Advanced Inspection System of Tunnel Wall Deformation using Image Processing

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We have developed an efficient tunnel scanner with line sensor cameras capable of taking high-precision panoramic annular images of the surface of a tunnel lining at low cost. In this paper, we first describe the improvement made to the focus adjustment method, and then propose an image processing technique to remove image fluctuation. We also describe the sub-pixel-style image processing algorithm developed to extract minute cracks from a standard wall image and measure their characteristics such as width, length, direction etc. to a high level of accuracy. As a result, the overall costs have been kept down and the practicability of this detection system has made significant progress.

Keywords: tunnel, deformation, crack, inspection system, image processing, line sensor camera

1. Introduction

Deformation affecting the structural soundness of railway tunnels (such as wall cracking) is currently inspected and treated through visual monitoring. However, the actual work environment is so adverse and the areas for monitoring are so extensive that it is very difficult to investigate all deformation that develops on walls. The modernization of maintenance and inspection methods is now an urgent business due to a shortage of labor and the aging of maintenance workers. The existing method 1) 2), which uses photography and lasers, presents problems with complexity, inspection speed, accuracy and data processing. The ultimate goal of our research is to develop an inspection system for tunnel walls that is capable of efficiently extracting deformations such as cracks from images and automatically drawing deformation charts.

2. Outline of tunnel scanner system

We have developed an efficient tunnel scanner with line sensor cameras capable of taking high-precision panoramic annular images of the surface of a tunnel lining at low cost, as shown in Fig. 1. The system does not require a special vehicle, but instead can be mounted on railcars used for construction or maintenance purposes. The photographic equipment involved is basic, and consists of cameras, lights, control devices and the like. A number of 5000-pixel line sensor cameras are mounted on the railcar and aimed at the tunnel walls as shown in Fig. 2. The railcar travels at 10 to 30 km/h, and can take images of the surfaces of a single-track tunnel with just one run. A double-track tunnel requires two runs (one on each track) to obtain images of the entire section, and continuous image-taking is possible for dozens of kilometers per run. In basic terms, only image-taking and recording are carried out on the railcar, with offline processing of image data being performed elsewhere. The performance of this new system far outstrips that of conventional photographic systems in terms of filming speed, recording time and memory. The resolution is determined by the number of camera pixels in the cross-sectional direction, but depends on the running speed and scan rate for the longitudinal direction. Under ordinary conditions, the pixel pitch setting is around 0.8 mm horizontally/vertically as shown in Table 1.
3. Improvement of focus adjustment

In this chapter, we describe the improvement made to the focus adjustment method. In general, it is technically difficult to make focal adjustments for line sensor cameras under static conditions. Taking advantage of the fact that the focal conditions can be judged using a picture signal waveform configuration as shown in Figs. 3 and 4, we devised a method of analysis that evaluates the sharpness of waveforms using threshold values derived from a first derivation histogram. Where a captured image lacks sharpness, a histogram of the sharpness (the first derivation of f(x)) as shown in Equation 1 indicates a higher frequency in low values of sharpness; in contrast, the frequency of high sharpness increases gradually coming into focus as shown in Figs. 5 and 6. Figure 7 shows the calculation results of the evaluation function shown in Equation 2. By quantifying the degree of focal accuracy, we have made it possible to automatically perform the required focal adjustments.

\[
|f'(x)| = \left| \frac{f(x + \Delta x) - f(x)}{\Delta x} \right| \quad \text{(1)}
\]

\[
\alpha \cdot \sum |f'(x)| \cdot h(|f'(x)|) \quad \text{(2)}
\]

4. Correction of blurred images based on characteristic features

In analyzing deformation such as cracks on tunnel
walls, one serious problem we faced was image blurring as a result of railcar vibration. If a line sensor camera is subjected to vertical vibration, the resulting image is conspicuously misaligned by one image line. It is desirable to perform such operation without using a specific sensor as much as possible in order to enable a simple vehicle installation system. To correct these one-line unit misalignments, we chose the track’s electric cables (which must be installed in a straight line) as a standard baseline, measured the amount of misalignment from the wave pattern edge, and then performed correction by shifting all lines in the image by exactly the amount of the measured misalignment. Figure 8 shows a flow chart of camera blur correction, and Fig. 9 shows the output images. The system does not use a special sensor, and can produce excellent images with misalignment corrected by applying the characteristic of the electric wire cable’s linearity.

![Flow-chart of camera blur correction](image)

**Fig. 8** Flow-chart of camera blur correction

### 5. Multiple image splicing based on characteristic points

Splicing multiple photographic images is conventionally performed by hand, but the proposed method generates an unfolded tunnel wall image without joints simply by designating an approximate conjunction point. In particular, the image mosaicing method we adopted for panoramic images permits the effective production of excellent-resolution panoramic annular pictures. Specifically, this automatic matching algorithm detects characteristic points based on differences in color and texture from the tunnel wall image captured using a plural line sensor camera, and whole cross-section images can thus be efficiently captured as shown in Fig.10.

![Output images of camera blur correction](image)

**Fig. 9** Output images of camera blur correction

### 6. Automatic extraction of cracks through image processing

#### 6.1 Preprocessing for noise reduction

Checking of the method for detecting deformation on tunnel walls revealed an insufficient level of distinction between images of actual cracks and those of concrete joints, cables and cable shadows. A substantial improvement in the detection rate of cracks can be expected if there is a method of removing and distinguishing the images of such concrete joints, particularly because con-
crete joints are found in most walls. These noise images are generally continued with a linear shape. Taking this fact into consideration, we developed ways of distinguishing concrete joints from cracks by using the image processing technique of horizontal and vertical projection as shown in Fig.11.

Fig. 10 Joining procedure based on characteristic points

Fig. 11 Pre-processing (noise removal)

6.2 A Practical method of crack extraction

We also developed an image processing algorithm for the automatic detection of cracks, which are a common type of deformation in tunnel linings. Generally, the images of cracks are darker than those of their surroundings, and take the form of indented, blackish wavy lines. Focusing on the existence of variations in the gradient of luminance along line edges, we selected cracks with more detailed luminous variation than could be recognized by the resolution of the cameras. We then adopted a hysteresis threshold-processing method as shown in Fig.12 that would select only edges joined to edges detected by high threshold values. Figure 13 shows the output images of the extracted cracks. Furthermore,
We describe adopt the sub-pixel-style image processing algorithm based on a Laplacian filter developed to extract minute cracks (0.5mm width) from a standard wall image and measure the characteristic values such as width, length, direction etc. to a high degree of accuracy. It is possible to prognosticate the growth of cracks and rank the degree of soundness based on this data. The method was applied to typical crack images to validate its effectiveness, and the experimental results show that the extraction performance of the algorithm has the potential for sufficient accuracy as shown in Fig.14.

7. Conclusions

As a result of our study, the total costs have been kept down and the practicability of this detection system has made significant progress. Our tunnel scanner is now being used by a number of railway operators, and we are planning to increase its efficiency and accuracy so that it can detect cracks with even greater precision in the future.

References