Journal of
Biomedical Optics

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Journal of Biomedical Optics 18(11), 116006 (November 2013)

Three-dimensional stereoscopic imaging modality based on a single optical channel and detector

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Abstract. A three-dimensional stereoscopic imaging modality (3D-SIM) based on a single optical channel and detector was developed to overcome some of the limitations of conventional 3D-SIM. It produces 3-D stereoscopic images by adjusting the angle of a transparent rotating deflector (TRD) to generate disparity between left and right images. The angular effect of the TRD was demonstrated to investigate the feasibility of the proposed method in 3-D stereoscopic image generation. Results indicate that image disparity increased as a function of the rotation angles of the TRD, while maintaining adequate 3-D perception. These results are expected to facilitate the practical use of a 3D-SIM in medicine. [DOI: 10.1117/1.JBO.18.11.116006]

Keywords: three-dimensional image; three-dimensional stereoscopy; single channel; transparent rotating deflector.

Paper 130563PR received Aug. 11, 2013; revised manuscript received Oct. 6, 2013; accepted for publication Oct. 9, 2013; published online Nov. 8, 2013.

1 Introduction

Since the early 19th century, three-dimensional (3-D) stereoscopic imaging technologies have been investigated, and various visualization methods, including stereoscopic, volumetric, and holographic methods, have been developed.[1] In 1838, stereoscopy was first invented and has been used in photogrammetry and entertainment through the production of stereograms.[2] In medicine, 3-D technology was first introduced in laparoscopy.[3]

Most 3-D stereoscopic imaging modalities (3D-SIMs) consist of three common major processes—image acquisition, conversion, and display—and are based on dual-channel video technology.[4,5] Although significant benefits have been demonstrated,[6–9] in clinical trials, 3D-SIMs have shown severe limitations that induce physiological side-effects such as headaches, nausea, ocular fatigue, and dizziness, owing to mismatches in image characteristics that may be caused by geometrical mismatches of optical channels and detectors.[9–12] Moreover, conventional 3D-SIMs have a system-dependent working distance (WD) owing to the fixed diameter of the objective lens and the limited separation of detectors.

Single channel video technologies such as shutter mechanism and insect eye technology, which generate 3-D stereoscopic images with a single optical channel and detector, have been developed by Storz and Visionsense.[5] However, these technologies have also limitations as follows: (1) the shutter mechanism produces weak 3-D perception because of small unpredictable image changes generated by a single optical detector and (2) the insect eye technology has been restricted by its low image intensity, which is originated from its microlens array.

Other previous studies have also generated 3-D image disparity by using a single camera combined with a planar parallel plate or biprism.[13,14] Chunyu and Ahuja generated 3-D image disparity by rotating a planar parallel plate which is very similar to our study. However, unlike our study aim to generate 3-D stereoscopic image, they aimed to reconstruct the 3-D structure of objects and did not go into detail of the analysis for image disparity in 3-D stereoscopic image.[14]

To partially address the limitations of conventional 3D-SIMs, and further, to achieve adequate 3-D perception at a close WD, the present study aimed to develop a 3D-SIM based on a single optical channel and detector. The proposed 3D-SIM utilizes a simple transparent rotating deflector (TRD) to induce the image disparity in a 3-D stereoscopic image. Here, the principle of TRD-based 3D-SIM is introduced and its feasibility is experimentally demonstrated.

2 Materials and Methods

2.1 *Principle of Imaging Modality*

Figure 1(a) shows a schematic diagram for an adequate stereoscopic viewing mechanism of human eyes, which are generally separated by a distance (D) of approximately 60–65 mm.[4] To perceive adequate 3-D stereoscopic images with normal human eyes, the angle (α) should be maintained at approximately 7.44 deg.[9] The closer the object gets, the more eye strain increases by the process of accommodation and convergence of the eyes.[7] In contrast, the 3-D perception becomes weaker as WD increases.

Figure 1(b) shows a schematic diagram explaining the principle of TRD-3D-SIM to obtain an adequate 3-D stereoscopic image. The light beams passing through the TRD as indicated by the solid and dotted lines are separated by the distance (d) and diverted parallel to the optical axis forming the right and left images at two different visual orientations on the objective lens. Consequently, the right and left images for 3-D stereoscopic viewing are acquired in an alternating sequence by rotating the TRD. In contrast to conventional dual-channel 3-D stereoscopic technology, in which distance (d) is fixed owing to a

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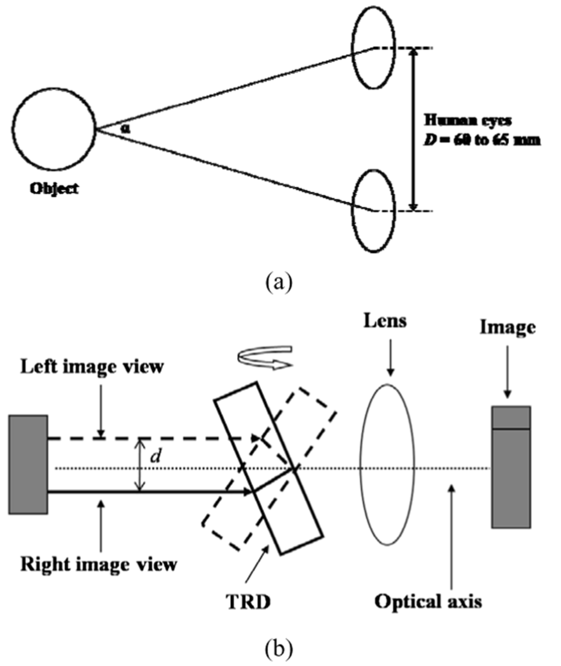


Fig. 1 (a) Schematic diagram of an adequate stereoscopic viewing condition for a human. (b) Schematic diagram of the transparent rotating deflector (TRD) action in three-dimensional (3-D) stereoscopic imaging modality (SIM) in which solid and dotted lines indicate the viewing angles of right and left images, and "*d*" indicates the image disparity between the right and left images, which can be varied by adjusting the rotation angle of the TRD.

fixed dual-optical channel, TRD-3D-SIM can manipulate distance (d) and therefore, control 3-D depth perception.

The right and left images can be obtained in three different ways for identical TRD angle depending on the rotational direction: (1) an angle equally rotated both clockwise and counter-clockwise (symbolized as E); (2) angle rotated clockwise (symbolized as R); and (3) angle rotated counter-clockwise (symbolized as L). For example, a TRD angle of 40 deg can be defined as follows: (1) rotated -20 deg (clockwise) for left image and rotated $+20$ deg (counter-clockwise) for right image (E 40 deg); (2) rotated 0 deg for left image and rotated -40 deg (clockwise) for right image (R 40 deg); and (3) rotated 0 deg for left image and rotated $+40$ deg (counter-clockwise) for right image (L 40 deg).

2.2 *Optical Setup*

Figure 2 shows a simple optical setup for verifying the feasibility of TRD-3D-SIM consisting of a target object, TRD, and DSLR with a zoom lens. The image conversion and display of 3-D stereoscopic images were processed by a conventional method.[5] Unlike conventional 3D-SIMs, the right and left

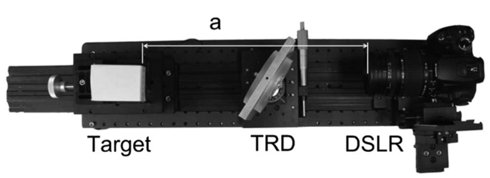


Fig. 2 Simple optical setup to demonstrate the feasibility of the novel TRD-3D-SIM. In the figure, "a" indicates the working distance (WD).

images are acquired in an alternating sequence from two different visual orientations generated by adjusting the TRD angles.

The TRD was made from a transparent acryl ($n = 1.49$) and designed to be large enough to cover the camera lens. A Canon digital single-lens reflex (DSLR) camera (Canon EOS 350D, Canon Inc., Tokyo, Japan) with a Tamron zoom lens (AF28–300 mm, F/3.5–6.3, Tamron, Japan) was used to acquire 3-D stereoscopic images at two different visual orientations and to guarantee an adequate field of view and WD.

2.3 *Characterization of Imaging Modality*

To verify the feasibility of TRD-3D-SIM, 3D stereoscopic images of a target object were acquired at three different TRD angles of E 20 deg, E 60 deg, and E 100 deg. For quantitative analysis of image disparity (ID), right and left images were obtained as a function of TRD angle from 10 deg to 80 deg in 10-deg intervals and WDs of 153 and 250 mm. All images were obtained at the angles of "R," "L," and "E" for identical TRD angles.

The theoretical modeling of IDs as a function of TRD angle was performed by applying Snell's Law. It was assumed that the refractive index of TRD was approximately 1.49 and the boundaries were perfectly flat. Internal reflections inside the TRD were not considered.

Red-cyan anaglyphs were processed using a toolbox in MATLAB. Because corresponding features in the 3-D stereoscopic images are on the same row, image rectification was not conducted before the entire image process.[15]

3 Results

3.1 *3-D Stereoscopic Images*

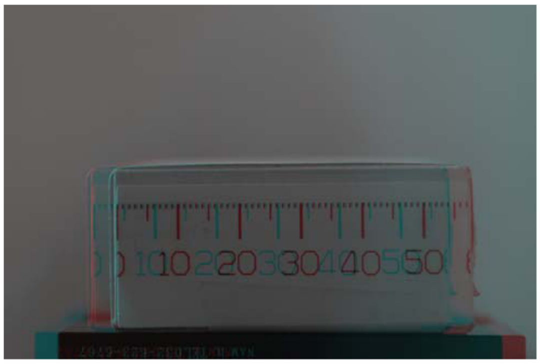
Figures 3(a), 3(b), and 3(c) show pairs of the right and left images acquired at TRD angles of E 20, E 60, and E 100 deg, respectively. The images are overlapped to generate anaglyphs. As expected, the image pair at E 100 deg has a greater ID than those at E 20 and E 60 deg. The anaglyphs in Fig. 3 show noticeable 3-D horizontal cues which may be observed in a dual-channel 3-D system. Some barrel distortion appears at the boundaries of the images taken at a short WD. For practical application, this distortion could be corrected by employing a distortion–correction function.[16]

3.2 *Characterization of Imaging Modality*

Figure 4 shows IDs between right and left images as a function of TRD angle. The theoretical and experimental results show a similar pattern of IDs as a function of TRD angle, regardless of WD. The calculated values agree well with the measured values up to a TRD angle of 20 deg where the ID increases linearly. The ID at "E" angle increases linearly as a function of the TRD angle; however, IDs at "L" and "R" angles increase exponentially as a function of TRD angle and tend to be larger even at the same TRD angle.

4 Discussion

The binocular disparity in normal human stereoscopic vision is a cue to depth information. In the brain, images formed on the retinas of the right and left eyes are synthesized, allowing depth perception.[4] Modern 3D-SIMs are also based on human stereoscopic perception, and since they meet the needs of the user and provide the potential for precise depth perception, they have



(a)

(b)

(c)

Fig. 3 3-D stereoscopic images of a target at the TRD angles of (a) E 20 deg, (b) E 60 deg, and (c) E 100 deg. "E" indicates the angle equally rotated both clockwise and counter-clockwise. For example, E 10 deg means rotated −5 deg (clockwise) for the right image and rotated +5 deg (counter-clockwise) for the left image.

been continuously developed in medical technologies.[17] However, the natural process of 3-D visual recognition by the human eye has not been completely adapted for conventional 3D-SIM.

Conventional 3D-SIMs are based on dual-channel video technology with dual- or single optical channel systems and have been used accordingly under different circumstances.[4,9] The interocular distance in a dual optical channel system is fixed by the design of the 3-D imaging system. However, TRD-3D-SIM can have a variable interocular distance by adjusting TRD angle and therefore, adjusting the depth perception of 3-D stereoscopic image as shown in Fig. 3.

TRD-3D-SIM enables the use of a single optical channel and detector to generate 3-D stereoscopic images (Fig. 3).

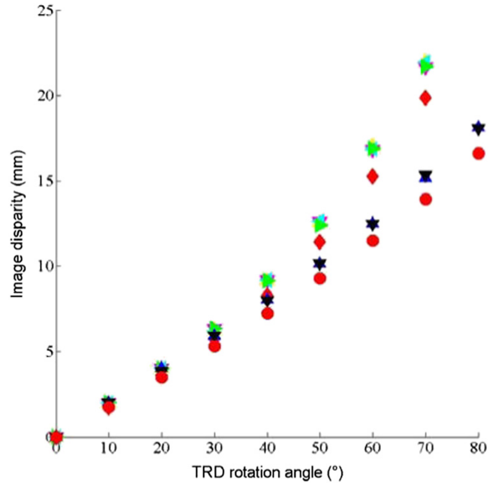


Fig. 4 Image disparity as a function of TRD angle at WD of 153 and 250 mm. In the figure, yellow upward triangle: "L" angle and 250 mm WD, pink downward triangle: "R" angle and 250 mm WD, green left triangle: "R" angle and 153 mm WD, turquoise left triangle: "L" angle and 153 mm WD, red diamond: theoretical data, blue upward triangle: "E" angle and 153 mm WD, black downward triangle: "E" angle and 250 mm WD, and red circle: theoretical data.

According to the previous studies,[5,8,12] TRD-3D-SIM may have the following advantages: (1) simple manipulation of magnification, focus, and exposure time with a single optical channel, (2) complete synchronization of right and left images, (3) identical geometric matching (no rotational error, no size difference, and no vertical/horizontal shifts) between right and left images, and (4) identical image characteristic matching (color, white balance, and brightness). Furthermore, the limitations of conventional technologies[5] may not appear in the TRD-3D-SIM. The structure of TRD-3D-SIM allows simple acquisition of 3-D stereoscopic images enabling generation of an adequate binocular ID (Figs. 3 and 4).

The calculated values of the ID presented an identical trend to that of the measured values. However, the difference between the measured and calculated values becomes greater as a function of TRD angles (Fig. 4). A possible explanation for this difference is that the assumptions for the theoretical calculation were not fully applied to the experimental measurement. The TRD surface might be not perfectly flat, so that the differences would be greater as the TRD angle increases. Such reasons might also explain the reason why the TRD angles of "L" and "R" tend to have larger ID even at the same TRD angle (Fig. 4).

Although this study investigated the effect of ID only as a function of TRD angle, the ID may also be affected by the thickness and material of the TRD. In future studies, other various factors must be considered and characterized to improve image quality. Furthermore, the TRD can be placed either in front of the optical channels or between them, depending on the application of imaging modality. In addition, the size of the TRD can be greatly reduced by placing it at the focal point of the optical channel.

The simple principle of TRD-3D-SIM can be easily applied to optical imaging modalities in medicine. In present, we are developing a TRD-3D-SIM based on a DSLR camera for dermatological application. In further studies, TRD-3D-SIMs may be developed for visual guided surgery in ophthalmology and endoscopy by developing TRD which is automatically rotated by being synchronized with a camera.

5 Conclusion

A novel TRD-3D-SIM was developed not only to overcome the limitations of conventional 3D-SIMs but also to produce optimal 3-D stereoscopic images. The results showed that it is possible to generate binocular ID, and further, to control the degree of 3-D depth perception by adjusting the TRD angle.

Acknowledgments

This research was financially supported by the "Electronic medical equipment part & material industrialization foundation construction program" (R0000665) through the Ministry of Knowledge Economy (MKE) and Korea Institute for Advancement of Technology (KIAT).

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