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3D Imaging System for Tele-Manipulation

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1. Introduction

In accordance with the advancement of flat panel display technologies, recent researches of 3D display technologies are mostly focused on thin 3D displays using parallax barriers, lenticular lenses, or fry-eye lenses. Though some products based on these technologies have already been commercialized, they have not acquired many users. One of the main reasons why these 3D displays have not attained commercial successes is that most of these displays are developed for general purposes, not for a specialized purpose. In general, realization of 3D display has to sacrifice resolution. Also 3D displays give the viewer more eyestrains than 2D displays. In addition to these factors it should be noted that most 3D information can be obtained from 2D display with the intelligence of the viewer. Therefore 3D displays cannot be an attractive option unless they can offer substantial merits besides the impact at first impression.

Then where 3D displays become necessary and essential? To answer this question, let us consider how we perceive 3D information from 2D displays. There are several factors which can help depth perception from a simple 2D image. One of the most important factors is motion. Near objects tend to move faster than far objects in the 2D image. When the motion comes from the camera work, this relation always holds as long as the objects themselves are static. In this case it can be said that motion pictures on 2D display are presenting 3D information composed of x axis, y axis, and time axis. In other word, 2D displays cannot present 4D space composed of x axis, y axis, z axis, and time axis, which 3D displays showing motion pictures can present.

Then when 4D perception is necessary? One answer is real-time operation of 3D space. In real-time tasks such as tele-manipulation of robots or remote car driving, the operators or the drivers are required to grasp 3D location of the objects on the real-time basis. They cannot spare time to wait and see the change of image to perceive depth.

Real-time interaction systems where the viewer needs to perceive 3D space instantly include interactive visualization, 3D drawing, surgery simulations, etc. besides robot tele-operation and car driving. Since interactive systems can be used for various kinds of tasks, desired design of the system varies depending on the features of interaction. Therefore ready-made 3D displays cannot meet up with the requirement of the users. To increase the number of 3D display users for specialized purposes, it is important to present 3D displays designed for each use with low cost because we cannot expect cost reduction by mass production.

One ideal form of 3D interaction is that the viewer can work as if he or she were touching 3D objects directly with his or her hands and can feel that he or she is part of the 3D world. To achieve it, however, 3D space should be presented in the air so that the display may not interfere with the motion of the viewer. To present 3D image in the air conventional stereoscopic displays need to fabricate large artificial parallax. Unfortunately human depth perception does not rely only on the parallax but also on the focal accommodation of the eyes. Dependency on the focal accommodation of the eyes in depth perception increases when the viewer sees nearer objects. Therefore the contradiction between the binocular convergence of the eyes based on the parallax and the focal accommodation of the eyes (convergence-accommodation conflict) causes severe eyestrain or failure of depth perception especially when 3D image near the viewer is to be presented.

Besides convergence-accommodation conflict, motion parallax is also an important factor to realize physical 3D interaction. In the real world the objects are often located so that they hide one another. To give proper operation in the complex space, the operator has to move his or her head often to see what is hidden behind. Therefore realizing motion parallax is essential to let the operator work properly. Unfortunately, however, most conventional 3D displays cannot show motion parallax with wide viewing angle.

In the first half of this chapter, we measure the influence of motion parallax and convergence-accommodation conflict on depth perception of the operator. In the latter half of this chapter we introduce coarse integral volumetric imaging system, where both convergence-accommodation conflict and imperfection of motion parallax are overcome. This chapter is organized as follows. In Section 2 a couple of imaging systems which can show motion parallax are discussed and compared. In Section 3 effect of convergence-accommodation conflict on depth perception is discussed. In Section 4 a new 3D display system which can show motion parallax without convergence-accommodation conflict is explained.

2. Depth Perception by Motion Parallax

Clues of human depth perception are roughly categorized into two factors. One is the psychological factor. People can grasp rough 3D structure in the image even through 2D displays by perspective, motion, or occlusion relationship among the objects in the image. The other is the physiological factor.

The most famous and major physiological factor of depth perception is binocular parallax based on stereo disparity, which cannot be given by conventional 3D displays. Generally the phrases “stereoscopic display” or “3D display” are used to the displays which can show binocular parallax to the viewer. As for parallax, motion parallax, the change of view in accordance with the viewer’s motion, is also a physiological factor of depth perception.

To show motion parallax to the viewer who controls robots in a remote place, we can think of two major options. One is to use a master-slave camera system where the camera follows the viewer’s motion. The other is to use multi-camera system.

In the former system, we measure motion of the viewer with a 3-D position sensor and send the information to the slave camera system, which is controlled so that it moves to the position where the necessary texture can be best taken. This mechanism is expected to work well when the viewer moves slowly. The viewer can observe exact motion parallax as long as the position of the slave camera is correct. When the viewer moves faster, however, it is

impossible to catch up with the motion of the viewer because of the delay of mechanical control, which becomes larger as the motion of the viewer becomes faster. When the delay is large, the image presented to the viewer has large geometrical distortion.

In the latter system, the images which correspond to the positions of the viewer's right and left eyes are selected and sent to the viewer. Since the image can be switched instantly, delay is negligible as long as broadband signal transmission system is available. The problem of this system is that it cannot express continuous motion parallax. Since images are switched as the viewer moves, motion parallax is discrete, which can give unnatural impression to the viewer.

To evaluate the influence of delay and discretization of motion parallax, we have made computer applications with 3D CG which simulate delayed and discretized motion parallax. We set 6 conditions for simulations as follows:

- (1) Continuous motion and binocular parallax without delay,
- (2) Continuous motion parallax without delay, but no binocular parallax,
- (3) Discretized motion and binocular parallax (3cm) without delay,
- (4) Discretized motion and binocular parallax (6cm) without delay,
- (5) Continuous motion and binocular parallax with delay (1 second),
- (6) Continuous motion and binocular parallax with delay (2 seconds).

As for the hardware for the experiments, we use a CRT monitor which has 120Hz refresh rate, a pair of LCD shutter glasses which synchronize with CRT refresh rate and deliver 60Hz image to each eye (odd frames for the right eye and even frame for the left eye), and a magnetic 3D position sensor as shown in Fig. 1. With the LCD shutter system binocular parallax can be given to the viewer, while motion parallax is generated by changing the image to follow the viewer's position detected by the magnetic sensor.

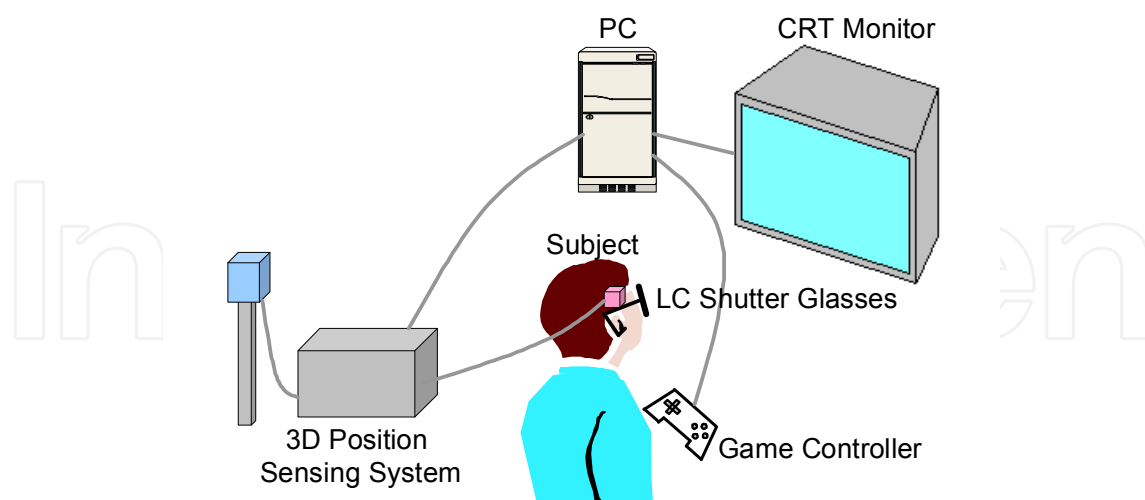


Fig. 1. Components of simulation system to test depth perception with delayed or discretized parallax.

To evaluate the effect of discretization and delay of motion parallax, we have made 3 simulators which require depth perception. The first simulator requires a simple task of hitting an approaching ball with a small pad bounded in a 2D plane parallel to the display

screen. The subject can move the pad in the first 8 seconds. Since the ball reaches the plane which includes the small pad 12 seconds after the ball is launched, the subject has to fix the position where he expects the ball reaches 4 seconds before it goes through the hitting plane. The time left for pad control is shown with the bars as shown in Fig. 2. The result of the experiment is shown in Fig. 3. Here 7 subjects have tried 18 trials each. The ball moves inside the box whose size is 24cm (width) X 12cm (height) X 24cm (depth). As the figure shows, the ideal condition with no delay and discretization (condition 1) marked the best result. The difference between the ideal condition and the other conditions, however, are relatively small in this experiment.

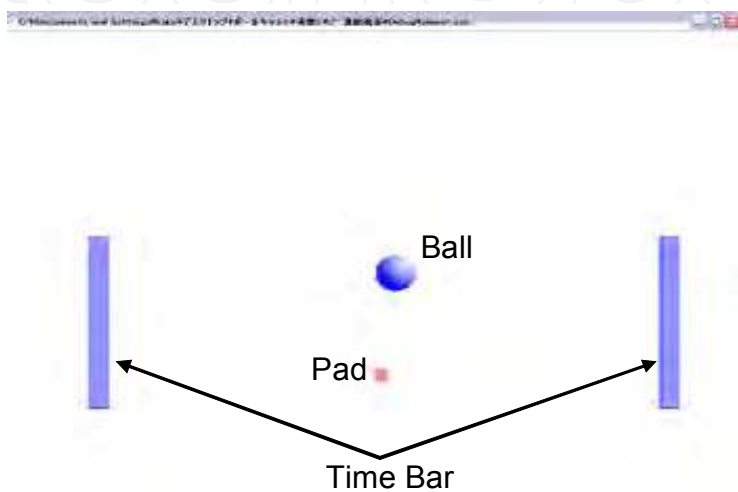


Fig. 2. Screen shot of the simulator to hit an approaching ball with a small pad.

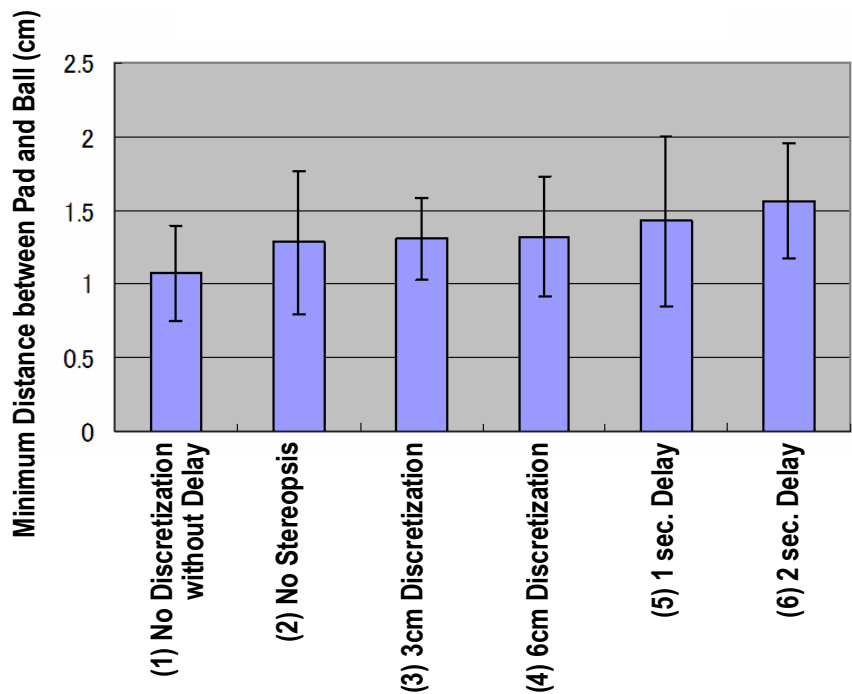


Fig. 3. Experimental results of subjects’ performance in the ball-hitting simulator under various parallax conditions.

The second simulator is a crane game where the subject is required to pick up the target object. Since the target is static in this task, we can evaluate precision of depth perception more directly. While the subject is pushing the first button, the crane moves leftward. After the subject releases the button, the crane starts going forward. When the subject pushes the second button, the crane stops moving and it goes down to pick the target.

Here we have prepared two kinds of settings for the experiment. In the first setting, the target lies on the floor with textures (Fig. 4 (a)). In the second setting the floor does not exist and the target looks like an object floating in the air (Fig. 4 (b)). The former setting is expected to be easier because the subject can perceive depth from the perspective information also, while the subject is required to grasp depth only from the binocular and motion parallax in the latter setting, which is the best condition to test the effect of delay and discretization of parallax.

The result of the experiment is shown in Figs. 5 and 6. Here the number of subjects is 7 and the size of the workspace is 28cm (width) X 28cm (depth). The speed of the sliding motion of the crane is 2.5cm/s and the height of the crane from the target is 10.5 cm. 10 trials are given to each subjects and the average performances under different conditions are compared.

As Fig. 5 shows superiority of the condition without delay and discretization is weak when the floor is shown, while it becomes obvious when the floor is not shown. Without the floor, the subject has little psychological clues such as perspective to grasp the positional relationship among objects in the image. Therefore he or she has to rely on physiological clues such as binocular parallax and motion parallax to perceive depth. In this case lack of binocular parallax (condition 2), rough discretization of binocular and motion parallax (condition 4), and delay of motion parallax (conditions 5 and 6) can have strong influence on the performance of the operator.

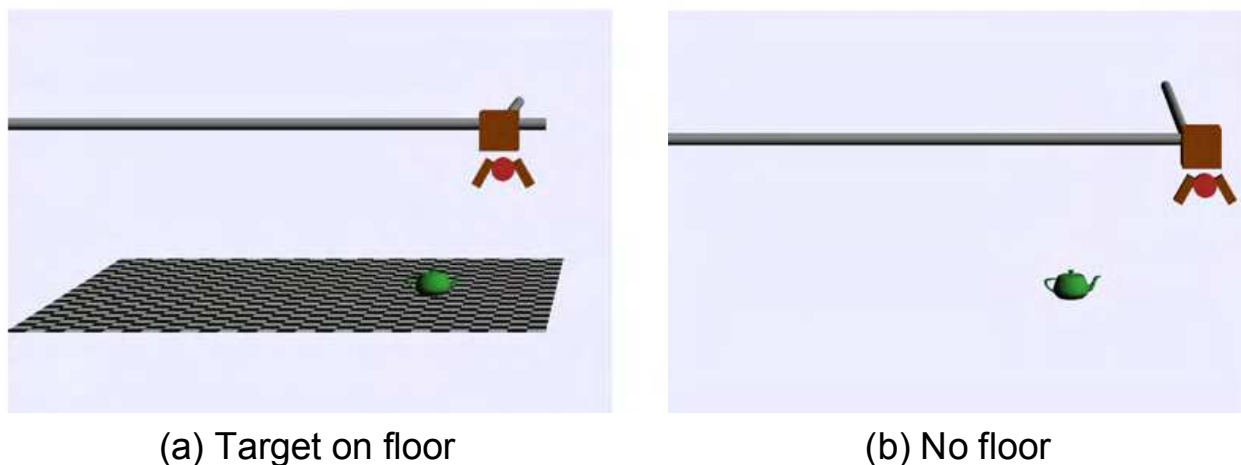


Fig. 4. Screen shots of crane game simulator with textured floor (a) and without floor (b).

The third and the last simulation is remote control of helicopter as shown in Fig. 7. The first and the second simulators explained above require only simple operations, while the third simulator requires more complex operations. The subject has to use 8 buttons as shown in Fig. 8 to control the helicopter. Also since this simulator is based on physical dynamics of the real world, the helicopter has inertia, which makes the control even harder.

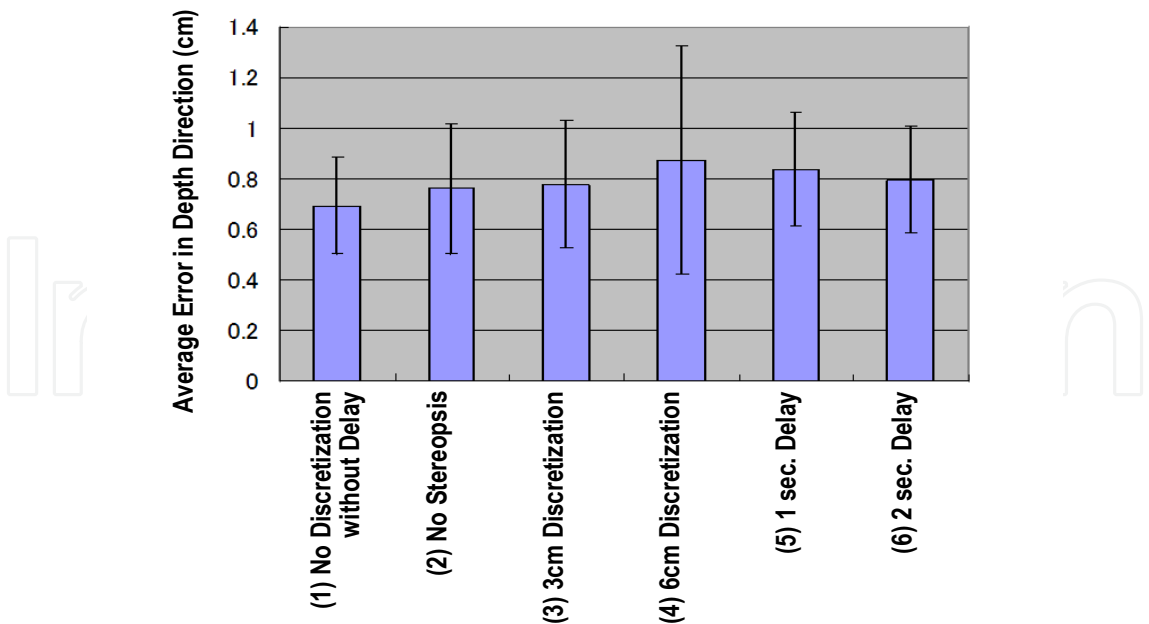


Fig. 5. Experimental results of subjects’ performance in the crane game simulator with textured floor.

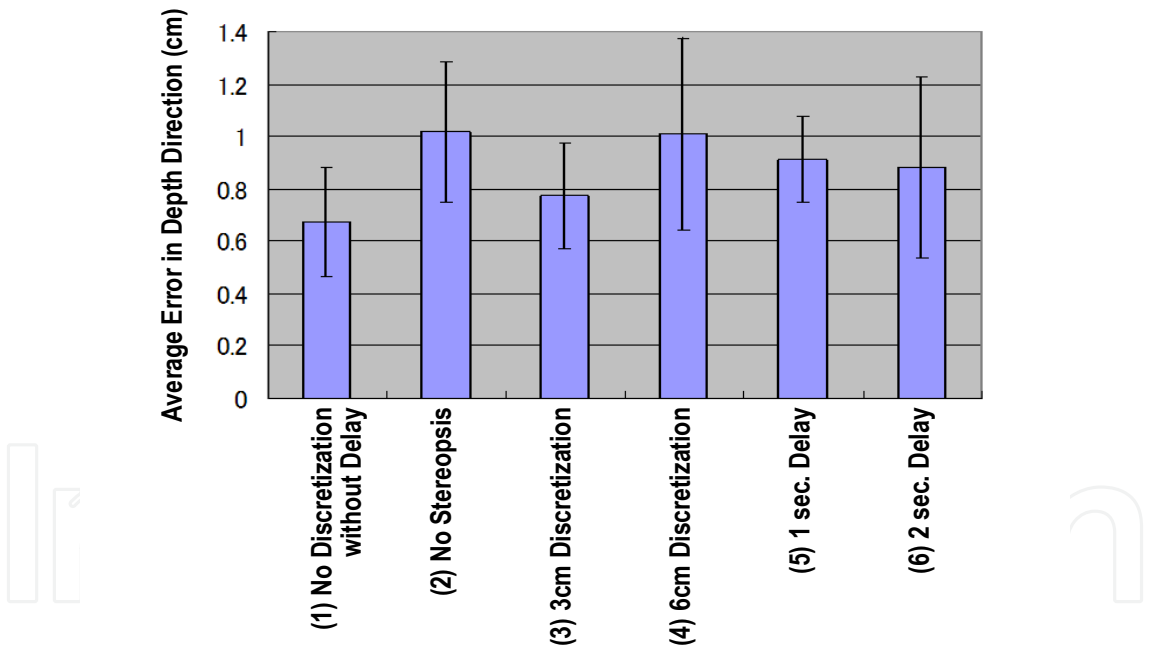


Fig. 6. Experimental results of subjects’ performance in the crane game simulator without floor.

The subject is required to let the helicopter go through the ring floating in the air, which requires precise depth perception of the ring and the helicopter. The other difference of this simulation from the former simulations is emergence of occlusion. In the environment where the target ring and the helicopter can hide one another, motion of head to check the occluded area becomes important, where precise motion parallax can play an important role for depth perception.

The result of the experiment is shown in Fig. 9. Here 20 trials are given to each of the 7 subjects and the average failure rate of the task for each condition is calculated. The helicopter can move inside the box with the size of 24cm (width) X 12cm (height) X 24cm (depth). The maximum speed of the helicopter is 4cm/s and the subjects are required to let the helicopter go through the ring within 15 seconds.

In this experiment lack of stereopsis affects the performance of the operator most as shown in Fig. 9. Discretization and delay of motion parallax also affects the performance when the extent of discretization and delay is large.

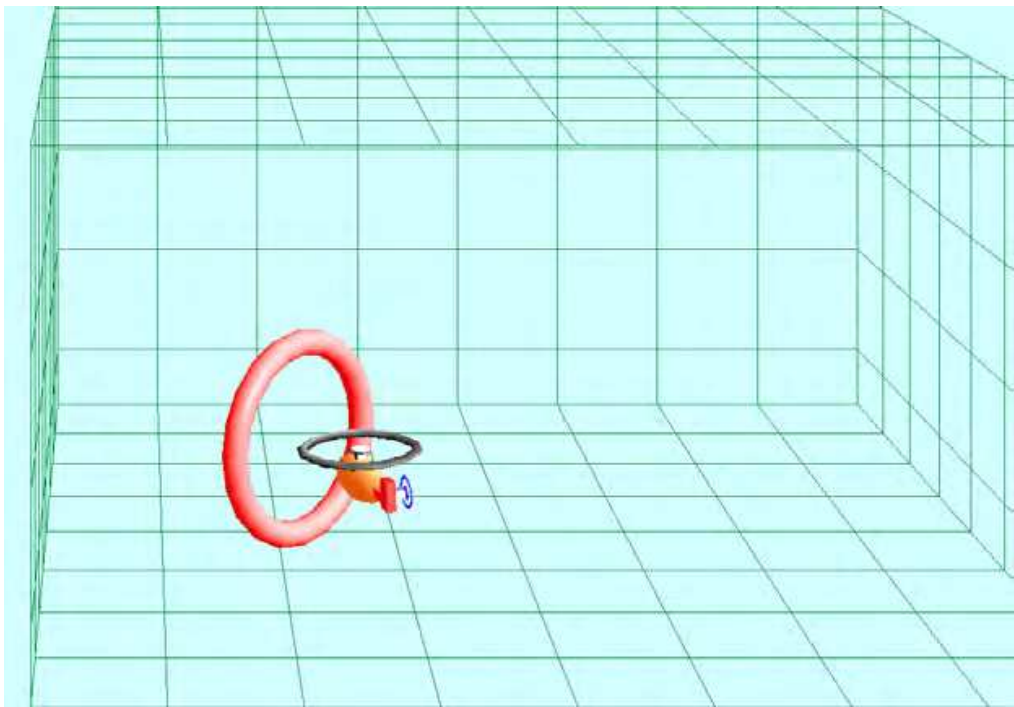


Fig. 7. Screen shot of helicopter remote-control simulator.

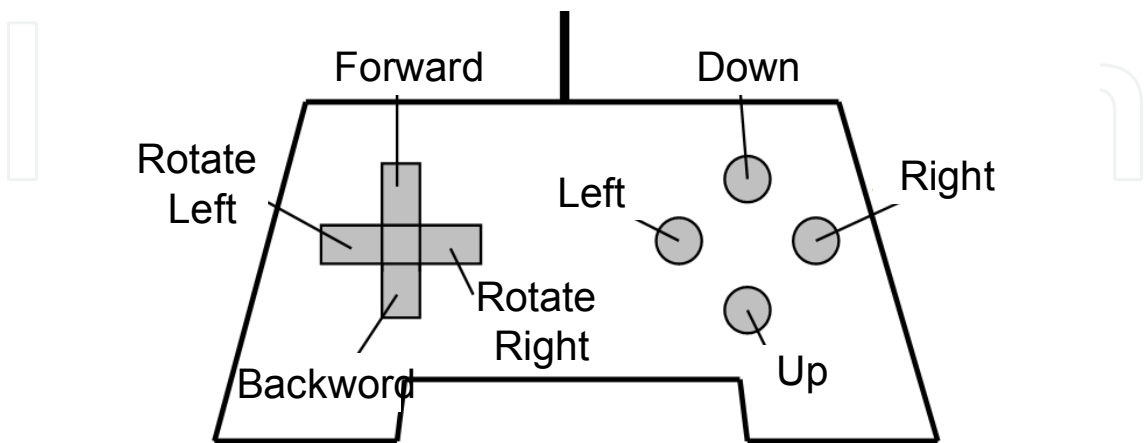


Fig. 8. Alignment of buttons in the pad to control helicopter remote-control simulator.

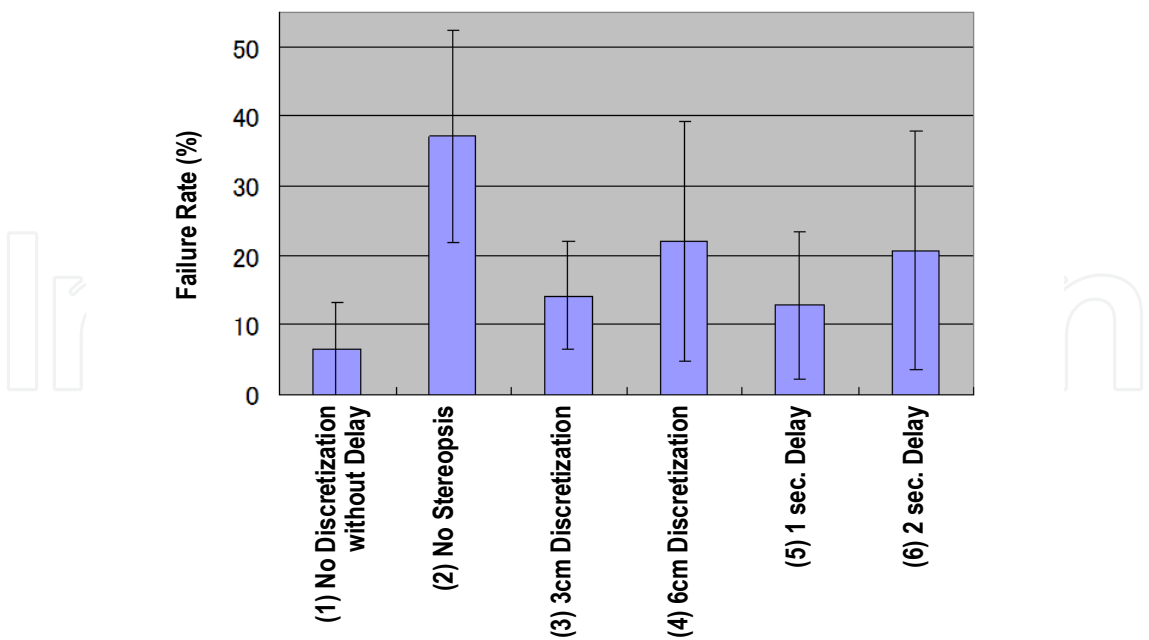


Fig. 9. Experimental results of subjects’ performance in the helicopter remote-control simulator.

To sum up the results of these 3 experiments, we can say that smooth motion parallax with little discretization and delay is important in the tasks where the psychological depth cues are limited or the objects in the space occlude one another, which is often the case in complex tele-operation tasks.

3. Depth Perception by Accommodation

3.1 Convergence-Accommodation Conflict

For human depth perception, lack or imperfection of motion parallax is not the only problem of conventional 3D displays. Convergence-accommodation conflict can also affects depth perception of the observer.

When we watch a certian point in the scenery, we focus on that point so that it can be seen clearly. Then the points far from the focused depth are blurred. In the natural scene we unconsciously keep on controlling focus of our eyes so that we can see the objects of interest clearly. When we see typical stereoscopic displays, however, our focus is always fixed on the screen because they rely only on the setereo disparity to show depth of the space. Usually stereoscopic displays emit light from one plane, where the focus of the viewer is always fixed, while binocular convergence of our eyes chnages depending on the stereo displarity of the object we look at.

Under natural circumstances the status of binocular convergence and focal accommodation has stable one-to-one correspondance. Since both convergence and accommodation are unconsciously coordinated physiological processes, loss of correspondance has bad influences on physiology of human vision. Concretely the viewers of stereoscopic display often experience eyestrain or sickness peculiar to stereo vision. This loss of correspondance between binocular convergence and focal accommodation has been one of the major problems of stereoscopic display researchers.

Besides eyestrain and sickness, convergence-accommodation conflict can also affects depth perception, which can be a fatal problem for robot tele-operation systems. In the next subsection we show the results of the experiment to examine the effect of convergence-accommodation conflict on depth perception of the viewers.

3.2 Effect of Convergence-Accommodation Conflict on Depth Perception

As for the experiment we use the crane game used in the last section. To prepare the setting where the convergence-accommodation conflict is reduced, we produce the experimental system as shown in Fig. 10. In this system we use two displays and the points in the middle is depicted in both displays with DFD algorithm (Suyama 2000, Suyama 2002, Suyama 2004), where the points are depicted brighter on the nearer display. We trace the head position and use it to depict each point on both displays so that the points on both displays are overlapped and perceived as one point. The light from two displays can be combined by using a half mirror as shown in Fig. 11.

Here we have let 8 subjects try the crane game described in the previous section under 1 display condition and 2 display condition. The subjects have repeated 10 trials and the average performances are compared. The result of the experiment is shown in Fig. 12.

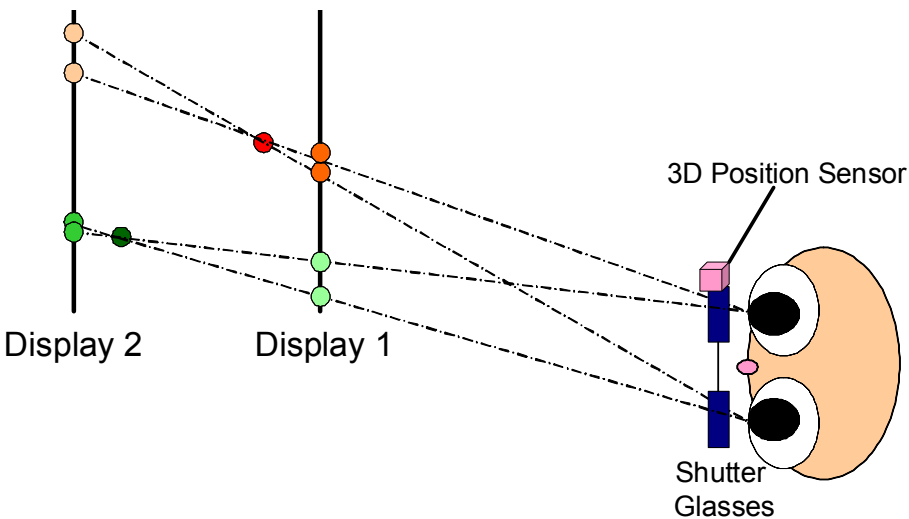


Fig. 10. Experimental system with 2 displays to ease convergence-accommodation conflict.

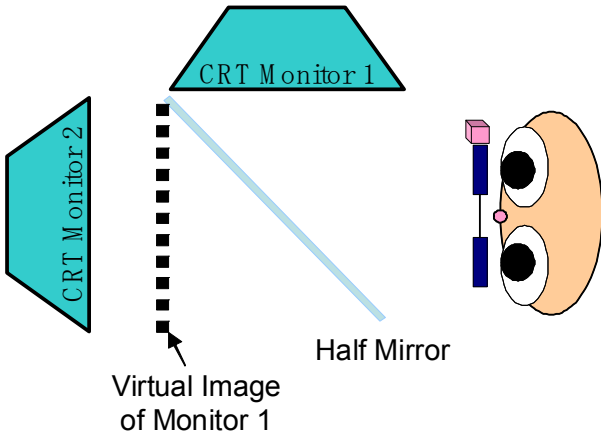


Fig. 11. Experimental instruments to merge images from 2 displays at different depths.

Though 2 display condition is better on average, the difference between two conditions are not very wide. It should be noted, however, that all of those who have performed poorly under 1 display condition have improved their performances under 2 display condition. It suggests that those who are not good at traditional stereopsis can perceive depth better when convergence-accommodation conflict is eased by inserting another display at different depth.

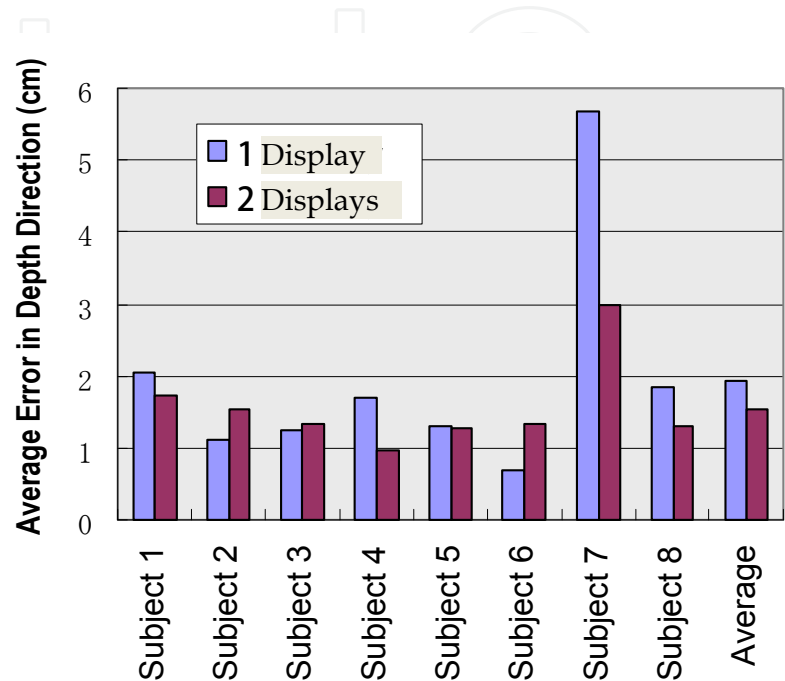


Fig. 12. Experimental results of subjects’ performance in the crane game under 1-display and 2-display conditions.

4. Coarse Integral Volumetric Imaging

As described in the previous sections, to let the operator of robot grasp precise depth, a 3D display system with smooth motion parallax and little convergence-accommodation conflict is required. In this section we introduce a new 3D display system which can meet these requirements.

4.1 Concept of Coarse Integral Volumetric Imaging

Integral imaging, which combines fly-eye lenses and a high resolution flat display panel, is a prominent 3D display system in the sense that it can show not only horizontal parallax but also vertical parallax. In the conventional integral imaging, the number of pixels each component lens of the fly-eye lens sheet covers is usually the same as the number of views, which means that the viewer perceives each component lens as one pixel. Therefore the focus of the viewer’s eyes is always fixed on the screen (fly-eye lens sheet), which makes it hard to show realistic images far beyond the screen or popping up from the screen. Besides the orthodox integral imaging described above, we can also think of integral imaging where each component lens is large enough to cover pixels dozens of times more than the number of views. We have defined this type of integral imaging as coarse integral

imaging (Takeya 2008). In recent years coarse integral imaging has been studied by the research group lead by Prof. Byongho Lee (Lee 2002, Min 2005). The advantage of coarse integral imaging is that it can induce focal accommodation off the screen, for it generates a real image or a virtual image with the lenses. Thus we can show realistic images far beyond the screen or popping up from the screen. Yet it cannot overcome the problem of convergence-accommodation conflict because the eyes of the viewer are always focusing on the real image or the virtual image generated by the lens array.

To solve this problem, the author has proposed coarse integral volumetric display method, which combines volumetric solution with multiview solution based on coarse integral imaging (Takeya 2008). In the proposed system layered transparent display panels are used instead of a single layer display panel for the coarse integral imaging. When we use multi-layered display panels, we can show volumetric real image or virtual image. To express pixels between image planes we can apply DFD approach, where 3D pixels are expressed with two adjacent panels, each of which emit light in inverse proportion to the distance between the 3D pixels and the panel. With this method we can overcome the shortcomings of multiview displays and volumetric displays at the same time.

Conventional volumetric displays can achieve natural 3D vision without contradiction between binocular convergence and focal accommodation, while they cannot express occlusion or gloss of the objects in the scene. On the contrary multiview displays can express the latter while it cannot achieve the former. The coarse integral volumetric display can realize both natural 3D vision and expression of occlusion and gloss.

4.2 Detail of Coarse Integral Volumetric Imaging

Before explaining detail of coarse integral volumetric imaging, we give a brief review of coarse integral imaging. As explained above, coarse integral volumetric imaging has real image version where the 3D image is popping up and the virtual image version where the 3D image is shown beyond the screen. Here we explain the real image version, for it can show 3D structure of remote spaces better because of the closeness.

In the real-image coarse integral imaging we usually keep the distance between the display panel and the lens sheet (convex lens array) the same as the focal distance of the component lenses of the lens array. With this configuration only, the light is just collimated and real image is not generated. To generate real image, we use a large aperture convex Fresnel lens as shown in Fig. 13. Then the real image with little aberration is generated at the focal distance of the Fresnel lens away from the Fresnel lens surface.

We can make a multiview system where the whole image observed in each eye switches alternately when we keep the distance between the lens array and the large aperture Fresnel lens long enough to generate the real image of the lens array, which corresponds to the viewing zone where the view for each eye changes alternately (Takeya 2007).

The merit of this configuration is that the center of the image from all the viewpoints goes through the optical axis of each component lenses. If we try to converge light only with small component lenses, the light which goes to the center of the image is not perpendicular to the optical axis of each component lenses. Then the distance between the LCD panel and the lens array in the optical path becomes larger as the viewpoint becomes farther from the center, which makes the distance between the lens array and the real image shorter. With the configuration shown in Fig. 13, the distance between the center of the image on LCD and

the center of the lens is constant regardless of the difference of viewpoints. Thus we can form real images almost on the same plane with the help of the large convex Fresnel lens.

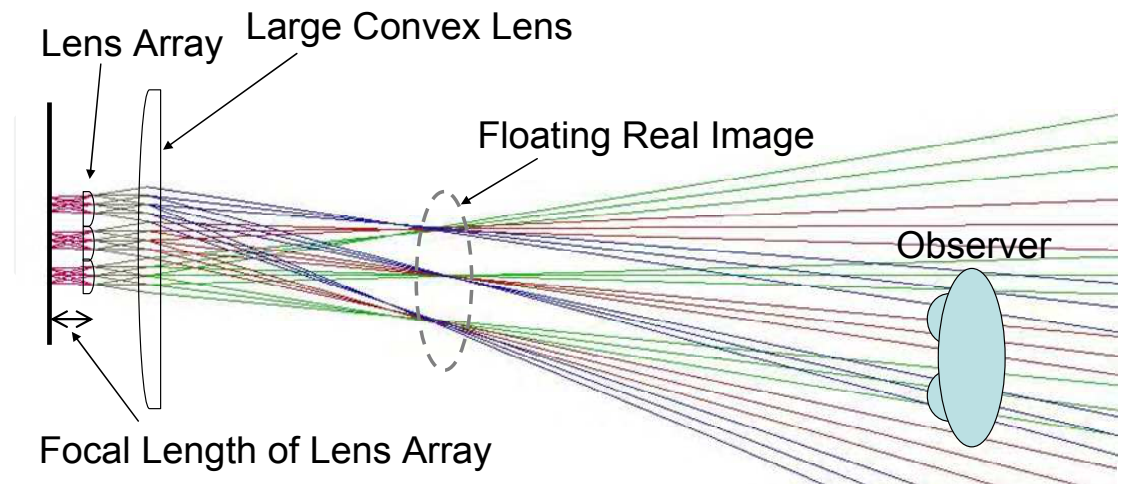


Fig. 13. Optics of real-image coarse integral imaging display.

The main differences between this system and the conventional integral imaging displays are the size of the component lenses of the convex lens array and the use of large aperture Fresnel lens. In this system each component lens of the lens sheet covers about hundred by hundred pixels. In the traditional integral imaging all the edges of the image are in the plane of lens sheet, because each component lens of the lens sheet corresponds to one pixel. In coarse integral imaging, however, the image through each lens includes large number of pixels, whose edges can induce the viewer to focus on the real image produced by the lenses. Thus the image produced with coarse integral imaging can be perceived as an image floating in the air.

Though coarse integral imaging can show images off the screen, the problem of convergence-accommodation conflict still exists, for it can only generate one image plane. This can deteriorate depth perception of the viewer as discussed in Section 3. Besides convergence-accommodation conflict, coarse integral imaging has another major problem which can severely damage the quality of the image. It is discretization of parallax as discussed in Section 2. When the distance between the lens array and the large aperture Fresnel lens is not far enough, multiple images from different component lenses are observed at the same time. In this case discontinuity of the images from different lenses becomes severe because of the parallax discretization when the 3D image to be shown has large depth. To show depth of the image, this system depends only on the parallax given by multiview principle. The parallax among the images from different lenses has to be larger as the depth of the 3D object to be shown becomes wider. Consequently discontinuity of the images on the boundaries of the lenses becomes apparent as shown in Fig. 14, which damages the image quality.

To solve the problem of convergence-accommodation conflict and discontinuity of image at the same time, we have proposed coarse integral volumetric imaging, which is based on the idea of introducing volumetric approach in addition to multiview approach (Yasui et al. 2006, Ebisu et al. 2007).

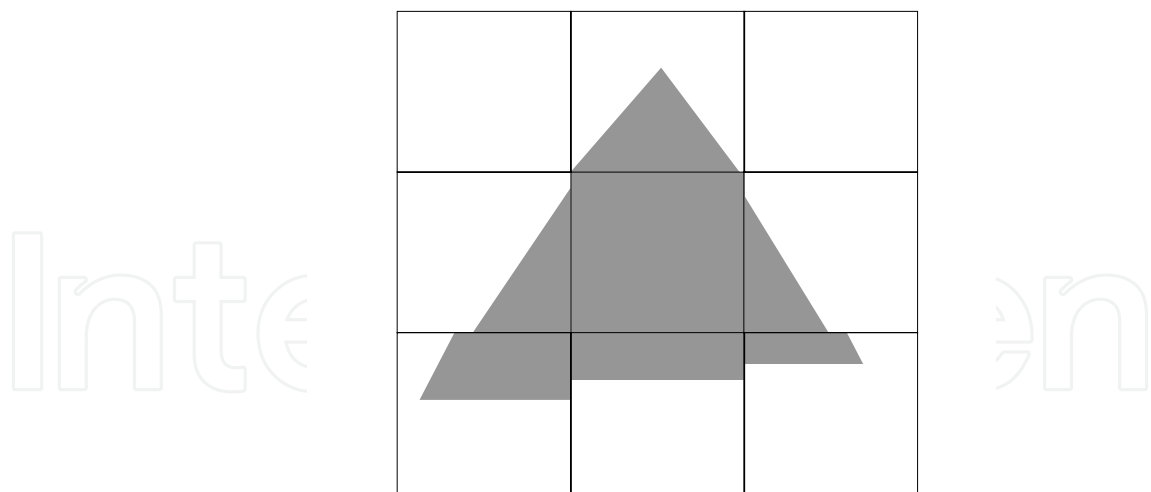


Fig. 14. Discontinuity of image in coarse integral imaging because of parallax discretization.

As shown in Fig. 15, multiple display panels are inserted to generate volumetric real image to keep the parallax between the images from two adjacent lenses small enough. Since artificial parallax is kept small, discontinuity between images from adjacent lenses are also kept small. Convergence-accommodation conflict is also reduced since each 3D pixel is displayed at the real-image layer near the right depth.

To express pixels between two panels we can use DFD approach, where 3D pixels are expressed with two adjacent panels, each of which emit light in inverse proportion to the distance between the 3D pixels and the panel. Thus natural continuity of depth is realized.

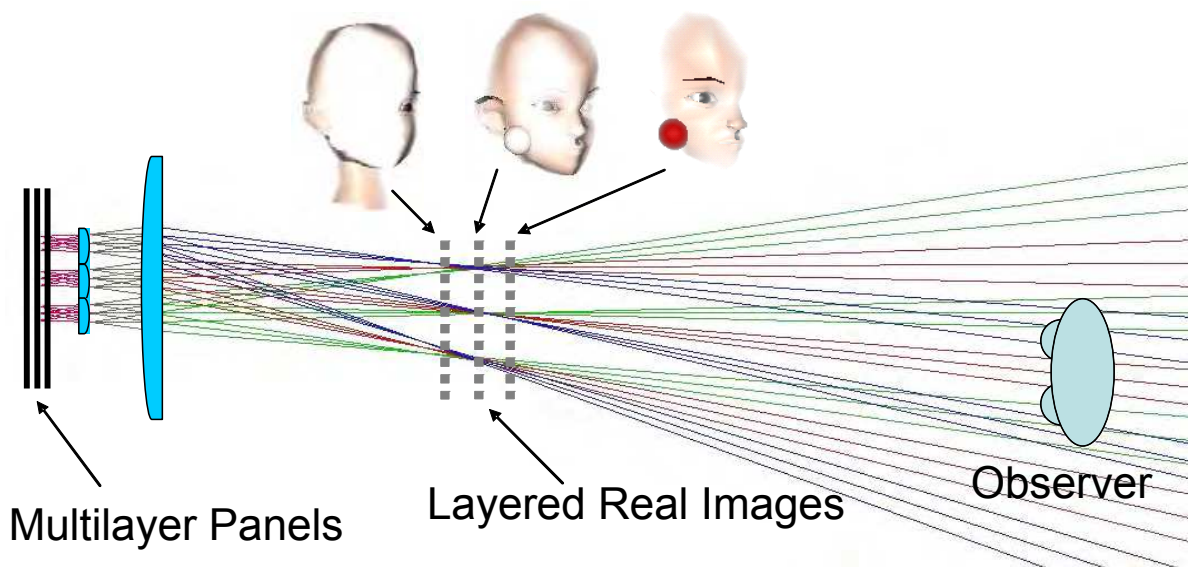


Fig. 15. Principle of coarse integral volumetric imaging.

4.3 Improvement and Application of Coarse Integral Volumetric Imaging

Fig. 15 approximates that the real-image planes are flat. In reality, however, the real image is curved and distorted as shown in Fig. 16. Not only the generated image plane is distorted,

but also the image planes generated by component lenses of the lens array are not uniform. The image planes generated by the component lenses off the optical axis of the large aperture Fresnel lens do not have line symmetry about the optical axis, but are slanted toward the optical axis. The slant becomes greater as the component lens goes farther from the optical axis.

To compensate these distortions, each 3D pixel should be drawn on the adjacent two distorted image planes so that the brightness may be in inverse proportion to the distance to each plane as shown in Fig. 17. Since ways of distortion are different among component lenses, we apply this method for each component image by modifying the parameters so that each pixel is drawn at proper 3D positions (Kakeya 2009).

Fig. 17 shows a 3D still picture shown with the coarse integral volumetric display using DFD for distorted image plane. Here to increase connectivity between adjacent images, hexagon lenses are used for the component lenses of the lens array, for less artificial parallax is needed when the lens pitch becomes shorter.

To apply coarse integral volumetric imaging to tele-manipulation, we need electronic display and camera system for it. Currently it is hard to obtain inexpensive volumetric display with resolutions high enough to be applied to integral imaging. With the advancement of current display technologies, however, it is expected that we can obtain inexpensive solution to realize high resolution volumetric displays in a couple of years. With the current technology we have realized an electronic display for coarse integral volumetric imaging by merging images from different depths by half mirrors, though the hardware becomes bulky (Fig. 18).

As for camera system, coarse integral volumetric imaging needs not only images from multiple cameras, but also depth of pixels in the image from each camera. One way to realize it is stereo-matching. This algorithm, however, requires much calculation and frame rate becomes low unless we use high-spec computers. Further research is needed to overcome this problem.

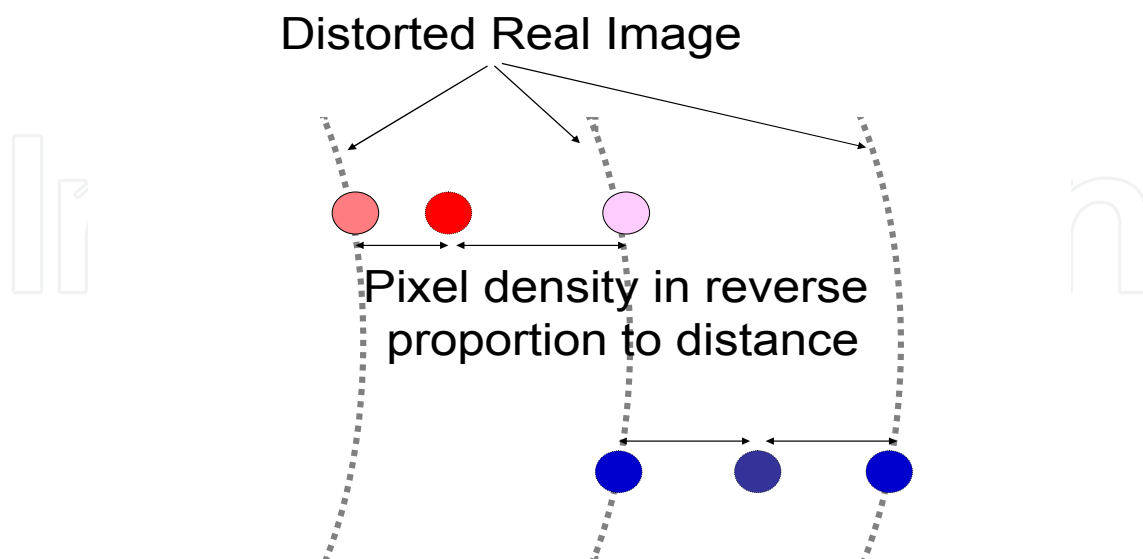


Fig. 16. Distortion of image planes and DFD algorithm for distorted image planes



Fig. 17. Prototype of coarse integral volumetric display using DFD for distorted image plane and hexagon component lenses (left) and the images observed from two different viewpoints with the prototype system (middle and right).

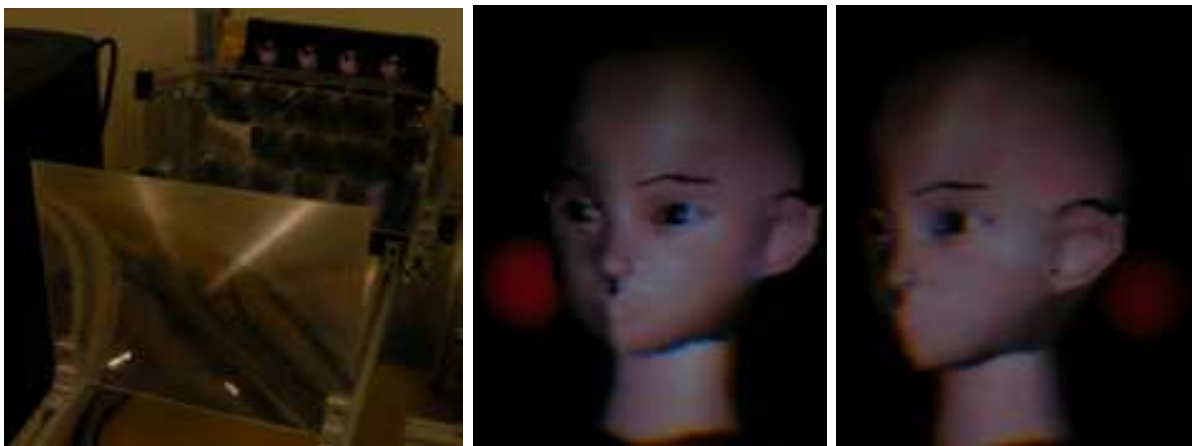


Fig. 18. Electronic version of coarse integral volumetric display using a half mirror (left) and the images observed from two different viewpoints with this display (middle and right).

7. Conclusion

In this chapter, we have discussed the influence of imperfect motion parallax and convergence-accommodation conflict on depth perception of the operator. Smooth motion parallax with little discretization and delay is important in the tasks where the psychological depth cues are limited or the objects in the space occlude one another. Also convergence-accommodation conflict has bad influence on depth perception.

To overcome these problems we have introduced coarse integral volumetric imaging, which can show smooth motion parallax and reduce convergence-accommodation conflict. In the coarse integral volumetric display, multi-layered display panels are used for each component image, which is refracted by a small component lens of the convex lens array and a large aperture Fresnel lens to generate volumetric real image or virtual image. To express pixels between two panels, 3D pixels are expressed with two adjacent panels, each of which emit light in inverse proportion to the distance between the 3D pixels and the panel. It has been confirmed with a prototype system that coarse integral volumetric imaging can realize smooth motion parallax.

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Robot manipulators are developing more in the direction of industrial robots than of human workers. Recently, the applications of robot manipulators are spreading their focus, for example Da Vinci as a medical robot, ASIMO as a humanoid robot and so on. There are many research topics within the field of robot manipulators, e.g. motion planning, cooperation with a human, and fusion with external sensors like vision, haptic and force, etc. Moreover, these include both technical problems in the industry and theoretical problems in the academic fields. This book is a collection of papers presenting the latest research issues from around the world.

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