Structure Gauge Measuring Equipment Using Laser Range Scanners and Structure Gauge Management System

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Periodic measurement of the structure gauge is essential to ensure safe train operation. Measuring the clearance gauge however, is time and labor intensive given the vast number of trackside facilities. An inexpensive and efficient measuring device using laser range scanners was therefore developed. A management system is also being developed, which maps measured three-dimensional point cloud data to facility data. This paper describes the problems and solutions related to applying the laser range scanners for structural gauging, and presents results obtained from experiments. This paper also describes progress achieved in the development of the management system.

Keywords: laser range scanner, LiDAR, structure gauge, clearance car, facility management, 3-D point cloud

1. Introduction

The structure gauge or clearance gauge is the space around the track, into which no part of a trackside structure should enter on any account. Figure 1 shows an example of the structure gauge applied on railways in Japan. Periodic measurement of the structure gauge is essential to ensure safe train operation. Measuring the structure gauge however, is time and labor intensive given the vast number of trackside facilities. In Japan, a clearance car which measures the structure gauge while traveling using contactless scanners based on the light-section method, was developed in 1990s [1]. The clearance cars are effective but are expensive and therefore require a high initial investment.

A less expensive and equally efficient measuring equipment using laser range scanners was thus designed. A management system, which maps the measured three-dimensional point cloud data to the facility data is also being developed.

This paper describes the problems and solutions related to applying the laser range scanners for structure gauging, and presents results obtained from experiments. This paper also describes progress achieved in the development of the management system.

2. Outline of the proposed measuring equipment

2.1 Purpose

Conventional structure gauge measuring requires manual use of plum-lines and tape measures. More recently, hand-held laser range finders have been used and making the measurement process more efficient. In the case of manual measurement of structure gauges however, only one point on a structural surface can be measured at a time; making the process very time and labor intensive. In addition, measurement results may differ from person to person. Measurements made with an on-board device on a clearance car however, allows multiple points of multiple structures to be measured continuously. As mentioned previously however, clearance cars are expensive.

Given these problems, work was commenced to reduce the cost and increase the efficiency of structure gauging using measuring equipment which can detect any fouling of the structure gauge continuously. The purposes of the proposed equipment are shown in Fig. 2. The aim of the proposed equipment, was to provide a reliable, less time and labor intensive means to measure structure gauges that was less costly than the existing clearance cars. An-

Fig. 1 An example of the structure gauge on Japanese railways
In order to ensure that the proposed equipment would be ready for use as early as possible, it was decided that new technologies under development, which were not yet ready for practical use, should not be used. Made-to-order items were also avoided, even if they used existing technologies. As such, the proposed equipment had to be made from mass-produced components such as sensor units, as much as possible.

### 2.2.2 Purchase cost

The initial purchase cost of the proposed equipment had to be much lower than the existing clearance car. To this end, a design using inexpensive sensors that could simply be attached to an existing vehicle was selected. In addition, the sensors had to be compact and light.

### 2.2.3 Measurement scope and accuracy

The main scope of the measuring equipment being developed was trackside electric equipment. Trackside electrical equipment comes in a variety of shapes, e.g. mast-like equipment such as catenary poles, cube-shaped equipment such as instrument boxes, and plate-like equipment such as signal panels. The proposed equipment therefore had to be able to make measurements regardless of the shape of the target.

The average accuracy of the measurements had to be better than the maximum error in manual measurements (about 100 mm). Although error distribution was unknown at the stage of defining requirements, the maximum error was set to 200 mm applying the central limit theorem, to ensure that the average error was 100 mm or less.

### 2.2.4 Night and day operation

In order to facilitate operations, the proposed equipment ideally had to be operational both in daytime and at night. For train scheduling purposes in particular, it was necessary to ensure that the sensors could be used at night. For the sensors to work properly during the daytime, it was necessary to consider resistance against direct sunlight, safety of waiting passengers on platforms and so on.

#### 2.2.5 Target sections

The proposed equipment had to be designed for use on any type of line (DC/AC/non-electrified) or track (single/double), and with any kind of structure (open sections/tunnel) or train protection system.

#### 2.2.6 Coupling with a locomotive

In order to ensure that the proposed equipment can be operated on any type of line, the new device would have to be installed on a trailer vehicle hauled by a powered vehicle. The proposed equipment would therefore be installed on a vehicle coupled with a locomotive.

#### 2.2.7 Running speed

If the maximum running speed of the measuring vehicle is too low, it could affect other train operations, making it difficult to make measurements during normal operating hours. Therefore, assuming that the measuring vehicle is towed by a diesel locomotive, the maximum running speed was set to 80 km/h or above.

#### 2.3 Selection of sensors

The sensing technology and devices for structure gauge measuring were selected on the basis of requirements described in Section 2.2. Distance sensors using laser beams called laser range scanners or LiDAR (Light Detection and Ranging) were examined. The laser range scanner can measure two- or three-dimensional distances while changing the beam direction by rotating the inside mirrors or the sensor itself. In the case of on-board measurement, given that the one-dimensional distance along the track is provided by the direction in which the vehicle is traveling, three-dimensional measurements can be made possible with a two-dimensional scanner. It was therefore decided to use two-dimensional laser range scanners.

Laser range scanners fall roughly into two categories: those based on the phase-shift principle, and those that use

### Table 1 Specifications of the laser range scanner

<table>
<thead>
<tr>
<th>Specification</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Field of application</td>
<td>Outdoor</td>
</tr>
<tr>
<td>Light source</td>
<td>Infrared (905 nm)</td>
</tr>
<tr>
<td>Laser class</td>
<td>1, eye-safe (IEC 60825-1 (2007-6))</td>
</tr>
<tr>
<td>Field of view</td>
<td>190°</td>
</tr>
<tr>
<td>Scanning frequency</td>
<td>100 Hz</td>
</tr>
<tr>
<td>Angular resolution</td>
<td>0.667°</td>
</tr>
<tr>
<td>Max. range</td>
<td>26 m (10% reflectivity)</td>
</tr>
<tr>
<td>Systematic error</td>
<td>± 25 mm (1 m ... 10 m)</td>
</tr>
<tr>
<td>Statistical error</td>
<td>± 7 mm (1 m ... 10 m)</td>
</tr>
<tr>
<td>Weight</td>
<td>3.7 kg</td>
</tr>
<tr>
<td>Dimensions</td>
<td>160 mm × 155 mm × 185 mm</td>
</tr>
</tbody>
</table>
the time-of-flight (TOF) principle. TOF scanners are generally more compact and inexpensive than phase-shift scanners. Since the scanners would be installed on the outside of the vehicle, dust- and water-proof TOF scanners were selected. Table 1 shows the specifications of the selected scanners. The requirements were met by installing multiple scanners on the end panel of the vehicle.

2.4 System configuration

The system configuration diagram of the proposed equipment is shown in Fig. 3. The proposed equipment consists mainly of laser range scanners, a GNSS (Global Navigation Satellite System) sensor, an IMU (Inertial Measurement Unit) sensor and a PC.

The laser range scanners were installed on the end panel of the vehicle, and arranged so that their beams were not intercepted by the locomotive as shown in Fig. 3. The GNSS sensor consists of an antenna and a receiver, and is used for acquiring the absolute position of the vehicle and the time. The IMU sensor is used to obtain the speed or the relative position of the vehicle. To acquire the position and the speed of the vehicle, an odometer or tachometer generator may be used instead of the GNSS and IMU sensors. The PC is used for recording and processing the measurement data. The measurement data form the three-dimensional point clouds.

3. Problems and solutions related to LiDAR application

3.1 Scanner positioning

The selected scanners may satisfy the requirements, but their actual performance depends on their position, orientation, and their number. Positioning of the scanners is therefore important.

Figure 4 schematically shows the relationship between beam scan plane orientation and detectability of trackside equipment. Detection of structure gauge fouling is determined from the cross section vertical to the track surface plane, therefore, it is reasonable to set the orientation of the beam scan plane at an angle of 90° to the rail in the longitudinal direction. However, in the configuration shown in Fig. 4 (a), the scanner may miss equipment which is thin in the rail longitudinal direction, such as signal panels. As shown in Fig. 4 (b) and (c), setting the orientation at an oblique angle to the rail longitudinal direction, can reduce the number of undetected thin objects. Figure 4 (c) shows however that when this angle to the rail longitudinal direction is small, items can be obstructed by objects in front and go undetected. Although it does not appear in Fig. 4, in real conditions, there may be cases where the locomotive itself becomes an obstacle, restricting the positions where scanners can actually be installed.

When the orientation of the beam scan plane is oblique to the rail longitudinal direction, the beam does not necessarily hit the point on the surface of a structure which is closest to the center of the track. This creates uncertainty about the coordinates of the closest points in the measurement data, especially for plate-like equipment. This uncertainty depends on scanning frequency, scanner orientation, and speed of the vehicle.

Finally, the scanners were positioned as follows: two scanners on both the left and right sides of the end panel of the vehicle, with horizontal and vertical offsets, and set facing outward at an angle of 45° in the rail longitudinal direction. This positioning and angle prevents the beam being obstructed by the locomotive. Use of multiple scanners improves spatial resolution, and it is possible to reduce coordinate uncertainty to 200 mm or less at 80 km/h.

3.2 Train position and speed detection

Since two-dimensional scanners are used on the proposed equipment, it is necessary to accurately detect vehicle speed in order to restore the three-dimensional shapes from the measured time-series data. In addition, when measuring structure gauges, it is necessary to match the facilities to the measured points which foul or might foul the structure gauge. Since facilities are roughly identified by their location, i.e. kilometre points, it is also important to accurately detect the absolute location of the vehicle.

In the proposed equipment, vehicle speed is acquired through the IMU sensor and the GNSS sensor. Some IMU sensors based on MEMS (Micro Electro Mechanical Sys-
tems) have practical accuracy for the three-dimensional shape restoration. They are not accurate enough however to determine absolute location, or for inertial navigation. As such, it is necessary to have an additional correction mechanism based on the absolute location. Geodetic information on latitude and longitude recovered by the GNSS sensor is therefore used for this correction in the proposed equipment, together with the railway GIS (Geographic Information System) which provides the geometric coordinates of the railway lines. Instead of the GNSS and IMU sensors, an odrometer may be used as mentioned in Section 2.4.

3.3 Carbody vibration correction

In the proposed equipment, scanners are installed on the carbody. Certain components between the wheels and the carbody such as axle springs and air springs cause elastic movement; consequently the carbody vibrates asynchronously with the wheels. In addition, when the vehicle is traveling through a curve, the center of the vehicle end panel shifts outwards from the center of the track. For these reasons, the position of the scanners relative to the rails changes continuously, although structure gauges are defined in relation to rail position.

To solve this problem, some conventional clearance cars use a numerical technique to cancel vehicle vibrations by extracting the rail position using the light-section method. The proposed equipment uses a similar technique with two downward laser range scanners to detect extract data on rail position. The relative positions and orientations of the scanners are modified based on the detected rail positions; therefore the point clouds are transformed correctly. The paper [2] is an example of the rail extraction algorithm.

3.4 Association with cab view videos

Visible light images of trackside facilities are useful for identifying the facilities which from the measured point clouds foul or appear to foul the structure gauge. Conventional laser range scanners including the scanners used in the proposed equipment cannot obtain color information. Moreover, it is not easy to acquire visible light images with cameras while the on-board structure gauge measuring equipment is working, because the locomotive narrows the field of vision and measurement is sometimes made at night.

A method was therefore developed to utilize the cab view videos taken with a portable camera installed temporarily on a train operating during the daytime. Kilometric points are assigned to each video frame as it shoots, using image processing technology without positioning sensors. The measured point clouds are then associated with the cab view videos using the kilometric point references.

4. Evaluation of the proposed equipment

4.1 Evaluation criteria and conditions

The performance of the proposed equipment was tested in field experiments on in-service railway lines. The evaluation criteria included: conformity with requirements, accuracy compared to manual measurement and effectiveness of cab view video image association.

In the experiments, the proposed equipment was installed on an existing track inspection car. A picture of the inspection car and the installed sensors is shown in Fig.5. The inspection car was towed by a diesel locomotive and its maximum speed in the experiment was over 80 km/h.

On-board measurements were made between 7 a.m. and 7 p.m. (after sunset), in both sunny and cloudy conditions. The inspection car travelled on AC, DC and non-electrified sections, and on single and double track sections including tunnels during the experiments.

A hand-held laser range finder was used to be able to make comparisons with manual measurements. The target trackside facilities for the accuracy evaluation included all three types of typical equipment shape: signal poles, instrument boxes and signal panels. A total of 10 trackside facilities were measured, of seven different types.

4.2 Experimental results

Figure 6 shows a cab view image and a three-dimensional point cloud acquired by the proposed equipment. The cab view image was taken with a portable camera from a commercial train on the day before the structure gauge measuring. In the point cloud in Fig. 6, the colors indicate the RSSI (Received Signal Strength Indication); the darker and lighter colors indicate changes in intensity. The point cloud in Fig. 6 shows that other facilities such as catenary poles and level crossings, which were also photographed in the cab view image, were also measured. All 10 facilities selected to evaluate accuracy were detected by the proposed equipment without omission. Surrounding conditions such as type of track sections and sunlight did not affect the performance of the proposed equipment or the measurement results.

The color light signal shown in Fig. 7 is given as an example to compare measurements made with the proposed equipment and manual measurements. The left-hand picture in Fig. 7 shows the appearance of the signal and spots corresponding to manual measurements. The center image in Fig. 7 shows the result of the manual measurements, while the right image shows the results from the proposed equipment as cross-sectional views. Figure 7 illustrates that the proposed equipment is able to capture the outline
As shown in Fig. 8, there was no point with an error of 200 mm or more; the total number of spots on the 10 facilities was 52. Each point in Fig. 8 corresponds to a manually measured axis. Furthermore, measurements made by the on-board system lead to acquisition of vast amounts of data in a short time, which could not be obtained through conventional manual measuring techniques. The collection of large volumes of data does not per se lead to time saving in the management of clearance gauges, because the data has to be processed. To make the process less labor intensive, it is therefore also necessary to be able to systematically manage the acquired data relating to the facilities. A structure gauge data management system is therefore being developed, which maps the measured point cloud data to the facilities data. The concept is described below.

4.3 Consideration

4.3.1 Conformity to requirements

It was confirmed that the proposed equipment satisfied requirements. We think that the technology with respect to the functional requirements has been established and the proposed equipment has achieved a high operability.

4.3.2 Measurement accuracy

Although the basic requirement for measurement accuracy was satisfied, it is important to further reduce errors. Figure 8 shows that there is a correlation between the errors and the vertical position, it is presumed therefore that the influence of carbody vibrations, especially carbody rolling, is significant.

4.3.3 Association with cab view videos

Figure 6 shows that the cab view images and point clouds agree well; then it is suggested that this association technique could be useful for identifying facilities included in point cloud data. However, matching precision depends on the frequency of the absolute position correction which may require manual intervention. Therefore, it is necessary to evaluate the cost-effectiveness of such a correction.

5. Development of a structure gauge management system

5.1 Need for a management system

Practical application of the proposed equipment would lead to acquisition of vast amounts of data in a short time, which could not be obtained through conventional manual measuring techniques. The collection of large volumes of data does not per se lead to time saving in the management of clearance gauges, because the data has to be processed. To make the process less labor intensive, it is therefore also necessary to be able to systematically manage the acquired data relating to the facilities. A structure gauge data management system is therefore being developed, which maps the measured point cloud data to the facilities data. The concept is described below.

5.2 Spatial and temporal management

The proposed equipment can measure multiple facilities in one journey continuously. This produces a high density of information on the spatial (i.e. kilometric point) axis. Furthermore, measurements made by the on-board equipment are more frequent than those made manually; consequently, there is a higher density of information on the temporal axis as well.

Managing trackside facilities using both the spatial and temporal axes, provides a better overview of the objects to be managed. For example, it is possible to detect the inclination of a piece of equipment caused by ballast outflow. Also, detecting a sudden change of its position makes it possible to correct records of equipment being removed or installed.
5.3 Integration of on-board measurement and manual measurement

If points are found by the on-board equipment, to be fouling the structure gauge, fresh measurements need to be made afterwards, manually. If on-board and manual measurements are handled separately, it is difficult to keep track of on-board measurement follow-up. In addition, the construction, removal, and relocation of equipment, also make tracking difficult over time.

The management system therefore integrates on-board measurements, manual measurements and records relating to construction, removal etc. of equipment. A screenshot of the prototype management system is shown in Fig. 9: integration of data highlights that the reason for a change in distance between two on-board checkups was that a piece of equipment was replaced.

![Fig. 9 Screenshot of prototype management system](image-url)

6. Conclusions

This paper describes the development of a structure gauge measuring equipment and a structure gauge management system. In the proposed equipment, multiple laser range scanners or LiDARs are attached to the end panel of an existing vehicle and are set at an angle of 45° to the rail longitudinal direction to avoid beam interception and to improve the spatial resolution. Field tests to evaluate the performance of the proposed equipment concluded that the proposed equipment satisfied requirements and achieved a high operability. In terms of accuracy, the maximum distance error was less than 200 mm after carbody vibration correction. For the structure gauge management system, an integrated approach was proposed to manage on-board measurements, manual measurements and records relating to construction, removal etc. of trackside equipment. The developed solutions have made it possible to reduce the cost and increase the efficiency of the structure gauge measuring and the structure gauge management.

References


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