3D-scanning system for railway current collector contact strips

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Undisturbed collection of current from a contact wire of the catenary constitutes one of the basic elements in reliable operation of electrified rail transport, particularly when vehicles move at high speed. Quality of current collection is influenced by the construction of catenary and current collectors, as well as by the technical condition and regulation of these two elements. Total contact force of a current collector head on contact line and the condition of contact strip surface determine the quality of the contact between a current collector and contact line.

This paper presents an innovative stand for diagnosing contact strips on current collectors with the use of 3D imaging technique. The stand has been tested in laboratory and during trial exploitation on a railway line. Implementation potential of the proposed method has been confirmed.

KEYWORDS: 3D machine vision, current collector, railway safety, shape measurement, measurement by laser beam

1. Introduction

An electric vehicle is a specific example of a moving receiver of electrical energy. Electric vehicles can be divided, in respect of supply method, into traction vehicles and autonomous vehicles. Traction vehicles draw power from contact line with the use of current collectors. One of the components of a current collector is a collector head, on which contact strips, i.e. the elements directly cooperating with contact line are installed, together with their mountings. A current collector should fulfil certain requirements in order to ensure continuity of supply and, consequently, reliability and safety of transport. By virtue of Commission Decision 2012/464/EU Technical Specifications for Interoperability (TSIs) are binding in member states of the European Union. In accordance with the Specifications the material from which contact strips are made ought to be mechanically and electrically compatible with the material used in contact wire, in order to avoid excessive wear of the surface of both the contact strips and contact wire. Carbon contact strips or metallised carbon strips [1, 8] are used in cooperation with contact wires made of copper or copper alloys.

Until recently contact strips on train current collectors exploited in Poland were made of copper alloy. They enabled for collection of high-value traction currents from contact wire. The disadvantage of copper contact strips is relatively high degree of friction wear (even when lubricant is used) of both the strips and contact wire. At the beginning of 2011 all contact strips were changed from copper to carbon ones. That change concerned all the vehicles using the railway infrastructure operated by PKP Polskie Linie Kolejowe.

Research conducted by the Railway Institute shows that, in Polish conditions, wear of carbon contact strips may reach the level of over 0.2 mm for every 1000 km travelled by a vehicle. This wear is even more extensive in winter [7]. Exploitation data obtained from largest rail companies show that the distance which a locomotive can cover with one set of contact strips is 30,000 km on average, which can be translated into about 3.5 months of exploitation [4].

Fig. 1 presents pictures of contact strips with different degree of wear, resulting both from normal exploitation conditions (a) and from fault situations (b).

Fig. 1. View of exploited carbon contact strips: a – worn out, b – totally damaged

2. Assessment of contact strip condition

Contact strips are exchangeable parts of current collector head, which remain in direct contact with contact wires and thus subjected to wear. Wear and tear of a contact strip can occur in either regular or instant way (Fig. 1). Sudden loss of substantial pieces of a contact strips or its complete damage is usually caused by inappropriate cooperation between a current collector and contact line. The quality of this cooperation, particularly when vehicles move at high speed, is determined by contact force of a current collector on contact line, condition of the contact strip surface, construction of catenary and the current collector, as well as by the technical condition and regulation of these two elements of current collection system. Quality of maintenance is significantly influenced by use of technical diagnostics.

Some railway companies implement solutions included in the system of on-board diagnostics, which means equipping current collectors with sensors. However, such solutions are expensive and limited only to a certain category of vehicles. There are also suggestions to create a centrally managed system of check stands, located at different points in the railway network, receiving signals from sensors integrated with contact strips.

One of the methods for automatic monitoring of carbon strip damage is using air duct or optical fibre located inside contact strips in such a way that wear out or damage of a contact strip results in unsealing of the air duct or damage of optical fibres. When such a thing occurs, it is detected and interpreted as defect, which usually leads to automatic lowering of a current collector. The disadvantage of this method is that only complete damage or wear out of a contact strip can be detected.

Also vision systems are used for monitoring of the technical condition of current collectors. Paper [5] describes a solution of automatic diagnostics, where several cameras and linear laser illuminators were used respectively to intercept strip profiles and locate, with precision, the pantograph in space. Image analysis allows for defining selected dimensions for each of the contact strips and assess, in percent, the loss of material. A significant disadvantage of this solution is the extremely complex optical-mechanical system, which requires the usage of sophisticated techniques for event synchronisation, so that it might be possible to obtain a three-dimensional geometry of a collector head based on two-dimensional images. This implies a very complex algorithm for visual data processing.

Another solution is the Pancam system [2]. The main camera is used to asses the condition of a contact strip. An additional camera serves to assess the horns of a collector head. Techniques of analysis are based on processing of a two-dimensional image. This system is simpler and less functional than the one described in [5]. The main disadvantage of this solution is the necessity to apply special background panels which eliminate all the elements of image background intercepted by the camera. The background panels are also used to increase the contrast between the profile of a collector head and the remaining elements of a photographed scene. The conducted experiments show that, on average, in 20% of cases it was not possible to make a correct diagnosis of technical condition of a current collector.

In Poland the condition of current collectors is assessed periodically, during technical inspection of locomotives in depots. The maintenance consists in manual measurement of thickness of a contact strip in its most worn area. Operation and maintenance manuals define the minimum thickness which requires replacement of contact strips. Simultaneously, it is allowed to extend the period of exploitation in the situation where the user acquires more operational experience. It is advised to replace both contact strips on a collector head at the same time. Apart from the assessment of wear of carbon, it is also necessary to check edge chipping, grooving, sparking damage on sheath. Chippings which do not exceed 30% of the contact strip surface are permissible. In the case of grooves, the important factor is their shape and location. The most dangerous grooves are the ones which appear across the strip. With regard to cracks, their location, number and size are of significance. Damage of aluminium sheath occurs as a result of arcing (Fig. 1). The depth of burnt carbon surface, solely local in their character, may not increase 30% of the thickness of the carbon strip [6].

As it can be inferred from the above-mentioned advice included in operation manuals of contact strips, their inspection is time-consuming, expensive and depends on subjective assessment of the diagnostician who performs the measurement.

3. 3D measurement method

Application of machine vision and image processing methods in various areas of control and measurement technology is developing intensively. The development is becoming more and more dynamic due to continuous progress in the technology of digital image processing, which results in lowering the costs of implementation and exploitation. Currently the methods of obtaining and processing two-dimensional images are quite well known and widely applied in the industry. 3D imaging began to develop simultaneously with 2D technology. Methods of obtaining three-dimensional representations of objects as a result of repeated photographing of a scene from different angles or with the use of so-called stereo cameras are well-known.

In the presented solution the system for monitoring and diagnosing technical condition of contact strips of current collectors is based on analysing images of these contact strips, obtained when a rail vehicle passes the measurement stand equipped with a fast 3D camera [3].

The laser triangulation is applied in imaging the shape and dimensions of an object. The contact strips are illuminated by a laser line generator from one direction, while the camera registers the image of this object from another direction (Fig. 2). The laser line which appears on the surface of the object is registered by the image sensor of the camera. Based on this, and with the use of parametrised algorithms implemented into the microprocessor of the camera, the height of every point in the cross-section is defined by analysing the course of the laser line on the sensor image.

The result of the measurement is a profile which contains one value for each of the measured points along the cross-section – for example, the height of an object along its width. In order to measure the third dimension of an object, it has to move in relation to the set of the camera and the illuminator. Therefore, the result of such scanning is a collection of profiles, where each profile contains a measurement of the cross-section at a certain point along the direction of movement.

Measurement values generated by the 3D camera are not calibrated, i.e.:

- height values (coordinate z) are given as a number, dependent on the number of lines or pixels located on the camera sensor;
- location of point along the cross-section (coordinate x) is given as a number representing the column of the sensor where the point has been measured;
- location of point along the movement direction (coordinate y) is represented by, for example, the next measurement number and recalculated based on the known movement velocity or measured directly.

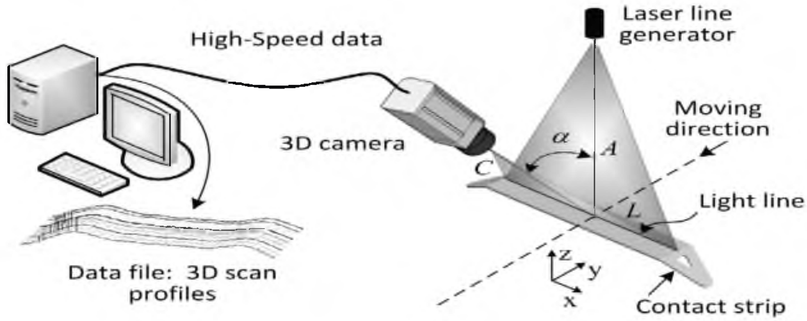

Fig. 2. Basic diagram of a contact strips 3D scanning system, where:
A – laser-strip distance, C – camera-strip distance, L – length of light line

In order to obtain calibrated measurements, i.e. coordinates and heights in millimetres, coordinates of the camera image sensor have to be converted into a system of real coordinates *x*, *y*, *z*. This conversion depends on many factors, for example the distance between the camera and the object, the angle between the camera and the laser beam, as well as the lens characteristics. This transformation is described by a sequence of simple formulas with a very limited number of open parameters, and parametrised at two stages. First the lens correction followed by perspective correction is performed. The perspective mapping is also known as a homography.

Lens distortions are corrected based on a standard radial polynomial model, which allows for converting sensor coordinates (*u*, *v*) to lens plane (*u*', *v*'):

$$\begin{aligned} & u' = u + u_0\left(c_1 r^2 + c^2 r^4\right) + 2c_3 u_0 v_0 + c_4\left(r_2 + 2u_0\right) \\ & u' = u + u_0\left(c_1 r^2 + c^2 r^4\right) + 2c_3 u_0 v_0 + c_4\left(r_2 + 2u_0\right) \\ & u_0 = u - u_c \\ & v_0 = v - v_c \\ & r = \sqrt{u_0^2 + v_0^2} \end{aligned} , \qquad (1)$$

where (u_c, v_c) is the optical centre of the sensor, and c_1, c_2, c_3, c_4 are parameters defining lens distortion. This model is sufficient for the majority of standard lenses, apart from wide angle fish-eye lenses. The optical centre of the sensor belongs to so-called internal parameters, i.e. the parameters which depend on construction features of the camera. Other typical internal parameters, which might be taken into consideration in the model, are the imperfections in assembling or production of the sensor. Assessment of distortion coefficients is performed experimentally, based on scanning of a flat target element. Since the flat target contains no information along the flat surface there is no possibility to measure distortions along the target. It is therefore important to expose the target with different tilt.

Correction of perspective, i.e. mapping of lens plane to the plane on which the light from the laser illuminator is directed, is of the kind which shows the scale, rotation and perspective. It is defined with the use of homogeneous coordinates as:

$$\begin{bmatrix} X \\ Z \\ s \end{bmatrix} = \mathbf{H} \begin{bmatrix} u' \\ v' \\ 1 \end{bmatrix} = \begin{bmatrix} b_{11} & b_{12} & b_{13} \\ b_{21} & b_{22} & b_{23} \\ b_{31} & b_{32} & b_{33} \end{bmatrix} \begin{bmatrix} u' \\ v' \\ 1 \end{bmatrix}. \tag{2}$$

Real coordinates (x, z) are obtained through introduction of the standardisation coefficient s:

$$x = \frac{X}{s}, \; y = \frac{Y}{s}. \tag{3}$$

Theoretically, all nine coefficients of the matrix **H** can be defined by measurement based on one scanning of a saw-shaped target whose dimensions are known. However, in practice, numerous scans are performed, so that the entire visual field of the camera is covered.

4. Structure of the stand

In accordance with the presented concept and measurement method, a stand for monitoring the technical condition of contact strips was constructed [4]. This stand was tested in laboratory conditions and then installed on the rail line. The main measurement system was located on the support construction of the catenary in the area of high voltage (Fig. 3).

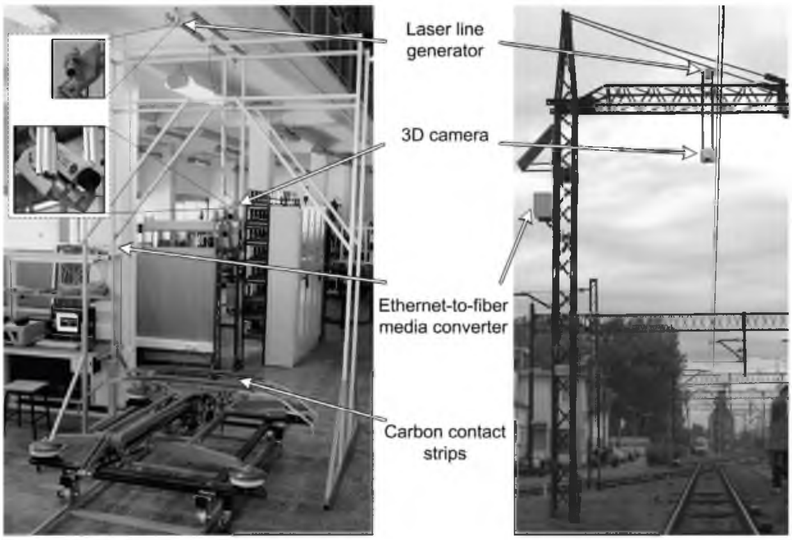

Fig. 3. 3D vision system during contact strip scanning in laboratory and on the railway line

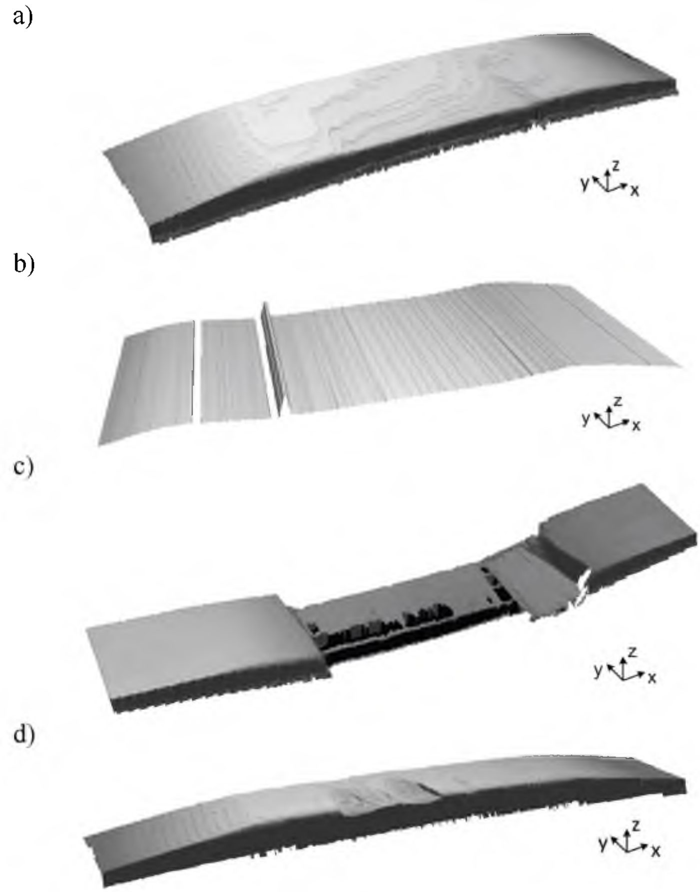

Fig. 4. Examples of 3D visualisation of contact strip scanning results: a) quite new – data from laboratory test stand; b) quite new – data from railway line test stand; c) totally damaged; d) chipped

Apart from auxiliary construction supporting the 3D camera and the laser line generator, a photovoltaic module cooperating with the supply system was installed. This supply system includes a buffer VRLA battery, together with necessary control components and Ethernet to fibre media converters. The system for detecting a passing locomotive, and at the same time performing the measurement of its speed, is installed on the next support construction. There is also a camera used to identify the number and type of the vehicle, as well as to define which of the current collectors is raised. Following the installation and activation of individual components of the stand, the mounting system of the 3D camera and the laser line generator were coordinated in relation to track axis and to the axis of current collectors of tested vehicles. Displacement of contact wires of the catenary (stagger), the effect of occlusion of light generated by the laser, which is caused by the presence of the contact line, as well as the displacement of contact line by the current collector cooperating with it were all taken into consideration.

After the installation and activation of the stand, a few dozen of contact strips on current collectors in normally exploited locomotives were tested. Before the 3D scanning the locomotives were subjected to a technical check-up, during which the thickness of contact strips was manually inspected and measured. Fig. 4 presents visualisation of the results of contact strip scanning. It constitutes the image of height values obtained during the measurement process and, as far as monitoring of the condition of contact strips is concerned, is regarded only as auxiliary information.

Elaboration of the algorithms of automatic wear assessment is an important element of the stand. The algorithms for processing measurement data constitute the superior component of software. A detailed description of 3D data analysis algorithms principles were included in the chapter titled: "Wear estimation of current collector contact strips by analysis of a 3D scanning results".

5. Summary

The paper presents the system of monitoring the technical condition of the current collector contact strips, in exploitation conditions on the railway line, using the 3D scanning technique. Vision diagnostics methods, significantly reduces the time required to perform the measurements, and at the same time ensures a high degree of accuracy, as well as repeatability of the obtained results.

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