ISSN 2409-9066. Sci. innov. 2017, 13(2): 33—42 doi: https://doi.org/10.15407/scine13.02.033

Shapovalov, Ye.V., Koliada, V.O., Topchev, D.D., Lutsenko, N.F., and Mangold, A.M.

Paton Electric Welding Institute, the NAS of Ukraine, 11, Bozhenko St., Kyiv-150, 03680, Ukraine,
tel.: +380 44 200 4779, fax: +380 44 528 0486, office@paton.kiev.ua

DEVELOPMENT OF HARDWARE AND SOFTWARE FOR THE SYSTEM OF REMOTE CONTROL OF GEOMETRICAL PARAMETERS OF RAILCAR WHEELSETS

A hardware-software complex for the system of remote control of geometrical parameters of railcar wheelsets has been developed. The system is designed for non-contact scanning of wheel working surface profiles and automatic evaluation of wheelset technical condition in motion. The application of results to the railways carriage facilities will significantly improve the qualitative and quantitative control of wear parameters and will raise traffic safety due to timely detection of wheelset dangerous defects.

Keywords: wheelsets, railcars, remote inspection, geometric parameters, laser triangulation sensor, and sensor units.

Problems related to traffic safety, optimization of use of available resources and minimization of operating costs require fast implementation of active monitoring and diagnostics of technical condition of rolling stock in the railway sector. The use of advanced technologies can help solving important problems associated with improved quality control, extension of list of controlled parameters, automated data processing, reduction in the share of manual labor and operating costs of control. Railcar wheelset is one of the major and most important parts of railway rolling stock. They bear the weight of train, guide its motion along the rail track and absorb all shocks from track irregularities thereby materially affecting the track structure. This leads to elastic and plastic deformations of wheels, i.e. wear of their friction surfaces [1]. The operation of damaged wheelsets entails an excessive wear of components of railway tracks and can cause accidents. In Ukraine, a method based on visual inspection and measurement of specific parameters by manual measuring instruments is used to inspect the technical condition and the timeliness of retirement from operation of wheelsets that threaten the train safety and to exercise quality control of repaired wheelsets [2]. This means that inspection of wheelsets can be made only during stops, with the results of the measurement control largely depending on human factor. Recently, many countries have paid great attention towards solving the problem of on-the-move operational control of geometrical parameters of railcar wheelset tread via contactless systems [3—4]. Implementation of such systems can significantly improve the quality and repeatability of test results due to computerized obtaining and processing of measurement data and enable to quickly identify inadmissibly worn wheelsets. Therefore, the development of domestic equipment for remote monitoring of wheelset condition is an important and urgent task.

STRUCTURE OF HARDWARE AND SOFTWARE OF THE SYSTEM FOR REMOTE CONTROL OF WHEELSET GEOMETRIC PARAMETERS

The outer surface (tread) of wagon wheels has a special profile consisting of flange, tread and back surfaces and end chamfer. For the proper functioning of railcar wheelset, the geometrical parameters of working part of wheels must meet the established standards. Also, distance between the inside edges of the wheels is rigidly standardized. To obtain initial data on the profile of wheel tread the most appropriate way is to use 2D optical sensors operating based on the principle of laser triangulation [5]. The sensor projects a laser spot onto the surface of measurement object. The reflected light falls incident onto a receiving element of camera as 2D digital image. Following the processing of images and the identification of the object profile, the required geometrical parameters are determined.

It is impossible to get a full profile of wheel working part from one observation point therefore, to realize each measurement channel (for both left and right wheels) two sensor units with laser triangulation sensors shall be used. The structure of any 2D laser triangulation sensor includes:

- Video camera that incorporates lens, light filter, and a sensor matrix;
- Camera controller for getting digital images, their pre-processing, and transfer of resulting data out;
- Semiconductor laser module equipped with special optics for laser beam sweep.

Time of profile record should be synchronized with wheel appearance in the working area of sensors using additional fast-response wheel approach sensor. To get a complete profile of the wheel working part from the sensors of measuring channel and to transmit it to the workstation operator it is advisable to use an intermediate controller (data collection controller) installed in one of the sensor units. The sensor units shall work year-round in a wide temperature range (–40...+55 °C). Commercial electronic components can work under these conditions, but the temperature range of semiconductor lasers is much narrower, especially, at low temperature (–10...+40 °C). Therefore, each sensor unit must be equipped with internal thermal stabilization subsystem. Temperature inside the sensor unit can raise due to a heating element, and decrease due to forced air cooling. It is also advisable to use the outgoing air stream for blowing the exit viewports to prevent their misting and contamination. The best solution to protect viewports from damage during the system downtime is a mechanical protective shutter triggered by outer signal from TAS installed at a certain distance from the control position. All microprocessor controllers and workstation computer must have special software. The structure of hardware and software required for realizing one measuring channel is showed in Fig. 1.

According to the proposed flowchart, for realizing the interaction between the camera controllers (CVC_{11}, CVC_{12}) and the video cameras (VC_{11}, VC_{12}) two interfaces are required: the parallel interface ($S_{в1}^{п}$, $S_{в2}^{п}$) and the serial interface of I^2C type (serial data bus for connecting the integrated circuits) The parallel interface is used to serve the data (digital images) transfer channel, while the I^2C interface is required for setting the camera mode (frame format, exposure time, linear signal amplification, etc.). The camera controllers are equipped with analog outputs for the formation of signals $S_{л1}^{a}$ *and* $S_{л2}^{a}$ to control laser brightness of modules LM_{11} and LM_{12}, respectively.

The data collection controller DCC1 is equipped with two discrete inputs, three discrete outputs, and RS-485 serial interface. The discrete inputs $S_{п}^{д}$ and $S_{к}^{д}$ are used for receiving pulse signals from TAS S_t and WAS S_{w1}, respectively. The output discrete signal $S_{c}^{д}$ is a clock signal transmitted to the cameras via one of parallel interface lines. The output discrete signals $S_{T}^{д}$ and $S_{ш}^{д}$ are used to control subsystems for temperature stabilization inside the sensor units (STS_{11}, STS_{12}) and mechanisms of protective shutters (PS_{11}, PS_{12}). The RS-485 serial interface is responsible for command/data exchange between the camera controllers and the data collection controller. Using Ethernet interface the data collection controller is connected to PC of operator's remote workstation (WS PC). Insofar as the system includes two independent sensing channels, in order to connect them to the computer a network switch (NS) is required.

The algorithm proposed for the operation of sensing channels of the system for remote control

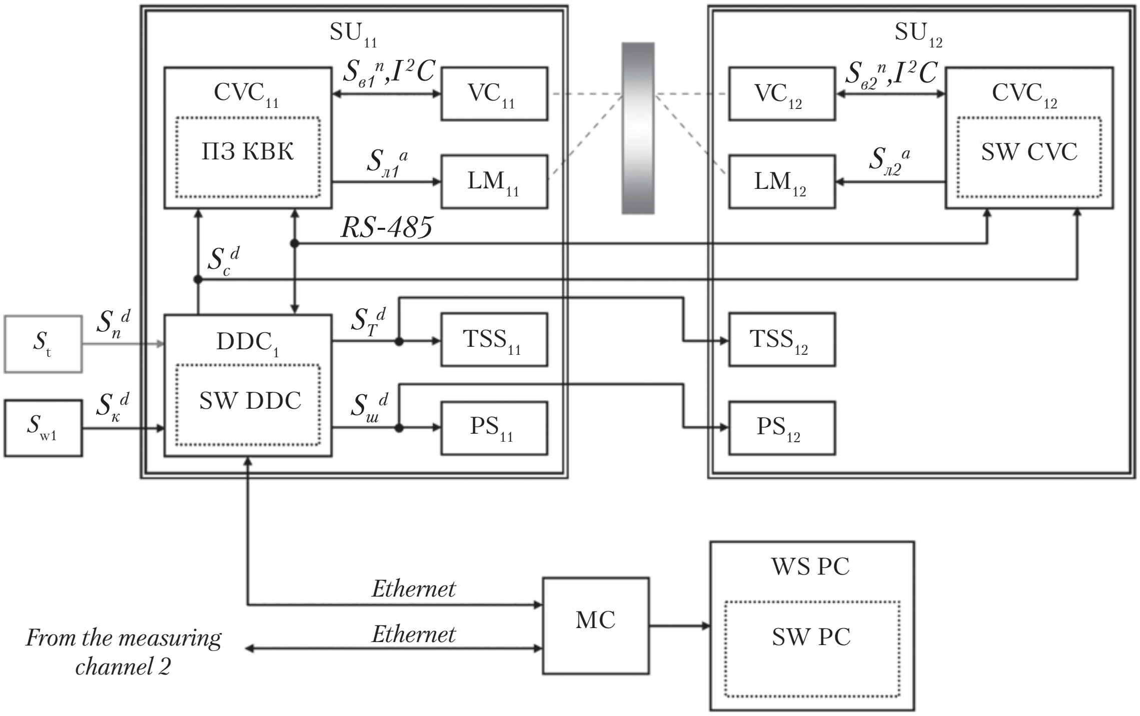

Fig. 1. Flowchart of measuring loop of the system for remote control of railcar wheelset geometric parameters: S_t — train approach sensor; S_{w1}, — wheel approach sensor; SU_{11}, SU_{12} — sensor units of measuring loop 1; CVC_{11}, CVC_{12} — video camera controllers; DCC_1 — data collection controller, VC_{11}, VC_{12} — video cameras; LM_{11}, LM_{12} — laser modules; TSS_{11}, TSS_{12} — temperature stabilization subsystems; PS_{11}, PS_{12} — protective shutters; MC — Ethernet switch; WS PC — computer of operator's workstation; SW — software

of wheelset geometric parameters is as follows. As power is supplied, the camera controllers automatically transmit preset parameters of operating mode to photo-sensor matrices via I^2C interfaces (*initial parametrization*). In standby mode, the laser modules should be turned off to extend their service life, with zero voltage set at the analog outputs $S_{л1}^a$ and $S_{л2}^a$. Also, in standby mode, the viewports should be shut by setting a logical «0» on the discrete output of data collection controller S_{sh}^{∂}. The thermal stabilization subsystems should run continuously from the start of power supply, with heating element turning on if required by temperature sensor embedded in the data collection controller (discrete signal S_T^{∂}). Upon signal from TAS S_t, the system switches to the basic operation mode, with shutters opening and laser modules turning on. Upon arrival of each signal S_{w1}^{∂} from WAS S_{w1}, the data collection controller DCC_1 forms clock pulse S_c^{∂} simultaneously transmitted to CVC_{11} and CVC_{12}. The camera controllers form signals requesting frames from photosensor matrices of video cameras VC_{11}, VK_{12}. As camera operating cycle is completed, the obtained digital images arrive at camera controllers for preprocessing. Based on its results the segments of 2D profile of wheel working surface are identified. The profile segments are transmitted via RS-485 serial interface to DCC where the complete profile of wheel working surface is formed. Then, the full profile via Ethernet interface comes to WS PC, where it is finally processed, analyzed, and saved. The two last complete profiles received from different channels are used to determine distance between inner edges of the wheels.

In a certain time after the arrival of last signal S_{w1}^d the system switches to standby mode: the laser modules turn off and the protective shutters close.

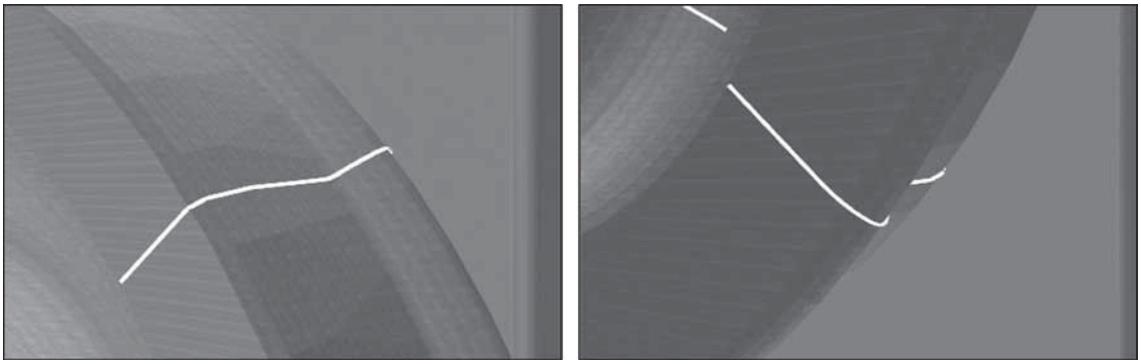

Fig. 2. Light spot on the working surface of railcar wheel obtained using sensor units

The proposed algorithm for operation of sensing channels shows that both DCC and camera controllers should operate strictly in real-time mode, while for the WS PC real time is not a crucial factor and it can be operated by general operating system.

ALGORITHMS AND SOFTWARE

The main task of camera controller is to obtain digital images from photo-sensor matrix and to process them for identification of light spot profile following the shape of controlled object. In digital images, the light spot corresponding to wheel working surface is represented by group of pixels a little bit brighter as compared with the background (Fig. 2).

To detect the filamentary objects corresponding to the light spot, the most advisable is to use one-dimensional concordant sampled filter (CSF) and to analyze its responses [6]. The output signal of one-dimensional CSF is a result of discrete convolution of pixel brightness corresponding to the image column with pulse function:

$$y(i) = \sum_{n=-b\backslash 2}^{b\backslash 2} x(i+n)\cdot h(n), \qquad (1)$$

where y is result of the convolution; x is pixel brightness; b is filter base; i is image line number, and h is CSF pulse function. The maximum CSF response is reached if the pulse function $h(n)$ correlates with characteristics of useful signal.

To decide whether the point belongs to light spot profile it is necessary to compare CSF responses with some threshold values. In this case, the amplitude of maximum filter response $y_{\max}(j)$ for various parts of image can essentially differ (j is column number). This is associated with limited focusing depth of the camera objective and significant range in terms of distance between the wheel elements and the observer (video camera). Also, reflective ability of different wheel surfaces can vary. Therefore, the use of constant limit for processing of the entire image can lead to useful signal losses. It has been proposed to use the endpoints function $g(j)$, depending on statistical characteristics obtained from processing of both previous and current images. So, to decide whether the point (i_{max}, j), corresponding to maximum filter response $y_{\max}(j)$ belongs to the light spot profile or not the following decisive rule is:

$$(i_{\max}, j) \in \text{c},\ y_{\max}(j) > g(j), \qquad (2)$$

where $g(j) = \sigma_{image}\cdot k_1 - \sigma_j\cdot k_2$; σ_{image} is standard deviation of CSF responses obtained for the whole previous image; σ_j is standard deviation of CSF responses for columns of current image; c is array of contour points; k_1 k_2 are experimental coefficients determined at presetting of sensor unit. No estimates of mathematical support in the decisive rule (2) apply, since the mean CSF response is always close to zero. Function $g(j)$ enables to reduce limits for the image columns with larger variance of responses that potentially can contain a light spot and, therefore, to reduce useful signal losses (Fig. 3). The results of processing of the pair of images obtained

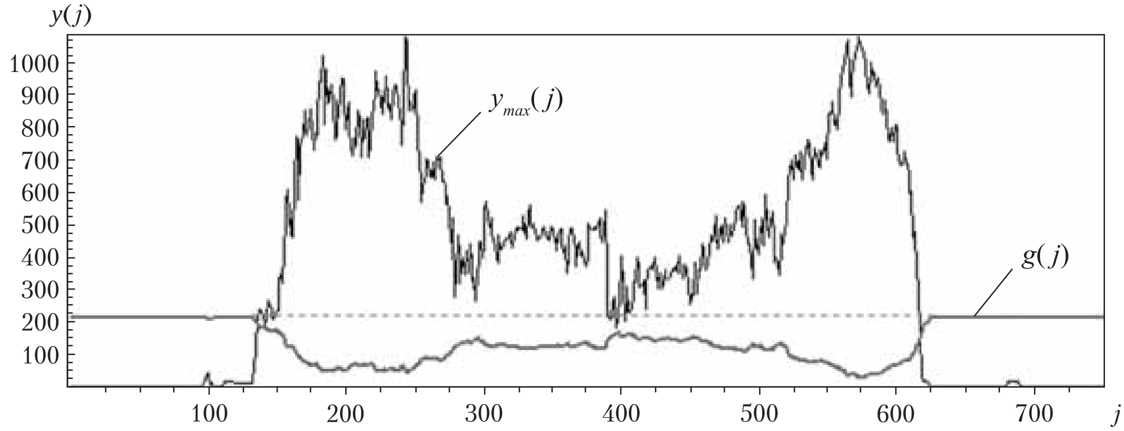

Fig. 3. Formation of endpoints function $g(j)$ for deciding on whether the point belongs to the light spot contour

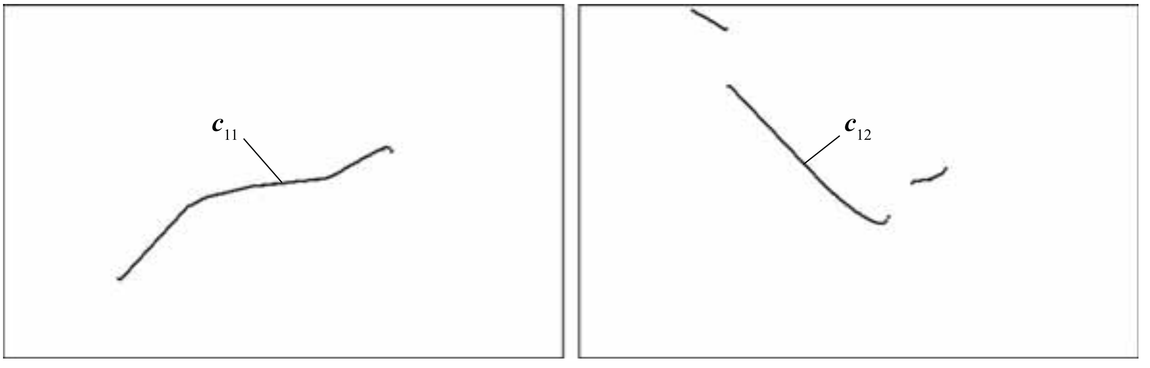

Fig. 4. Results of identification of light spot in the images obtained from coupled sensor units

from coupled sensor units are light spot profiles c_{11} and c_{12} given in display coordinates (Fig. 4).

To determine the geometric parameters of the wheel working surface it is necessary to transform the display coordinates of found profile points into the metric reference coordinate system of sensor units. To do this transformation it is proposed to use a mathematical model of the optical system consisting of two transformations: the direct, from the object to its image, and the inverse, from the image to the object:

$$(x_e, y_e) = P(x, y, z, A, \theta), \quad (3)$$

$$(x, y, z) = P^{-1}(x_e, y_e, A, \theta), \quad (4)$$

where (x_e, y_e) are display coordinates of the point; (x, y, z) are spatial coordinates of the point in the reference metric coordinate system; A is array of camera spatial position with respect to reference coordinate system; θ is horizontal angle of view of camera objective [7]. In this case, the most interesting is the inverse transformation (4). The matrix depends on camera's rotation angles α, β and γ around OX, OY and OZ respectively, and displacement vector $[\Delta x, \Delta y, \Delta z]^T$. Angle θ depends on focal distance of objective f and effective width of photo-sensor matrix w_m:

$$\theta = arctg\left(\frac{w_m}{2 \cdot f}\right). \quad (5)$$

w_m and f parameters depend on the characteristics of video camera. Nominal values of α, β, γ, Δx, Δy, and Δz can be assumed known, insofar as they depend on selected optical scheme of the sensor

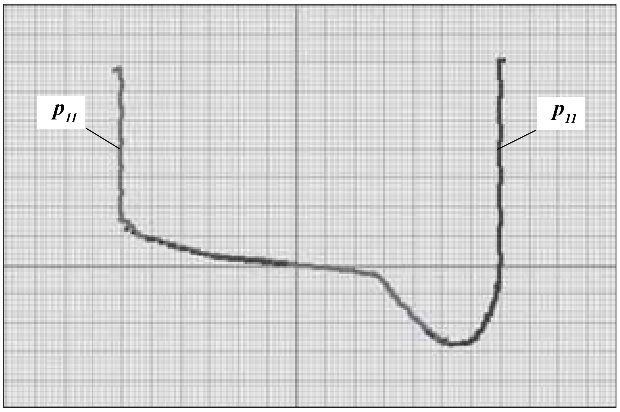

Fig. 5. General metric profile describing the wheel effective part

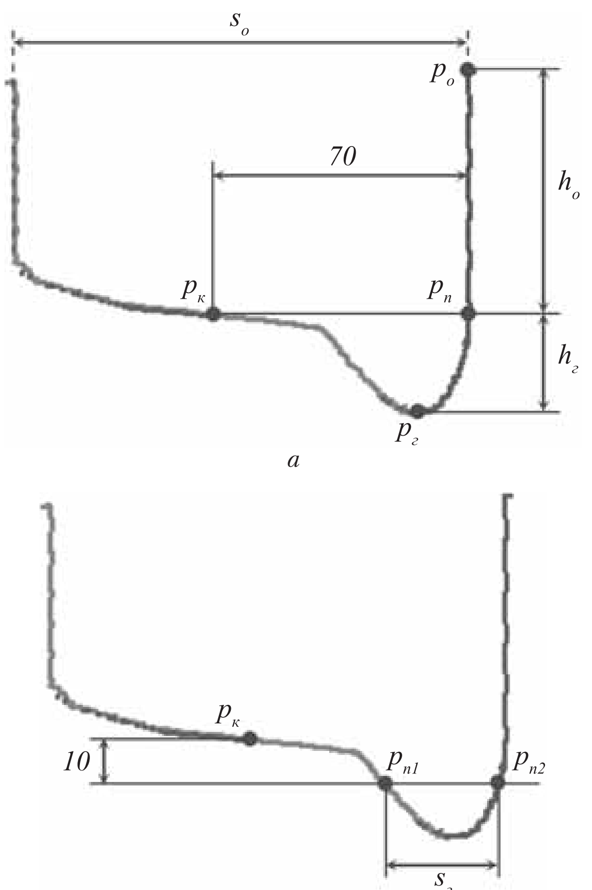

Fig. 6. Determination of railcar wheel geometric parameters: *a* — rim width $s_о$, rim thickness $h_о$ and flange height $h_г$; *b* — flange thickness $s_г$

unit. If required, the real values of parameters, which can differ from the nominal ones because of manufacturing and assembling errors, are identified using procedure for calibration of video cameras [8].

For the purpose of transformation (4) additional conditions should be introduced, inasmuch as the display coordinates of image points themselves do not contain any information on the distance to the object. The operating range of laser triangulation sensor is limited with a plane coinciding with the plane of laser module radiation, i.e. one of object coordinates always equal to zero. Thus, one can assume that *OZ* axis of the reference coordinate system is perpendicular to the laser radiation plane, i.e. $z = 0$. Hence, the metric coordinates of the point have 2D coordinates (x, y) corresponding to the display coordinates (x_e, y_e). According to the chosen optical scheme the mathematical models of sensor units (SU_{11}, SU_{12}) have the following nominal parameters: $\alpha_{11} = \alpha_{12} = 40°$; $\beta_{11} = -35°$, $\beta_{12} = 35°$; $\Delta x_{11} = 0$ mm; $\Delta x_{12} = 40$ mm; $\gamma_{11} = \gamma_{12} = 28$ mm°; $\Delta z_{11} = \Delta z_{12} = 334.5°$ mm. The nominal values of inherent parameters of the video cameras are the same: $f = 8$ mm; $w_m = 4.51$ mm. According to the formula (5), the objective horizontal angle of view have the following nominal values: $\theta_{11} = \theta_{12} = 31.5°$, i.e. the arrays of camera spatial positions A_{11}, A_{12} for the sensor units SU_{11} and SU_{12} can be assumed known. Having made transformations for each point of the contours c_{11} and c_{12} using the arrays and angles A_{11}, θ_{11} and A_{12}, θ_{12}, respectively, one could obtain two components of the metric profiles p_{11} and p_{12} of wheel working surface combined in one reference coordinate system. Provided the mathematical model corresponds to the real parameters of the sensor unit, the profiles p_{11} and p_{12} form a general metric profile of wheel working surface (Fig. 5).

Having got the general metric profile of wheel tire, it should be processed for obtaining values of controlled parameters, namely: flange height, flange thickness, width and thickness of the wheel rim. Also, it is necessary to check presence/absence of vertical flange worn sharp higher than 18 mm. The general profile contains two linear segments oriented almost vertically. To identify the linear seg-

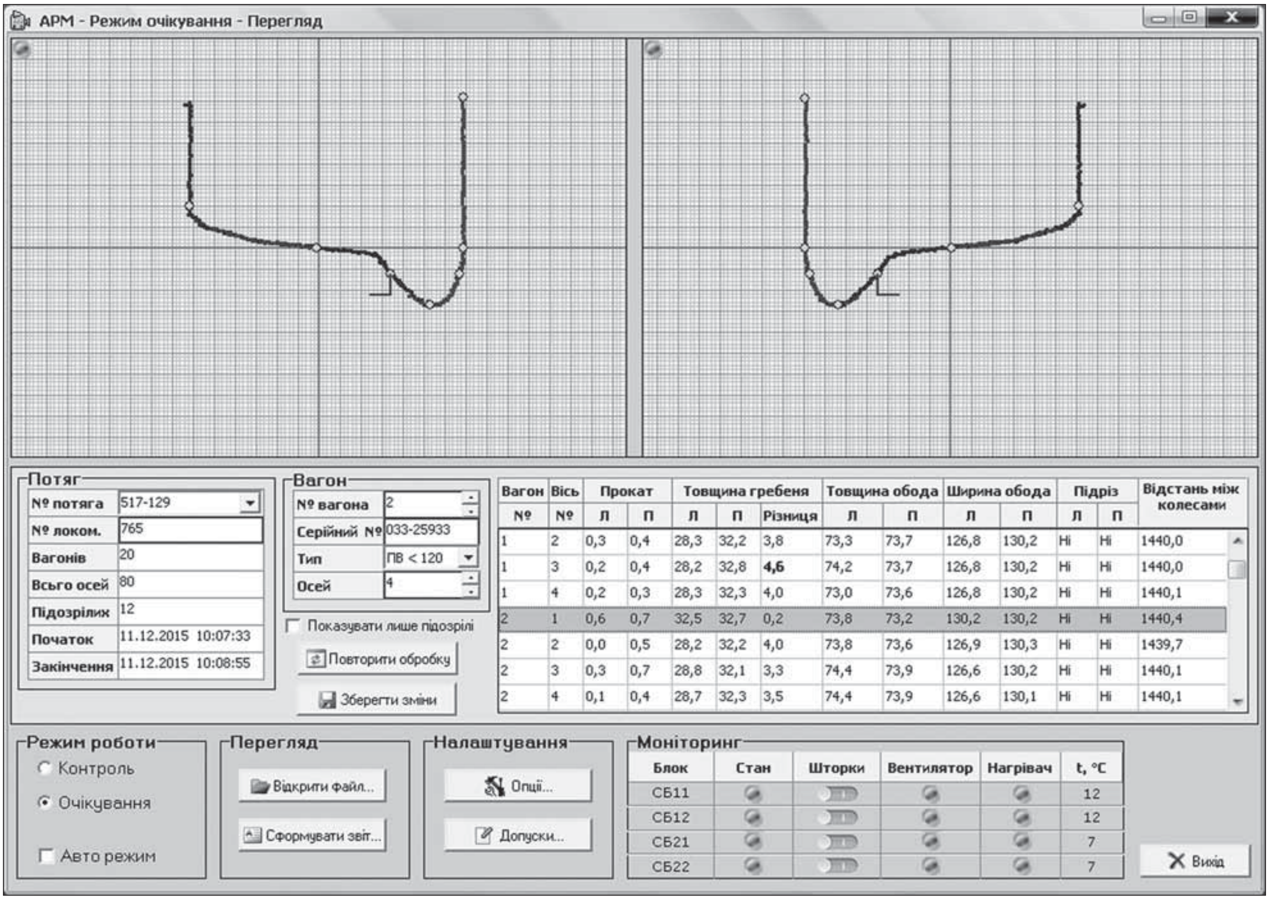

Fig. 7. Main dialog box of ARM math software

ments in the images it has been proposed to use the Hough transform technique [9] based on iterative search of angular and linear parameters of straight line equation and determination of such parameters at which the maximum number of points belongs the straight line. To optimize the algorithm speed it is advisable to rotate the image around fixed point (for example, around the center of image, which enables to search by only one angular parameter). Distance between detected vertical lines is assumed a width of rim s_o (Fig. 6, *a*). Flange height $h_г$ is determined as difference in ordinates of points $p_г$ and p_n, where $p_г$ is the point with minimum ordinate; p_n is point of intersection of the profile and the horizontal straight line running from point $p_к$ that corresponds to mean tread circle and is distanced 70 mm from the wheel inner edge. The ordinate difference between points p_o and p_n is assumed the searched thickness of wheel rim h_o, where point p_o is the point with maximum ordinate. To define the flange thickness $s_г$ it is necessary to find two characteristic points. To this end, it is necessary to draw a horizontal straight line 10 mm lower than point $p_к$ and to find two points of intersection with profile curves p_{n1} and p_{n2} (Fig. 6, *b*). The presence of «flange worn sharp» defect is controlled by simulating the installation of special pattern used for detection of this defect on the flange.

In accordance with proposed algorithms for processing images and arrays of discrete points a respective software for microprocessor controllers of the system has been developed in Visual DSP. The algorithm speed has been optimized, which enables to process all frames coming from photo-sensor

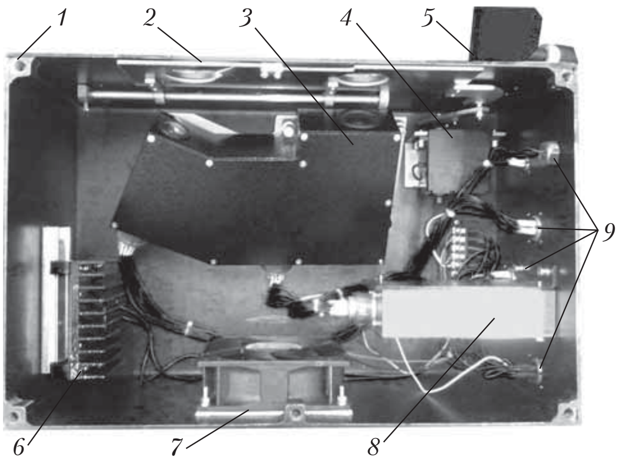

Fig. 8. Ready-assembled sensor unit (without cover plate): *1* — main body; *2* — protective shutter with actuating device; *3* — laser triangulation sensor; *4* — electric drive of shutter actuator; *5* — wheel approach sensor; *6* — heater; *7* — fan with dust filter; *8* — relay unit; *9* — connectors

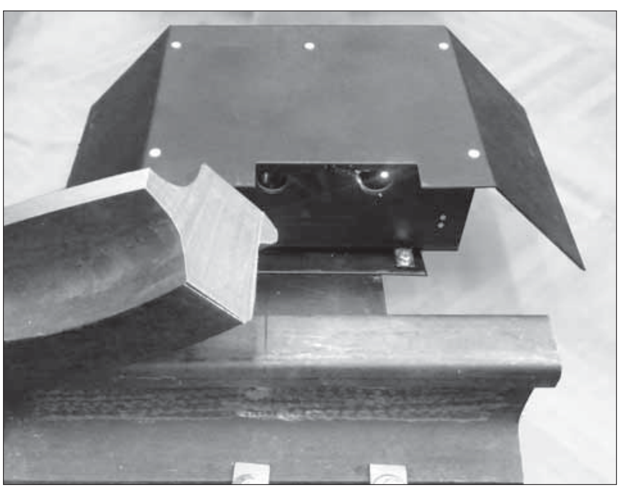

Fig. 9. Trial bench for sensor unit testing

matrix with a rate of 60 frame/s, in real time. Mathematical support of operator's computerized workstation has the following functions:

- To exchange commands and data with data collection controllers of sensor units;
- To store, review, and to analyze obtained measurement results; to control the actuating devices of sensor units;
- To monitor the condition of equipment and to form reporting documents.

To perform all necessary functions, ARM software has been developed (Fig. 7). In the upper part of main dialog box, there are two graphical panels to display the obtained profiles of working surfaces of left and right wheels of wheelset. The middle part is for reviewing and editing digital and symbol information. The *Train* and *Carriage* panels contain fields for displaying and editing data on the train and each carriage, respectively. The results of measurement of wheelset geometric parameters are presented in tables. The bottom part of dialog box is for realization of control functions of system operation mode (Standby or Control), review and record of results of control, setting of the system, and visualization of monitoring of equipment condition. The reports are formed as checklist that can be printed out or saved in file.

HARDWARE

To realize the microprocessor means of sensor units, specialized controllers CamContol548 and DAQ532 manufactured by Paton EWI are used. CamContol548 controller is characterized by high computation capacity and relatively small size. The controller's compute core is based on digital signal processor used for processing thread-specific data to which series of video frames belong. To connect the cameras a 12-bit parallel interface is foreseen. The interaction with external devices is realized via high-speed serial interface RS-422/485. Also, a separate differential interface for clock signal based on hardware driver RS-422 is foreseen.

The data collection controller DAQ532 that is used for simultaneous operation with the two camera controllers contains three separate processors. The central one is a digital signal processor, the two others are additional specialized processors for handling data floating decimal point. The central processor is responsible for general monitoring of controller operation, while the additional ones deal with parallel processing of data flows in real time.

Two separate serial interfaces RS-422/485 are provided for interaction with camera controllers; Fast Ethernet (up to 100 Mbps) interface is used for data transfer to operator's WS. Also, two differential outputs for synchronizing the video camera are provided. Additionally, the controller is equipped with discrete inputs/outputs to control subsystems of thermal stabilization and shutter actuators incorporated in the sensor units.

The sensor unit cameras are respective modules manufactured by the Paton EWI. The camera modules can be completed with various photo-sensor matrices depending on the specifications of sensor units. For this case, a monochrome matrix with a resolution meeting WVGA standard (752×480 pixels) has been chosen. The matrix is based on global shutter technique at a frequency of frames of 60 Hz. Between the objective and the photo-sensor matrix there is fixed an interference filter with a length of central wave corresponding to laser module radiation wavelength. Foreign-made standard laser modules have been chosen and completed. The laser modules usually have a lens capable of focusing laser beam in a point at a certain distance. For laser beam sweeping the modules are completed with a special cylindrical lens. The camera and laser modules are assembled in cylindrical cases, which ensures additional mobility for their adjustment due to possibility of rotation around longitudinal axis.

High-speed photoelectric sensor has been chosen as proximity sensor. Its operation is based on overlapping of its operating area by the object. The operating area of chosen model ranges 30–175 mm, maximum response time is 330 μs. The design of body elements of sensor units is based on double case configuration with laser triangulation sensors assembled in proper sealed cases and other equipment installed inside larger cases directly contacting with environment (Fig. 8). Required orientation of sensors is ensured by angular brackets.

The external viewports of sensor units shut/open using electro-mechanically driven protective shutter. Inside the cases air is heated by electric heaters equipped with radiators. Air stream for forced blowing of viewports is formed using fans with dust filters. For direct control of actuating devices of sensor units, relay boxes assembled in proper sealed cases are used. On the front panel of sensor units installed between rails, there are located brackets for fastening of rail approach sensors. Also, a bracket for installation of sensor units on rails and elements for fastening the bracket to rails, which ensure insulation between rail lines have been designed and manufactured.

For presetting and testing of the system actuating devices and measuring equipment, wheelset samples (sectors) with various deterioration level have been used (Fig. 9).

Upon the results of experiments it has been established that the designed sensor system can automatically record full profiles of wheel working surface and measure geometrical parameters of wheelsets with accuracy of ± 0.5 mm, directly on the move with a velocity of up to 60 km/h. The system software enables to perform all required functions related to visualization, recording, and computerized analysis of the results of control of wheelset technical condition.

CONCLUSIONS

The system for remote control of geometric parameters of wheelsets is a sophisticated hardware and software complex realized using modern intelligent recorders and means of processing of digital signals. Implementation of proposed solutions in the national railway sector will enable:

- To essentially raise qualitative and quantitative aspects of control of wheelset geometric parameters;
- To computerize obtaining and processing of measurement data on the condition of wheel treads;
- To shift from the planned repair works for maintenance of wheelsets to the repair based on their actual condition;
- To raise traffic safety on railways due to timely detection of severe defects of wheelsets.

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Recieved 31.10.16

Є.В. Шаповалов, В.О. Коляда,
Д.Д. Топчев, Н.Ф. Луценко, А.М. Мангольд

Інститут електрозварювання ім. Є.О. Патона НАН України,
вул. Боженка, 11, Київ-150, 03680, Україна,
тел.: +380 44 200 4779, факс: +380 44 528 0486,
office@paton.kiev.ua

РОЗРОБКА АПАРАТНОГО ТА ПРОГРАМНОГО ЗАБЕЗПЕЧЕННЯ СИСТЕМИ ДИСТАНЦІЙНОГО КОНТРОЛЮ ГЕОМЕТРИЧНИХ ПАРАМЕТРІВ КОЛІСНИХ ПАР ЗАЛІЗНИЧНИХ ВАГОНІВ

Розроблено апаратно-програмний комплекс технічних засобів системи дистанційного контролю геометричних параметрів колісних пар залізничних вагонів. Система призначена для безконтактного сканування профілів робочих поверхонь коліс та автоматичного оцінювання технічного стану колісних пар під час руху потягів. Впровадження отриманих науково-технічних результатів у вагонне господарство залізниць дозволить суттєво покращити якісні і кількісні показники контролю параметрів зношеності вагонних коліс та надасть змогу підвищити безпеку руху за рахунок своєчасного виявлення небезпечних дефектів колісних пар.

Ключові слова: колісні пари, залізничні вагони, дистанційний контроль, геометричні параметри, лазерно-тріангуляційний сенсор, сенсорні блоки.

Е.В. Шаповалов, В.А. Коляда,
Д.Д. Топчев, Н.Ф. Луценко, А.Н. Мангольд

Институт электросварки им. Е.О. Патона НАН Украины,
ул. Боженко, 11, Киев-150, 03680, Украина,
тел.: +380 44 200 4779, факс: +380 44 528 0486,
office@paton.kiev.ua

РАЗРАБОТКА АППАРАТНОГО И ПРОГРАММНОГО ОБЕСПЕЧЕНИЯ СИСТЕМЫ ДИСТАНЦИОННОГО КОНТРОЛЯ ГЕОМЕТРИЧЕСКИХ ПАРАМЕТРОВ КОЛЕСНЫХ ПАР ЖЕЛЕЗНОДОРОЖНЫХ ВАГОНОВ

Разработан аппаратно-программный комплекс технических средств системы дистанционного контроля геометрических параметров колесных пар железнодорожных вагонов. Система предназначена для бесконтактного сканирования профилей рабочих поверхностей колес и автоматической оценки технического состояния колесных пар во время движения поездов. Внедрение полученных научно-технических результатов в вагонное хозяйство железных дорог позволит существенно улучшить качественные и количественные показатели контроля параметров износа вагонных колес и даст возможность повысить безопасность движения за счет своевременного обнаружения опасных дефектов колесных пар.

Ключевые слова: колесные пары, железнодорожные вагоны, дистанционный контроль, геометрические параметры, лазерно-триангуляционный сенсор, сенсорные блоки.