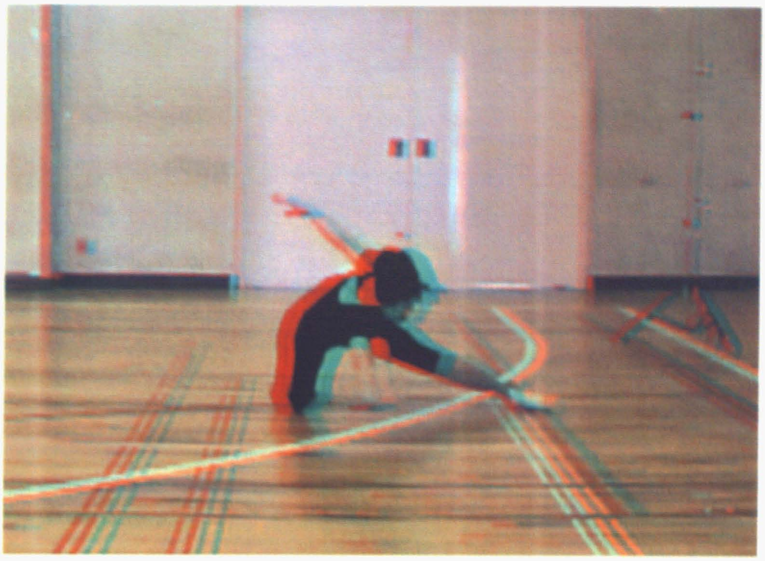


Fig. 2.4 An example of color anaglyph stereo image in turn motion.

Fig. 2.5 An example of color anaglyph with three people.

2.4 Conclusion

Anaglyph visualization in rhythmical movements is introduced to understand the role of stereo images for evaluating the performance of gymnasts. Planar, monochrome anaglyph and color anaglyph images are presented. Anaglyph provides more information in depth, so that anaglyphs are easier to expect the sequence of motion rather than planar images. Color anaglyph can be used if colorific information is important for evaluation; however, monochrome anaglyph is more suitable for high speed motion such as vertical jump motion, due to the higher frame rate of the standard cameras.

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Chapter 3

Anaglyph Stereo Visualization by the Use of a Single Image and Depth Information

Nomenclature

d	Parallax displacement
f	Focal length
L	Distance between two cameras
x, y, z	Physical coordinates
x', y'	Imaginary coordinates
α, β	Coefficients of matrix determined by least-square method

3.1 Introduction

Three-dimensional visualization is well known and becoming popular in recent years to understand the target object and the related physical phenomena. The progress of three-dimensional visualization is greatly accelerated in recent years by the development of new multi-media devices, such as three-dimensional projector, monitor and so on. Such visualization technique is known useful for expressing the depth information on the two-dimensional image, so that there is a wide range of application in the field of scientific visualization (Bruno et al., 2006). Now, there is variety of method, which can provide the three-dimensional information of images, such as stereogram (Radvanyi, 1999), anaglyph (Glen, 1985; Smith et al., 1999; Sakashita et al., 2005), polarization glasses (Matsushita et al., 1998), stereo projector and monitor (Hernandez et al., 1998) and so on. For conducting such stereo visualization, images are normally taken from binocular camera, which consists of two parallel imaging devices with a certain distance equivalent to that of human eyes, 64 mm. However, the necessity of such special imaging devices keeps away from popularization of the three-dimensional visualization in the present conditions. It would be very helpful to generate the three-dimensional images from a standard single camera, which is available in general market.

In principle, the information from image pair from binocular imaging system is equivalent to the one of images and the depth information (Ideses and Yaroslavsky, 2005). Therefore, the three-dimensional image can be generated from a single imaging device, once depth information is available from other methods. This means that the stereo visualization can be carried out using a single image in combination with the depth information.

Anaglyph is one of the most economical methods for expressing the depth information and is also most popular method among many three-dimensional visualization techniques. However, there are fewer studies to improve the visual quality of anaglyphs in literature (Ideses and Yaroslavsky, 2005; Yaroslavsky et al., 2005). This method uses red-cyan (or red-blue) glasses in three-dimensional visualization of stereo images. The depth information can be observed by the parallax of the red-filtered images on the left and the cyan-filtered image on the right. Therefore, the anaglyph can reproduces the three-dimensional information, but the color of the target may not be reproduced correctly due to the loss of red and cyan information, which have already been used for getting the parallax information. In spite of such drawback, the anaglyphs are accepted as a simple method of three-dimensional visualization (Matsuura et al., 2006) and applicable to the visualization of scientific art (Nakayama et al., 2004; Hertzberg and Sweetman, 2005; Fujisawa et al., 2007; Burge, 2007).

In the present paper, the experimental techniques are studied for stereo imaging and three-dimensional visualization based on a single image and the depth information from other methods. An attention is placed on the generation of monochrome and color anaglyphs for application to scientific art.

3.2 Experimental method

3.2.1 Experimental setup

An illustration of the experimental setup is shown in **Fig. 3.1**, which consists of imaging device, LCD projector and frame grabber installed to a personal computer. As a basic imaging device, monochrome CCD camera (648 x 494 pixels, 8-bit) or digital color CCD camera (3008 x 2000 pixels, 8-bit) is used for imaging the target object. The position of such base camera is placed in front of the target object. In this study, the distance between the base camera and the target object is set to 1.2 m. A LCD projector is placed just behind the camera to project a random dot pattern on the target object. Each dot is 3 mm in diameter and is white on the black background. It should be mentioned that the monochrome CCD camera is used for generating the monochrome anaglyph and the color CCD camera is for the color anaglyph. In order to obtain the depth information of the target object, other monochrome CCD cameras are located in parallel to the base camera with a certain distance.

3.2.2 Camera calibration

The camera calibration is carried out using a calibration plate to eliminate the effect of lens distortion and minor misalignment of the camera positions. The calibration plate is a planar white plate having an area of 600 mm x 800 mm, where many black markers of 3 mm in diameter are located in an array with an interval of every 20 mm. The plate is fixed on an electric traversing device to move in the depth direction (z direction, see **Fig. 3.1**). The calibration plate is set at five different positions in the depth direction, which is at every 70 mm intervals. Note that the relationship between image and physical coordinates is approximated by third-order polynomials;

$$x=\sum_{j=0}^{3}\sum_{i=0}^{3}\alpha_{ij}x'^{i}y'^{j},\quad y=\sum_{j=0}^{3}\sum_{i=0}^{3}\beta_{ij}x'^{i}y'^{j}\quad (i+j\le 3) \tag{3.1}$$

where x', y' are image coordinates, x, y are physical coordinates, and α, β are coefficients of matrix determined by least-square method using the calibration plate (Soloff et al., 1997).

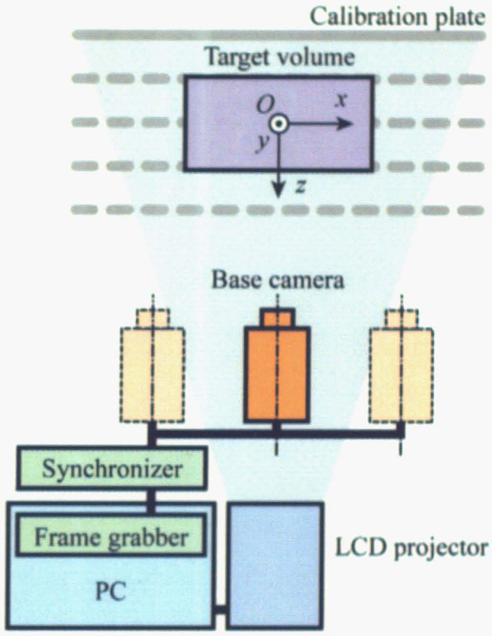


Fig. 3.1 Experimental setup for three-dimensional visualization.

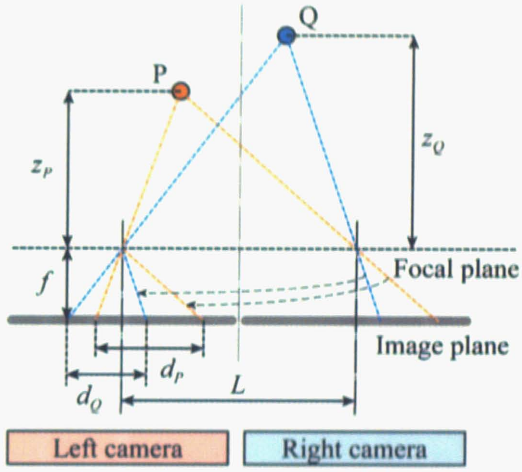


Fig. 3.2 Depth information and parallax displacement.

3.2.3 Depth information

The depth information of the target object can be obtained from two parallel cameras placed side by side. Assuming that two cameras are parallel, the depth information z of the target object can be expressed by the following simple equation:

$$z=\frac{fL}{d} \tag{3.2}$$

where d is a parallax displacement on the image plane, f is a focal length of the camera lens and L is a distance between two parallel cameras (**Fig. 3.2**). Since z is inversely proportional to d, parallax displacements of the points P and Q, which are denoted by

d_P and d_Q, respectively, are found to be $d_P > d_Q$. Note that the parallax displacement d between two images is evaluated from the correlation-based template matching analysis with sub-pixel interpolation (Kiuchi et al. 2005, Fujisawa et al., 2006). The correlation window size is set to 23 x 23 pixels. Then, the depth information z can be obtained from Eq. (3.2), which results in $z_P < z_Q$ in **Fig. 3.1**. On the other hand, Eq. (3.2) is used for evaluating the parallax displacement from the depth information z to generate the displacement image of the anaglyph.

3.3 Generation of anaglyph images

3.3.1 Monochrome anaglyph from given geometrical information (Case 1)

Usually, anaglyph stereo images are generated by simply synthesize the image pair taken from the binocular camera having a lens distance of human eyes. Thus, the depth information is automatically supplied through the parallax of stereo image pair. On the other hand, the anaglyph stereo images can be generated from a single image in combination with the depth information taken from the other information, such as the geometry of the target object and the experimentally measured depth information. The procedure of anaglyph image generation in these cases is described as case 1 in **Fig. 3.3**.

When a single image is taken from a CCD camera, the image can be used as the base image of the stereo image pair and the other image can be generated from the base image and the depth information. An example of anaglyph image generated through the known geometry of the target object is shown in **Fig. 3.4**. In this case, the depth information can be easily evaluated from a single image (**Fig. 3.4 (a)**) by detecting the characteristic points, such as the corners of the target and the geometrical information of the cube (**Fig. 3.4 (b)**). Then, the parallax displacement is calculated pixel by pixel from Eq. (3.2), and the displacement image is generated from the base image taken from the monochrome CCD camera. Note that the base image should be calibrated to remove the influence of lens distortion and misalignment of the camera. **Figure 3.4 (c)** shows an example of anaglyph image of the cube, which has a 70 x 70 x 70 mm^3 in physical space. The three-dimensional information can be seen by the observation with red and cyan filtered glasses.

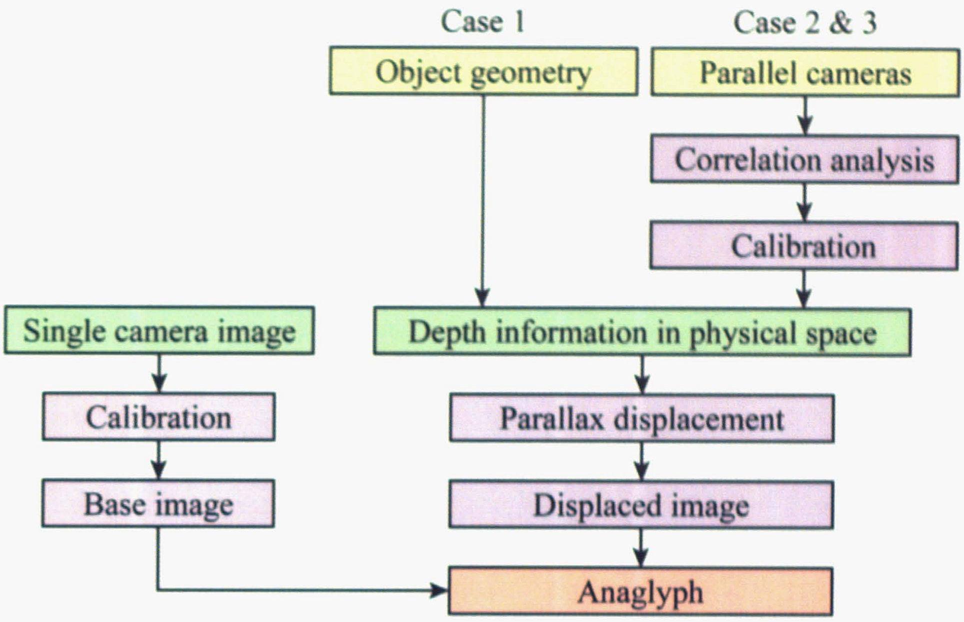
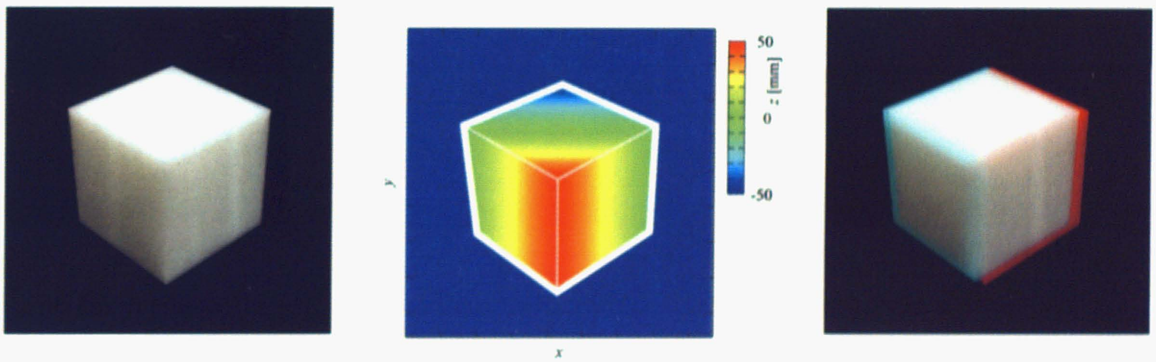


Fig. 3.3 Flowchart of anaglyph generation.



(a) Base image (b) Depth information (c) Monochrome anaglyph

Fig. 3.4 Monochrome anaglyph of cube from given geometrical information.

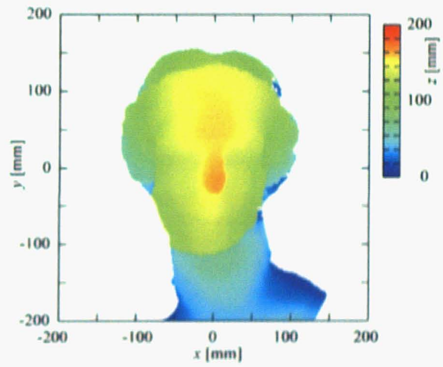
3.3.2 Monochrome anaglyph from experimental depth information (Case 2)

When the depth information is not given, it has to be evaluated by experimental observation. In this case, the depth information can be evaluated from the image from the base camera and the CCD camera placed in parallel. Note that a monochrome CCD camera (648 x 494 pixels) similar to the base camera is used for getting the depth information in the present study. The depth information is evaluated from the correlation-based template matching analysis of the pair of images. Then, the depth information is transformed into the parallax displacement at each pixel of the image at the base camera position using Eq. (3.2). Note that the image information is transformed into the physical coordinates by the calibration to remove the influence of lens distortion and minor misalignment of the camera positions. Then, the anaglyph stereo images are generated by the use of the displacement image and the base image after the image calibration.

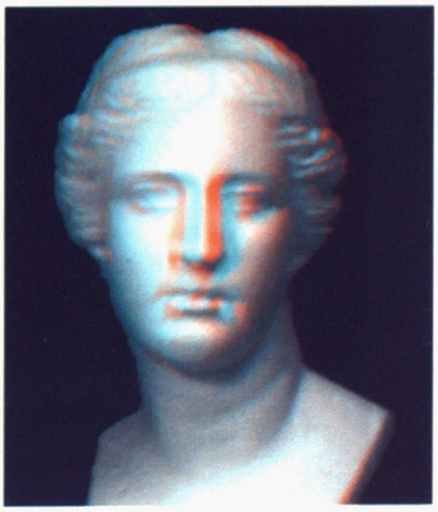
The procedure of stereo imaging and the generation of anaglyphs for three-dimensional visualization are described in **Fig. 3.5**, which shows a target object of plaster figure under white light illumination (**Fig. 3.5 (a)**), that in a random dot pattern (**Fig. 3.5 (b)**), the depth information of the plaster figure obtained from the stereo imaging (**Fig. 3.5 (c)**) and the anaglyph image of plaster figure generated by the present method (**Fig. 3.5 (d)**). Note that the anaglyph image generated by the present method is obtained from the two parallel cameras with a distance L = 128 mm. The successful generation of the anaglyph is found from the observation with red-cyan filtered glasses.

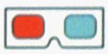
(a) Base image

(b) Random dot pattern



(c) Depth information

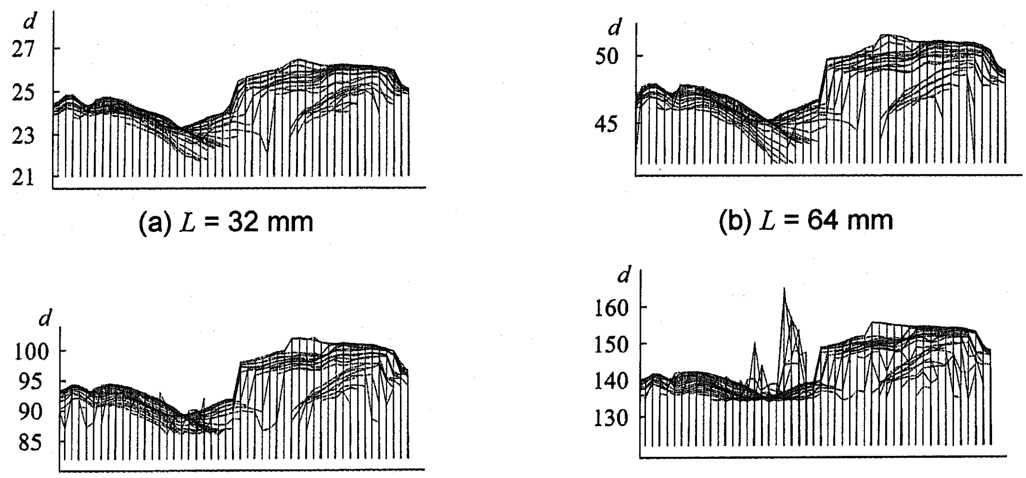




(d) Monochrome anaglyph

Fig. 3.5 Monochrome anaglyph of plaster figure from experimental depth information.

It is expected that the inaccuracy of depth information is influential on the visual quality of the anaglyph. **Figure 3.6** shows the side views of the plaster figure at various camera distances L, which are taken by a CCD camera in front of the plaster figure. The result indicates some errors in the depth information, which are dependent on the distance between the cameras and that between the cameras and the target object. It is found that errors appear in the depth information at larger parallax displacement, which is due to the error in the correlation-based template matching analysis near the boundary of the plaster figure. However, the smaller parallax displacement produces an inaccuracy in the depth information due to the sub-pixel error, which can be seen around the nose of the plaster figure. Thus, the present result indicates that the optimum camera distance L is considered as L = 64-128 mm. It should be mentioned that the RMS error in the present experiment is found to be about 3 mm in L = 64-128 mm, which is obtained from the calibration study.

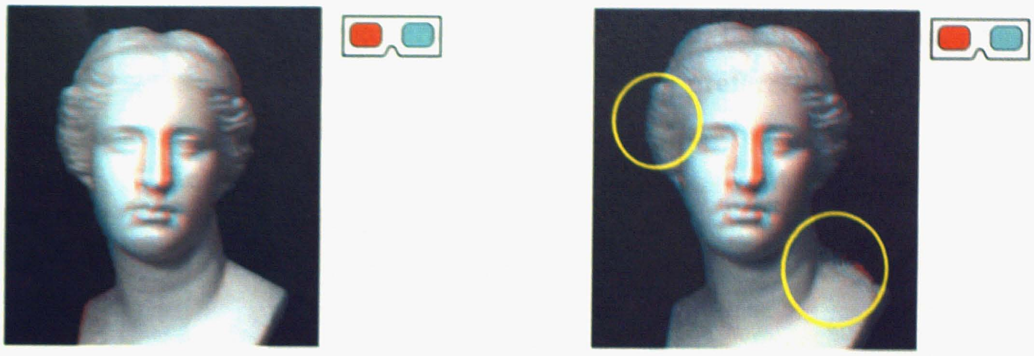


(a) L = 32 mm (b) L = 64 mm

(c) L = 128 mm (d) L = 192 mm

Fig. 3.6 Depth information of plaster figure taken from various camera distances.

Examples of anaglyphs with erroneous depth information are shown in **Fig. 3.7 (a), (b)**. It is found that three-dimensional visual quality of the anaglyph is partly lost due to the error in the depth information at the narrower camera distance, though it is not clearly seen (**Fig. 3.7 (a)**). On the other hand, an example of anaglyph at wider camera distance is shown in **Fig. 3.7 (b)**, which shows the influence of artifacts on the left shoulder and on the rugged hair of the plaster figure, which is marked by yellow circles. Thus, the error in the depth information is influential on generated anaglyphs.



(a) L = 32 mm (b) L = 192 mm

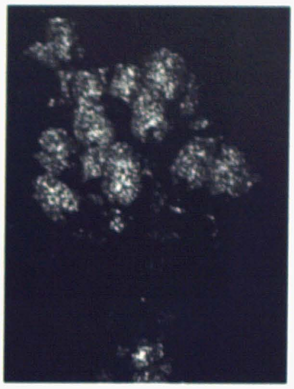
Fig. 3.7 Anaglyphs generated from erroneous depth information.

3.3.3 Color anaglyph from experimental depth information (Case 3)

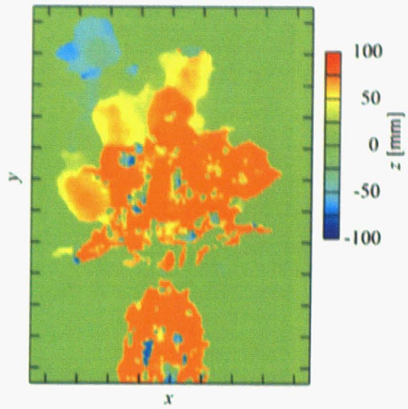
In case of color anaglyph, the procedure of image generation is similar to the case of monochrome anaglyphs. Only the difference is that the parallax displacement obtained from the correlation-based template matching analysis has to be added to the color image, where the HSI color format (H: hue, S: saturation, I: intensity) is preferred to minimize the error in the image generation. It should be mentioned that bilinear interpolation of image is introduced into the generation of anaglyph to match the image size of the depth information with the base color image, because the image size of the color CCD camera is generally different from that of the monochrome CCD camera, which is the case in this study. In the present study, the two monochrome CCD cameras (648 x 494 pixels) are placed on both sides of the color CCD camera (3008 x 2000 pixels) to evaluate the depth information of the target object. Note that the distance between the monochrome CCD camera is set to L = 100 mm in the present experiment.

Figure 3.8 shows a target object of artificial flowers under white light illumination (**Fig. 3.8 (a)**), that in a random dot pattern (**Fig. 3.8 (b)**), the depth information (**Fig. 3.8 (c)**) and the color anaglyph of the artificial flower (**Fig. 3.8 (d)**). Several points seem to have erroneous depth information in **Fig. 3.8 (c)**, which is due to the darkness of the random dot pattern on the target surface, as observed on the leafs and the flower vase. However, these errors may not deteriorate so much the visual quality of anaglyph, because they are dark enough to be detected. For generating the color anaglyph, the RGB color information of the base image is transformed into HSI color space to reduce the unexpected noise in the image processing, which occurs near the color boundaries. Then, the parallax displacement from the depth information is added to each color. The successful generation of the color anaglyph can be observed through the red-cyan filtered glasses. It is noted that red or cyan color should be avoided from the target image for generating color anaglyph, because each color has already used for getting the parallax information. The preferred color for color anaglyph is purple, yellow and white.

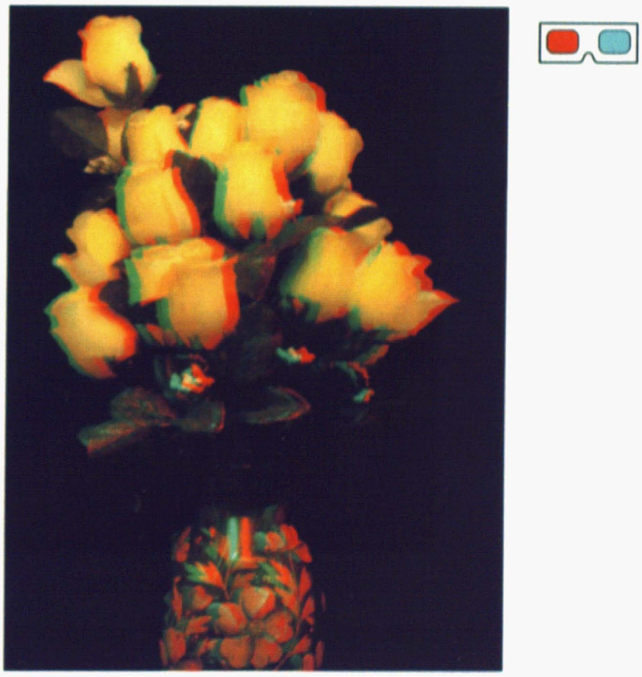
(a) Base image



(b) Random dot pattern



(c) Depth informaion



(d) Color anaglyph

Fig. 3.8 Color anaglyph of artificial flowers from experimental depth information.

Figure 3.9 shows the other example of anaglyph stereo imaging and the generated color anaglyph, which is a target object of flower arrangement in white light illumination **(a)**, that in a random dot pattern illuminated by a LCD projector **(b)**, the depth information analyzed by correlation-based-template-matching analysis **(c)** and the anaglyph stereo image generated by this method **(d)**. The spatial resolution of anaglyph stereo image is high enough (3008 x 2000 pixels) to reproduce well the brilliance of flower arrangement, which is designed by S. Fujisawa and J. Endo.

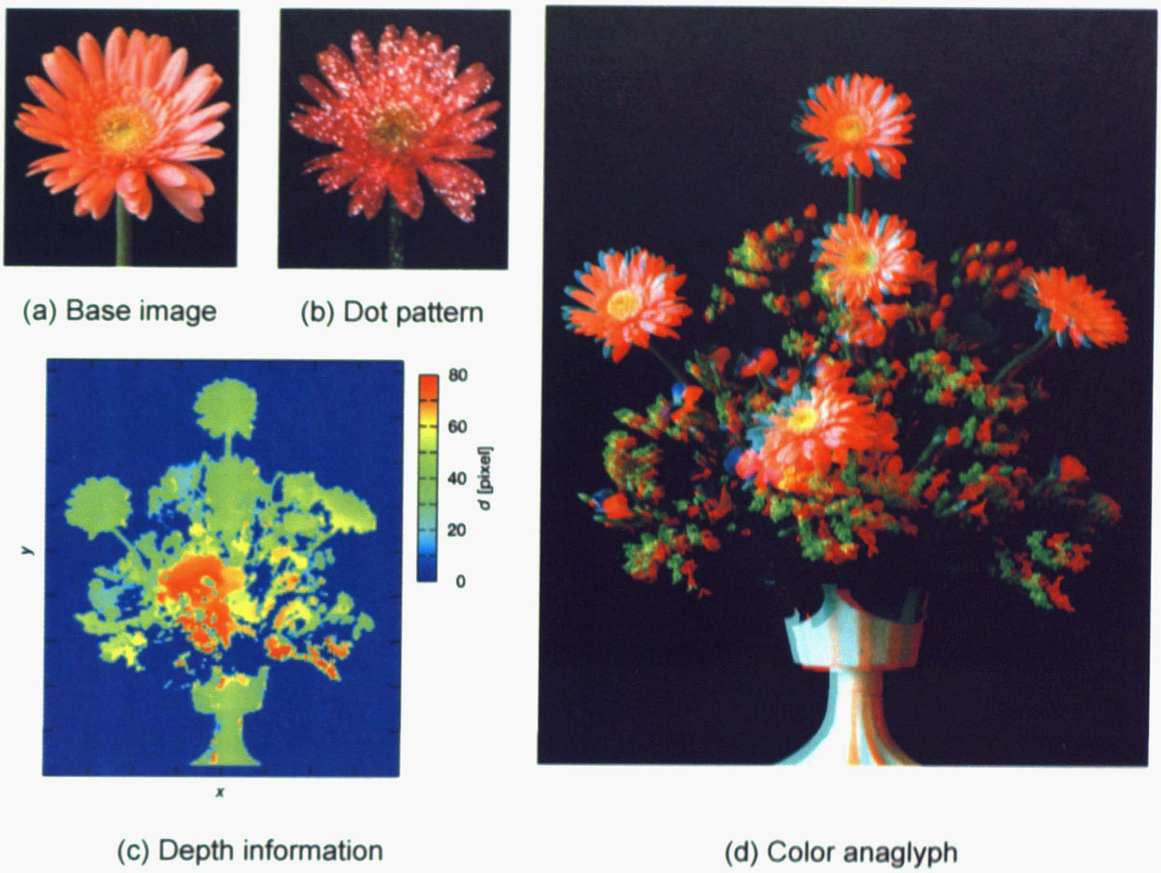


Fig. 3.9 Anaglyph stereo visualization of flower arrangement using depth information.

The creatable anaglyph image is limited between the parallel placed cameras by the method proposed in this chapter. The complicated camera calibration is also necessary, in order to use the depth information into a base image which is taken by a different camera or lens. From the point of view of the general usage, these limitations should be reduced. Further studies are described in the Appendix 2.

3.4 Conclusion

The three-dimensional visualization by anaglyph stereo image is studied by the use of a single image and the depth information of the target object. This technique allows the generation of anaglyph stereo images without the standard binocular camera. Three cases are considered in the present paper, which cover the monochrome anaglyph generated from target geometry, the monochrome and the color anaglyph generated from experimental depth information, which are obtained from other CCD cameras with an illumination using random dot pattern and the correlation-based pattern-matching analysis. These results indicate that anaglyph stereo images are successfully generated by the single image and the depth information, which indicates the validity of this technique. The visual quality of the anaglyph is greatly influenced by the inaccuracy in the depth information, but it depends on the darkness of the images. The examples of anaglyph stereo images are shown as the scientific art, such as the cube, the plaster figure, the artificial flowers and a flower arrangement, which are successfully observed through the red-cyan filtered glasses.

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Chapter 4

Conclusion

4. Conclusion

In this thesis, three-dimensional visualization technique for the application to the Scientific Arts was studied through the development of three-dimensional visualization technique. The results can be summarized as follows.

Chapter 1 shows the background of this research, which focuses the three-dimensional visualization technique for the application to the Scientific Arts. It also involves the explanation and survey of the visualization techniques, such as binocular visions.

Chapter 2 is the three-dimensional visualization of the rhythmical movements. It describes the impact of three-dimensional visualization on the field of the rhythmical movement. The examples of the anaglyph stereo images are presented, which are generated from the present experiment. A turn motion and vertical jump motion of gymnasts are selected here as a typical example. The liveliness of rhythmical movement can be seen in a series of stereo images, such as wave, wind, water flow and so on. These movements flow from the center of the body to peripheral parts of the body. Note that anaglyph images can be generated from both monochrome and color images. In both cases, the target color should be purple, yellow or white, because these colors transparent both red and cyan color filters.

Chapter 3 is the study on the development of anaglyph stereo visualization technique by the use of a single camera image and the corresponding depth information. The anaglyph stereo visualization technique using depth information allows 3D visualization of target object by commercial digital color cameras in parallel placement with a certain distance. This technique is applicable to the generation of highly brilliant stereo color images of a cube, a sculpture, artificial flowers and flower arrangements with reasonable cost in comparison with the standard method. In this chapter, three cases are concerned: generating anaglyph with given geometrical information (Case 1), generating monochrome anaglyph with experimentally obtained geometrical information (Case 2) and generating color anaglyph with experimentally obtained geometrical information (Case 3). The object of the case 1 is to create anaglyph if the geometrical information can be obtained by the specification of the target object (for instance, industrial product) or by the other devices, such as three-dimensional measuring equipments or three-dimensional cameras. The application of the visualization technique to sculpture is further studied in Appendix 2.

In summary, three-dimensional visualization techniques are developed for the application to the visualization of the Scientific Arts. It reveals that the visualization techniques are effective to the Scientific Arts.

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Appendix 1

Obtaining geometrical information

Nomenclature

C	Characteristic points
d	Parallax displacement
f	Focal length
L	Distance between two cameras
P	Intensity of the first image
P_m	Mean intensity of the first image
P_{sub}	Sub-pixel displacement
R	The cross-correlation coefficient in pixels
S	Intensity of the second image
S_m	Mean intensity of the second image
x, y, z	Physical coordinates
x', y'	Imaginary coordinates
α, β	Coefficients of matrix

A1.1 Direct cross-correlation function

When obtaining geometrical information from two pair of images by cameras placed different positions, the same point in real coordinate system must be searched from the images. For finding the parity point, template matching technique by direct cross-correlation function with sub-pixel analysis is used. Following equation (A1.1) gives the cross-correlation coefficient and equation (A1.2) gives sub-pixel displacement:

$$R(\Delta x, \Delta y) = \frac{\sum_{i=1}^{N}\sum_{j=1}^{N}\{P(X_i, Y_i) - P_m\}\{S(X_i + \Delta X, Y_j + \Delta Y) - S_m\}}{\sqrt{\sum_{i=1}^{N}\sum_{j=1}^{N}\{P(X_i, Y_j) - P_m\}^2 \sum_{i=1}^{N}\sum_{j=1}^{N}\{S(X_i + \Delta X, Y_j + \Delta Y) - S_m\}^2}} \tag{A1.1}$$

$$P_{sub} = i - \frac{1}{2}\frac{\ln R_{i+1} - \ln R_{i-1}}{\ln R_{i+1} - 2\ln R_i + \ln R_{i-1}} \tag{A1.2}$$

A1.2 Calibration

To compensate lens distortion, misalignment and origin point, the calibration of the CCD cameras is carried out using a calibration plate, which consists of 40 x 30 grid-line patterns. Note that the grid-lines are approximated by third order polynomial functions, which can be written as follows:

$$x = \sum_{j=0}^{3}\sum_{i=0}^{3}\alpha_{ij}x'^{i}y'^{j}, \quad y = \sum_{j=0}^{3}\sum_{i=0}^{3}\beta_{ij}x'^{i}y'^{j} \quad (i + j \leq 3) \tag{A1.3}$$

where x', y' are image coordinates, x, y are physical coordinates and α, β are coefficients to be determined by the least square method. These coefficients are calculated for each camera. In this study, linear interpolation is used for correcting the image deformation. After the correction of misalignment and lens distortion, anaglyphs are generated without any arbitrarily adjustment, which is often necessary in the generation of qualitative anaglyphs.

Appendix 2

Application of Anaglyph Stereo Visualization to Sculpture

Nomenclature

C	Characteristic points
d	Parallax displacement
f	Focal length
L	Distance between two cameras
x, y, z	Coordinates

A2.1 Background

In Chapter 3, the author proposed a method for creating an anaglyph by the use of a single camera image and the corresponding depth information (Matsuura and Fujisawa, 2008). The anaglyph stereo visualization technique using depth information allows 3D visualization of target object by commercial digital color cameras in parallel placement with a certain distance.

In this appendix, to reduce the limitation of camera position, anaglyph is generated from a single camera image taken at arbitrary position with pre-captured depth information of target domain. The position of camera should be obtained from the other devices to create anaglyph images to determine the depth information to be used. A plaster figure is selected for the typical example.

A2.2 Experimental method

Figure A2.1 is an illustration of the experimental setup, which consists of imaging device, LCD projector and frame grabber installed to a personal computer. A digital color CCD camera (3008 x 2000 pixels, 8-bit) with $f = 55$ mm lens is used for imaging the target object. The target object is placed on a turntable, so that the object can be spun around. In this study, the distance between the base camera and the target object is set to 2.4 m. A LCD projector is placed nearby the camera to project a random dot pattern on the target object surface. Each dot is 2-3 mm in diameter (5 pixels on the recorded image) and is white on the black background. In order to obtain the depth information of the target object, CCD cameras are located in parallel with a distance of 64 mm.

The camera calibration is carried out using a calibration plate to eliminate the effect of lens distortion. Note that the plate is cleared away before imaging the object. The calibration plate is not moved but fixed at one point in physical space, just for compensation the lens distortion effect. This calibration is required just once after lens is attached to the camera.

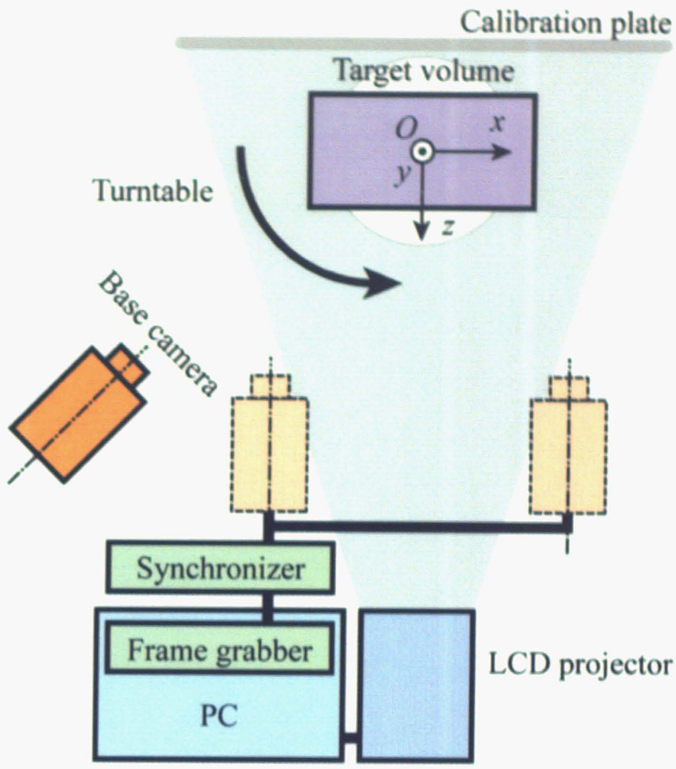


Fig.A2.1 Experimental setup for three-dimensional visualization.

A2.3 Generation of anaglyph images

Figure A2.2 shows the work flowchart of the generation of anaglyph images. Firstly, the depth information of target object is taken by parallel placed cameras. Take a picture with random dot pattern illumination, and then turn 5 degree. Repeat this process. Secondly, take a single camera image in the range of the depth information is captured. Displaced image is generated from the parallax displacement corresponds to the base image, from nearest depth information. Anaglyph is generated by the composition of the base and displaced image.

Figure A2.3 shows characteristic points of the depth information (horizontal direction.) Choose two depth information taken, which is the nearest the base image. From the depth information, find the inflection points. These points are indicated as C in **Fig. A2.3**. Assuming each characteristic point corresponds to the point in the other depth information. For instance, C_1 is corresponding to C_1'. The depth information for the base image is internally dividing points of each line segment: $\overrightarrow{C_0C_1}$ and

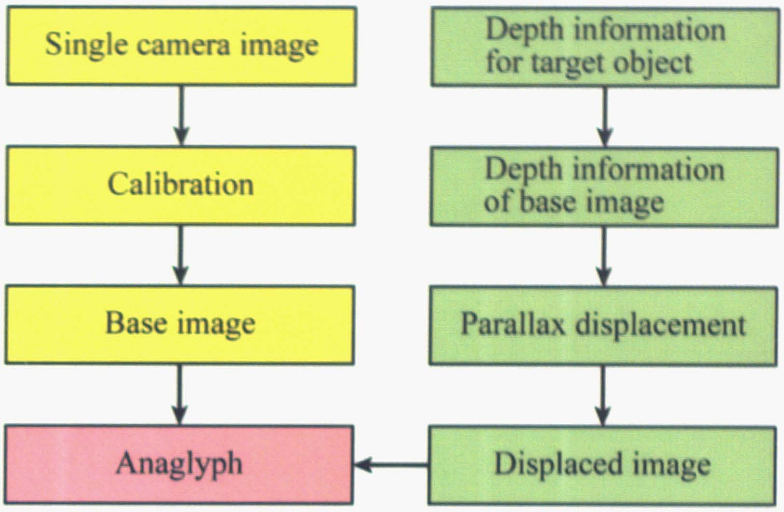


Fig.A2.2 Work flowchart

$\overrightarrow{C_0'C_1'}$, $\overrightarrow{C_1C_2}$ and $\overrightarrow{C_1'C_2'}$, and so on. Repeat this for all the lines in vertical direction.

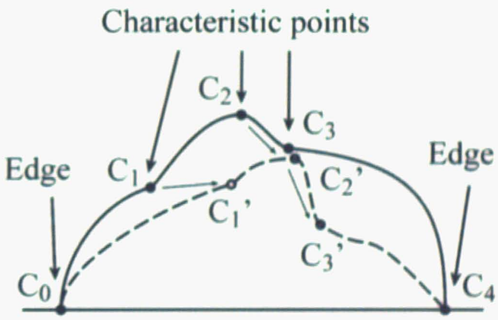


Fig.A2.3 Characteristic points of the depth information (horizontal direction.)

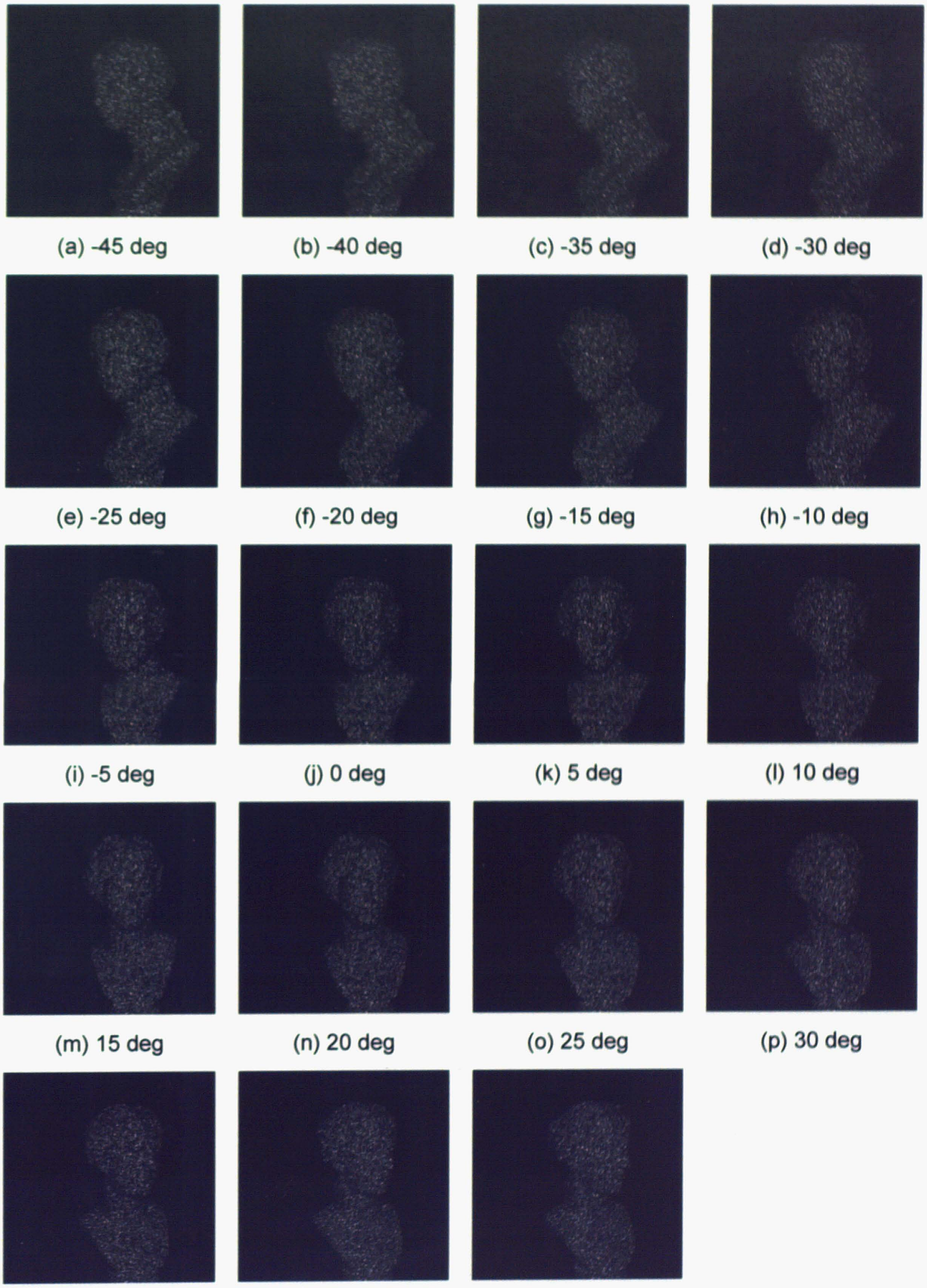
A2.4 Result and discussion

Figure A2.4 shows experimental images with random dot pattern projection. Each image is taken at the interval of 5 degree. **Figure A2.5** shows experimental images with white light illumination, which corresponds to random dot pattern images. Note that the images with white light illumination are not used in the present method.

Figure A2.6 shows the depth information calculated from the random dot projected images, at -30 and 0 degree. Note that the depth information is calculated by the method described in Chapter 3.

Figure A2.7 (a) shows the depth information at -15 degree calculated from two depth information which is shown in **Fig. A2.7**. **Figure A2.7 (b)** shows the experimentally obtained depth information at the same angle as **Fig. A2.7 (a)**. Note that the random dot images used here are only -30 and 0 degrees. The dynamic range in depth of calculated result is less than that of experimental result; however, it does not affect so much for anaglyph visualization.

Generated anaglyph image is shown in **Fig. A2.8**. To reduce cracks arise in a displaced image due to the occlusion, low-pass and median filters are processed. Ideses et al. (2005) proposed that one of the image pair can be blurred without decreasing image quality, so that this image processing does not make quality worse.



(a) -45 deg (b) -40 deg (c) -35 deg (d) -30 deg
(e) -25 deg (f) -20 deg (g) -15 deg (h) -10 deg
(i) -5 deg (j) 0 deg (k) 5 deg (l) 10 deg
(m) 15 deg (n) 20 deg (o) 25 deg (p) 30 deg
(q) 35 deg (r) 40 deg (s) 45 deg

Fig.A2.4 Experimental images with random dot pattern projection.

(a) -45 deg (b) -40 deg (c) -35 deg (d) -30 deg

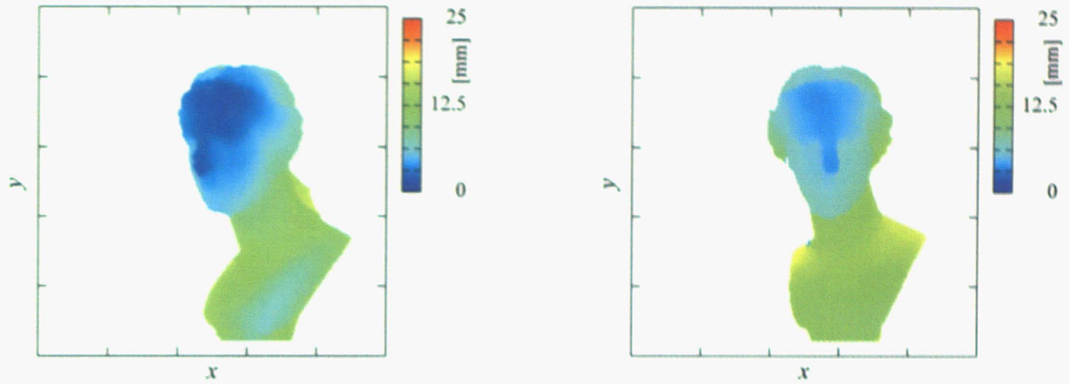
(e) -25 deg (f) -20 deg (g) -15 deg (h) -10 deg

(i) -5 deg (j) 0 deg (k) 5 deg (l) 10 deg

(m) 15 deg (n) 20 deg (o) 25 deg (p) 30 deg

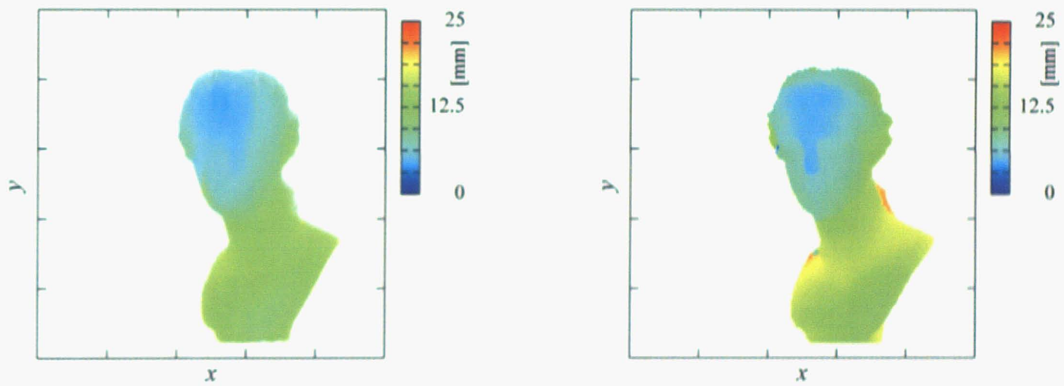
(q) 35 deg (r) 40 deg (s) 45 deg

Fig.A2.5 Experimental image with white light illumination.



(a) -30 deg (b) 0 deg

Fig.A2.6 Depth information.



(a) Calculated from -30 and 0 deg (b) Experimental

Fig.A2.7 Depth information at -15 deg.

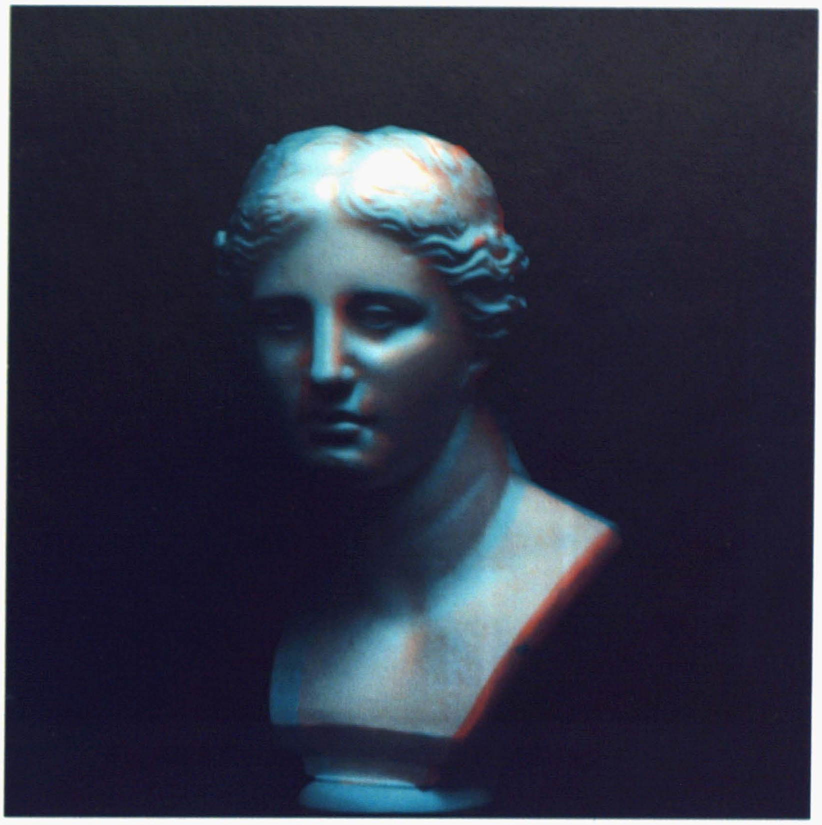


Fig.A2.8 Generated anaglyph at -15 deg.

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