Collaboration Projects

We will introduce a new category of "Collaboration Projects," which will highlight DoCoMo's joint research activities with universities and other companies. DoCoMo carries out R&D to build up mobile communication, however, we also engage in cutting-edge joint research activities with universities and other companies in order to maximize the results of our R&D and to explore new research areas.

We expect that new joint research frameworks can be created, and that new research areas can be established through mergers of various different fields. Moreover, we strongly hope that this promotion will lead to further activation of the Japanese mobile communication industry as a whole, resulting in reinforcement of international competitiveness of Japan.

Natural Viewing 3D Display

We made a 3D display prototype that allows natural 3D vision, eliminating the need of special glasses and has smooth motion parallax. This device has a simple configuration where a renticular sheet is laminated on a high-definition display, and the display looks three-dimensional from a wide range of angles. This research was conducted jointly with the Takaki laboratory (Professor Yasuhiro Takaki), the Department of Electrical and Electronic Engineering, Faculty of Engineering, Tokyo University of Agriculture and Technology.

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1. Introduction

The advancement of display technologies used for portable terminals such as mobile terminals and portable video game machines is significant. One of the directions in which the technologies are moving is toward higher resolution, while another is toward three-dimensional (3D) display. The main approach to 3D display is based on stereoscopic viewing, exploiting the principle of the binocular parallax[*1]; a wide variety of methods have been proposed and commercialization of various technologies has actively been promoted. However, the usefulness of 3D displays adopting stereoscopic viewing has been restricted by the fact that it is necessary to wear special eyeglasses or that the positions from which the display looks three-dimensional were limited when seen with the naked eye. When considering the usage of 3D displays in mobile environments, it is necessary that the images must look three-dimensional from any direction, so that the user will not have to adjust the position in order to find a viewing angle where the 3D effect is satisfied without glasses. Moreover, the size of such displays is required to be compact, from the size of mobile terminal displays to sub-note computer displays (e.g., B5 size). Until now, 3D displays of this size have not been examined actively. For this reason, we first listed up requirements for 3D displays (portable 3D displays) that would be used for applications in mobile environments. We then selected a design that satisfies these requirements, and actually made a prototype of a portable 3D display terminal.

This article presents the development overview and discusses the evaluating results whether the prototyped display satisfies the requirements.

2. Requirements of Portable 3D Displays

2.1 Requirements from the 3D Content Side

At the 3D Consortium [1] in 2004, a survey involving experimental distribution of 3D content (CG or static photo images) to mobile terminals was conducted. According to the results of this survey, the respondents answered that they would

*1 Binocular parallax: Differences between images reflected on the light-sensitive parts (retina) of the left and right eyes. We process these differences with the brain to perceive depth.

like to see various content displayed in 3D, including picture books, photo albums, movies and animations [2]. From this result, it is inferred that users demand a sense of reality in the 3D images. In a mobile terminal context, this "reality" can be interpreted as an impression of "visual presence" of the 3D images and a "feeling of holding the objects in one's hand."

2.2 Requirements Based on Physiological Factors

The main physiological factors causing humans to perceive three-dimensional space include accommodation*2, binocular parallax, motion parallax*3, convergence*4 and field of view (realistic sensation). In addition, psychological factors, such as size and pattern difference, and overlapping of objects, also have an influence on the perception. **Figure 1** shows the ranges of distances between an observer and a display image where each of these depth perception factors operates. For instance, if the observation distance is long, conventional stereoscopic displays are sufficient, whereas reproduction of the accommodation function becomes necessary as the observation distance becomes short. Reproducing these functions is particularly important in order to eliminate fatigue from eye strain caused by disagreement between accommodation and convergence.

Moreover, considering that the display should be used in mobile applications, the relative position between the display and the viewer's head (viewing point) cannot be fixed. For this reason, the major requirements include achievement of smooth motion parallax, where the distance at which the display can be viewed is not restricted, and the way objects look different according to the motion of the viewer's head, and a wide view range where the viewer's head is allowed to move freely.

*2 Accommodation: Focus adjustment by eyes. Refers to adjusting the focus to look at an image by changing the thickness of the eyes' crystalline lens. We perceive depth through the relaxation of the muscles that change the thickness of these lenses.

*3 Motion parallax: Changes in the relative position of an object caused by motion of the viewer's head. We perceive depth by these changes.

*4 Convergence: A slight rotation of both eyes toward an object when looking at the object. Since this rotation angle changes depending on the distance to the object, we can perceive the depth from the rotation of the pupils.

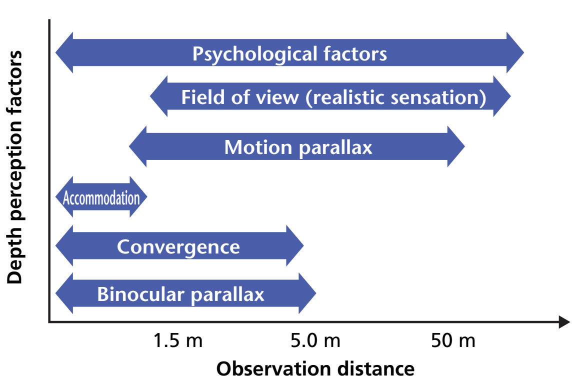


Figure 1 Relationship between depth perception factors and observation distance

2.3 Requirements for Portable 3D Displays

From the aforementioned considerations, we narrowed down the requirements for portable 3D displays to three categories: "viewing angle," "smooth motion parallax" and "range of depth perception." Furthermore, specific, quantitative requirements were identified for each of these categories.

1) Viewing Angle

The viewing angle refers to the range in which it is possible to see images displayed on a display. We examined the distance between the display and the viewer's eyes when observing the display of a mobile terminal in typical mobile environments, and found that the typical observation distance is approximately 40 cm. If the minimum viewing angle required to achieve smooth motion parallax is assumed to be at least twice the distance between the viewer's eyes, a viewing angle of at least 15 cm is required at a typical observation distance of 40 cm. We thus set the requirement that the view range angle must be at least 21 degrees.

2) Smooth Motion Parallax

In order to achieve smooth motion parallax, it is desired that the horizontal display angle pitch at which the images are displayed in the different visual axis directions (viewing angles) is less than the width of the pupil. This means that if the observation distance is 40 cm, the interval (angular pitch) at which to display images in each visual axis direction must be less than 1 degree. Thus, if the viewing angle requirement found in the previous section (21 degrees or more) is taken into consideration, it is necessary to present images in least 21 different visual axis directions.

3) Range of Depth Perception (Feel as if Holding Objects in One's Hand)

In order to reproduce the feeling of actually picking up and holding an object shown on a 3D display in one's hand, the appropriate display size is compact sizes, from that of mobile terminal displays to sub-note computer displays. In our work, we attempted to recreate the feeling of holding a rectangular solid object with a depth similar to the width of the display size. In case of a display of sub-note size, it is possible to assume that the depth should be around 10 cm.

3. Prototype of Portable 3D Display

Based on the requirements identified in the previous chapter, we used the high-density generation of directional images method [2] to construct a prototype 3D display from a commercially available high-resolution Liquid Crystal Display (LCD) panel. The details are explained below.

3.1 High-Density Directional Images Display Method

The high-density directional images display method is a 3D display method where many directional images, which are orthographic projection images of a display target, are rendered from slightly shifted orthographic projection directions and presented so that they correspond to these orthographic projection directions. This method has been shown to have the potential of activating the accomodation [3], and motion parallax can be achieved effectively as well [4]. Using this method, a high-density display can be achieved in the crosswise (horizontal) direction of the display and a highly smooth motion parallax can be obtained by adopting a configuration where a thin slanted renticular sheet is laminated on a normal 2D LCD panel; we thus adopted this method.

3.2 3D Information Presentation Method

In case of normal 2D images, one intensity value (pixel) of the display corresponds to one point on the surface of the displayed target object in a 1-to-1 relation. That is, the same pixels are seen from any viewing direction. In case of 3D vision, on the other hand, the display projection of one point on the target object changes according to the viewing direction; it is thus necessary to store information of multiple pixels in order to render each point on the surface of the object in a three-dimensional manner, so that it can be observed only from each direction (hereinafter, such a set of multiple pixels is referred to as a 3D pixel). A renticular sheet is used as the means of presenting the light from the multiple pixel values held in these 3D pixels in each direction. The renticular sheet is a sheet consisting of vertically arranged troffer lenses (cylindrical lenses) as shown in **Figure 2** (a). As seen in Fig. 2 (b), the horizontal cross-section of the renticular sheet forms an array of aligned convex lenses. That is, the renticular sheet functions as a lens. The cross-section in the vertical direction is as shown in Fig. 2 (c); it simply diffuses light in the same way as for normal glass. Hence, the light radiates from each pixel towards the viewer in the same manner even if the position is changed in the vertical direction of the lenses, but if the viewpoint is changed in the horizontal direction, the incidental point at which the light hits the lens in front of the pixel changes, and the direction of the transmitted light thus changes as well. In the prototype we made this time, we set the requirement that it must be possible to present 30 visual axis directions and thus assigned information of pixels corresponding to 30 visual axis directions to each 3D pixel.

3.3 3D Display

Figure 3 shows the method overview of generating the high-density directional images displayed on the prototype 3D display (**Photo 1**). First, create image I# (i, j) of the target observed in parallel projection from cameras positioned at N locations (14 places in case of Fig. 3). For example, the upper left corner pixel (0, 0) of camera image I#1 taken from the position of camera #1 is assigned to the 3D pixel at the upper left corner on the 3D display. At this point, as shown in Fig. 3, the image is not placed on the conventional RGB pixel grid, but placed in parallel with the inclination of the renticular sheet [5] [6]. By using a tilted renticular sheet, images whose positions in the vertical direction are different can be used as images with the same horizontal direction. For example, as shown in Fig. 3, by using 6 pixels in the vertical direction to generate rows of

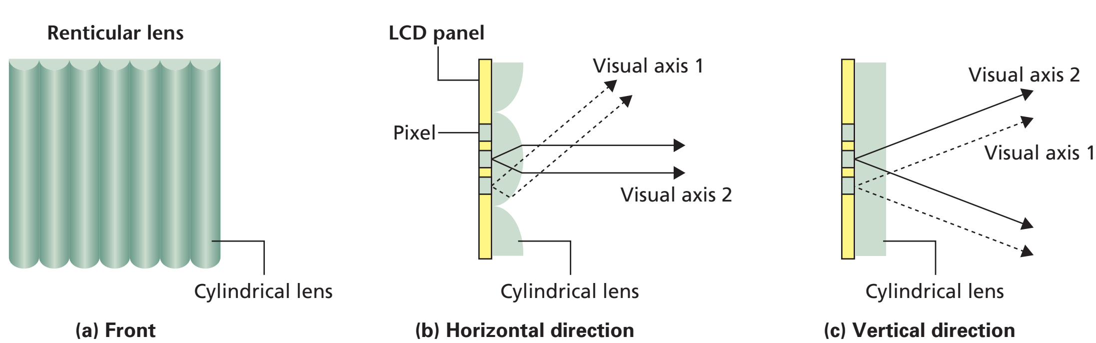


Figure 2 Renticular sheet

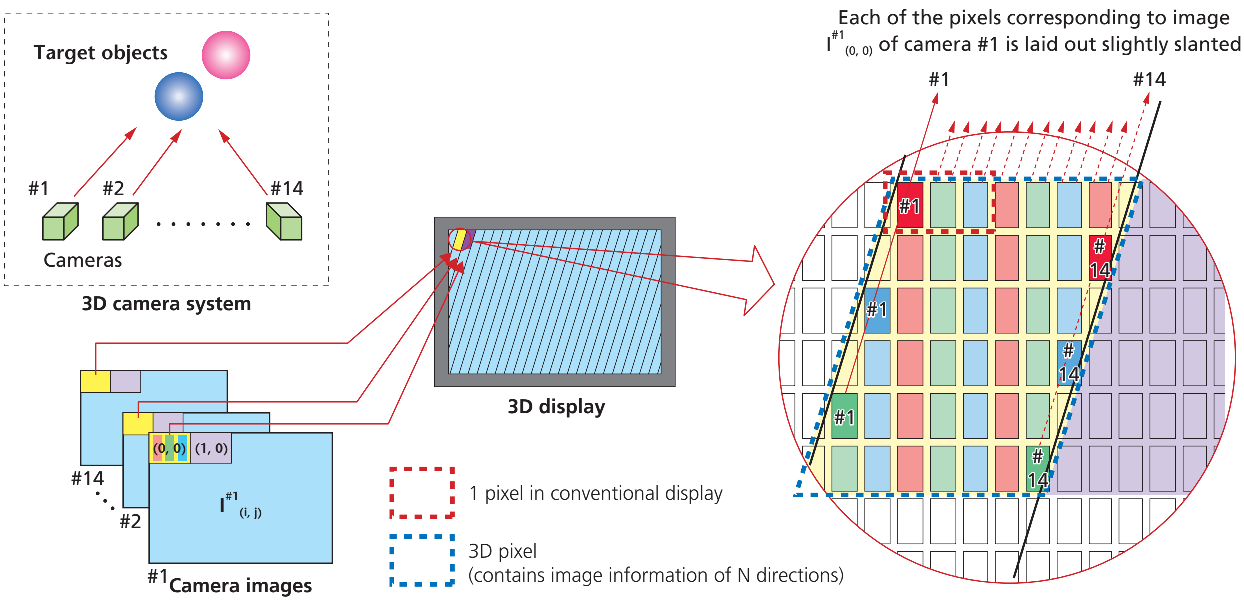


Figure 3 High-density directional image generation method

Photo 1 Prototype 3D display

images in the horizontal direction, pixels corresponding to each of the 14 visual axis directions of cameras #1 to #14 can be displayed at a high density along the width of the display, even if the original display was only able to display images from two cameras (2 pixels each for RGB) in the horizontal direction.

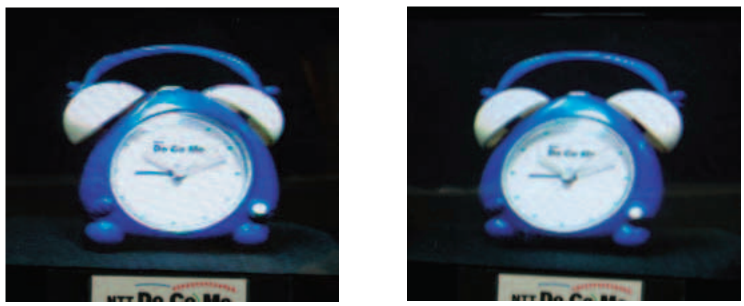
We designed the prototype to display directional images in 30 visual axis directions using a standard LCD panel (1280 × 768 pixels, 7.2 inches). In this case, the images have a horizontal resolution of 1/5 and a vertical resolution of 1/6 of the underlying 3D display, i.e., the 3D pixel resolution that can be displayed is 256 × 128. We then generated a group of directional images (bitmaps) by interpolating and rearranging images in each visual axis direction using the procedure shown in Fig. 3; the 3D vision is achieved simply by displaying these images on a 3D display at the same magnification. **Photos 2** (a) to (c) show results of rendering CG models of three balls with different depth positions, placing the red ball in the front and the blue ball in the background, and displaying them in a 3D display. Comparing (a) where the display is seen from the left side, (b) where the display is seen from the front and (c) where the display is seen from the right side, it can be confirmed that the relative positions of the three balls placed at different depths change. It is also possible to observe how smoothly the display of the target objects (balls) changes by moving the head from left to right (in other words, smooth motion parallax is achieved). Moreover, it is possible to achieve 3D vision using photographs taken on the spot, by taking photos of an actual object from several positions with a camera and converting these into high-density directional images using the same procedure as shown in Fig. 3. Photos 2 (d) and (e) show examples of 3D vision using photographs of an actual object. By comparing these photos, it can be seen that the area where the lighting source is reflected (the upper part of the dial plate) shifts as the position of the viewpoint shifts. In other words, in addition to the reproduction of a feeling of depth, a sufficiently realistic feel is reproduced since the changes of light reflection on the clock when observed by holding it in the hand and moving the head to the left and right can be naturally reproduced.

3.4 Evaluation against Requirements

1) Viewing Angle

The prototype device we created during this work has a viewing angle of approximately 21 degrees and the same images are repeatedly displayed for each angle. The closer the viewpoint is to the display, the higher the definition of the range

(a) Display seen from the left side (b) Display seen from the front (c) Display seen from the right side



(d) Display seen from the left side (e) Display seen from the right side

Photo 2 Example of 3D display

where repeated images can be seen. Since mobile terminals are hand-held devices, a wider view is required considering that the mobile terminals themselves are tilted freely by the users in order for them to see the displays properly.

2) Smooth Motion Parallax

The interval at which the images are presented along the different visual axis directions is no more than 1 degree, and a sufficiently smooth motion parallax has been achieved.

3) Range of Depth Perception

A natural three-dimensional feel could be perceived when displaying the real object (shown in Photos 2 (d) and (e)). We could confirm that the feeling of reality (feeling of depth) increases if appropriate patterns/texture are present on the display targets. We presented a series of images where the depth of the target object was gradually shifted in 1 cm increments and evaluated whether or not three dimensional space could be perceived. With the device developed this time, the depth perception could be naturally felt around 7 cm in front of and behind the display. Thus, the requirement related to spatial perception of objects, where the viewer feels as if holding the object in his/her hand, was mostly satisfied. However, it was also observed that the edges of displayed objects tend to become blurred at distances of about 7 cm from the display. The greater the distance between the display and the position of the object, the larger the degree of blurring. This time, the number of directional images was set to 30 and the interval of presenting directional images 1 degree or less, but it is considered necessary to improve the directionality further in order to achieve sharp 3D vision at positions further away from the screen, because the reason for the blurring is that the light beams become diffused as the viewpoint is moved further away from the screen.

In addition to this, it should be pointed out that the resolution of the 3D images themselves adopted in this prototype display was 256 × 128, which is quite low compared to the conventional 2D display size of 7.2 inches. When we displayed actual objects, we found out that the roughness of the resolution was not very disturbing. However, the resolution is not sufficient to display detailed textures such as digits on clocks, and a higher resolution is desired.

4. Conclusion

We created a prototype of a 3D display that allows natural 3D vision. Smooth motion parallax and reproduction of real 3D feel, which have so far been very difficult to achieve with conventional displays, were made possible with this novel portable display. We intend to examine 3D displays with wider fields of view and higher resolutions in the future.

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ABBREVIATIONS

LCD: Liquid Crystal Display