Analysis of errors on the depth perception through binocular disparity in integral imaging

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Abstract
Integral imaging is a three-dimensional display method which has full parallax and continuous viewpoints. However, we found an error between the depth expressed by integral imaging and the depth perceived by the observer through binocular disparity. We analyze the depth perception errors of the three-dimensional image constructed by integral imaging.

1. Introduction
Integral imaging[1] (InIm) is a three-dimensional (3D) display method which was proposed by Lippmann in 1908. Despite the long periods after the proposal of the method, InIm began to gather attentions of many researchers after the development of two-dimensional (2D) display devices with high resolution. InIm system is composed of 2D display device and lens array as shown in Fig. 1. On the 2D display device, elemental image is drawn and observed through the lens array. Elemental image is a set of small images with different perspectives, and it is integrated into a 3D image when observed through the lens array.

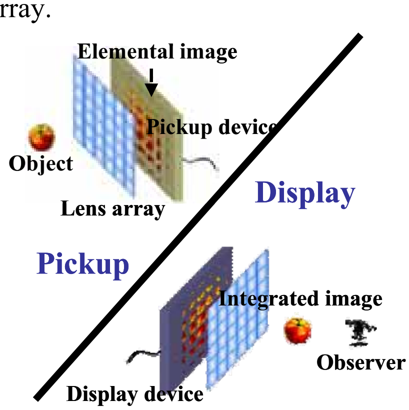

Fig. 1. Concept of InIm.

InIm possesses continuous viewpoints and full parallax, but it has limitation on the viewing angle and the expressible depth range. There have been many researches about improving the viewing angle and the expressible depth range[2-4]. However, it had never been pointed out that there can be an error on depth perception in the sense of binocular disparity. In this paper, we analyze the error on depth perception and verify it with experimental results.

2. Analysis
The depth perception error is due to the mismatch between the integration plane and the central depth plane[5]. First, we explain central depth plane and the analysis will follow.

2.1 Central depth plane
In InIm, there is a central depth plane on which the 2D display panel itself is imaged by the lens array. The central depth d_c, the focal length of the lens array f_c, and the gap between the 2D display device and the lens array g, satisfy the lens law shown in Eq. (1).

$$\frac{1}{f}=\frac{1}{d_c}+\frac{1}{g}. \qquad (1)$$

Therefore, the central depth is fixed when the gap g is determined. However, InIm is a 3D image display technique and should express the 3D image placed out of the central depth plane. This is achieved through the integration of the 3D image at the location out of the central depth plane. Figure 2 shows the case for a single point object.

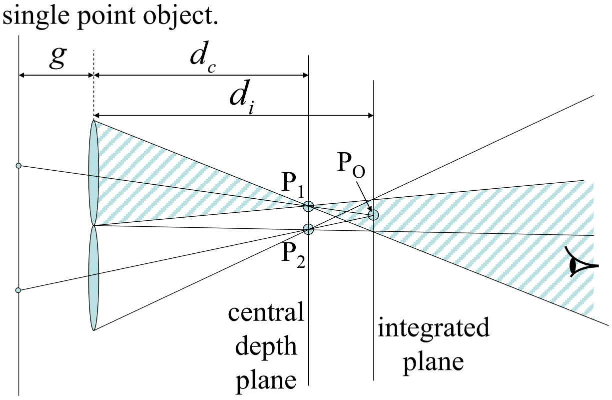

Fig. 2. Observation of a single 3D image point out of central depth plane.

In Fig. 2, d_i is the distance between the integrated plane and the lens array. When the observer is watching the point P_O as in Fig. 1, he or she is actually watching P_1 through the upper lens. To the observer, the observed lateral position of the point P_1 will agree with the lateral position of P_O only when the point P_O, the point P_1, and the position of the eye are lying on a straight line. It is this difference between the actual lateral position of P_O and the perceived lateral position of P_O which brings about the degradation of overall 3D image and limits the expressible depth range.

Moreover, the difference between the positions of P_1 and P_2 causes the depth of P_O to be perceived with an error. Conventionally, it is conceived without proof that the observer would perceive the correct depth of 3D images on the integration plane, regardless of the errors on the perception of the lateral position of P_O. But there are errors in the depth perception and it will be explained in the following.

2.2 Depth perception error in the sense of binocular disparity

Here we confine the cue of depth perception to the binocular disparity only. Consider Fig. 3 where left eye of the observer is watching P_O through P_1 and right eye is watching P_O through P_2.

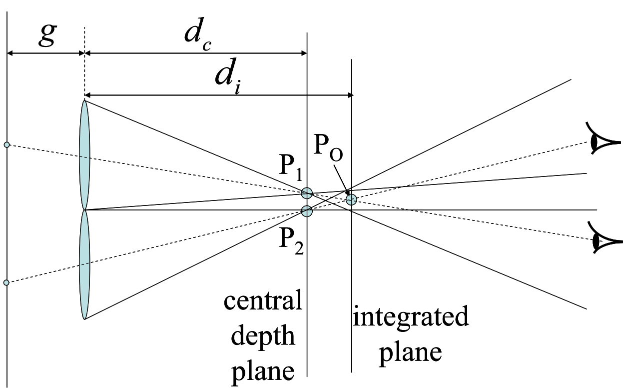

Fig. 3. Correct depth perception.

Figure 3 shows a special case in which both eyes of the observer perceive correct lateral position of P_O and thus the binocular disparity gives the correct feel of depth to the observer. In this case, left eye, P_O and P_1 are lying on a straight line, and also are right eye, P_O and P_2. Correct perception of the depth is preserved while the observer maintains the distance to the lens array, though it can cause errors on the perception of the lateral position. This is because the intersection of the two dashed lines moves only in lateral direction since the distance between two eyes is unique for a person, typically 65mm. But the error on the depth perception appears when the observer moves towards or away from the lens array.

First, consider when the observer moved towards the lens array as shown in Fig. 4.

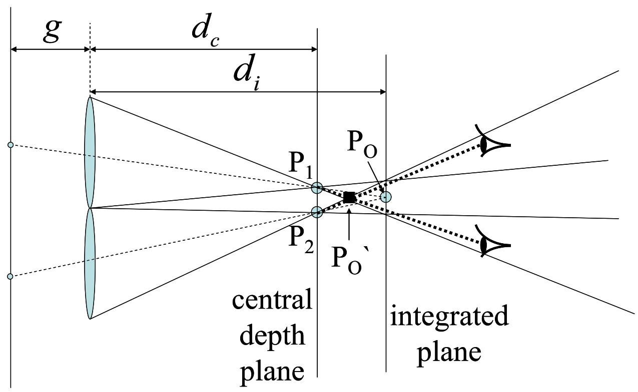

Fig. 4. Erroneous depth perception.

In Fig. 4, right eye watches P_O through P_2, and left eye watches P_O through P_1 as in Fig. 4. Therefore, the observer perceives as if P_O is located at the position of P_O\`, where the thick dotted lines intersect. The difference between the depth of $P_O$\` and P_O is the error on the depth perception.

Similar situation occurs when the observer moves farther from the lens array than in Fig. 3, as described in Fig. 5.

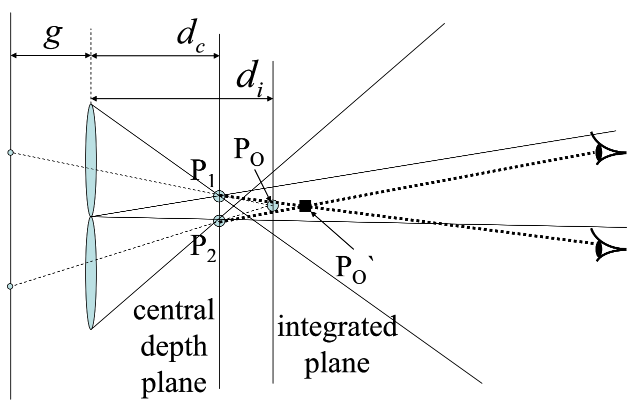

Fig. 5. Erroneous depth perception.

In Fig. 5, the perceived position of P_O is P_O\` where the thick dotted lines intersect. In this case, the perceived position of P_O is closer to the observer than where P_O is actually integrated.

So far, the image point is assumed to be observed through different lens. However, when the observer moves more farther from the lens array, then some points are observed through the same lens. Such points increase as the observer moves farther, and they are perceived as if lying on the central depth plane.

In Fig. 6, the observer feels as if the point P_O is at the central depth plane. The observer moves so far away from the lens array that both eyes are watching P_O through single point on the central depth plane P_2 in Fig. 6.

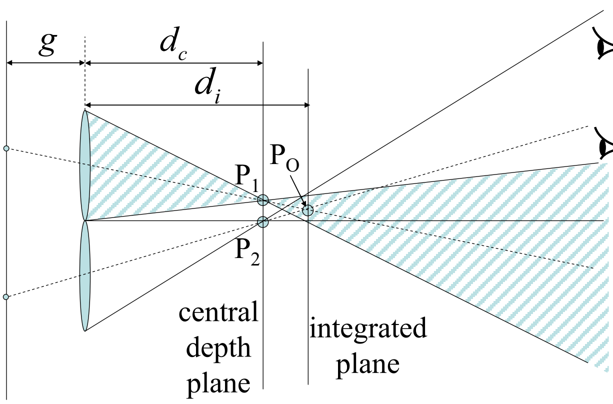

Fig. 6. Extreme case of the error in depth perception.

This can make some portion of the 3D image to be perceived as if flatly lying on the central depth plane.

3. Experimental results

In this section, we verify our analysis with experimental results. The geometry of the experimental setup is described in Table 1.

Table 1. Experimental parameters.

Setup	Specifications	Characteristics
Lens array	Focal length Lens pitch Number of elemental lenses	22mm 10mm 13(H) × 13(V)
Object	Central depth plane Integrated plane	80mm 100mm
White pole	Location in depth	100mm

We implemented an InIm system in which central depth plane is located at 80mm in front of the lens array. A 3D image located at 100mm in front of the lens array is constructed by the InIm system. To compare perceived depth and intended depth, we put a white stick at the integrated plane of the object.

Figure 3 shows a situation when correct depth is perceived. By using proportional relationship, it can be calculated that the observer will perceive correct depth when located 65cm in front of the integrated plane, which is 75cm in front of the lens array.

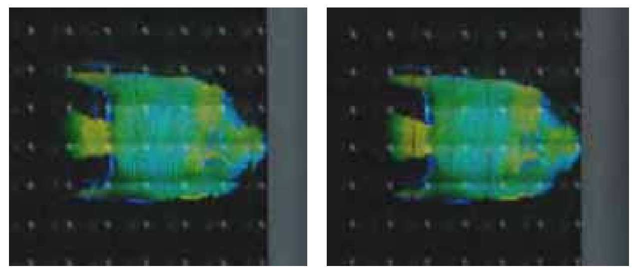

Fig. 7. Correct depth perception.

Figure 7 shows the left image and the right image when the camera is located at the 75cm from the lens array. When taking the left picture, the position of the camera was 65mm (the positional difference of the eyes of human) left compared to the position of the camera when the right image is taken. The relative positions between the nose of the fish and the white pole are the same in both pictures. It means that the depth of the fish is perceived as the same depth of the white pole, which is located at the integrated plane.

Figure 8 shows the experimental results when the camera is moved farther from the lens array, 130cm from the lens array.

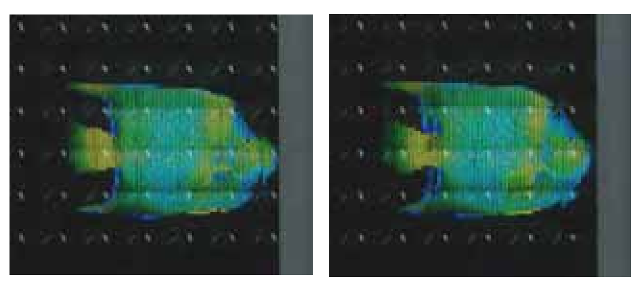

Fig. 8. Erroneous depth perception.

Here, the relative positions between the nose of the fish and the white pole are different. In the left image, the nose of the fish is located closer to the white pole. Thus, the perceived depth of the fish is closer to the observer than the depth of the integrated plane. This result agrees with the situation described in Fig. 5.

Finally, Fig. 9 shows the experimental result of the situation depicted in Fig. 6. Here, camera is located at 210cm away from the lens array. In this situation, much portion of the image points is observed through the same lens in both eyes. Being opposed to the result in Fig. 8, the fish is closer to the white pole in the right image. It is as described in Fig. 6.

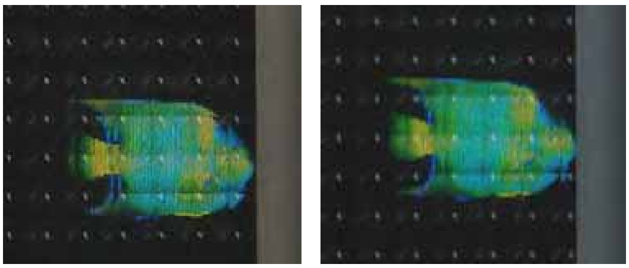

Fig. 9. Erroneous depth perception.

4. Conclusion

We analyzed the InIm system to show that there is a depth perception error in the sense of binocular disparity. Since binocular disparity is the most important depth cue when human perceives objects located less than 10 meters away, the analysis given in this paper is very important. However, when the lens array is located at the focal length distant from the 2D display device, the depth perception error would be minimized.

Acknowledgment

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5. References

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