Development of Motion-Blur-Compensated High-Speed Moving Visual Inspection Vehicle for Tunnels

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***Abstract*—In Japan, many infrastructures are several decades old or more, and since those structures are gradually deteriorating, efficient and precise monitoring methods are strongly required for maintaining safety. In particular, tunnels on highways must be monitored regularly; however, frequent traffic restrictions should be avoided. Accordingly, visual inspection of tunnels from a moving vehicle is an efficient method for rapidly discovering faults. However, despite the need for high image quality, motion blur deteriorates the image quality considerably, especially under high-speed motion. In the work described in this paper, we developed a motion-blur-compensated visual inspection system that uses a motion blur compensation method based on the back-and-forth motion of a galvanometer mirror. In field trials using a system installed on an actual vehicle, we confirmed the effect of motion blur compensation when using scales attached to the ceiling of a tunnel. The vehicle on which the inspection system was installed exceeded the minimum speed for Japanese highways, and the system was capable of distinguishing black-and-white stripes with widths of 0.2 mm. Additionally, this method can be used with conventional systems.**

***Index Terms*—monitoring of structures, visual inspection vehicle, safety, tunnel, motion blur compensation, high-speed motion**

I. Introduction

The total length of highways in Japan is approximately 8,998 km, and 40% of this length and 21% of the tunnels are more than 30 years old [1]. Hence, it is necessary to develop countermeasures against their deterioration to prevent accidents. Realistically, maintenance is more practical than rebuilding due to the high costs [2]. The global market for monitoring systems for infrastructure is predicted to reach approximately 240 billion dollars in 2030 [3], and efficient and precise monitoring methods will be essential for a sustainable society. In particular, tunnels on highways have a comparatively high risk of deteriorating due to their structures, and it is difficult to enforce the frequent traffic restrictions that are needed for their inspection. Therefore, there is an increasing demand for systems that can monitor tunnels from a moving vehicle. In particular, as a substitute for human visual inspection, high-quality images of tunnel surfaces are necessary for accurately judging faults like cracks and stains in the structures. Actually, some systems have already been developed and have succeeded in reducing inspection time and labor costs [4], [5]. However, there is a trade-off relationship between efficiency and precision, and high-speed motion deteriorates the quality of images due to motion blur. To overcome this problem, conventional systems use extremely bright illumination with limited exposure times so as to avoid motion blur of the captured images. However, as well as needing a lot of electricity, strong illumination may cause accidents since it forces drivers to look away, and hence motion blur must be compensated for using another method to ensure safety and sustainability. Moreover, the amount of motion blur increases as the resolution of the captured images and the vehicle speed increase, making it more difficult to capture sharp images that include detailed textures.

In general, motion blur is one of the main causes of degradation of images captured by a camera [6]. A number of methods have been proposed for compensating for motion blur, including blind deconvolution [7], [8], deconvolution using additional hardware [6], [9], [10], stacking of captured pictures [11], optical image stabilization [12], and so on. On the other hand, we have proposed a motion blur compensation method [13] and have developed a system [14] having high temporal resolution and high precision, unlike other methods which have longer exposure time to lower the intensity of the illumination.

Here we propose a motion-blur-compensated visual inspection vehicle using a motion blur compensation method. We installed the system on a vehicle, while considering optimization, and verified the fundamental performance of the system in experiments conducted in a tunnel. Our goal in this research is to establish a tunnel surface visual inspection method having high efficiency and precision.

II. Optimization of Motion Blur Compensation Method for Visual Inspection of Tunnels

A. Motion Blur Compensation Method

Our motion blur compensation method based on optical gaze control is highly effective in compensating

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for the motion blur caused by high-speed one-dimensional motion between a camera and a target [14]. The system is constituted of a galvanometer mirror, a high-speed color camera, an illumination unit, a lens, and a control PC, without the need for any additional sensors (see Fig. 1, in which the PC is not illustrated). We use a lightweight galvanometer mirror for gaze control, allowing fast mirror rotation for following the target. Additionally, we employ back-and-forth oscillating motion of the galvanometer mirror in synchronization with a high-speed camera, to achieve quick motion that can rapidly respond to changes in the speed of the target (see Fig. 2). This back-and-forth motion is realized by applying a sinusoidal driving pattern, and the exposure timing is synchronized with a particular angle so that the rotation can be considered to be linear. In the case where the angular speed of the mirror (ω_m) and the relative speed of the camera and target correspond, the exposure time of the camera can be increased without causing motion blur. Hence, the S/N ratio will not change, and will thus not limit the exposure time, and high-spatial-resolution images can be obtained without motion blur. Here, ω_m is given by

$$\omega_m = 2\tan^{-1}\left(\frac{x_d}{width}\tan\frac{\alpha}{2}\right) \quad (1)$$

where x_d is the positional difference between two successive images expressed at the number of pixels, $width$ is the width of each image, and α is the angle of view of the camera. This equation is based on high-speed image processing algorithms in order to realize sufficient temporal resolution for real-time applications. Since we assume that the target is flat, Equation (1) does not include the distance between the camera and the target. As a result, it is not necessary to install additional sensors, and it is possible to calculate ω_m using only information in the captured image; thus, the system has good accuracy and low cost. The amplitude of the sine wave for driving the galvanometer mirror is given by

$$A = \frac{\omega_m}{4f} \quad (2)$$

where f is the frequency of the system. Finally, the angle of the galvanometer mirror is given by

$$\theta = A\sin(2\pi f t) \quad (3)$$

where t is time.

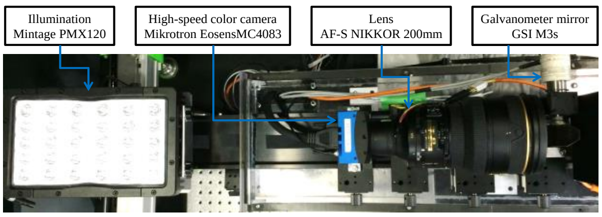

Figure 1. Photograph of motion blur compensation system

As a result of experiments, we verified that motion blur was compensated when f was 100 Hz, the speed of a target (a conveyor belt) was 30 km/h, and the distance from the camera to the target was 3.0 m; however, we could not set a higher f due to the reduction in gain, and we found that the compensation rate reduced as the speed increased.

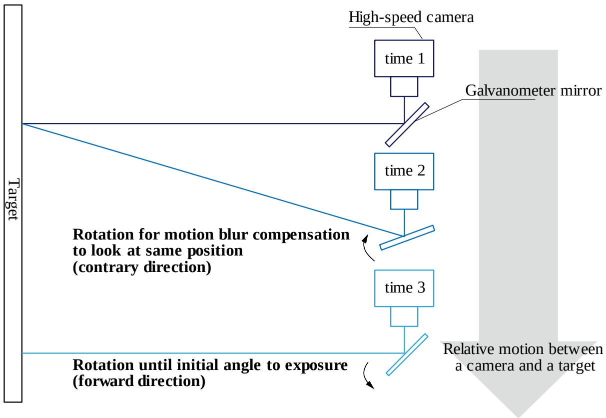

Figure 2. Concept of motion blur compensation method. (For simplicity, we illustrated only the center optical path. Actually there is inclination due to the lens.)

B. Gain Amplification of Galvanometer Mirror for Optimization for Visual Inspection of Tunnels

In Japan, the minimum speed of vehicles on highways is set at 50 km/h. The average height of tunnels is approximately 7.0 m, and so the distance from the camera to the ceiling is 5.0 m. If the distance becomes shorter, more motion blur occurs; hence, the distance is also an important factor, in addition to driving speed. In previous research the distance was 3.0 m, and the speed was 30 km/h, which corresponded to the Japanese minimum driving speed in tunnels on highway, in a relative manner. However, the compensation rate decreased when the speed increased, and therefore, here we propose a method that gives greater compensation at higher speeds. For calculating ω_m, we assume that the reduction in compensation rate occurs due to the decreasing size of the overlap regions between continuous captured images, and therefore, we propose setting a higher f, at 333 Hz, to give larger overlap regions. In actual use of the visual inspection system in a tunnel, the tunnel surface is assumed to be almost flat, and therefore, equation (1) is valid for the visual inspection system that we developed. Additionally, since ω_m is defined based on relative angular speed, our motion blur compensation method is effective even when the camera and the target moves, unlike conventional optical image stabilization [12].

On the other hand, when we use a higher f, it is known that the gain of the galvanometer mirror decreases [14], and therefore, in this research we amplify ω_m with a coefficient k:

$$\omega_m{}' = k\omega_m \quad (4)$$

Moreover, to ensure linearity of the driving pattern of the galvanometer pattern, ideally we should apply a linear path described by

$$\theta = \begin{cases} \omega_m{}'t & \left(\frac{n}{f} < t \le \frac{2n+1}{2f}\right) \\ -\omega_m{}'t & \left(\frac{2n+1}{2f} < t \le \frac{n+1}{f}\right) \end{cases} \quad (5)$$

where n is a natural number. However, since the required acceleration at the turning points will be huge in this case, we use a sinusoidal driving pattern at the turning points of the linear path.

III. Development of Motion-Blur-Compensated Visual Inspection Vehicle for Tunnels

A. Requirement Definition and Prototype Design

In addition to the above updated motion blur compensation theory; we need to consider how to apply the theory to a visual inspection system installed on a moving vehicle. Unlike a laboratory situation, this system is used on roads, and hence we need to consider stability for rough terrain. Usually optical systems are mounted on rigid frames made of metal, and in this system also, we used rigid aluminum frames as a base for the entire system. Additionally, we used vibration-isolation mounts between roof carrier bars of the vehicle and system (See Fig. 3(a)).

Figure 3. Each update of prototype. (a) Lateral view with fixing parts, (b) back side view with actuators.

Moreover, flexibility of the system is also an important factor for practical use. If the system can change the optical path used for image capturing of the target, the system does not need multiple cameras. This will contribute to reducing cost (see Fig. 3(b)). Therefore, we prepared actuators for changing the optical path. Additionally, if the system is compatible with general vehicles, the manufacturing cost of the inspection vehicle will be significantly lower than specially designed vehicles. For that reason, we used commercially available roof carrier bars to attach the system onto a vehicle (see Fig. 3(a)).

Figure 4. Prototype motion-blur-compensated visual inspection system.

B. Prototype of Motion-Blur-Compensated Visual Inspection Vehicle for Tunnels

Fig. 4 illustrates a prototype of the motion-blur-compensated visual inspection vehicle for tunnels. We developed a prototype to upgrade from an indoor experimental system to an actual inspection system that can be used in field trials. We used a Toyota Landcruiser Prado, and used two sets of commercially available roof carrier bars and mounts to install the motion blur compensation system onto the vehicle. The optical path could be changed horizontally by 600 mm and rotated by 90 degree to cover half the area of tunnels on the outgoing part of a round trip.

IV. Performance Verification of Motion-Blur-Compensated Visual Inspection Vehicle

A. Experimental Environment

To verify the performance of our system, we conducted road tests in April 2014 in a box culvert in the Toyota Conservation and Service Center in Toyota-shi, Aichi-prefecture, and which is private land that is suitable for implementing this primary test. The box culvert, illustrated in Fig. 5, is a kind of tunnel. The width of the box culvert was 11.5 m, the height was 5.0 m on average, and the length was 71.2 m. Since the height of the camera from the ground was 2.0 m, the distance from the camera to the ceiling was 3.0 m, and therefore, the spatial resolution of the captured images was 0.13 mm/pixel horizontally and vertically.

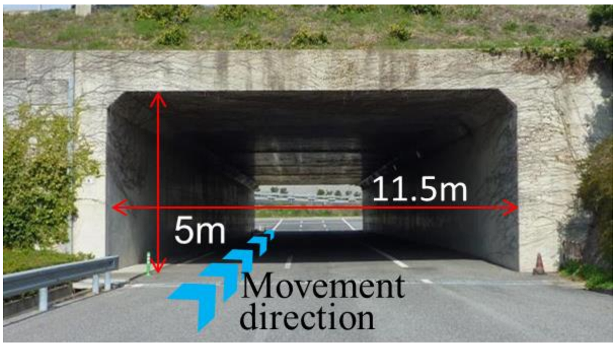

Figure 5. A box culvert in Toyota Conservation and Service Center.

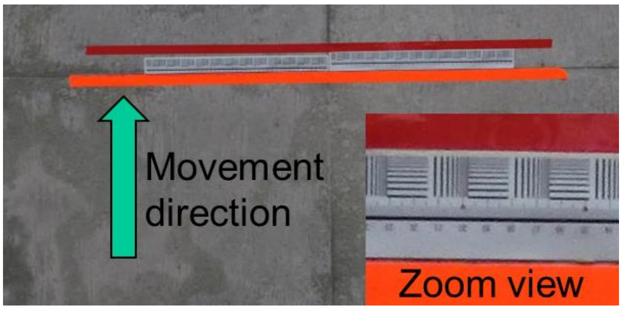

Figure 6. Ceiling of the box culvert on which scales and markers were attached. (This image was taken by a compact digital camera, not by the camera in the system.)

B. Experimental Setup and Procedure

To verify the performance of the system in compensating for motion blur in the driving test, we pasted scales and markers onto the ceiling of the box culvert (see Fig. 6). The scales had stripes of different widths, from 0.2 mm to 1.0 mm horizontally and vertically. Additionally, the markers were used to simplify the calculation of ω_m. Our algorithm was based on the feature value of a texture surface; however, the purpose of this experiment was to determine the performance of the system in terms of the motion blur compensation rate, and so we simplified the procedure to use markers. Additionally, there were only a small number of cracks in the box culvert, and since the system will be based on the result of fundamental verification, we only focused on scales as targets.

We set the exposure time to 1 ms, which is small enough compared with the system cycle time to ensure linearity. After manually adjusting the parameters, we set k to 1.05.

The speed of vehicle was limited to 60 km/h according to the regulations for private land, and the moving direction was the upward direction illustrated in Fig. 6.

We conducted the driving test with motion blur compensation on and off at each speed.

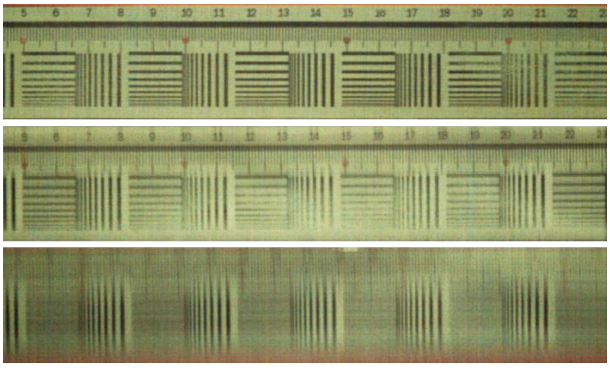

Figure 7. Results of motion-blur-compensated visual inspection system (image was trimmed and flipped vertically and horizontally. The contrast was adjusted). Motion blur occurred vertically in this image. (top) Still image, (middle) motion blur compensation on when the speed was 40 km/h, (bottom) motion blur compensation off when the speed was 40 km/h).

C. Experimental Results and Evaluation

Fig. 7 and Fig. 8 (a)-(c) illustrate a captured still image, and captured images with motion blur compensation off and on, when the speed of the vehicle was 40 km/h. In the case where the speed was 40 km/h, the vehicle moved forward approximately 11 mm within 1 ms, and hence, Fig. 8(c) includes a lot of motion blur. In contrast, in Fig. 8(b), the motion blur was well compensated compared with that in Fig. 8(c), although we observed degradation in Fig. 8(b) compared with the still image in Fig. 8(a). This is assumed to be due to driving vibrations and imperfect control. If we use the motion blur compensation method in which the exposure time is limited, the exposure time will be approximately 12 μs, and hence our system had an exposure time 83-times better. However, as we mentioned above, since Fig. 8(b) still has blur, we estimate that our system has an exposure time 10 to 50 times better. Incidentally, a moving speed of 40 km/h in the box culvert corresponds to a moving speed of 66 km/h in a normal tunnel on Japanese highways. Fig. 10 illustrates the speed of the vehicle and the width of stripes which we could distinguish. Since the minimum stripe width which we could distinguish from Fig. 9 was 0.2 mm, when the speed was 24 km/h (Fig. 9(a)), 30 km/h (Fig. 9(b)), and 40 km/h (Fig. 9(c)), our system compensated for motion blur precisely. Moreover, when the speed was 50 km/h (Fig. 9(d)) and 56.5 km/h (Fig. 9(e)), motion blur was also compensated. Actually without motion blur compensation, we could not distinguish stripes at all due to the strong motion blur. On the other hand, the motion blur compensation rate decreased at 50 km/h and 56.5 km/h. However, we verified that this system is effective for monitoring under millimeter-sized targets with prolonged exposure time without using brighter illumination.

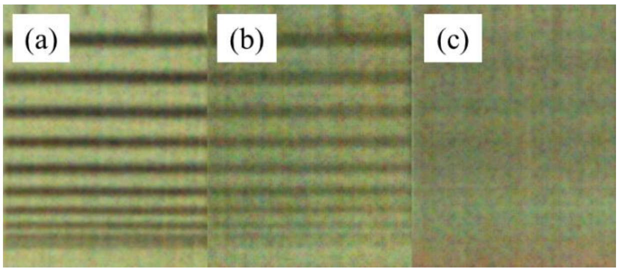

Figure 8. Results of motion-blur-compensated visual inspection system (images was trimmed and zoomed and the contrast was adjusted). Motion blur occurred vertically in this image. (a) Still image, (b) motion blur compensation on when the speed was 40 km/h, (c) motion blur compensation off when the speed was 40 km/h.

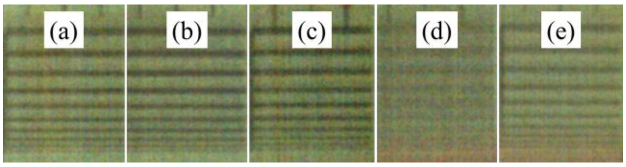

Figure 9. Results of motion-blur-compensated visual inspection system (images was trimmed and zoomed and the contrast was adjusted). Motion blur occurred vertically in this image. Motion blur compensation on when the speed was (a) 24 km/h, (b) 30 km/h, (c) 40 km/h, (d) 50 km/h, (e) 56.5 km/h.

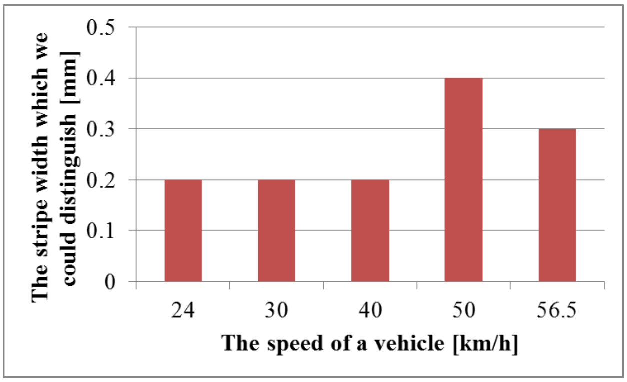

Figure 10. Distinguishable stripe width corresponding with each speed (by authors' subjectivity).

V. Discussion and Future Work

Since our system improved motion blur with prolonged exposure time 10 to 50 times, if the conventional systems use our method, their intensity of illumination is possible to be reduced 10 to 50 times with similar results. However, our system is still a prototype, and there are still many obstacles to be overcome before the system is suitable for practical use. First, the system must operate at higher vehicle speeds. On Japanese highways, the maximum speed is 100 km/h, so our system should be able to operate at this speed. However, the compensation rate decreased at higher speeds, and the system was effective only up to speeds of 40 km/h, as illustrated in Fig. 10. This is assumed to be due to inaccuracy of the coefficient k and the driving pattern of the galvanometer mirror. As future work, we should try various values of k, and other methods and driving patterns.

Second, the system performance should be evaluated quantitatively. In the experiments, we evaluated the results visually. Although this process is more efficient and less expensive compared with visual inspection using the human eye, to achieve higher efficiency, we should try to develop an automatic crack recognition system using image processing to realize a fully automated inspection system. As a preliminary experiment, we should capture actual images of cracks in authentic tunnels.

VI. CONCLUSION AND FUTURE PROSPECTS

In this paper, we optimized a motion blur compensation method and adopted it in a motion-blur-compensated visual inspection vehicle for tunnels. Additionally, by amplifying the gain of the galvanometer mirror, we could compensate for motion blur when the target height was 5 m and the speed of the vehicle was 40 km/h. Although this differed from the usual conditions used in inspecting tunnels, where the target height is 7 m and the speed of the vehicle is 66 km/h, it satisfied the minimum driving speed on Japanese highways. As a result, we established a fundamental method of inspecting crack, stains, and so on with a size of under one millimeters, and extended the exposure time without changing the intensity of the illumination.

Moreover, this system is expected to be applicable to conventional systems for diagnosis of structures, not only highways, but also railways, airports, harbors, and so on.

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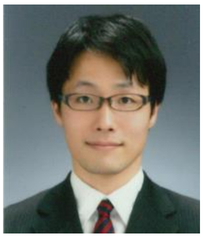

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