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Advanced and Efficient Monorail Facility Inspections Using Optical Measurement Technologies, Including Laser and Imaging

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ABSTRACT: To support safe operation of monorail systems, periodic track inspections for line maintenance and structural inspections of the concrete girders and steel beamway that form the track are necessary, and efficient inspections and highly accurate inspection results are required. Since conventional inspections centered on manual measurement and visual inspection, there were issues in terms of the safety risk associated with work in high places and work efficiency. Furthermore, in visual inspections, it was not possible to gain an adequate understanding of deterioration over time due to the difficulty of quantitative evaluation. This paper presents an example of a non-contact inspection technique in which industrial area cameras, laser displacement sensor and a high-speed 2D laser profiler were installed on the inspection vehicle, and track displacement, visible deterioration trolley wire wear are measured while the vehicle is traveling. Although inspection work at the work site had required half a year with the conventional technique, the introduction of this technique shortened the inspection time to only 4 days, realizing improved efficiency and reducing the man-power required in site work. Future goals include sustainable infrastructure maintenance and improvement of track safety through efforts in trend analysis of the progress of deterioration based on an expanded range of inspection items and analysis of various types of accumulated data.

KEY WORDS: Structural Condition Assessment; Performance Evaluation; Laser Scanning; Non-Destructive Testing; Infrastructure Monitoring.

1 INTRODUCTION

1.1 Background and Issues of Monorail Inspection

Monorails are widely used as a key part of transportation infrastructure in urban areas and tourist destinations. Figure 1 shows a photograph of a monorail train traveling along the track beam above automobile street traffic. In proper maintenance management of this track structure, appropriate maintenance (line maintenance) is demanded from the viewpoints of safe operation and long service life. However, several issues arise in inspections of monorail systems.

Investigations of equipment degradation by conventional manual work center on judgments based on the experience and subjectivity of the inspection worker. However, in inspection work, objective and quantitative assessments are required for numerical management of the track condition. Manual inspection work is also extremely time- and labor-intensive, and securing work safety is also an issue because work is frequently performed in high places or at night. Although automation and digitization utilizing laser measurement and image analysis techniques have been promoted in recent years, techniques adapted to the structures and environmental conditions peculiar to monorails have not been adequately established[1][2][3].

1.2 Purpose and Significance of this Paper

In the current state of monorail inspections, the 3 issues of “Efficiency,” “Quantifiable Results” and “Safety” may be mentioned.

To solve these problems, this paper proposes a non-contact inspection technique utilizing industrial area cameras and laser displacement sensor. In addition to a very substantial reduction in work time achieved by mounting sensors on an inspection vehicle and performing measurements during vehicle travel, the quantifiable results of the inspection results is also improved by quantification and visualization of the measured data. Cracks and other surface damage are detected using image analysis with the cameras, and displacement of the track beam and wear of the trolley wire are captured with high accuracy by analyzing the data acquired by the laser displacement sensor as point cloud data. Higher efficiency and improved safety in inspection work and more advanced maintenance management can be expected by introduction of this technique.

Figure 1. Photograph of a monorail

2 VISUAL AND MANUAL INSPECTION TECHNIQUES AND THEIR ISSUES

Since the track structures of monorail systems are subject to progressive deterioration in the forms of rail displacement and beamway deformation when used repeatedly day after day, railway operators are legally required to conduct periodic inspections and perform appropriate maintenance management. In particular, since monorails play a key role in urban transportation, securing their safety is an extremely important social obligation. However, the current inspection methods still

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depend on visual inspections and manual work, and higher efficiency and more advanced methods are needed.

2.1 Conventional Inspection Techniques by Close Visual Inspection

In conventional inspections of monorails, the inspectors checked the structures directly, and the general method was judgment of abnormalities based on Close Visual Inspection. Concretely, inspectors conducted a "Visual Inspection" for structural deterioration by visually checking the structure surface for cracks, peeling, discoloration, etc., and "Track Displacement Measurement," in which deviations in the height and levelness of the travel surface and misalignment of joints between beam segments and the gap between the beam segments were measured. The inspection items are shown in Table 1 and Table 2, and photographs of the conventional techniques used in rail displacement measurements are shown in Figure 2.

Table 1. Inspection items in Visual Inspections

Inspection equipment
PC track beams (including beam underside surface), steel track beams, lower part of steel beams, cross beams, PC track beam bearings, joint devices, signs, track circuit boundary markers
Inspection items
Cracks and other damage (fissures, etc.)
Paint peeling and deterioration (corrosion)
Paint peeling/corrosion of bearings (PC beams, steel beams)
Paint peeling/deterioration of lower part of steel beams and cross beams (except flange parts)
Other abnormalities (damage of resin mortar, presence/absence of damping materials, looseness of bearing anchor bolts and nuts, confirmation of signs and boundary markers)

Table 2. Inspection items in Track Displacement Measurements

Inspection equipment	
Position of expansion joints of PC/steel track beams (including branch beams, median lines and pullup lines)	
Inspection item	**Content of inspection**
Partial longitudinal level irregularity measurement	Measure changes in height of track beam
Partial horizontal alignment irregularity measurement	Evaluate linearity of track beam, and detect horizontal bending
Cross level irregularity measurement	Measure levelness (inclination) of beam
Vertical/horizontal misalignment measurement	Measure vertical level difference in joints and horizontal differences in the level of girder joints
Joint gap measurement	Measure gap between beams at beam joints

Level difference at joint (vertical)

Rail joint gap

Misalignment at joint (horizontal)

Cross level irregularity (inclination of beam)

Figure 2. Conventional inspection techniques

2.2 Issues Related to Efficiency, Quantifiable Results and Safety

2.2.1 Issues related to efficiency

Many of the target sections of monorail inspections have been in service for more than 25 years, and since many lines were also constructed in the same period, demand for inspections and repairs is tending to increase. Because the target section in this paper has a total constructed length is 28.6 km and contains a large amount of infrastructure, enormous amounts of time and labor when an inspection is conducted. Thus, it is necessary to reduce the work load on inspection workers. However, a single inspection by the conventional method requires as much as several months, and securing speed (high efficiency) is an issue.

2.2.2 Issues related to quantifiable results

Partial deterioration of the track beam with age has already been confirmed from the inspection results, and further progress of deterioration is also expected in the future. Because inspection workers judge abnormalities by visual inspection and manual work, a large part of the conventional inspection method depends on the individual experience and senses of the inspectors. For example, when measuring the width of cracks, there are variations in the results depending on the measurement position and angle, and in some cases, there are differences in the evaluation depending on the inspector, even when inspecting the same damage. Since it is difficult to check for deterioration of facilities over the wide inspection area by a single standard, securing quantifiable results is an issue.

2.2.3 Issues related to safety

Because the track beam of monorails is generally installed in an elevated location, inspection worker must use a high-lift work vehicle or scaffolding to conduct inspections. Inspections

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are frequently carried out at night, which increases the possibility of accidents due to fatigue or decreased concentration. Because this work involves a risk of falling or contact accidents, securing work safety is an issue.

3 PROPOSED NON-CONTACT INSPECTION TECHNIQUE

3.1 Necessity of Digital Measurement Technique

In recent years, infrastructure inspections using non-contact measurement technologies have been widely adopted, and more accurate and efficient inspections are expected to be possible by utilizing laser measurement and image analysis techniques. This can achieve improved worker safety and labor-saving in inspection work. In addition, it can also contribute to predictions of long-term deterioration and sustainable infrastructure maintenance by accumulating and analyzing data.

This paper introduces a non-contact inspection technique utilizing laser displacement sensor and industrial area cameras and describes its effectiveness. The laser displacement sensor enable quantitative evaluations of the displacement of structures and wear of trolley wires. Highly accurate image analysis, without depending on visual inspection, is possible by using the industrial area cameras in combination with the laser displacement sensor. Although it was difficult to accumulate numerical data in conventional visual inspections, the proposed technique enables precise measurement and evaluation of visible deterioration and wear with high quantifiable results by combined use of the industrial area cameras and laser displacement sensor.

3.2 Outline of the Technique and Sensor Configuration

As described in this paper, a non-contact measurement technique was constructed in order to gain a highly accurate understanding of the condition of the track beamway and the trolley wires of monorails and quantitatively evaluate the current condition of deterioration.

In this technique, sensors were mounted on a monorail inspection vehicle, and data are acquired while the vehicle was traveling. The main sensors and their inspection items were industrial area cameras (visible deterioration, joint gap measurement), laser displacement sensor (for longitudinal level irregularities, horizontal alignment irregularities and vertical and horizontal misalignment of joints) and a high-speed 2D laser profiler (for trolley wire wear).

The sensor installation arrangement was designed to extract the maximum possible measurement accuracy. The cameras were installed on the front of the vehicle, and photography was performed with a total of 16 units so as to cover the entire surface of the track girder, including the beamway, side surfaces, under beam area, bearing parts and track beamway substructure. The laser displacement sensor were installed at equal intervals under the vehicle and capture information on the distance to the beamway. A high-speed 2D laser profiler was also installed on the vehicle underbelly to capture information on wear of the trolley wire. Introduction of the cameras, lasers and various other sensor makes it possible to collect data continuously, and achieves more comprehensive deformation analysis than is possible with conventional spot measurements. The images of the installation positions of the industrial area cameras and image of installation of the laser displacement sensor are shown in Figure 3 and Figure 4, respectively, and photographs of the installed sensor are shown in Figure 5.

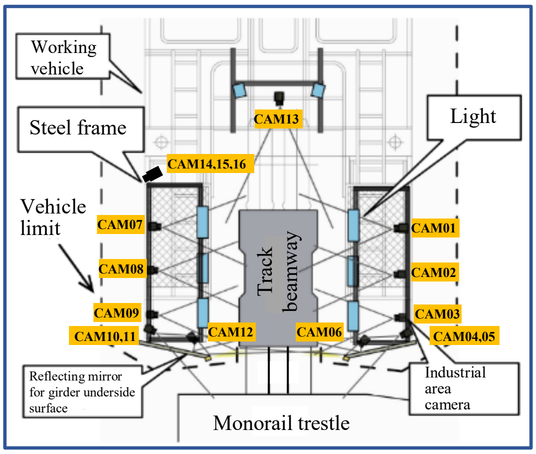

Figure 3. Image of installation positions of industrial area cameras

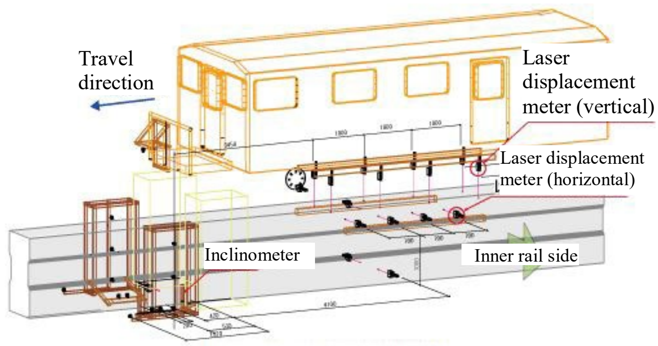

Figure 4. Image of installation positions of laser displacement sensor

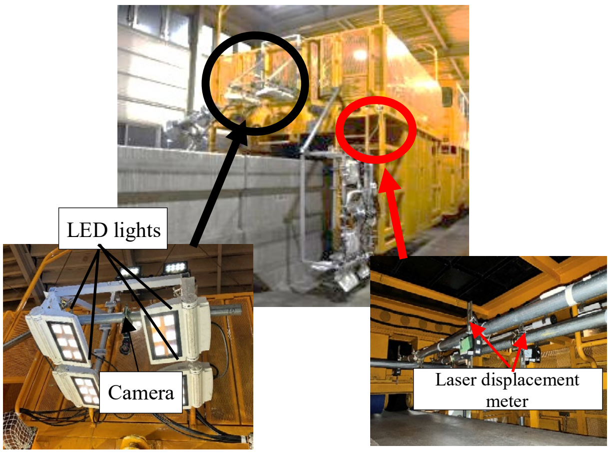

Figure 5. Photographs of site installation condition

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3.3 *Visual Inspection by Industrial Area Cameras*

3.3.1 Camera installation method and arrangement

In visual inspections for facility deterioration, industrial area cameras are employed to capture surface cracks and paint degradation. Compared to line scan cameras, area cameras offer greater flexibility in installation and imaging conditions, as they can capture full-frame images in a single exposure without requiring continuous motion of the object. A total of 16 compact area scan cameras with 2.35 megapixel resolution and a framerate (fps: frames per second) of 30 fps are used. A dedicated camera frame was designed to enable photography with the same quality from positions equidistant from the object of photography. An appropriate lighting arrangement and photographing distance for extraction of cracks with a width of 0.2 mm were planned. The cameras used to photograph the running surface and side surfaces of the beamway were arranged directly facing those objects, and the cameras used to photograph the bearings and underside of the steel beamway were arranged to photograph those objects from an oblique angle. Arranging the cameras so there is an overlap in the camera angle of view of the beam side surfaces enables sure data acquisition, with no gaps between the photographs of each image. Since it would be difficult to photograph the underside surface of the girder directly from within the vehicle limit width, a method of photographing images reflected by a mirror was adopted. Table 3 shows the specification of the cameras mounted on the vehicle.

Table 3. Specification of high-resolution cameras

Product name	GO-2400C-PMCL
Appearance	
Standard	1936 x 1216 px
Sensor	1CMOS
Sensor size	1/1.2 type
External dimensions	29 x 29 x 41.5 mm
Weight	46 g

3.3.2 Issues in photography and countermeasures

Since photography while the vehicle traveling is affected by vehicle vibration and shaking, the shutter speed of the cameras used in this technique was set to 1/4 000 s. This made it possible to minimize the effect of blurring caused by vibration and shaking. On the other hand, if this setting is used, the images will be dark because the short exposure time limits the light available when photographing an image. In order to acquire high quality image data even in dark areas, multiple LED lights were arranged so as that the entire surface of the girder received an appropriate, uniform amount of light.

3.4 *Track Displacement Measurement by Laser displacement sensor*

Track displacement, including unevenness, level differences, and inclination, is measured using a total of 14 laser displacement sensors, each capable of high-precision, single-point distance measurements that enable the detection of subtle structural shifts. Since the sampling frequency is 2 000 Hz, measurement at a pitch of about 2 mm in the travel direction at a travel speed of 15 km/h. The spacing of the laser displacement sensor was adjusted to 400 mm, which is the median value of the measurement range, and were installed so as to enable capture of displacement of the upper limit value (±100 mm). The specification of the laser displacement sensor is shown in Table 4.

Table 4. Specification of laser displacement sensor

Product name	LK-G405
Appearance	
Measurement range	300 to 500 mm
Wavelength	655 nm (visible light) Laser class: 3Ror2
Sampling period	20 to 1 000 µs
Protection structure	IP67 (IEC60529)
External dimensions	3.6 x 10.8 x 8.5 cm
Weight	Approx. 380 g (including cord)

3.5 *Trolley Wire Wear Inspection*

To investigate wear of the trolley wire located on the side face of the beamway, a high-speed 2D laser profiler is used to perform continuous scanning of cross-sectional shapes, enabling precise visualization and quantification of wear, misalignment, and other geometric anomalies. As in the case of the above-mentioned laser displacement sensor, because the sampling frequency is 2 000 Hz, measurement at a pitch of approximately 2 mm in the travel direction is possible, assuming a travel speed of 15 Km/h. Since it is necessary to grasp the compete image of the trolley wire when investigating wear, the high-speed 2D laser profiler was installed so that the entire trolley wire can be scanned from a position directly facing the wire. The specification of the high-speed 2D laser profiler is shown in Table 5.

Table 5. Specification of high-speed 2D laser profiler

Product name	LJ-V7300
Appearance	
Measurement range	155 to 445 mm
Wavelength	405nm (visible light) Laser class: 2
Sampling period	Max. 16 µs
Protection structure	IP67 (IEC60529)
External dimensions	5.7 x 17.3 x 8.8 cm
Weight	Approx. 1 000 g

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4 ANALYSIS OF MEASURED DATA

4.1 Preparation of Composite Image and Investigation of Visible deterioration

After geometric correction, magnification correction and color correction, the images captured by the industrial area camera are composed as continuous composite images. Geometric correction is a type of correction processing in which images that contain distortion and deformation are adjusted to produce orthorectified images with an accurate shape and positional relationship. Creating composite images makes it possible to check each of the girders and beams of the track over a wide range, and at the same time, understand their actual positional relationships. Figure 6 shows composite images of the beamway running surface and side surface.

Damage is extracted using the crack drawing support software "k-TRACE" (Figure 7), which was developed by this company (KRC: Keisoku Research Consultants Co.)[4][5]. When the inspector clicks the line of a crack with the mouse, k-TRACE analyzes the shading of the color around the line joining the clicked points and automatically outputs the shape and width of the crack. Application of this tool is not limited to cracks, as the software can also extract the positions of peeling, water leaks and free lime at the same time. This processing makes it possible to obtain a comprehensive understanding of the exact position and scale of the damage from images, without going to the site, thereby securing "Safety" and "Quantifiable Results."

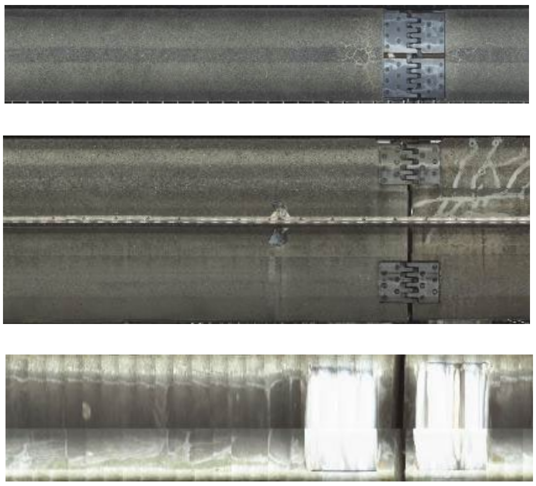


Figure 6. Composite images of beamway (top: running surface, middle: side surface, bottom: underside of girder)

Figure 7. "k-TRACE": crack drawing support software

4.2 Joint Gap Measurements

For joint gap measurements, analysis is performed based on the photographed images. An image showing the joint part in the center is extracted from multiple images, and the width of the joint gap is calculated from the number of pixels at the gap position in the image. The calculated joint gap is standard value are then compared, and the locations of joints where the gap exceeds the control standard value are extracted. A photograph of the joint gap image is shown in Figure 8.

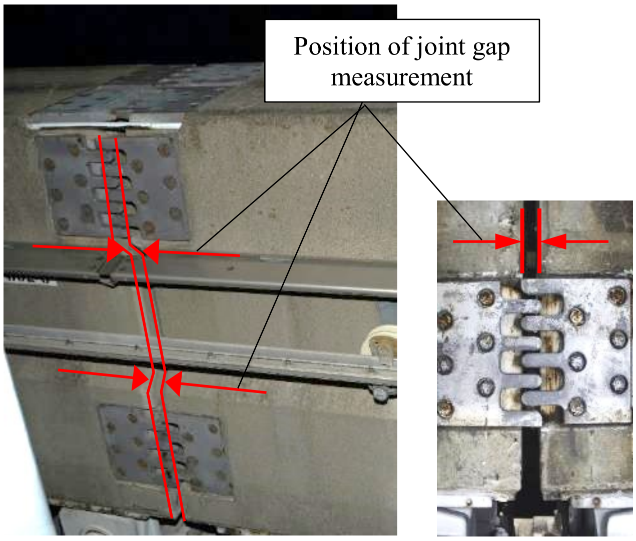
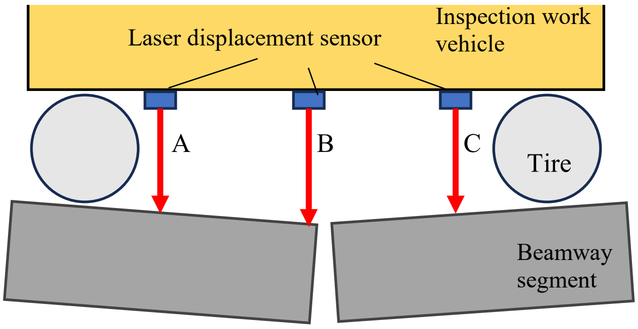


Figure 8. Position of joint gap measurement

4.3 Partial Longitudinal Level Irregularity Measurement

Displacement of the height of the beamway running surface (partial longitudinal level irregularity) is measured by using 3 laser displacement sensor (A, B, C) installed at 1 m intervals in the travel direction. The partial longitudinal height displacement h_d is calculated as the difference between the average distance measured by the first and last units (A+C)/2 and the distance measured by the center unit B. The calculated values are arranged for each beamway segment, and locations that exceed the control standard value are extracted. An image of the height calculation method is shown in Figure 9.



$$h_d = B - \left(\frac{A + C}{2}\right) \quad (1)$$

Figure 9. Image of height value calculation

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4.4 Partial Horizontal Alignment Irregularity Measurement

Similarly to the partial longitudinal level irregularity measurement method, lateral deviations of the beam side are measured by 3 laser displacement sensor installed at equal distances in the travel direction. The data calculation method is also similar to that used in partial longitudinal level calculations. The waveform obtained in a horizontal alignment irregularity measurement is shown in Figure 10.

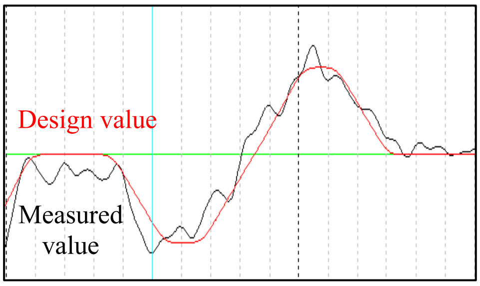
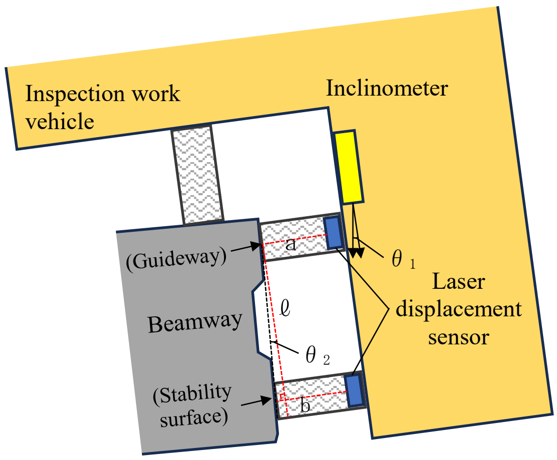


Figure 10. Waveform in horizontal alignment irregularity measurement

4.5 Cross Level Irregularity (Inclination) Measurement

The inclination (cross level) of the beamway is measured by using an inclinometer and laser displacement meter. If the beam and the vehicle are parallel, the cross level θ can be measured using only the inclinometer, but there will be a slight variation in the inclination. Therefore, displacement is measured by using laser displacement sensor installed on the guideway and the stability surface of the beamway side surface to correct for the difference in inclination, and the difference in the inclinations of the track beamway and the vehicle is obtained from the respective measured values of *a* and *b* and positional relationship l between the displacement meters. Since the measured values of the inclinometer are also affected by centrifugal force, the cross level θ of the beam can be calculated by adding a corrected value $\Delta\theta c$, which is calculated based on the beam linearity and speed values. An image of the relationship of the inclinometer and the beam side surface and the numerical expression are shown in Figure 11.



$$\theta_2 = \tan^{-1}\left(\frac{b-a}{\ell}\right) \tag{2}$$

$$\theta = \theta_1 - \theta_2 + \Delta\theta_c \tag{3}$$

Figure 11. Relationship of inclinometer and beam side surface

4.6 Vertical and Horizontal Misalignment Measurement

Vertical misalignment and horizontal misalignment are measured at beamway joints (total of 6 positions of the running surface, guideway and stability surface) using laser displacement sensor. The amount of displacement is calculated from height of the fingerplate surface measured before and after passing the joint, and the vertical and horizontal misalignment of each joint is evaluated. Figure 12 shows a position diagram of the laser displacement sensor when measuring vertical and horizontal misalignment, and Figure 13 shows the waveform of vertical misalignment measurement results.

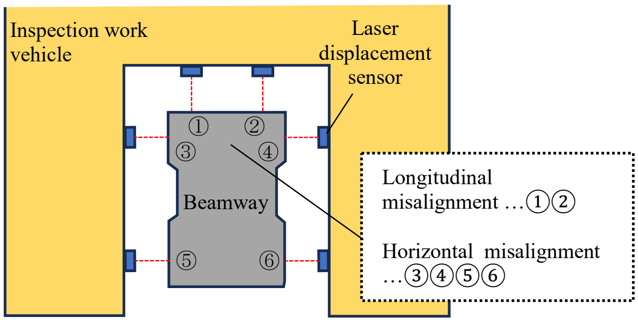


Figure 12. Position diagram of laser displacement sensor for vertical and horizontal misalignment

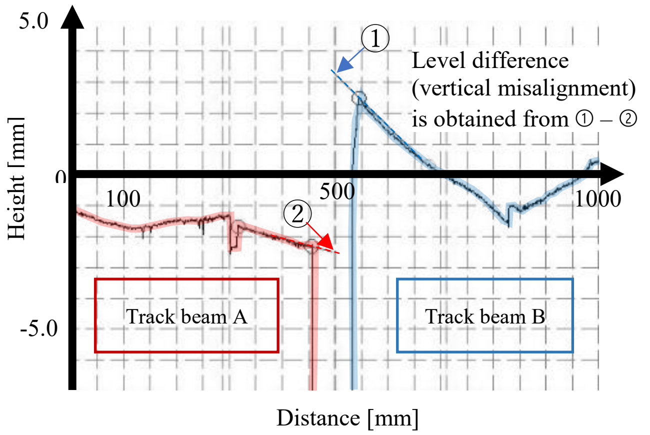


Figure 13. Result of vertical/horizontal misalignment measurement

4.7 Trolley Wire Wear Measurement

In wear inspections, the cross-sectional shape of the trolley wire is measured using a high-speed 2D laser profiler, the result is compared with the design cross section, and the wear amount ΔW is calculated. Here, ΔW is the difference between the design value of the trolley wire thickness W_{design} and the measured thickness of the remaining part of the wire W_{meas}. The thickness of the remaining part W_{meas} is calculated by acquiring point information on 1 point (point A) at the tip, which is the wear zone of the trolley wire, and 2 corner points (points B and C) of the metal part were wear has not occurred, and calculating W_{meas} from the relationships of distances *a*, *b* and *c* between the each of these points and the laser displacement meter.

Using the high-speed 2D laser profiler enables more complete, quantitative wear measurement than is possible by

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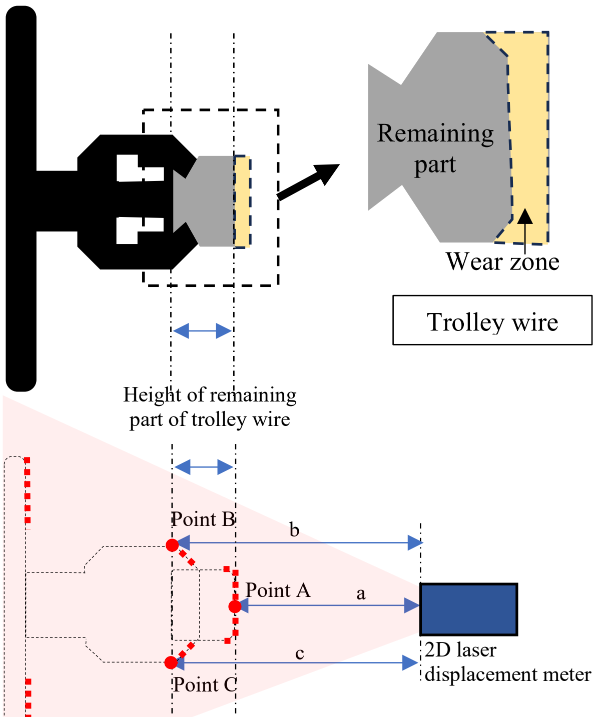
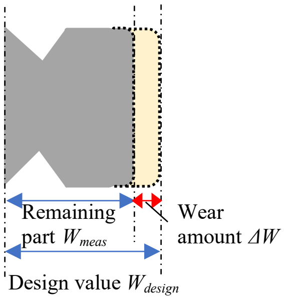
conventional manual measurement. It is also possible to analyze the trend of wear progress and carry out systematic trolley wire maintenance and exchanges by accumulating measurement results over the long term. Figure 14 shows an image of the trolley wire and wear and the numerical expression for the wear calculation. Figure 15 shows the data used to create the composite waveform of the high-speed 2D laser profiler.



$$W_{meas} = \frac{b+c}{2} - a \tag{4}$$



$$\Delta W = W_{meas} - W_{design} \tag{5}$$

Figure 14. Image of trolley wire and wear

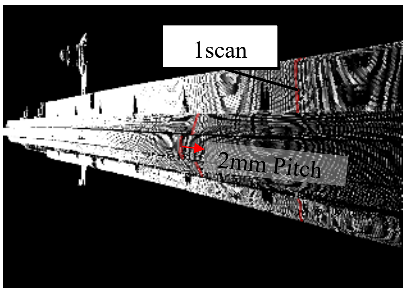


Figure 15. Point cloud composed using scan data from the 2D laser profiler

5 DISCUSSION

5.1 *Improvement of Work Efficiency*

With the proposed method, site working time was shortened from half a year by the conventional method to only 4 days because many types of measured data can be collected at one time while travelling. This shortening of site working time not only improves work efficiency, but also contributes to improved safety. On the other hand, the load of office work, such as processing and analysis of acquired data, is large, so efforts for improvement for reduction of the volume of work are necessary. Nevertheless, digitization of inspection results has lightened the work involved in arranging and managing measurement results and improved the convenience of data use.

5.2 *Improvement of Quantifiable Results*

By using the proposed technique, measured results with quantifiable results based on numerical values, and evaluations of damage based on those results, have become possible by using industrial area cameras and laser displacement sensor. In detection of cracks, semi-automatic measurement of the width and length of the damage is possible by utilizing image analysis, and quantitative comparison with past data is now easy. In measurements of track displacement, measurement results and evaluations with high quantifiable results have also become possible by using laser displacement sensor.

5.3 *Improvement of Safety*

With the proposed technique, it is no longer necessary for workers to enter dangerous areas because the sensors are mounted on the inspection vehicle and measurements are carried out while the vehicle is traveling. The use of non-contact sensors rather than contact-type measurement methods has not only reduced the loads on structures during measurements, but has also realized stable measurement.

6 CONCLUSION AND FUTURE OUTLOOK

6.1 *Conclusion*

The proposed technique is a system in which sensors are mounted on an inspection vehicle, and track displacement and visible deterioration are measured while the vehicle is traveling. Cracks and other surface damage are detected by utilizing image analysis of images acquired with industrial area cameras, and displacement of the track beamway is measured with laser displacement sensor. Highly precise evaluation of trolley wire wear has also become possible by applying an analysis technique utilizing point cloud data. Although conventional site inspection work had required half a year, the application of these techniques has shortened the site work time to only 4 days, realizing improved work efficiency and a reduction of the work load. Improved safety could also be secured by shortening the site work time of workers.

By using the industrial area cameras, creation of composite images, understanding the overall deterioration of facilities, and comparison of deterioration between two time periods have become easy, and in measurements of track displacement, it is

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now possible to obtain measurement results with high quantifiable results as a result of the acquisition of high-accuracy data using the laser displacement sensor and establishment of methods for calculating the amounts of various types of displacement using that data. Likewise, in measurements of trolley wire wear, quantitative evaluation of the amount of wear has become possible by a technique using a high-speed 2D laser profiler. Based on the above, in comparison with conventional inspections, it can be said that improvement of the reproducibility of inspection results, understanding of changes over time and quantitative evaluations are now possible.

6.2 Future Outlook

The introduction of the proposed technique has realized high efficiency and improved quantifiable results in inspection work. However, we intend to address the following issues in order to development more advanced techniques and enable long-term operation.

6.2.1 Reduction of the data processing load and automation

With the proposed technique, on-site measurements can be completed in significantly less time compared to conventional methods. However, the analysis of the acquired images and point cloud data still requires a certain amount of processing time. In particular, damage detection and evaluation by image analysis involve work that requires specialized knowledge. Therefore, the introduction of AI technologies is expected to improve the efficiency of post-processing and reduce reliance on expert interpretation.

- AI automation of image analysis:
  Analysis time can be shortened and variations in accuracy can be reduced by automatic recognition and classification of cracks and other damage by machine learning. We will also study a system for diagnosis and evaluation of structures from damage extracted for each girder/beam.

6.2.2 Further expansion of range of application

Although this technique has been applied mainly to evaluations of displacement and damage of the track beamway and trolley wire wear, application to other inspection items should also be studied in the future.

- Deployment to various structures on the track:
  The aim here is to realize comprehensive infrastructure monitoring by expanding the objects to inspections to include bridges on the track, peripheral equipment, stations, etc.
- Selection of the optimum sensor technologies:
  In addition to the existing image and laser technologies, LiDAR, thermal infrared camera technology, etc. will also be studied in order to establish a multifaceted deterioration detection technique.

6.2.3 Confirmation of linkage of individual inspection items

Causal relationships also seem to exist between respective inspection items such as longitudinal levelness, horizontal levelness, misalignment, etc. These will be utilized for appropriate line maintenance by clarifying their relationships based on accumulated data.

6.2.4 Prediction of long-term deterioration risk

In the future, the establishment of a technology for predicting the future deterioration of structures by using accumulated data will be demanded.

- Creation of risk assessment model:
  Based on acquired data, a technique for assessing the rate of progress of deterioration and the range of its effects, and quantitatively judging the priority of repairs and maintenance, will be developed.
- Deterioration prediction using risk assessment model:
  Based on the risk assessment model, the progress of displacement and wear of the track beamway and trolley wire will be predicted to optimize maintenance management plans.

In the future, we promote higher efficiency and more advanced techniques by solving these issues, with the aim of realizing more sustainable and precise infrastructure maintenance management.

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