Rail Deterioration Detection Method using Image Spectral Analysis

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Since many Railway facilities are visually inspected, the use of camera images is being encouraged to improve inspection efficiency. A hyperspectral camera can acquire two-dimensional spatial information of a photographed object and spectral information spectroscopically divided into several dozens or more wavelengths. Using this camera, we expect to be able to capture changes in materials that are difficult to detect visually, from changes in wavelength distribution and intensity of specific wavelengths. This paper describes a basic test applying the proposed method using a hyperspectral camera for detecting rail deterioration, and reports on the obtained results.

Keywords: hyperspectral camera, rail deterioration, spectral analysis of images

1. Introduction

Most railway facilities are installed outdoors and deteriorate under the direct influence of natural conditions such as rain, snow, wind, sunlight, and temperature. Railway operators regularly inspect the condition of track equipment in order to ensure vehicle running safety. Many of these inspections are conducted visually or manually, which is time and labor intensive. Therefore, to mechanize and improve the efficiency of these inspections, technologies are being developed around the world to help determine the state of facilities using image processing and machine learning. Normal digital cameras are acquiring information by dividing reflected light from sunlight into several bands in the visible range. The purpose of these sensors is to detect obvious deterioration or damage that can be visually confirmed, such as bolts which have fallen off a fish plate or a rail fastener system.

The purpose of this study, however, is to develop a method using the spectral analysis of the image to quantitatively grasp the deterioration and its progress from changes in the composition and crystal structure of track material, which cannot be visually inspected.

For the purpose, first, we investigated the applicability of using a hyperspectral camera to inspect the initial deterioration of a rail surface. Hyperspectral cameras can simultaneously acquire two-dimensional spatial information from a photographed object and spectral information (hyperspectral) dispersed into dozens of wavelengths or more. In this paper, we report the results of basic tests conducted with a hyperspectral camera on rails with white etching layers and gauge corner head checks confirmed visually.

2. Overview of hyperspectral camera

Light is a type of electromagnetic wave with energy according to its wavelength. Depending on the structure, material, and condition of a material, light of a certain wavelength is reflected, and light of other wavelengths is absorbed, thereby decreasing light intensity. Therefore, it is possible to identify a material by obtaining information such as composition and crystal structure from the spectrum of reflected light.

The human eye and normal digital cameras classify wavelengths into three colors: red, green, and blue. They detect the reflected light from a material to identify the color. Hyperspectral cameras, however, disperse reflected light from an object into dozens of wavelengths to acquire spectral information. Therefore, it is possible to analyze the spectrum of a material image taken with a hyperspectral camera and capture changes in the properties of the material that cannot be grasped by the human eye or a normal digital camera. In other words, it is expected that these properties will make it possible to use the camera for quantitatively grasping the initial deterioration of materials used in railway facilities.

Figure 1 outlines the information that can be acquired by a hyperspectral camera. Figure 1 shows that in a hyperspectral image, 200 million pixels can be obtained by splitting wavelengths from 350 nm (near ultraviolet) to 1100 nm (near infrared) into 151 wavelength bands at 5 nm intervals with a 1.31 million pixel camera.

Volume of information = 1.31 million pixels × 151 wavelengths ≈ 200 million pixels

Fig. 1 Hyperspectral camera
3. Image spectrum analysis method and image capture method

3.1 Outline of laboratory test

We examined the method for analyzing images taken by a hyperspectral camera for rails. In rail inspections, although damage inside the rail such as the length of transverse cracking is quantitatively measured by a rail flaw detection car or a flaw detector, deterioration of the rail surface is determined visually.

Table 1 shows the main specifications of the hyperspectral camera used in this test. Given the vast amount of information acquired by hyperspectral camera, the standard time required to capture one image with this camera can be long as 7.7 seconds. As for the light source used in the test, there are no prior examples of shooting a rail with a hyperspectral camera, therefore, the spectral distribution of the reflected light from the rail is unknown. Therefore, we used a halogen light that includes the entire wavelength band that can be acquired by this camera.

First, in order to examine the basic analysis method after grasping the spectrum of the reflected light from the rail, we photographed the normal rail as a test rail, on which a white etching layer was confirmed on its surface, as shown in Fig. 2 [1]. We also set eight imaging conditions that differed in the relative positional relationship between the camera and the rail, the irradiation direction of the halogen light, and the presence or absence of light diffusion, and confirmed the effect on the spectrum of the captured image. Figure 3 shows the conditions of the laboratory test, and Table 2 shows the imaging conditions.

Table 1 Main specifications of the camera

| Item                     | Specification                          |
|--------------------------|----------------------------------------|
| Resolution               | 1280 × 1024 pixel (131.1 million pixels) |
| Shooting speed           | 7.7 seconds as standard                |
| Data transfer rate       | 133 fps                                |
| Measurement wavelength   | 350 nm ~ 1100 nm                       |
| Wavelength interval      | 5 nm                                   |

Table 2 Imaging condition

| Positional relationship between camera and rail | Diffuse Light direction | Condition No |
|-----------------------------------------------|------------------------|--------------|
| Vertically upward (90°)                      | × Long                 | 1            |
|                                              | ○ Short                | 2            |
|                                              | × Short                | 3            |
| Diagonal (45°)                               | × Short (From the camera side) | 4            |
|                                              | × Short (From the other side of the camera) | 6            |
|                                              | × Short (From both sides of the rail) | 8            |

3.2 Examination of image analysis method

We photographed the test rail under imaging condition 1 indicated in Table 2 to obtain its hyperspectral image, shown in Fig. 4. Then we selected 5 spots shown in Fig. 4 as areas to analyze: spot ① (rust), spot ② (white etching layer), spot ③ (the boundary between spot ② and ④ where the presence or absence of the white etching layer is not clear), spot ④ (No white etching layer (≈ rail steel)), and spot ⑤ (Rail bottom). Figure 5 shows a spectral graph of the wavelength band from 350 nm to 1100 nm for each analysis area. The vertical axis of Fig. 5 is the spectral intensity representing the reflectance of light from the material. Since the magnitude of the spectral intensity changes depending on the angle of the light source and the brightness of the surroundings, the difference in the properties of the material appears as the difference in the shape of the graph in each analysis area. The spectral data
obtained by photographing with a hyperspectral camera is a combination of the spectral distribution of the reflectance of the material and the spectral distribution of the light source. Therefore, a white plate is photographed as a material to obtain the spectral distribution of the light source under the test conditions, and the spectral intensity of the object is obtained by (1).

$$\text{Spectral intensity} = \frac{\text{Spectral data of material}}{\text{White plate spectrum}} \times 400$$ (1)

where the coefficient of 4000 is the default value to be multiplied when calculating the spectral intensity with the software used for the processing of this camera. From Fig. 5, we found that there is a difference in the shape of the spectrum of each analysis area between the wavelengths of 505 nm to 635 nm and 950 nm to 1050 nm. Therefore, we focused on this band to examine an analysis method for grasping the white etching layer.

### 3.2.1 Tilt analysis

Tilt analysis, which is also called normalized spectroscopic reflection index analysis (NDSI analysis), is an analysis method that color-codes images based on the magnitude of the difference between spectral absorption and reflection. Tilt analysis is expressed by (2). NDSI, which is defined to reduce the influence of the error factor in the spectral waveform, is the value obtained by dividing the difference between the spectral intensities of the two selected wavelengths ($\lambda_1, \lambda_2$) by their sum.

$$\text{NDSI} = \frac{I_{\lambda_1} - I_{\lambda_2}}{I_{\lambda_1} + I_{\lambda_2}}$$ (2)

where $I_\lambda$ indicates the reflectance at the wavelength of $\lambda$ nm.

Figure 6 shows the results of setting the color-coded thresholds based on the difference in NDSI values. Fig. 6 shows that the two wavelengths from the tilt analysis are 505 nm and 635 nm and the presence or absence of the white etching layer is clearly distinguished between spot ② and ④. The parts with the white etching layer on the rail surface are color-coded in yellow, and the parts without the white etching layer are color-coded in black. However, since the spectral shapes of the analysis area with the white etching layer and the analysis area at the bottom of the rail look similar, it is determined that there is a white etching layer in a part of the bottom of the rail. The boundary of spot ③ was identified in the same way as the part with the white etching layer spot ②.

Figure 7 shows the results of the tilt analysis with two wavelengths of 950 nm and 1050 nm. In the figure, it is difficult to distinguish the presence or absence of the white etching layer. The reason for this result is that in the spectral graph of Fig. 5, there is no significant difference in the spectral shapes of spot ② and ④ between the wavelengths set by tilt analysis. However, since the spectral shapes of the analysis area with the white etching layer and the analysis area of the rail bottom are different in the wavelength bands of 950 nm and 1050 nm, the rail head and rail bottom are clearly color-coded. Therefore, it is considered that erroneous detection of certain parts with a white etching layer can be prevented by using the results of the two wavelength bands together.

### 3.2.2 Differential analysis

As shown in Table 1, the hyperspectral camera used in the test acquired spectral intensities with wavelength intervals of 5 nm. Therefore, after the spectral intensity was converted to a percentage using (3), the difference in spectral intensity between 5 nm was taken for each analysis area to obtain the change between each 5 nm interval.

$$\text{Spectral intensity(percentage)} = \frac{\text{Spectral intensity}}{4000} \times 100$$ (3)

Figure 8 shows the results of the differential analysis. Comparing the results of spot ① (rust), spot ③ (no white etching layer) with the results of spot ② (white etching layer) and spot ⑤ (the boundary between spot ② and ④) in the figure, we found that at wavelengths from 500 nm to 650 nm there were differences depending on the surface condition of the rail. However, setting a threshold value for identification would be difficult because the waveform variation of the numerical values in each state is large. Next, we calculated the average value for 5 data (from 25 nm intervals) in order to reduce the variation in numerical values. The results are shown in Fig. 9. The calculation result of the average value at a wavelength of 25 nm intervals within the differential analysis made the difference depending on the state of the rail surface clearer. The results of the difference analysis show the possibility of improving the accuracy of the color-coded detection of the tilt analysis by setting the wavelength and parameters of the tilt analysis. On the other hand, since the result from spot ⑤ (Rail bottom) was close to the result from the spot with the white etching layer, it was necessary to distinguish between them using results from different wavelengths, like a tilt analysis, or to exclude it when setting the analysis area.
3.3 Examination of image shooting method

We photographed the test rail under imaging condition ② indicated in Table 2 (short light direction) in order to grasp the effect of the light source condition at the moment of shooting on the spectrum. The spectral graph of the image is shown in Fig. 10.

Comparing Fig. 10 and Fig. 5, although the spectral intensities were reduced and the rate of reduction was different in all analysis areas, the spectral shapes were similar. Under imaging condition ②, it was considered that the spectral intensity decreased in all the analysis areas because the amount of light captured by the camera decreased. The reason is that the irradiation to the curved part of the top of the rail with light made the reflected light disperse.

Figure 11 shows the results of differential analysis to obtain the average value at a wavelength of 25 nm intervals. Comparing the results of spot ① (rust) and spot ④ (without white etching layer) with the results spot ② (with white etching layer) and spot ③ (the boundary between spot ② and ④), it can be confirmed that there is a clear difference in the spectral shape at wavelengths from 500 nm to 650 nm. Since the spectral intensity decreased overall, the differential analysis result of imaging condition ② was smaller than that of imaging condition ①. In addition, even under imaging condition ③ (light direction length, no diffusion) in which the light diffusion box was removed, the spectral intensities decreased, and the spectral shapes in all analysis areas were similar. It was also confirmed that the magnitude of the spectral intensity changes as the amount of light captured by the camera decreases under imaging conditions ⑤ to ⑧ where the positional relationship between the camera and the rail is 45°.

From the above-mentioned results, in order to accurately identify the state of the rail surface from the hyperspectral image, it is important to secure a certain amount of light during shooting, and to set the light source conditions and set the threshold value.

4. Identification of rail deterioration

4.1 Effect of rail material

We photographed the bainite rail shown in Fig. 12 under imaging condition ① to grasp the effect of the difference in rail material [2]. The spectral graph of the image is shown in Fig. 13.

The spectral intensities between the wavelengths of 505 nm and 635 nm used to distinguish the white etching layer on normal rails varied greatly in all the analysis areas of the bainite rails, in spite of the small difference in spectral shape.

Figure 14 shows the results of differential analysis to obtain the average value at a wavelength of 25 nm intervals. The bainite rail was sometimes identified even in the wavelength bands of 550 nm to 650 nm because there is a difference in spectral intensities depending on the presence or absence of a white etching layer. However, the analysis result was small on the normal rail, but it was large on the bainite rail in the area with the white etching layer.
These results demonstrate that different rail materials have different spectral shapes because the degree of light reflection or absorption is different. Therefore, we found that it is necessary to set the threshold value in consideration of the material when detecting the deteriorated part. In addition, it is possible that the same phenomenon will occur at the welded part of the rail.

4.2 Different rail deterioration (corrosion)

We examined corrosion which is a typical deterioration seen noticeably on the sides and bottom of rails. We photographed the corroded rail shown in Fig. 15 under imaging condition ① to obtain spectral information and compared it with the spectrum of the white etching layer. In Fig. 15, we can see significant corrosion on the side of the rail. Although the top of the rail does not appear to be corroded, it was confirmed that the composition of the analysis area was the same because the shapes of the spectral intensities were similar. This confirmed the detectability of the white etching layer on this rail. Figure 16 shows a comparison of the spectral graphs of rail steel, corrosion, white etching layer, and rust. We have shown that the white etching layer can be detected by focusing on the difference in the spectral shape around the wavelength of 500 nm to 650 nm. In addition, we found that the corrosion of rail differs in spectral shape around the wavelength of 900 nm to 1050 nm.

Next, Fig. 17 shows the average value at a wavelength of 25 nm from the results of differential analysis for each analysis area. From the figure, it is seen that corrosion is different from rail steel and white etching layer at wavelengths of 500 nm to 650 nm. Therefore, we found that the white etching layer of the rail and the corrosion can be distinguished by spectral analysis at wavelengths of 500 nm to 650 nm and wavelengths of 900 nm to 1050 nm because of the difference of spectral shapes.

5. Examination of portable hyperspectral camera

We found that it was possible to detect deterioration of the rail surface using its spectral shape. However, since the spectral intensity changes depending on the amount of light at the moment of photographing, it is necessary to photograph a deteriorated image under various conditions to examine an imaging method and an analysis method to propose a quantitative evaluation index.

The cameras in Chapters 3 and 4, which are often used indoors, are too large for use in the field, to picture railroad tracks. Therefore, we used a portable hyperspectral camera to photograph a corroded rail with only halogen lights to confirm whether corrosion could be detected.

Compared to a fixed camera, the portable camera used in this study had a wavelength resolution of 7 nm, which is slightly coarser, and needed about 35 seconds to capture one image. However, since the camera weighs only 1.5 kg and has a built-in simple spectrum display function, it was possible to check the photos taken of the railroad immediately.

We photographed the three rails shown in Fig. 18 at
the same time: a non-corroded rail, a normally corroded rail, and a heavily corroded rail (where the corrosion is likely to come off). After photographing the rails, we selected an analysis area from the head of each rail.

Figure 19 shows the differential analysis results of the analysis area, and Fig. 20 shows the identification result based on Fig. 19. In Fig. 19, since the analysis area with normal corrosion or significant corrosion is less likely to reflect light than the analysis area without corrosion, the difference in spectral intensity in differential analysis was small at the wavelengths between 500 nm and 650 nm. This result is consistent with the result of image differential analysis by a fixed hyperspectral camera. In addition, there was a difference between normal corrosion and significant corrosion at the wavelengths of around 600 nm to 700 nm. By color-coding the hyperspectral image based on the result of this differential analysis, it was demonstrated that each rail could be clearly identified as shown in Fig. 20. It should be noted however, that it would be necessary to increase the number of samples in the future to confirm why the spectral shape differs between normal corrosion and significant corrosion.

6. Summary and future prospects

For the purpose of improving the efficiency of inspection of various parts used in railway equipment, we investigated a method for detecting deterioration from characteristic changes in the spectrum using a hyperspectral camera. The basic test results for rail surface deterioration detection are described here:

(1) The spectral intensity of the hyperspectral image acquired by this camera is affected by the brightness of the surroundings at the moment of shooting. We found that it was important to secure a certain amount of light at the moment of photographing in order to detect deterioration and evaluate deterioration with spectrum analysis.

(2) Regarding the white etching layer and corrosion on the rail surface, there is a difference in the shape of the spectrum in the hyperspectral image between the wavelengths of 500 nm to 750 nm and wavelengths 900 nm to 1050 nm. Therefore, we found that the existing area in the rail cross-sectional direction can be quantitatively grasped by tilt analysis or differential analysis.

(3) The authors confirmed that the spectral shape and the result of the differential analysis change significantly because the reflection and absorption of light change depending on the material of the rail.

(4) We are planning to increase the number of image samples using a portable hyperspectral camera for analysis, to improve the detection accuracy of rail deterioration using spectrum analysis.

References

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