Fusion of inertial and optical data for monitoring the geometry of the rail track

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Abstract. Methods and means of monitoring the state of the rail track by a number of key geometric parameters are analyzed. The concept of joint use of inertial and optical technologies as an accurate and cost-effective solution in this area is proposed. An assessment of the influence of errors of individual measuring modules of an optical-inertial diagnostic system on the accuracy of determining the geometric parameters of a rail track has been carried out. Questions related to the recognition of the rail image in the readings of optical sensors against the background of stray lighting and sun glares are touched upon. Attention is paid to the methods of obtaining a priori data on the position of the rail head profile on the matrix of the scanner camera. The results of experimental testing of the proposed solutions are presented.

1. Introduction

Controlling the railway track geometry is one of the most important aspects of ensuring safety of rail transport. Even millimeter-scale changes of its parameters are significant and can lead to accidents; thus, they require regular monitoring [1]. Despite the fact that specific standards for the railway maintenance may differ from country to country, the main parameters of the track are subject to control on all railways in the world [1], [2]. These include: the width of the rail track (gauge), the curvature of the track in the horizontal plane, the elevation of one rail above the other (crosslevel), the longitudinal slope of the track, deviations of the rail shape from a straight line in the horizontal (alignment) and vertical (profile) planes, equivalent conicity (parameter of the track connecting the gauge and the crosslevel, as well as the shape of each of the rails in a specific section of the track and allowing to characterize the oscillatory motion of the wheelset when moving inside the track) [3].

The geometric parameters of the track can be controlled by various means. Among them, the manual measurements are historically the first and they still find application. For example, the track gauge and crosslevel can be measured with a manual gauge that comes into mechanical contact with the inner edges of the rails [4]. In fact, in such case the track gauge is measured with a ruler, and the crosslevel is measured with a bubble level. As for alignment, this parameter was originally defined as the deviation of the rail from a thread stretched between its two points. This approach is called “chordal”, and is illustrated in figure 1: the thread was stretched between points A and B, and then the
distance $a$ between chord AB and arc AB at point C was determined. Later this method was automated and implemented on track measuring cars.

![Figure 1](image_url)

**Figure 1.** Determination of alignment $a$ by the chord method, as deviation of the rail’s section C from the chord connecting two oppositely located sections A and B.

The main idea was to control the relative position of three points (A, B and C) on the rail and then analytically determine the desired distance $a$. Initially (such an implementation is still found on some railways of the world), the coordinates of the desired points were determined by contact method: using spring-loaded rollers rolling along the rail, mechanically spaced relative to each other on the car’s body at specified distances in such a way that they are in the sections of the path corresponding to points A, B and C respectively [5]. The movements of the rollers directly determined the coordinates of the inner edge of the rail in given sections. The bends of the track in the vertical plane (profile) were controlled in a similar way. Further step in the development of means for monitoring the rails position (measuring gauge, alignment, etc.) was the use of non-contact measuring devices – optical scanners of the inner profile of the rail head. Installing them on the car, in three sections (by analogy with contact/roller systems), made it possible to reproduce the chord measurement scheme shown in figure 1 [6].

It should be noted that the current solution for measuring the railway geometric parameters involves using six optical scanners (three on each side of the car) to control the bending of the right and left rails. However, determination of such parameters as crosslevel and curvature of the track also requires information about the railway’s orientation in space, which in modern laboratory cars is usually acquired using a strapdown inertial navigation system (SINS). When measuring crosslevel, it allows determining the horizon plane (in order to measure the elevation of one rail relative to the other, i.e. the difference in their vertical coordinates). As for the curvature of the track, it is defined as the increment of the car’s heading (also taken from the SINS readings) relative to a certain track length (in Russian standards, 25 meters). Finally, another mandatory element of such systems is the odometer, which allows determining the location of the track testing car on the rail track (i.e. distance traveled by the car) [7].

2. **The concept of an inertial optical system**

The previously described scheme for solving the problem of monitoring the railway geometry is, obviously, redundant in terms of using three measuring sections with optical scanners mounted on the car. The current trends lie in the development of universal measuring devices (which can be installed on any railway mobile unit, including cars or locomotives of regularly travelling trains), and thus suggest the cheapest and most compact solutions.

In order to ensure the possibility of measuring the railway geometric parameters while at the same time meeting the cost, weight, and size constraints, the concept of an inertial-optical system for railway track diagnostics was proposed [8]. In its essence, this concept suggests transition from the simultaneous physical measurement of the rail threads’ position in three sections to their sequential measurement, followed by recalculation of the measured position to the geographic coordinate system (GCS) by the way of using SINS. Thus, just two scanners become sufficient to obtain geometric parameters [9]. The general layout of the system is shown in figure 2.
3. Analysis of the error components of the inertial optical system

In accordance with European standard EN13848 [2], the accuracy requirements for the measurement of the main geometric parameters of the rail track are as follows:

- Gauge error – 1 mm;
- Crosslevel error – 5 mm;
- Alignment error – 1.5 mm.

Based on the methods for calculating the corresponding parameters [7], [12], it is possible to associate the errors of their determination with the errors of the used measurement instruments. The track gauge is defined as the distance between two specified points on the right and left rails, respectively. The coordinates of these points are determined directly from the readings of optical scanners. Therefore, the error of measuring the gauge can be written as

\[ \delta G = 2\delta x, \]

where \( \delta G \) is the error of determining the gauge; \( \delta x \) is the error of determining the horizontal coordinate of the rail section point according to the scanner readings.

The error of determining the horizontal and vertical coordinates of the points of the rail section is directly related to the scanner’s error and depends on the angle at which the scanner is installed on the car:

\[
\begin{align*}
\delta x &= \frac{\Delta}{\cos \alpha}, \\
\delta z &= \frac{\Delta}{\sin \alpha}
\end{align*}
\]

\[ \text{(2)} \]
where $\delta x$ and $\delta z$ are the errors of determining the horizontal and vertical coordinates of the rail section point according to the scanner indications, respectively; $\Delta$ is the scanner error; $\alpha$ is the angle at which the scanner is mounted in relation to the car’s body.

Undercarriage clearance requirements combined with the choice of operating ranges of mid-priced scanners available on the market determine an $\alpha$ value of about $30^\circ$; hence, in accordance with formulas (2) and (1):

$$
\begin{align*}
\delta x & \approx 1.15\Delta \\
\delta z & = 2\Delta \\
\delta G & = 2\cdot1.15\Delta = 2.3\Delta 
\end{align*}
$$

which, taking into account the required measurement error of the gauge, gives the minimum requirement for the scanner accuracy:

$$
\Delta \leq 0.43 \text{ mm} .
$$

The crosslevel of the track is determined in relation to the horizon plane; therefore, one first needs to measure the vertical coordinate of a point on the surface of each of the rails. These coordinates are determined by the readings of the scanners, which means that they are measured in the coordinate system associated with the bearing beam on which those scanners are installed. To recalculate them to the coordinate system associated with the horizon plane, it is necessary to take into account the apparent elevation of one rail above the other due to the deviation of the bearing beam relative to the horizon plane. This will require knowledge of the roll angle measured by the SINS and the track gauge measured by the scanners in the current section. Then the crosslevel measurement error will be

$$
\delta c = 2\delta z + \gamma \cdot \delta G + G \cdot \delta \gamma ,
$$

where $\delta c$ is the crosslevel determination error; $G$ is the gauge value; $\gamma$ and $\delta \gamma$ are the roll angle and the error of its measurement.

Taking into account the fact that in Russia the nominal gauge value is 1520 mm, and $\delta z$ and $\delta G$ are determined by (3), the crosslevel error is

$$
\delta c = 2 \cdot 2\Delta + \gamma \cdot 2.3\Delta + 1520 \cdot \delta \gamma .
$$

From (6), taking into account the required crosslevel measurement error and condition (4) for scanners, one can obtain the requirement for the roll angle measurement accuracy: $\delta \gamma \leq 7.5'$.

Analysis of the alignment measurement error is more complicated. Its measurement is carried out according to the previously described chordal (three-point) scheme. This means that the greatest error of determining alignment is

$$
\delta r = \delta r^{(1)} + \delta r^{(2)} + \delta r^{(3)},
$$

where $\delta r$ is the alignment error; $\delta r^{(1)}$, $\delta r^{(2)}$, $\delta r^{(3)}$ are the errors of determining the first (the beginning of the chord, point A in figure 1), second (the midpoint of the chord, point C in figure 1) and third (the far point of the chord, point B in figure 1) coordinates of the points of the chord method of alignment measurement, respectively.

The error of determining each of the points’ coordinates can be written as

$$
\delta r^{(i)} = \delta x + S \cdot \delta K + K \cdot \delta S ,
$$

where $\delta r^{(i)}$ is the error of determining the coordinates of one of the points of the chord method of alignment measurement; $S$ and $\delta S$ are distance along the rail from the first point of the chord method and its measurement error; $K$ and $\delta K$ are heading change since the beginning (first point) of the chord its measurement error.
Substituting (8) into (7) gives
\[
\delta r = 3\delta x + S^{(2)} \cdot \delta K^{(2)} + K^{(2)} \cdot \delta S^{(2)} + S^{(3)} \cdot \delta K^{(3)} + K^{(3)} \cdot \delta S^{(3)},
\]
where \(S^{(2)}\), \(S^{(3)}\) and \(\delta S^{(2)}\), \(\delta S^{(3)}\) are the distances along the rail from the first to second and third points of the chord method, respectively, and their measurement errors; \(K^{(2)}\), \(K^{(3)}\) and \(\delta K^{(2)}\), \(\delta K^{(3)}\) are changes of the heading since the moment of the chord’s beginning (first point) to second and third points, respectively, and their measurement errors.

Errors of determining the traveled distance and heading changes are associated with the measuring tools used: distance errors depend on the odometer, heading errors depend on SINS. Both are cumulative and can be represented by the expressions below:
\[
\begin{align*}
\delta S^{(i)} &= S^{(i)} \cdot \delta l \\
\delta K &= \delta K_r \cdot \frac{\pi}{180} \left( \frac{S}{3600V} \right)^{1/2},
\end{align*}
\]
where \(\delta l\) is the odometer error; \(\delta K_r\) is the random drift of the SINS azimuth gyroscope (°/√h); \(V\) is the average speed of the measuring instrument in the analyzed area (m/s).

Taking into account (3) and (10) and assuming that point 2 (C in figure 1) is in the middle of the chord, expression (9) gives us
\[
\delta r = 3.45\Delta + \frac{S^{(3)}}{2} \cdot 0.5 \cdot \delta K_r \cdot \frac{\pi}{180} \left( \frac{S^{(3)}}{2 \cdot 3600V} \right)^{1/2} + \frac{K^{(3)}}{2} \cdot \frac{S^{(3)}}{2} \cdot \delta l + \frac{1.35\pi}{180} \cdot \delta l \cdot \frac{S^{(3)}}{3600V} \left( \frac{S^{(3)}}{3600V} \right)^{1/2}.
\]

The worst case scenario – when the alignment equals its maximum possible value of 50 mm and the range of its determination equals its minimum value of 3000 mm – will give us the largest possible heading change during alignment measurement, corresponding to the standards:
\[
K^{(3)} \approx \frac{50}{3000} \approx 0.017 \approx 57''.
\]

The chord length depends on the standard used, and ranges from 3…15 m according to the EN13848 standard [2] to 20 m according to Russian standards [1]. Using the greatest chord length (20 m) and taking into account (12), expression (11) gives us
\[
\delta r \approx 3.45\Delta + \frac{5}{4} \cdot 0.017 \cdot 20000 \cdot \delta l + \frac{1.35\pi}{180} \cdot 20000 \cdot \delta K_r \cdot \left( \frac{20000}{3600V} \right)^{1/2} \approx 3.45\Delta + 425.00 \cdot \delta l + 1110.72 \cdot V^{-1/2} \cdot \delta K_r.
\]

Together with the above requirement (\(\delta r \leq 1.5\) mm), expression (13) sets a limit on the total error of three main elements of the system: the optical scanner of the inner surface of the rail head, the odometer, and the SINS (or rather its azimuthal gyroscope). The goal of selecting the components of the system is to ensure the total measurement error of the track’s geometric parameters, while at the same time minimizing the total cost of the system.
The second most expensive component is scanners. Most models of the middle price range have the accuracy of about 0.1 mm; the highest accuracy that can be obtained without the use of overly expensive high-precision models is about 10…15 μm [13].

Odometer error is a variable that depends on many factors, including direction, speed, and the state of the rolling surface of the wheel on whose axis the odometer is installed [7]. Traditionally, its level is estimated to be about 0.1% of the covered distance (i.e. \( \delta l \leq 0.001 \)). The team of authors has carried out a large amount of research aimed at correcting the odometer readings – using both a priori information about the traversed section of the track, and data from other measuring systems installed on the car. These include taking into account the shape of the rolling surface of the wheel [14], and evaluating other components of the odometer error by developing a specialized railway track navigation system. The odometer error achievable in this case can be as low as 0.01%.

Based on the given achievable error values for the scanners and the odometer, it is possible to calculate accuracy requirements for the SINS azimuthal gyroscope (which is the most expensive component of the whole system). Provided that the measurement system operates at speeds from 40 to 300 kmph, the permissible drift of the azimuthal gyroscope, in accordance with expression (13), should lie within the range of 0.004…0.001 °/h. The specified accuracy characteristics correspond to the commercially available SINS based on laser gyroscopes. The transition to cheaper SINS based on FOG without losing required accuracy can be possible using a specialized railway navigation algorithm. This method of increasing the accuracy of calculating the orientation and navigation parameters by taking into account the specifics of the car’s movement along the track, integrating data from heterogeneous sensors installed on the car, and using a priori known data about the track, is described in [7], [8], [15] and will not be considered in detail here.

4. Issues of locating the rail head profile in the scanner’s video signal

Nowadays the main method of non-contact, high-precision and high-speed analysis of the railway track is using laser scanners based on the triangulation principle (figure 3a). A triangulation scanner comprises a laser with a lens which turns the laser beam into a flat angle, and a CMOS/CCD matrix (or a pixel array, in case of rangefinders a.k.a. 1-D scanners), the main optical axis of which is located at a certain angle to the laser beam. When the scanner moves relatively to the studied object, the image of the surface illuminated by the laser moves along the matrix (array) due to the parallax effect. The position of this image is then recalculated into the surface profile of the studied object (figure 3b).

![Figure 3. An illustration of the operation of a laser triangulation scanner: (a) the principle of triangulation; (b) sequence of image transformations.](image)

Although there have been attempts to create non-contact diagnostic systems based on laser rangefinders [16], in order for the system to comply with modern track measurement standards it is necessary to use two-dimensional scanners. In particular, this is due to the fact that modern standards [1] prescribe to measure the gauge as the distance between the points of the rail heads lying 14 mm below the rolling surface. Thus, it is necessary to determine the rolling surface, find a point lying 14 mm lower (let us call this point the “characteristic” point of the rail), and then calculate the geometric parameters of the track based on the coordinates of these characteristic points of the left and
right rails. This requires the analysis of the entire railhead profile, which requires the use of two-dimensional (2-D) scanners.

As its output, a laser scanner generates a stream of profiles, each of which is an array of points in the form of two-dimensional coordinates \((x, z)\). The number of points is determined by the resolution of the scanner; for example, for the scanCONTROL 2750-100 it is 640 [13].

In normal operation conditions (i.e. when there are no foreign objects – grass, debris, etc. – between the scanner and the rail) these points should describe the transverse profile of the rail thread. The shape of said profile is known in advance and is determined by the nominal section of the rail (e.g. for Russian Railways – in accordance with GOST R 51685-2013). Depending on the scanner’s position relative to the rail, the profile measured by the scanner can have different position and angle of inclination. It is these parameters that need to be obtained in the process of analyzing the data received from the scanner.

Thus, the problem of recognizing the profiles received from the scanner boils down to finding such a set of transformations \(T\) that would map the nominal profile to the acquired set of points, while optimizing a certain parameter (let us call it the optimization parameter \(\theta\)).

The set of permissible transformations differs depending on the range of possible displacements of the scanner relative to the studied object. It is customary to distinguish two sets: rigid and non-rigid transformations. A rigid transformation is a congruent (isometric) transformation; in essence, this means applying rotation and parallel translation operations. A non-rigid transformation, in addition, allows affine transformations – scaling, tilting, etc. Since the scanners used in the system are fixed on a beam rigidly connected to the car’s bogie, the deviation of the scanner’s main optical axis from the perpendicular to the rail line can be neglected; this allows us to restrict ourselves to rigid transformations. In other words, the result of the image recognition algorithm should consist of three values – linear coordinates \((x, z)\), describing the position of the rail image on the camera matrix, and the angle \(\beta\) of the rail relative to the camera.

A good choice for an optimization parameter is the sum of the squares of the Euclidean distances between the points of the measured profile and the analytical model of the nominal profile

\[
d(T(M), D) = \sum_{m \in T(M)} \sum_{s \in S} (m - d)^2, \tag{14}
\]

where \(d()\) is the distance function; \(M\) is the set of points received from the scanner; \(D\) is the set of points describing the nominal profile; \(m\) and \(d\) are points of the sets \(M\) and \(D\), respectively. Optimization of such a function when using rigid transformations corresponds to the classic least squares minimization problem. However, this approach is extremely sensitive to outliers, and the algorithm based on it shows unstable behavior when analyzing noisy data.

To increase the stability of recognition, it is necessary to introduce into the algorithm (14) some robust function \(g()\):

\[
d(T(M), D) = \sum_{m \in T(M)} \sum_{s \in S} (g(m - d))^2. \tag{15}
\]

The formulation of the problem in the form of expression (15) is known as M-estimation [17]. To find the optimal solution, graph theory can be applied – namely, matching search algorithms. This approach allows to find the global optimum of the optimization parameter. However, this requires a significant amount of computation, which makes the use of such an approach impossible in real time; instead, algorithms are usually used to find the local optimum of the optimization parameter (instead of the global one).

Examples of implementation of the rail image search algorithm in the scanner readings are described in the authors’ works [9], [18], [19] and will not be reproduced in detail here. The disadvantage of such algorithms is the requirement for the initial proximity of the sets \(M\) and \(D\); otherwise, found local optimum might be incorrect, which will amount to a recognition failure.
It should be noted that, despite obvious advantages of using laser scanners (non-contact, high accuracy, high sampling rate, lack of inertia), this method, like all optical ones, is vulnerable to background illumination, false reflections, and lens contamination.

The first test runs of the system prototype showed strong noise in the resulting image caused by solar illumination. The team of authors has tried several approaches to solving this problem. The first step was to fit the camera lens with an Edmund Optics interference filter with a transmission frequency of 658 nm (corresponding to the nominal laser frequency) and a frequency window width of 10 nm. However, field testing has shown that the laser radiation frequency is unstable and varies significantly with temperature. Therefore, despite the obvious decrease in the noise level in the scanner video signal, some time after the start of operation the laser radiation spectrum leaves the transparency interval of the interference filter, and the image contrast drops dramatically; the recognition quality in this case turns out to be lower than in the complete absence of filtering.

The filter was replaced by a similar one with a wider transparency interval of 20 nm. This interval turned out to be sufficient for the laser radiation spectrum to remain inside of it over the entire operating temperature range. However, increasing the interval led to a considerable drop in filter efficiency. Based on the experimental data, it was concluded that optical filtering of the background illumination is ineffective and that an algorithmic approach in needed.

As mentioned above, the main problem of recognizing a highly noisy image is the extremely high sensitivity to the initial proximity of the sets $M$ and $D$ when searching for a local optimum. If at the beginning of the analysis of a frame the algorithm does not have a rough convergence of the $M$ and $D$ sets, the result will probably be incorrect recognition (i.e. another local optimum). In other words, to ensure a reliable and accurate determination of the rail head against the background of noise, the algorithm must have a priori information about the approximate position of the profile on the camera matrix.

The first attempt to obtain the initial (rough) value of the transformation vector for each frame was the assumption that the scanner movement in relation to the rail track is small. Thus, the results of processing the previous frame were used as the initial approximation of the profile search on the frame. When analyzing the data recorded during the system’s test drive, this approach showed its ineptitude. First, at high speeds, the massive car bogie retains its position relative to the center line of the track, being unable to bend around the local alignment of the rails; as a result, the position of the image on the camera sensor varies significantly from frame to frame. Secondly, in case of short-term losses of the rail from the camera’s field of view (for example, due to vegetation caught between the scanner and the rail), the rail manages to leave the admissible vicinity of the previous coordinates, which leads to the non-detection of the profile. An attempt to increase the search neighborhood dramatically decreases efficiency and leads to false recognitions.

The most convenient way to obtain a priori data on the position of the profile on the scanner camera’s matrix, in our opinion, is the use of GIS [7] which stores information about the previous diagnostic passes of the track measuring car. The proposed approach is illustrated in figure 4. The developed system can use GIS both for correcting the inertial navigation loop and for using a priori data about the track’s croslevel and gauge in the current section, in order to calculate the expected position of the rails relative to the scanner (and hence the profile’s position on the camera’s matrix) on their basis, using the current orientation parameters (data from SINS).

If GIS is unavailable, it is possible to use other methods of obtaining a preliminary estimate of the rail profile coordinates:

- Some track-measuring cars [20] are equipped with a ropes-and-pulleys system for measuring the relative position of the bogie and the car’s body, which consists of four ultrasonic linear displacement sensors connected with the axle boxes by a system of pulleys and steel cables. Although it is shown in [21] that such systems are not entirely adequate for metrological tasks (such as obtaining high-precision geometric parameters of the track), its accuracy is sufficient for an approximate estimate of the vertical position of the bogie (and hence the scanners) relative to the wheelsets (and hence and rail threads).
• In [21], a more promising method for measuring the position of the bogie relative to the car’s body was proposed, based on the parallax effect. The system described in that work consists of three CMOS cameras and three semiconductor lasers, which are used as reference marks. The system has numerous advantages over the ropes-and-pulleys system, including absence of inertia, absence of mechanical restrictions on the bogie’s rotation range, full determination of all six coordinates of the bogie (instead of just four for the ropes-and-pulleys system), etc. [22].

Figure 4. General view of the algorithm for processing scanner readings.

5. Experimental research
To test a number of proposed solutions, a prototype of the system was constructed. Scanners and SINS were installed on a rigid bearing beam. To keep the optical elements of the system clean, a pneumohydraulic cleaning system has been developed. Keeping the scanner’s temperature within the permissible range was ensured by the use of protective casings equipped with an electric heating
system and thermoresistive temperature sensors. Figure 5 shows the general view of the beam with an installed SINS and two scanners in protective covers with connected hoses of the cleaning system.

**Figure 5.** Appearance of the system prototype.

The working prototype was installed on a specially designed hand trolley equipped with a track sensor and a holder for equipment installation, as well as a laptop acting as an on-board data processor. With the help of this trolley, a series of sequential diagnostic passes along the same railway line was carried out, which made it possible to assess the repeatability of the measurement results. The results of the passes exemplified by the rail track’s crosslevel are shown in figure 6.

**Figure 6.** Field test results (crosslevel); blue line shows the “forward” measurement pass, red and green – the “backward” pass.

It can be seen that without the use of odometer correction, measurement repeatability is mediocre due to the track coordinate error. Gauge repeatability was 4.2 mm, alignment – 5.6 mm, crosslevel – 3.8 mm. In work [18] it is shown that the use of odometer correction algorithms allows obtaining repeatability between passages within the requirements of the EN 13848 standard.

### 6. Equivalent conicity

The last (and somewhat different) defined path parameter is the equivalent conicity. On Russian Railways this parameter is not standardized by any rigid instructions; therefore, when determining it, international documents are usually adhered to [3]. The need to determine the equivalent conicity is caused by the desire to know how stable the movement of known types of cars will be on the controlled section of the rail track. When determining this parameter, the profiles of the rail heads and the nominal (for Russian Railways – in accordance with GOST 10791-2011) profiles of the wheels of cars and locomotives are used. Formally, this value is given as

\[
t\sin(\gamma_e) = \frac{2x}{\Delta R},
\]

where \(\gamma_e\) is the equivalent conicity; \(2x\) is the range of oscillations possible within the track section; \(\Delta R\) is the difference between the radii of the wheels’ rolling circles of one wheel pair [23].

According to international standards, the equivalent conicity should not exceed 0.3 at speeds up to 250 kmph [3]. If these values are exceeded, the wheel’s flange can run over the side edge of the rail, which poses a threat of not only passengers’ discomfort, but also of the wheels leaving the rail track.

It should be noted, however, that the current approach to estimating this parameter considers the passage of a theoretical railcar with theoretical wheels, without taking into account the real dynamics...
of interaction. Therefore, authors consider it promising to use additional measurement systems based on inertial sensors installed directly on wheelsets [14], [15], to control these very dynamics – in other words, to migrate from the assessment of an intermediate parameter, indirectly indicative of the degree of bogie’s vibrations in the track, to direct control of these vibrations themselves.

7. Conclusion

Present work illustrates some of the problems that arise during creation of embedded systems for railway track diagnostics. To ensure the possibility of their installation on regularly running railway trains, such systems should boast small size, low (relative to traditional solutions) cost of installation and operation, and an increased degree of autonomy. As a result, it’s impossible to create them within the framework of existing concepts, so new structural, methodological and software-algorithmic solutions should be used.

The approach proposed by the team of authors is to migrate from using three measuring sections to using just one. That introduced additional requirements for the system design (installation of scanners and SINS on a single rigid foundation) and a change of the calculation methods for some parameters (alignment and profile). For this reason, it became necessary to analyze the influence of the errors of individual measurement instruments on the accuracy of monitoring the desired railway parameters. This analysis resulted in the requirements for the sensors used in the implementation of the proposed concept.

Consideration of the issues of extracting the rail head profile in the scanner’s video signal is a necessary step while designing measuring systems of such kind. Despite the obvious advantages of migrating from contact to non-contact means of monitoring the rail track geometry, some difficulties arise. In particular, weather conditions begin to influence measurement results to a greater extent. Current work presents the sequence of actions of the team of authors to solve the problem of combating solar illumination. Recommendations are given on the use of analytical filtering of images in addition to the use of interference filters.

The paper analyzes the options for solving the problem of recognizing the profiles received from the scanner. Based on the analysis carried out, it can be concluded that it is inexpedient to use algorithms that search for the global optimum, due to increased computational costs and therefore impossibility of their real-time implementation. Algorithms for finding the local optimum turn out to be extremely sensitive to the initial approximation of the rail profile’s position on the image. Various ways of solving this problem are presented, both using additional meters (ropes-and-pulleys or optical system for measuring the relative position of the railcar’s structural elements), and with joint use of SINS readings and a priori data from GIS to predict the expected position of the rail on the image.

Both design and algorithmic solutions proposed in the article have been tested. During the experiments, the possibility of using algorithmic filtering of images was confirmed, and the main railway geometric parameters were obtained. Repeatability of the measurement results was 4.2 mm for gauge, 5.6 mm for alignment and 3.8 mm for crosslevel, which once again demonstrated the need to correct the odometer readings during fusion of data acquired on several measurement passes. After carrying out such a procedure, the repeatability from passage to passage became satisfactory by the EN 13848 standard’s requirements.

It should be noted separately that images of the inner surface of the rail head can also be used to control such parameter as the equivalent conicity. This parameter is the result of the analysis of possible movements of an “ideal” wheel of railcar along a real rail in each of its sections. The team of authors has put forward an assumption that it should be useful for this to use additional systems based on inertial sensors installed directly on the wheelsets. Such approach should make it possible to directly control the dynamics of the bogie’s movement in the track, instead of indirectly assessing it.

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