

AUTOMATIC LASER SYSTEM FOR RAILWAY CONTACT WIRE INSPECTION

Chugui, Yu. V., Bazin, V. S., Kalichkin, S. V., Kalikin, V. E., Makarov, S. N.,
Stupak, M. F., Verkhogliad, A. G. and Vykhristyuk, I. A.

Technological Design Institute of Scientific Instrument Engineering (TDI SIE)
Siberian Branch of the Russian Academy of Sciences (SB RAS)
41, Russkaya str., Novosibirsk, 630058, Russia
Tel.: +7 (383) 333-27-60 Fax: +7 (383) 332-93-42 E-mail: chugui@tdisie.nsc.ru

Abstract: An optical structured light method and an opto-electronic system for automatic noncontact distant measurements of wear and defects detection for a contact wire electro-supply network are presented. The system industrial prototype can extract the main technological wire parameters, first of all, the remaining height with RMS error down to 0.15 mm and the wire cross-section area with RMS error of 1.5 mm². This information is sufficient for confident decision on operation of contact wire electro-supply network. This method could be applied for automatic wire wear measurement and defects detection for trams, trolleybuses and other electro-supply vehicles.

Key words: structured light method, non-contact remote inspection, profiling, shape measurement, contact wire.

1. INTRODUCTION

The railway safety requires the continuous inspection of the geometrical parameters of wearing parts. One of the actual railway tasks is inspection of the train's electro-supplying contact wire quality. During long operation period several defects appear on the surface of wire and it wears out. As a result the configuration of the wire is changed and it is permanently distorted. The measurement method has to be noncontact since the wire is always under the live voltage up to several tens of kV. The system developed has to be compact in size in order to allow its easy transportation. Due to the requirement of many cross-section wire measurements with small spatial steps (less than 10 mm), the method has to provide the corresponding resolution along the train's wire. The system must measure the remaining height of the wire with an error of no more than 0.2 mm while the train is moving.

As it is known, for solving of many industrial tasks the optical shadow method is used (Galiulin et al., 2002; Gromilin et al., 1999; Leopold & Günther, 2002; Weckenmann & Nalbantic, 2002). However, the shadow method has its own limitations. While obtaining the shadows from opaque concave objects, the geometry information is lost. One important disadvantage of this method is constraint that the source and receiver have to be located on the opposite sides of the object under geometrical inspection.

This article describes the noncontact structured light method (Skotheim & Couwleers, 2004) and an automatic opto-electronic system for distant wire geometry measurement and defects inspection. Below the measurement method, the structural scheme of the measuring module, the image processing algorithm and the experimental testing results of industrial prototype of the developed system in real railway conditions are presented.

2. THE MEASUREMENT METHOD

During long operation the contact wire can be subjected to some geometrical defects that require their timely detection and removal. Unworn-out contact wire (Fig. 1a) and possible geometrical defects are shown in Fig. 1 b, c, d. The main defect that leads to the increase of specific resistance and growth of contact wire break possibility is the decrease of the area of its cross-section because of continuous contact with collector (b). The wire can also be turned in cross-section plane (c) and made very thin in upturned position. The tension irregularity as well as some micro defects in wire can lead to the defect of "neck" type (d), when the wire section simultaneously decreases along all directions. The contact wire wear is described by two parameters (b), namely: width of wear W and wear depth D , i.e. by the distance from the surface of unworn-out wire up to the contact surface of the worn-out one.

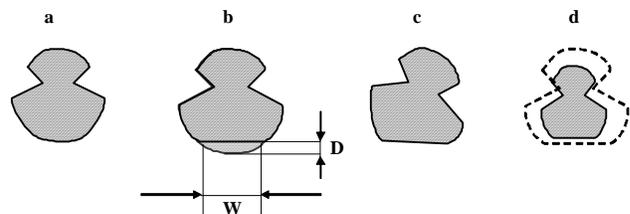


Fig. 1. New contact wire cross-section (a) and possible contact wire defects: standard worn-out wire (b), "rotated wire" defect (c), "neck wire" defect (d).

For automatic noncontact detection of the above mentioned defects as well as for measurement of wear parameters we have proposed to use a structured light method. The principle of this method is illustrated in Fig. 2. A special laser illuminator generates one or several

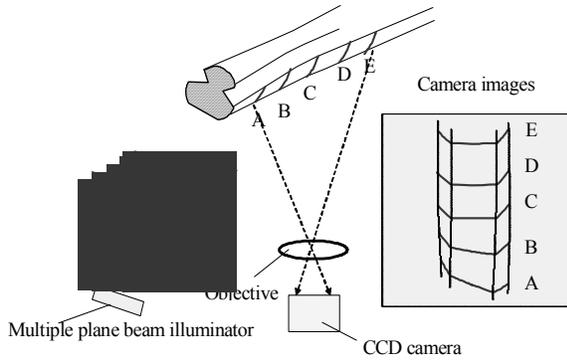


Fig. 2. The structured light method for cross-section wire parameters measurement

transversal plane-shaped beams (“light knives”), which incident on the wire surface at some angles to its axis. The scattered light is captured using video-camera from the other direction. The captured image represents the shape of the curve, which is formed by intersection of the plane-shaped beam with the curved wire surface.

The object image configuration is determined by the

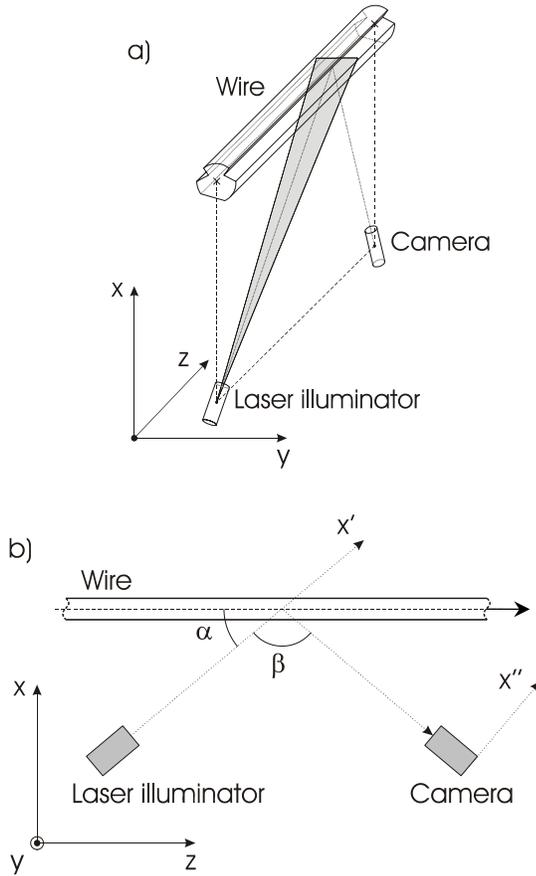


Fig. 3. The optical scheme configuration: (a) 3D view; (b) XZ plane projection

angular positions of the contact wire, the laser illuminator and the video camera. Let contour function $f_z(x, y)$ describes the configuration (contour) of the standard wire cross-section formed by plane XY (Fig. 3a). When it is

taken into account that the wire surface in the measurement zone is the cylindrical one (along the Z axis within the measurement area), one can achieve that the image cross-section line on camera corresponds to this form. If the angle between laser beam plane X'Y and axis Z is equal to α , then the contour function $f_z(x', y)$ of illuminated wire cross-section formed by plane X'Y will be obtained from function $f_z(x, y)$, using the affine transformation $x' = x / \sin \alpha$ (Fig. 3b).

If optical axis of camera intersects the plane X'Y under β angle, then “the camera projection” in plane X''Y is described by contour function $f_z(x'', y)$ that can be obtained by transformation $x'' = \sin \beta \cdot x' = R \cdot x$, where scale parameter $R = \sin \beta / \sin \alpha$. The results of two projection transformations are shown in Fig. 4.

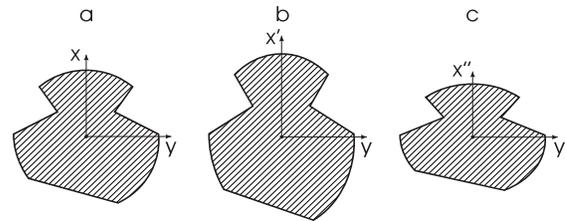


Fig. 4. The wire contour conversion by affine transformation: the initial contour $f_z(x, y)$ of wire cross-section in plane XY (a), the “illuminated projection” $f_z(x', y)$ in plane X'Y (b), and “the camera projection” $f_z(x'', y)$ in plane X''Y (c).

If angles α and β are equal, i.e. $R = 1$, then the configuration of projections $f_z(x, y)$ and $f_z(x'', y)$ in planes XY и X''Y will be identical. When angle $\alpha = \pi/2$ one can neglect the cylindrical shape requirement, however at $\alpha = \beta$ the sum of angles will be equal to π . That means that in this case the camera is located inside the wire. For

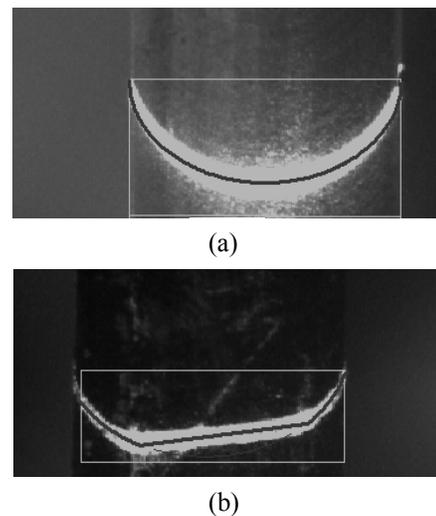


Fig. 5. The contact wire cross-section image obtained under the laboratory experiments: (a) unworn-out wire with the wear contact surface width $W=1.1$ mm ($D=0.0$ mm); (b) worn-out wire with wear parameters: $W=8.0$ mm and $D=1.4$ mm

design convenience, it was decided to choose $\alpha = \beta = \pi/4$. Under the average height of measured surface equal to 6 mm it is required to have the cylindrical shape within the Z axis about 8.5 mm.

As an example, the actual image of the wire, which was obtained by experimental system in the laboratory conditions, and calculated image parameters (see Fig. 1) are shown in Fig. 5. The dark curve demonstrates the predicted wire section profile, which is obtained by image processing of the light crescent (bright arc-type shape). The crescent is formed as a result of the wire surface intersection by laser beam plane.

3. THE MEASURING SYSTEM

Using this method we have developed an industrial system prototype. The measuring system consists of a measuring module placed on the carriage roof and a station for data accumulation and processing. The measuring module provides acquisition of the primary video information, which contains the geometrical parameters data of the contact wires under inspection.

The station for data accumulation and processing receives video information from measuring module, stores these data in database and processes it. As a result the required geometrical parameters are calculated and transmitted to database for the storage.

The measuring system design is constrained by additional requirements, which depend on the design of the train's electro-supply network. For the train contact wire the measurement field has the following dimensions: ~1000 mm in wide (since the wire can move in horizontal

plane) and ~1500 mm in depth (due to the possible vertical movements of wire relative to the rails). For such size of the measurement zone it is practically impossible to make such illumination distribution. Therefore, the solution of the problem was based on the tracking out of the wire's height by moving the laser illuminator and keeping the distance between this source and wire constant. Moreover, in order to meet the requirements to the optical focal depth of the camera lens, the camera is moved relative to the wire in order to keep constant distance between the camera and wire equal to 2500 mm.

Figure 6 demonstrates the structural scheme of the measuring module. It consists of optical, tracking and image registration subsystems. The optical subsystem has a moving laser and two mirrors: one of them is fixed statically and other is moveable in order to adjust illumination. A semiconductor laser ATC-C4000 was selected as a source with 810 nm emission wavelength. The tracking subsystem consists of a stepping motor and a controlling software application executed on PC104 microcomputer. The image registration subsystem provides acquisition of a cross-section wire image in the measurement zone. For this purpose we have used PIXELINK PL-A741 video cameras. Three similar cameras were evenly spaced in order to extend the field of view in the horizontal plane due to large "zigzags" in the horizontal plane, which is too large to be covered by a single camera. The camera lenses were chosen from COMPUTAR Company ($F = 50$ mm, $F/1.3$). The interferential very narrow band-pass filters for suppression of ambient illumination were placed in front of the camera lenses. The interferential filters were designed in such a

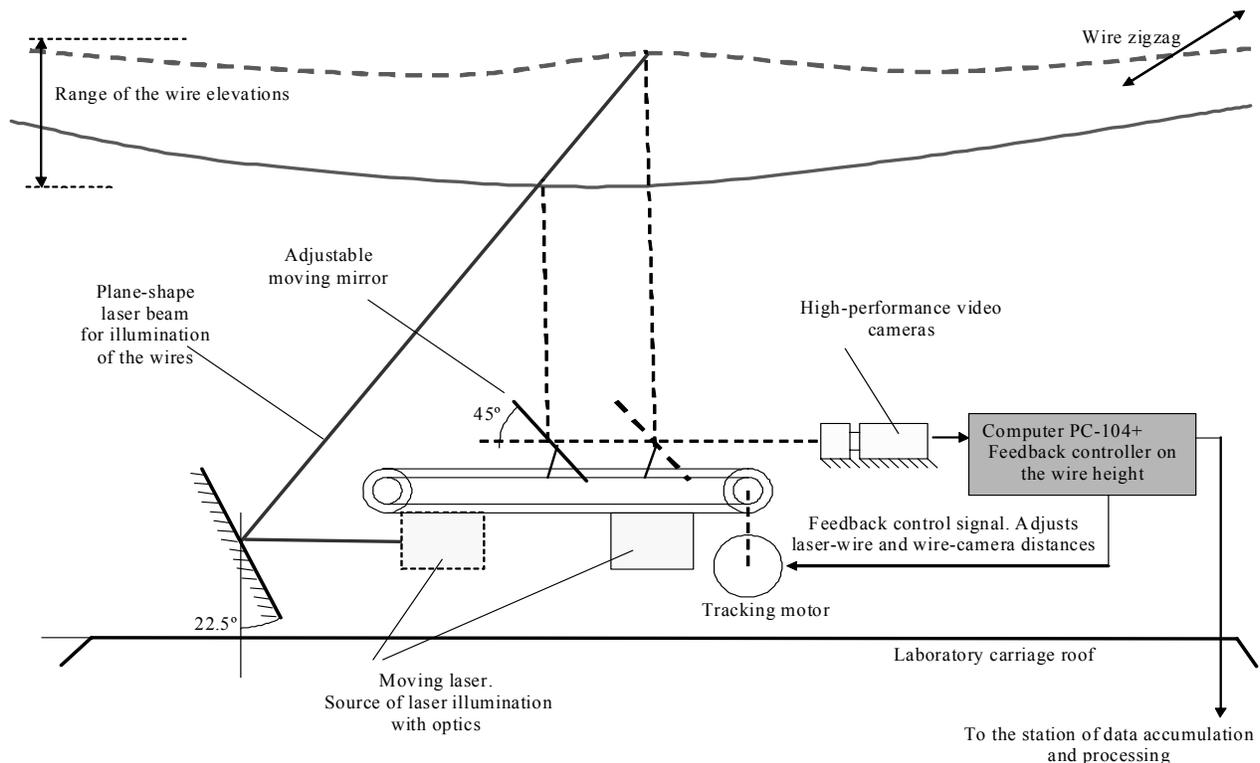


Fig. 6 The structural scheme of the measuring system



(a)



(b)

Fig. 7. The measuring module installed on the roof of railway inspection carriage: (a) side, and (b) front (b) views

way that under the deviation from the mentioned wavelength by 4 nm, the power transmission coefficient becomes approximately 100 times less. Under the above-mentioned parameters and the frame exposition time of ~ 0.1 ms the camera sensor illumination level was about $700 \mu\text{w}/\text{cm}^2$. The measuring module was installed on the roof of inspection carriage for industrial testing (Fig. 7).

4. THE IMAGE PROCESSING ALGORITHM

The development of a real practically working system takes the solving of some problems. One of them is insufficient spatial resolution of the observing camera. The second problem that determines the measurement accuracy is connected with the focusing capability of a laser beam into a very thin line at the distance of about 2 meters. The total analysis of the video images is divided into some stages.

The first step for image analysis is the search for video image informative sections, i.e. frame sections that contain the image of the wire dissection by laser beam.

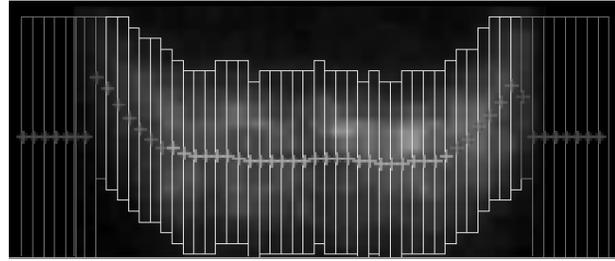


Fig. 8. The calculated centers of mass (denoted as '+') used for determination of wire cross-section

Such sections (we will call them “crescents” later) can be found as connected pixel regions with the sufficient number of pixels. At the second step the algorithm of center of mass was used. In this case for each vertical

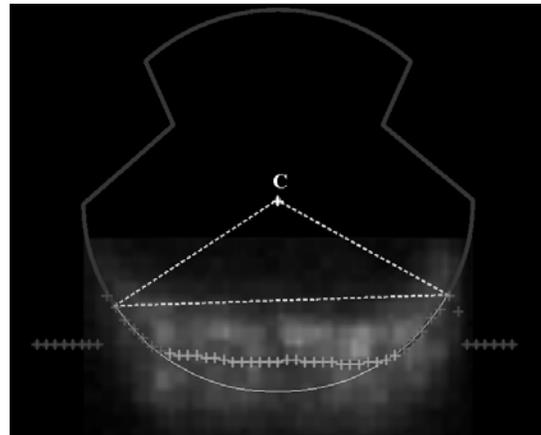


Fig. 9. The profile of the wire cross-section reconstructed by the calculated centers

column we have calculated the centers of mass (marked as '+') (x_{mc}, y_{mc}) according to: $y_{mc} = \frac{\sum_j I_j y_j}{\sum_j I_j}$,

where I_j is the intensity of j -th pixel of the crescent image in the vertical direction, and y_j is the j -th pixel coordinate (Fig. 8). After determination the wire cross-section profile using all calculated centers (points) one can fit a curve of the expected model wire shape into the set of points by the least squares method. The cross-section dimension and critical wear height are determined from the model parameters. The profile of contact wire cross-section reconstructed by the calculated centers is shown in Fig. 9.

The software of the video imaging station has the testing procedure for assessment of realized algorithm efficiency. It allows us to determine the presence of information about the defect under measurement. The images with information about critical wear as well as ones thrown away on post criteria are to be put into the special data base together with the processing results.

5. EXPERIMENTAL TESTING IN REAL CONDITIONS

The system has been tested in real conditions on the West-Siberian Railway (Russia). The main task of testing was to compare automatic measurements by our opto-electronic system with accurate manual measurements by micrometer. The automatic measurements were fulfilled at a train movement speed of 5 km/h. The measurement results by these two methods are given in the Table 1.

The device tested in the real railway conditions extracts main technological wire parameters, first of all, the remaining thickness with the RMS error of the wear area down to 0.15 mm and also the wear area with the RMS error about of 1.5 mm² (at the standard wire cross-sectional area of 100 mm²). This information is sufficient for confident decision-making as for safe operation of contact wire electro-supply network. This method could be applied for automatic wear measurement and defects detection for trams, trolleybuses and other electro-supply vehicles.

Table 1. Comparison of wire section measurement results by micrometer (standard manual method) and by the automatic opto-electronic system

Measurement No	Rail-Road Pillar No	Manual wear measurement, mm		Optical automatic wear measurement, mm		Measurement error, mm	
		Left wire	Right wire	Left wire	Right wire	Left wire	Right wire
1	32	10,3	10,75	10,16	10,64	0,14	0,11
2		10,25	10,05	10,14	10,06	0,11	-0,01
3		10,3	10,05	10,21	10,07	0,09	-0,02
4	34	10,4	10,2	10,62	10,23	-0,22	-0,03
5		10,2	10,15	10,25	10,26	-0,05	-0,11
6	36	10,35	10,6	10,19	10,55	0,16	0,05
7		10,3	10,35	10,12	10,17	0,18	0,18
8	38	10,9	10	10,72	10,21	0,18	-0,21
9		11,1	10,9	10,95	10,89	0,15	0,01
10	40	9,85	10,5	9,88	10,49	-0,03	0,01
		Mean deviation				0,09	0,02
		RMS deviation				0,12	0,14

The preliminary results of system testing demonstrate the good agreement of the measured data with the results of direct measurements. The RMS error of the wire height determination didn't exceed 0.15 mm and the RMS error of the wear area determination is about 1.5 mm² at the standard wire cross-sectional area of 100 mm². The measurement rate is ~150 meas./sec., that allows us to provide the spatial step (discreteness) about 10 mm along the entire wire length.

6. CONCLUSION

The optical structured light method and the system industrial prototype for wear measurements and defects detection of a contact wire electro-supply network are presented. Basic advantages of the system are high informativity and robustness, simultaneous direct cross-section measurement of multiple wires, measurement of acute geometrical defects of wires (like "neck", "rotation", etc), reliable measurements of contact wire parameters at support points (points of maximum wear), determination and analysis of geometrical parameters of wire support structural components, measurement of other important parameters of contact wire network, such as wire "zigzag" and wire "height", as well as the presence of extraneous objects.

7. REFERENCES

- Galiulin, R. M.; Galiulin, R. M.; Bakirov, J. M.; Bogdanov, D. R.; Vorontsov, A. V.; Tumashinov, A. V. & Petrov, S.V. (2002). Optoelectronic computer aided systems for inspection of gas-turbine engine complex objects, *Proc. SPIE, 7th International Symposium on laser metrology applied to science, industry, and everyday life*, Chugui Yu., Bagaev S., Weckenmann A., Osanna P.H. (Ed.), Vol. 4900, part one, pp. 178-184, ISBN 0-8194-4686-6, Russia, Novosibirsk, September 2002, Bellingham.
- Gromilin, O.G.; Kuchinskii, K.I.; Ladygin, V.I. & Yunoshev, S.P. (1999). *J. Pattern Recognition and Image Analysis*, Vol. 9, No. 1, pp. 141-142.
- Leopold, J. & Günther, H. (2002). Fast 3-D measurement of gear wheels, *Proc. SPIE, 7th International Symposium on laser metrology applied to science, industry, and everyday life*, Chugui Yu., Bagaev S., Weckenmann A., Osanna P.H. (Ed.), Vol. 4900, part one, pp. 185-194, ISBN 0-8194-4686-6, Russia, Novosibirsk, September 2002, Bellingham.
- Skotheim, O. & Couweleers, F. (2004). Structured light projection for accurate 3D shape determination. *Proc. 12th Int. Conf. on Experimental Mechanics*, Bari, Italy, August, 2004, McGraw-Hill Co.

Weckenmann, A. & Nalbantic, K. (2002). Measurement of conformity and wear of cutting tool inserts, *Proc. SPIE, 7th International Symposium on laser metrology applied to science, industry, and everyday life*, Chugui,

Yu., Bagaev S., Weckenmann A., Osanna P.H. (Ed.), Vol. 4900, part one, pp. 541-547, ISBN 0-8194-4686-6, Russia, Novosibirsk, September 2002, Bellingham.