

# Motion-blur compensation method using a transparent hexagonal prism

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**Abstract**— Although the use of a traveling monitoring system to inspect infrastructure structures improves efficiency, there are concerns about image quality degradation and inspection accuracy due to motion blur caused by movement. Therefore, this research aims to develop a method to rotate a transparent acrylic hexagonal prism and control the optical axis in accordance with Snell's law to capture images while compensating for the motion in real time. In the previous study, the same incident angle was visited only every quarter of a rotation because a cube was used, and the overlap region was not included in the continuous image in an optical system with a narrow angle of view. Experiments have confirmed that it is possible to capture continuous images of a moving object in a similar shape at a maximum speed equivalent to 70 km/h, while compensating for motion blur of the object without interruption.

## I. INTRODUCTION

Since inspection of deterioration and initial failure of objects that require safety and precision, such as transportation infrastructure and circuit boards, with high accuracy and efficiency can reduce maintenance and manufacturing costs, the technology to image objects while moving at high speed has become an important research topic. In particular, the maintenance of the transportation infrastructure is expected to be less expensive than the construction of new structures [1]. However, for high efficiency, it is important to perform diagnostic imaging while moving at high speed. Inoue et al. used a method to suppress motion blur in real time by controlling a galvano mirror that moves in two axes during the exposure time to track the object to be imaged and compensate for motion blur in objects moving at speeds up to 25[km] per hour [1]. Hayakawa et al. developed a technique to detect cracks as small as 0.2[mm] from 100[km/h] by extending the exposure time using a high-speed reciprocating motion of a galvanometer mirror [3], while since a galvanometer mirror requires a return motion, a method to compensate for motion blur by rotating a square acrylic prism in one continuous direction has been proposed [4]. However, since it needs to be rotated every 90 [deg] to reach the same angle of incidence, and because the frequency of capturing is insufficient, the object can be captured only intermittently when capturing with a lens that has a high magnification. On the other hand, there was a limitation that the spatial resolution of the image was reduced when capturing with a wide-angle lens.

Therefore, in this study, we propose a method of continuously capturing the object by introducing a regular hexagonal

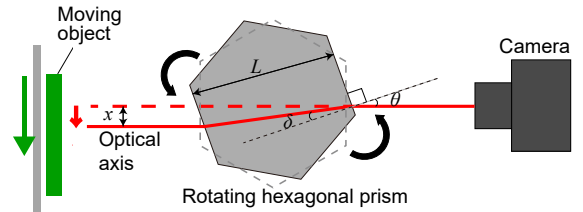


Fig. 1. Relation between angle of incidence and travel distance of optical axis during hexagonal prism rotation.

acrylic prism and capturing images when equal incident angles appear every 60 [deg], thus increasing the frequency of imaging by 50%.

## II. PRINCIPLE

As shown in Fig. 1, by rotating a transparent hexagonal prism with a refractive index different from that of air and moving the optical axis horizontally, scanning can be performed without the need for feedback motion.

The formulation for the velocity of the optical axis and the rotation speed of the prism. The refractive index of the cube is  $n$ , the length of one side of the prism is  $L$ [cm], the angle of incidence to the prism is  $\theta$ [rad], the angle of refraction is  $\delta$ [rad], and the displacement of the optical axis is  $x$ [cm]. Eq. 1 is derived using Snell's law.

$$\sin \theta = n \sin \delta \quad (1)$$

$$x = L \frac{\sin(\theta - \delta)}{\cos \delta} \quad (2)$$

Eq. 3 is obtained by substituting Eq. 1 into Eq. 2, which is expanded by the additive theorem.

$$x = L \sin \theta \left( 1 - \frac{\cos \theta}{\sqrt{n^2 - \sin^2 \theta}} \right) \quad (3)$$

Let  $\frac{d\theta}{dt} = \omega$ [rad/s] be the angular velocity of the rotating prism and  $v$ [cm/s] be the velocity of the optical axis, and Eq. 4 is obtained.

$$v = \frac{df}{d\theta} \omega \quad (4)$$

Therefore, when the speed of the object is known using tracking as describing in [4], it is possible to control the speed of the optical axis to cancel out the speed of the object by controlling the rotation speed of the prism.

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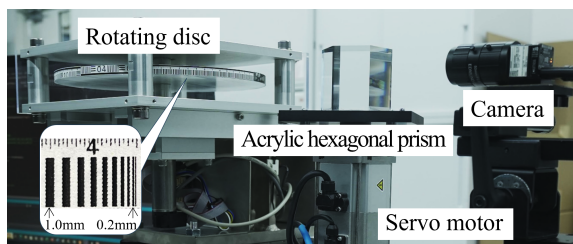


Fig. 2. Experimental setup using a transparent hexagonal prism.

### III. EXPERIMENT AND DISCUSSION

This experiment was conducted with the experimental apparatus shown in Fig. 2.

The object is a black-and-white stripe pattern with a width of 1.0 [mm] to 0.2 [mm] moving on a rotating disk. The camera (Ximea, MQ003CG-CM) with a focal length of 50 mm was used to capture  $648 \times 244$ [pixel] images. The camera exposure time was 4.0[ms], the length of opposite side of a regular hexagonal prism was 57[mm], the distance between the back of the prism and the disk was 130[mm], and the distance between the camera and the disk was 300[mm]. The object to be captured was the rotating disk with a diameter of 250 [mm] shown in Fig. 2, to which multiple patterns were preattached, and the surface was set to rotate at a speed of 3.5 [km] per hour. In the case of capturing infrastructure structures, for example, an expressway tunnel is about 6 [m] away from the camera to the surface, so the capturing conditions are equivalent to a speed of 70 [km/h] when the same spatial resolution is used. The angular velocity of the servo motor (Omron, R88D-KT02L) was adjusted so that the velocity when the angle of incidence between the optical axis and the prism is 0 [rad] matches that of the target. For comparison, an acrylic cube of 50 [mm] per side was also prepared and captured under similar conditions.

Figs. 3(a) and 3(b) show the images taken with a cube and a hexagonal prism, respectively, arranged manually. These images are obtained by cropping only the stripe pattern. The cube showed a gap between images, whereas the hexagonal prism showed no gap between images. Therefore, it is thought that this method can be used, for example, to inspect continuous wall surfaces. On the other hand, Fig. 3(c) shows the result of capturing the object without rotating

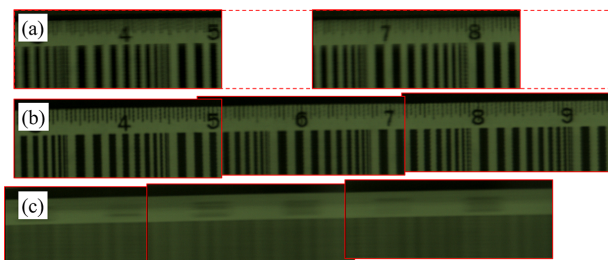


Fig. 3. Captured images at each conditions. (a) After compensation for cube, (b) after compensation for hexagonal prism, (c) without compensation.

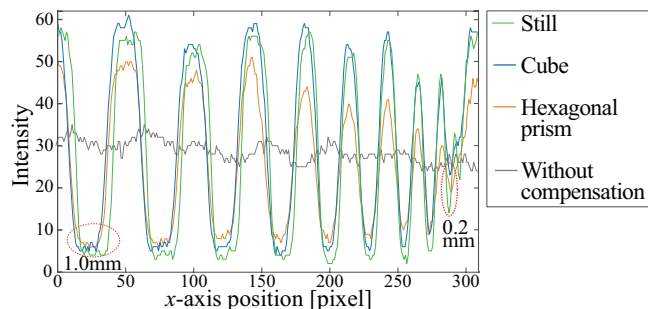


Fig. 4. Stripe pattern intensity change for peak-to-peak comparison.

the hexagonal prism. Although no gaps were observed, the motion blur was so severe that the image is not suitable for inspection.

Fig. 4 shows a peak-to-peak comparison by cropping only the striped portions of the obtained images. This result shows that the image with the acrylic cube stationary and the corrected image show comparable imaging results. In addition, although the cube is the best when only a single image is considered. However, even the regular hexagonal prism meet the index for inspection purposes because they can capture a peak of 0.2 [mm], which is required for inspections of expressways in Japan. In the future, we plan to review the manufacturing process and optical characteristics of the hexagonal prism so that the image quality can be as good as that of a cube even with a hexagonal prism. Furthermore, the octagonal prism can be replaced for rotating; however, larger number of surfaces may cause limitation of the angle of view.

### IV. CONCLUSION

Based on Snell's law, this study utilizes a device that can compensate for motion blur by rotating a regular transparent hexagonal prism to realize a tracking system that can continuously capture an object without gaps even with a telephoto lens. Experiments actually confirmed that the motion blur was compensated. In the future, we plan to improve the image quality by reviewing the materials and optical properties of the regular hexagonal prism.

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