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COMPUTER VISION TECHNOLOGIES IN CONTROLLING THE ELECTRIC DRIVE OF RAILWAY TRANSPORT

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Resume

Analysis of statistical data on accidents on railways shows that most often an accident occurs due to the influence of the human factor, obstacles on the track, curvature of the track, the phenomenon of skidding and slipping in dynamic modes. The novelty of the proposed work consists in development of a mathematical model and a study of the automatic speed control, depending on the curvature of the track or in the presence of obstacles, and track defects, as well as measuring the linear speed of the railway transport as one of the main elements of the slip protection system and the system for implementing the maximum traction force. The solution of these problems is possible with the help of a multipurpose sensor, which is a video camera, to form the feedback signals to the control system.

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1 Introduction

Rail vehicles include electric locomotives, diesel locomotives, commuter trains and metro trains, trams, mine electric locomotives and other types of mechanisms for moving along a rail track. These modes of transport carry out the main transportation in most industrialized countries. One of the main elements of the railway transport, which determines its most important technical and economic indicators, is the traction electric drive.

A modern traction electric drive is often built based on the "frequency converter - asynchronous motor" system. Such an electric drive, using intelligent control systems and computer vision technologies, makes it possible to increase the level of automation and traffic safety in accordance with the international standard IEC-62267 and, in some cases, eliminate the human factor leading to emergency situations. Analysis of statistical data on accidents on railways shows that most often an accident occurs due to the influence of the human factor, obstacles on the track, curvature of the track, the phenomenon of skidding and slipping in dynamic modes [1].

This raises the problem of automatic speed control depending on the curvature of the track or in the presence of obstacles, track defects, as well as measuring the linear speed of the railway transport as one of the main elements of the skid protection system and the system for implementing the maximum traction force [2].

The solution of these problems is possible with help of a multi-purpose sensor, which is a video camera to form the feedback signals to control system.

2 Literature review

Over the past decade, several researchers have made significant advances in artificial intelligence applications in railway systems. A variety of review papers have been published [3] in the literature that explore the utilization of artificial intelligence in railway systems. However, all of these publications only focused on a specific aspect of the combination of AI and railway sub-domains [4].

Maintenance and inspection - The field of Maintenance and Inspection is predominantly influenced by Machine Learning, which is the most engaged AI technology. Traditional machine learning methods, such as Support Vector Machines (SVM), Decision Trees (DT),

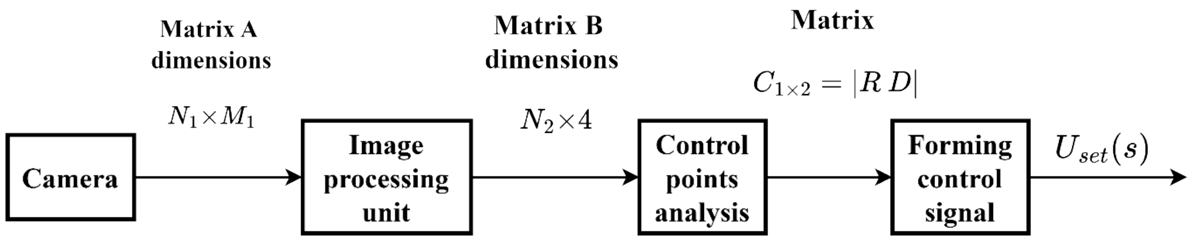


Figure 1 *Functional scheme of the image processing channel*

regression algorithms, and Artificial Neural Networks (ANN), have shown significant use in processing tabular datasets, particularly those that are labeled. In addition to the techniques previously mentioned, other approaches like the Big Data, Data Mining, and Pattern Recognition have been utilized in the realms of Fault Detection, Fault Diagnosis, and Failure Prediction. This integration has led to establishment of the decision support systems that enable the dynamic scheduling of maintenance and inspection tasks for railway tracks.

Safety and security - Hazardous events occur unpredictably, each possessing distinct spatial and temporal characteristics, which complicates the assessment of their potential consequences. The task of quantitatively identifying clusters of danger presents significant challenges for traditional machine learning algorithms, such as supervised learning models, as well as data mining techniques. This difficulty is exacerbated by the substantial disparity in sample sizes across various risk levels, where instances of low-risk events vastly outnumber those associated with severe hazards. Consequently, the less sophisticated models may fail to detect the latter. In the future, a synergistic approach that combines rule-based and case-based reasoning systems may enhance the decision-making capabilities regarding the allocation of safety resources. Furthermore, computer vision and image processing, characterized by their high degree of automation and robust detection accuracy in the real-world scenarios, have made considerable strides in the identification and analysis of environmental anomalies, as evidenced by the works of [5]. These methodologies typically leverage cloud-based information for comprehensive analysis.

Autonomous driving and control - The fusion of artificial intelligence with autonomous driving and control mechanisms has exhibited considerable potential, particularly in the realm of reinforcement learning [6]. Up to this point, researchers have largely demonstrated the effectiveness of vehicle control algorithms through theoretical simulations that combine real-world infrastructure with idealized characteristics of electrical traction motors. However, the actual conditions under which the trains operate are affected by numerous factors, including the deterioration of rail and wheel contacts, climatic variations, and unforeseen interruptions. Therefore, the existing theoretical simulations cannot be directly compared to practical real-world evaluations, which may lead to doubts about their applicability in genuine environments. An exception to this pattern is the paper [7] that utilizes Approximate Dynamic Programming, which introduces stochastic variations in both traction force and train resistance.

Traffic planning and management - The application of machine learning in optimization solutions may offer a hopeful trajectory for future advancements, combining the benefits of both exact and evolutionary methodologies. Conventional ML models (e.g., Regression Trees, RL algorithms), as an addition to the Bio-inspired algorithms. These algorithms have proven to be highly effective in addressing rescheduling challenges [8], the formulation of a schedule [9], and process of determining train paths [10-12].

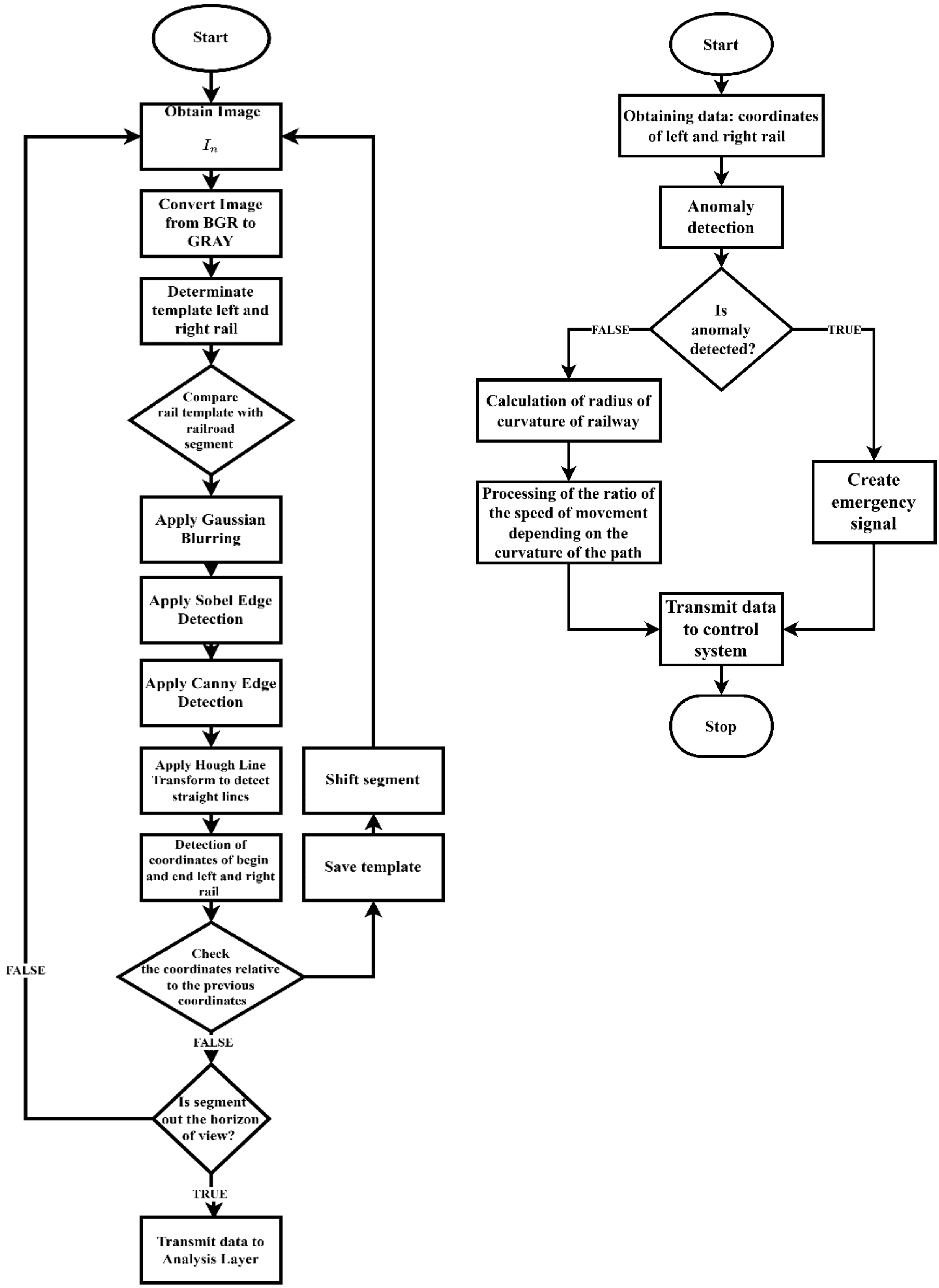
These four above domains are the main ones for consideration in scope of this articles; beyond this focus there is a *revenue management, transport policy and passenger mobility*, as well.

3 Description of image processing algorithms

A universal sensor with wide technical capabilities is a video camera. The information coming from it is processed using special algorithms. Such a technology in obtaining and processing information is called computer vision (CV) technology [13].

In accordance with this technology, a video camera is installed on the driver's cab. The image from the camera is processed in the sequence, which is explained by the functional diagram shown in Figure 1.

In this diagram, the camera forms a video stream, which is fed to the image processing unit frame by frame. To represent the frame, a matrix is used, the dimensions of which correspond to the height and width of the frame. Values depend on the camera setting. At the output of the image processing unit, matrix B is formed, the size of the columns of which correspond to the coordinates of the left and right rails, respectively. The size of rows N_2 is equal to the number of control points; it depends on the range view at the railway road that is limitaed by the horizon. Values of coordinates change with step approximation 0.3 m. Four columns of matrix B contain values of coordinates of control points that represent the geometry of railway road: $X_{left\ rail}\ Y_{right\ rail}\ X_{right\ rail}\ Y_{right\ rail}$. Values of these coordinates are represented by the pixels coordinates. To convert the coordinates from pixels' coordinates to C_i systems, the calibration value was applied, which was calculated from geometry of the railway transport: height and width of the train and the railway road geometrical parameters. The block for analyzing the obtained control points forms a matrix C, which stores two values of R and D. The value R is the radius of curvature of the rail;



(a) (b)

Figure 2 *The image processing algorithm (a); the algorithm for measuring the path curvature and identifying defects (b)*

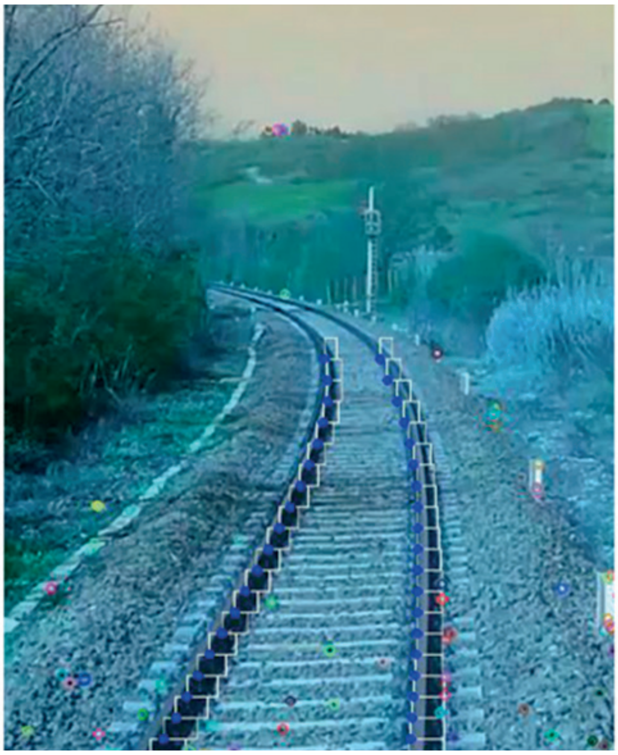


Figure 3 *Video frame showing control points*

D is equal to the defect code on the railway. The defect code is equal to 1 if a defect was detected, otherwise, the code is zero. The output device generates a speed set signal.

When processing the images, the open-source library of computer vision algorithms OpenCV is used [14]. The image processing algorithm is shown in Figure 2(a) and the algorithm for measuring the path curvature and identifying defects is shown in Figure 2(b).

The curve detection method, being the most traditional approach, involves pre-inputting the curve's position and curvature into a lookup table for subsequent use. For implementation of this method in vehicle control, it is imperative to accurately identify the curve's starting and ending points, as well as its position along the route. Whenever there is a change in the operating track, the curve data for the new track must be updated in the lookup table and employed accordingly. Any misjudgment in detecting the curve's position, while the vehicle is in motion, could potentially have adverse implications on both the safety and control of the vehicle. An internal measurement system, incorporating gyro sensors, acceleration sensors, and speed sensors, allows for the real-time measurements, while the vehicle is operational, enhancing accuracy and responsiveness. Nevertheless, this method is not without its drawbacks, as it is prone to offset errors stemming from the integration process within the curve extraction algorithm, and susceptible to variations in the vehicle's speed, which can impact its overall performance.

The performance of the algorithms was tested using mathematical modelling. For the numerical experiment, the ready-made video streams of the movement of rail vehicles in the presence of track curvature and track defects, are used. A frame of the finished video image with visualization of control points is shown in Figure 3. The blue dots positioned along the left and right rails serve as visual representations of control points, which are denoted by Matrix B in the diagram of the image processing channel. The white rectangles illustrate the segments of the rails, which are derived from the calculations of the control points.

4 Mathematical modelling of automatic speed control system depending on the path curvature

Mathematical model, in the form of a block diagram AC electric drive of the mainline electric locomotive DS3 [15], was compiled using generally accepted assumptions. In this case, the motor and converter are represented by aperiodic links, the clutch characteristic is approximated piecewise linearly. The model contains a neuroregulator that eliminates frictional self-oscillations that can occur in dynamic modes [16]. The block diagram has an additional speed control loop using an image channel from a video camera. Figure 4 shows the block diagram of the electric drive and the result of calculating the automatic speed reduction in the presence of path curvature.

Curves showing the railroad profile that are used for the simulation of the dynamics in the traction system are demonstrated in Figure 5. This test railroad profile

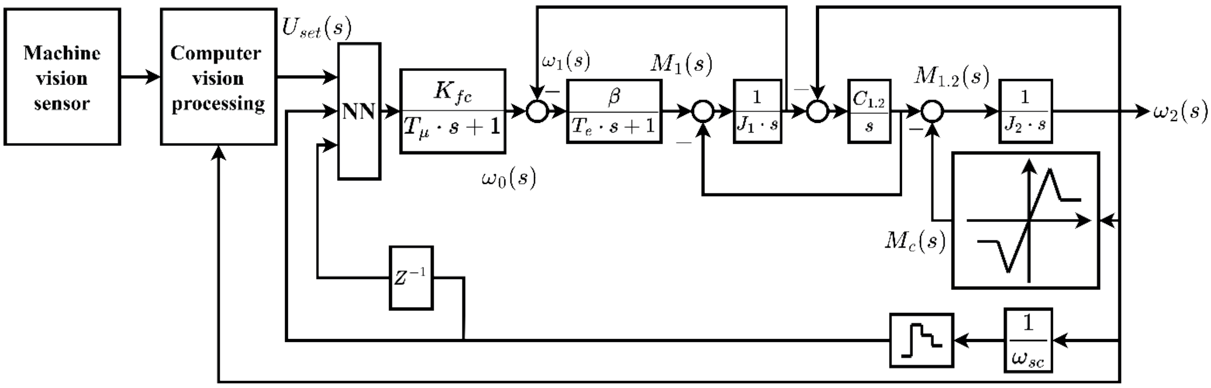


Figure 4 *Block diagram of traction AC electric drive DS3 locomotion*

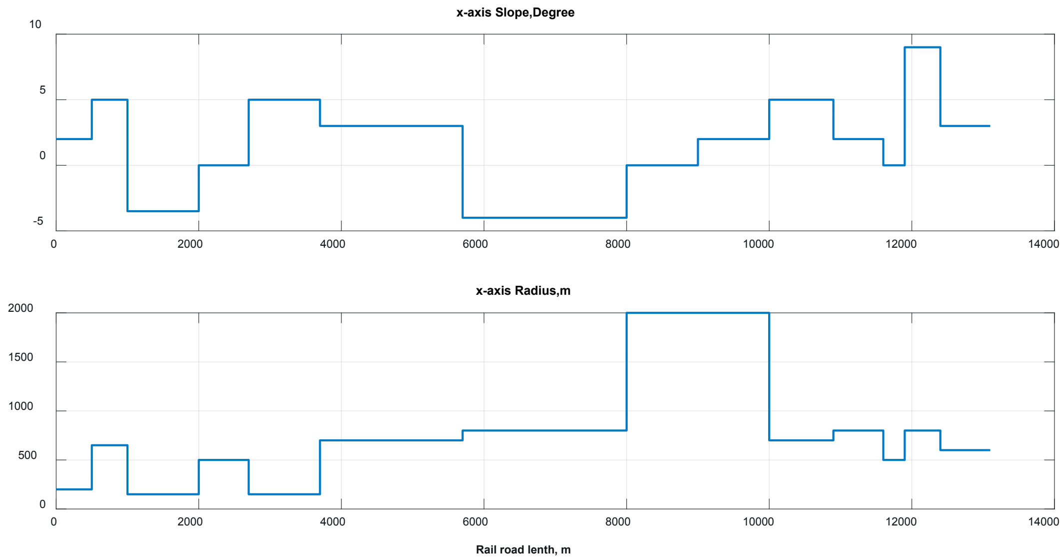


Figure 5 *Railroad profile for simulation load of traction system during moving*

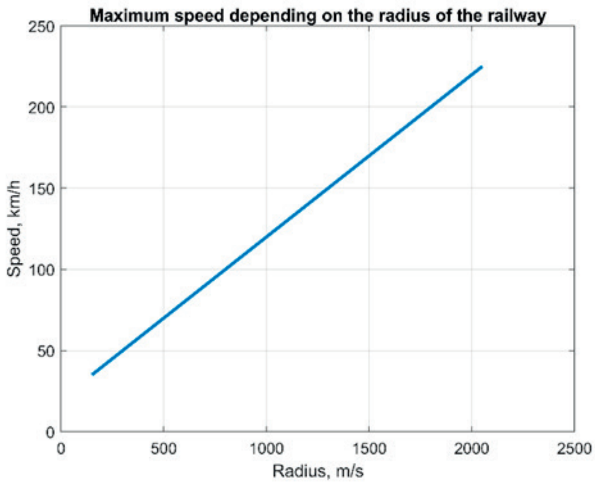


Figure 6 *Railroad profile for simulation load of traction system during moving*

contains combination of real world of railway parts and artificial parts that includes the emergency cases. Based on this profile the simulation model calculates resistance forces, that effect the traction system of the electrical locomotive DS3.

Integration of output signals from the image processing algorithms, in the chain of control railway traction system for simulation model is an issue of time of performance at this model and high load of processing data. To solve this issue, it was decided to get the time performance of image processing algorithms and substitute this block on a pure delay link. The

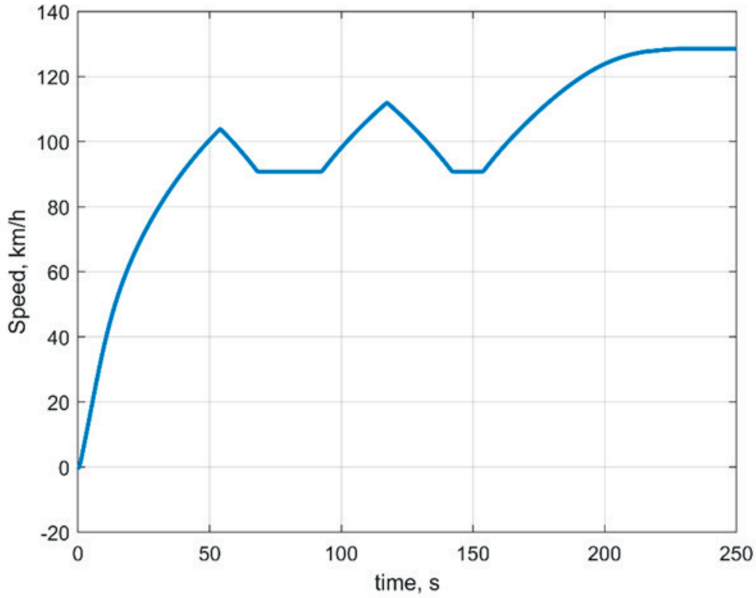


Figure 7 *Graph of automatic reduction of speed in the presence of path curvature*

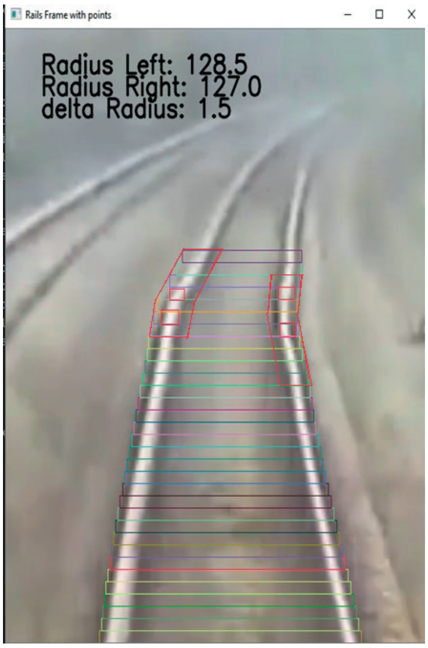


Figure 8 *Image of a rail track with a defect*

dependence of the speed on the radius of the railroad section is shown in Figure 6. These requirements were implemented in the simulation model as automation speed control depends on curvature.

Results of modelling the dynamical modes of traction electric drive with feedback from the video processing unit, are shown in Figure 7.

Similar calculations were performed for the AC electric drive of the T6B5 city tram. The tram moves along a path that has a defect due to thermal shift, as shown in Figure 8.

Passing such a defect at speed results in the tram derailing. The use of computer vision technologies allows to eliminate the human factor, slow down to a stop and thereby avoid an accident. The simulation of the electric drive of a city tram was performed using Simulink/ Matlab models [2], one of which is shown in Figure 9. The results of modelling and processing track defect detection system using computer vision are shown in Figure 10.

5 Algorithm for measuring the linear speed

For rail vehicles, measuring the linear speed makes it possible to solve the problem of protection against slipping and skidding, which, in turn, increases the traffic safety and reduces wasteful energy losses.

The use of radars, ultrasonic or inertial sensors significantly complicates the system and does not always

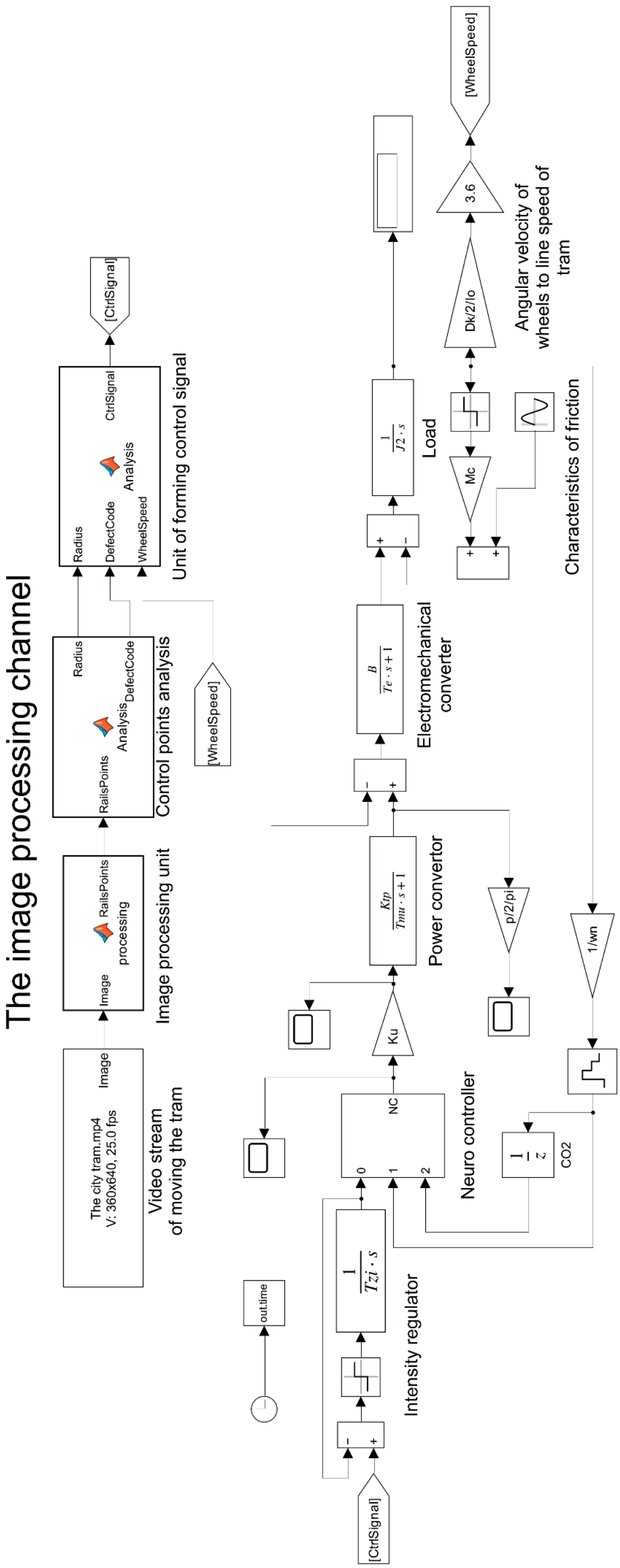


***Figure 9** Simulation model of AC electric drive of the T6B5 city tram with image processing channel*

provide the specified speed measurement accuracy, especially in the low-speed range.

Measuring the linear speed using a video camera is based on identifying the spatio-temporal differences in the sequence of images, identifying such functions that will differ when moving from one image to another. There is a number of analysis methods and algorithms for processing the optical flow from a video camera [17]. The Lucas-Canade algorithm is preferable because it works in real time, is insensitive to noise, and has sufficient accuracy [18].

The use of computer vision technologies makes it possible to measure the linear speed of rail vehicles. Determining the linear speed using the angular velocity

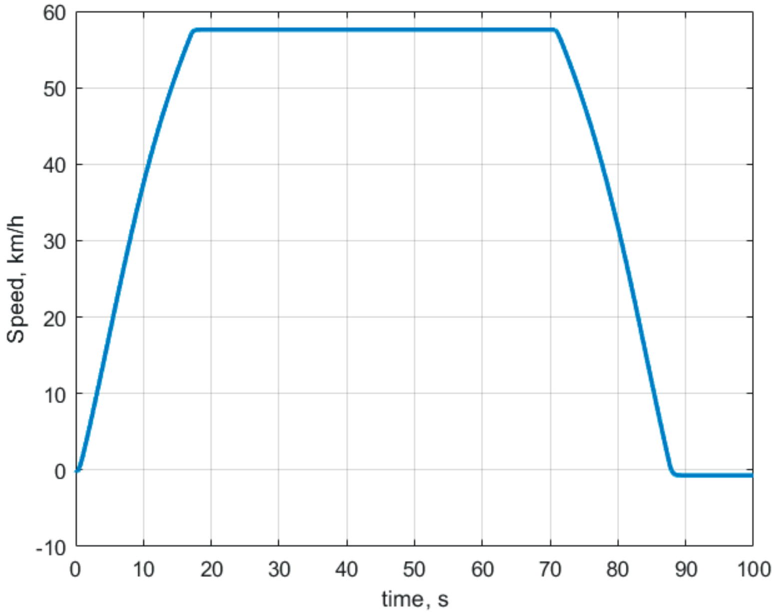


Figure 10 *Results of modelling a system with automatic speed control when a defect is detected*

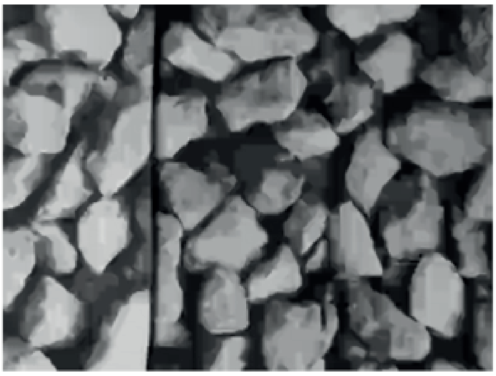


Figure 11 *Original images that simulate the surface over which the rail transport moves*

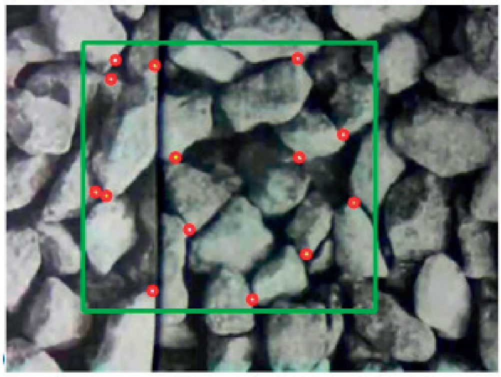


Figure 12 *Visualization of optical flow to obtain good features to be tracked*

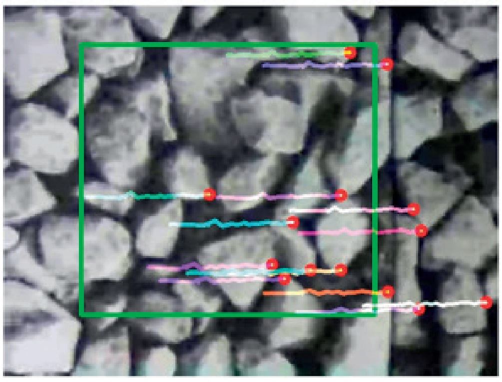


Figure 13 *Visualization of the movement of characteristic points in 50 frames*

sensors requires a wheel unit not connected to the traction motor, which is not possible in most practical cases. The use of radars, ultrasonic or inertial sensors significantly complicates the system and does not always provide the specified speed measurement accuracy, especially in the low-speed range.

Here $I_i(x, y, t)$ is a grayscale image at time t, with coordinates x, y, while $I_{i+1}(x+\Delta x, y+\Delta y, t+\Delta t)$ is the image at time, $t+\Delta t$, with coordinates $x+\Delta x, y+\Delta y$. Over time Δt the video camera has moved a distance d, which will lead to a shift in the characteristic points, as shown in Figures 11, 12, and 13.

The Kanade-Lucas optical flow algorithm is used because it is robust, accurate, insensitive to noise and non-uniform light intensity sources, and suitable for the real-time computation. In this method, let I_i be the greyscale image at time t_i and I_{i+1} be the greyscale image at time t_{i+1}. During this time interval, let the image be translated by distance = $(\Delta x, \Delta y)$, if A is a feature window in I_i and B be the same feature window in I_{i+1} as shown in Figure 14.

Then, the objective is to find d by minimizing the residual function $\in(d)$:

$$\in(d) = \iint_w (I_i(p) - I_{i+1}(p+d))^2 dxdy, \tag{1}$$

where: P_0 = the pixel coordinate of a generic image point. The upper left corner pixel coordinate is (0,0) and the lower right corner pixel coordinate base line skip is $n_x - 1$, $n_y - 1$ where n_x and n_y are the width and height of the image, respectively;
I_i and I_{i+1} are the greyscale values of the first image and the second image, respectively;
W is the feature window area, of size equal to $(w_x - 1, w_y - 1)$;
$d = (\Delta x, \Delta y)$ is the optical flow output or distance between features of two subsequent image frames.

In practice, the solution of minimizing can be achieved by using an iterative algorithm like the Newton-Raphson method.

6 Experimental measurements of the linear velocity at a test rig

The experimental setup consists of a moving carriage to which is attached a camera driven by a stepper motor. The motor drives a belt attached to the carriage and moves the camera at a controlled speed, as shown in Figure 15. The actual speed of the carriage is calculated from the known distance and time of movement of the carriage. The camera is an IMX219 module with an 8-megapixel sensor and has an extended field of view of 160 degrees, as shown in Figure 16. The camera can be set to different frame rates for certain frame sizes; at higher frame rates, the frame size that can be captured decreases, and vice versa. The maximum frame rate is 90 frames per second with an image size of 640 x 480 pixels.

The actual speed of the carriage is calculated from the known distance and time of movement of the carriage. Linear velocity calculations are based on the basic camera view, which is shown in Figure 17.

The obtained coordinates of characteristic points and their time changes, taking into account the camera model, allows to obtain equations for finding real coordinates, as:

$$X = Z_c \cdot \frac{x}{f}, \tag{2}$$

$$Y = Z_c \cdot \frac{y}{f}, \tag{3}$$

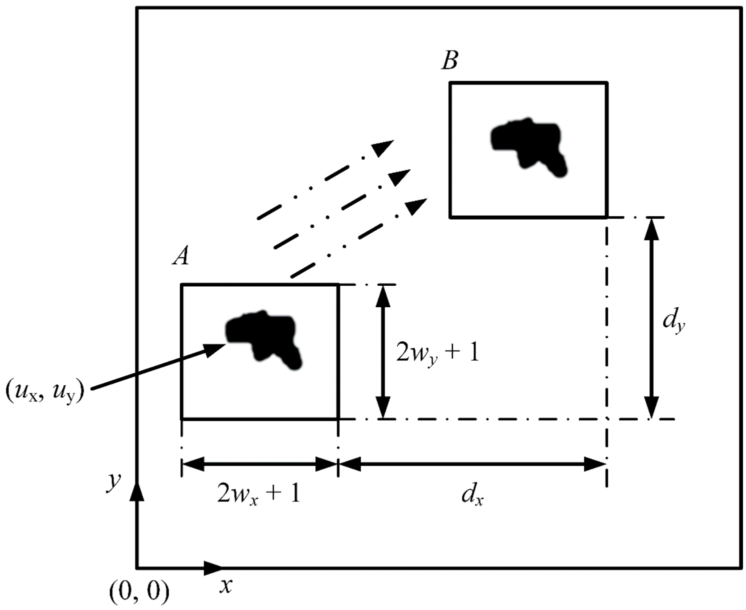


Figure 14 *Optical flow features and flow field*

where: Z_c is the real distance between the center of the camera sensor and the surface over which the camera is moving;
f is the focal length;
x, y is coordinates of characteristic points on the image;
X, Y is coordinates of the characteristic point in real space relative to the projection of the camera center onto the plane.

Calculation of the speed of movement of a characteristic point in pixels in the image is shown in the formula:

$$v_x = \Delta x \cdot \frac{1}{F}, \quad (4)$$

$$v_y = \Delta y \cdot \frac{1}{F}, \quad (5)$$

where $\Delta x, \Delta y$ - feature point displacement, calculated by the optical flow algorithm, F = frame rate per second (FPS), determines the time during which the characteristic point has shifted on the optical flow value.

The experimental setup allows to neglect the speed along the Z axis. Due to the rigid attachment of the camera to the carriage, and low movement speeds, which does not cause vertical vibrations, the surface was also assumed to be absolutely flat in the experiment. Based on the above listed assumptions and levels, the linear speed level was obtained.

Figure 18 shows the flow chart of algorithm to calculate the line speed based on optical flow.

The results of the experiment are shown in Table 1, where, V is the actual linear speed of the carriage obtained by calculation, V_{cv} is the linear speed of the carriage obtained using computer vision, Δ is the measurement error expressed as a percentage.

7 Conclusions

The camera is a multi-functional sensor that, together with the computer vision technology, allows to determine the movement parameters and makes it possible to respond to the environment in which the movement occurs.

Incorporating a video stream processing channel into the electric drive control system increases the

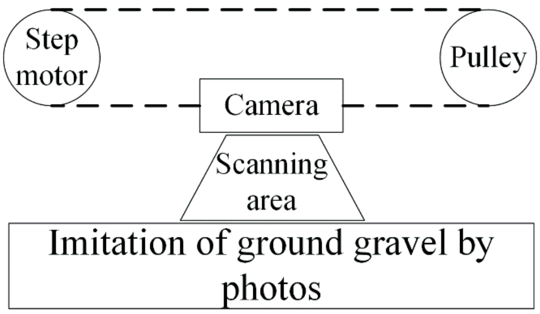


Figure 15 *Diagram of a test rig for measuring the linear speed*

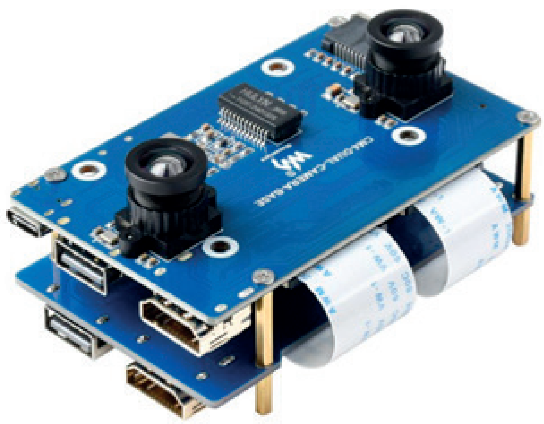


Figure 16 *Binocular camera board, designed for the Raspberry Pi 4 Compute Module*

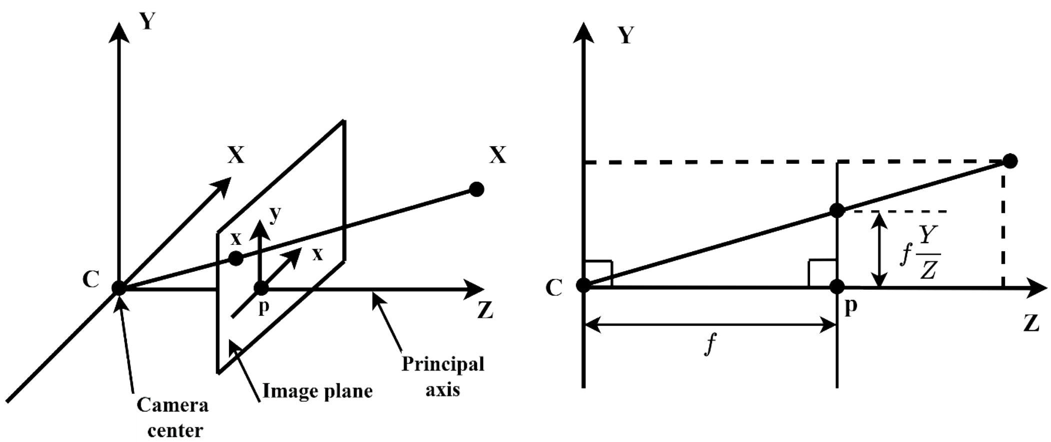


Figure 17 *Mathematical model of the camera*

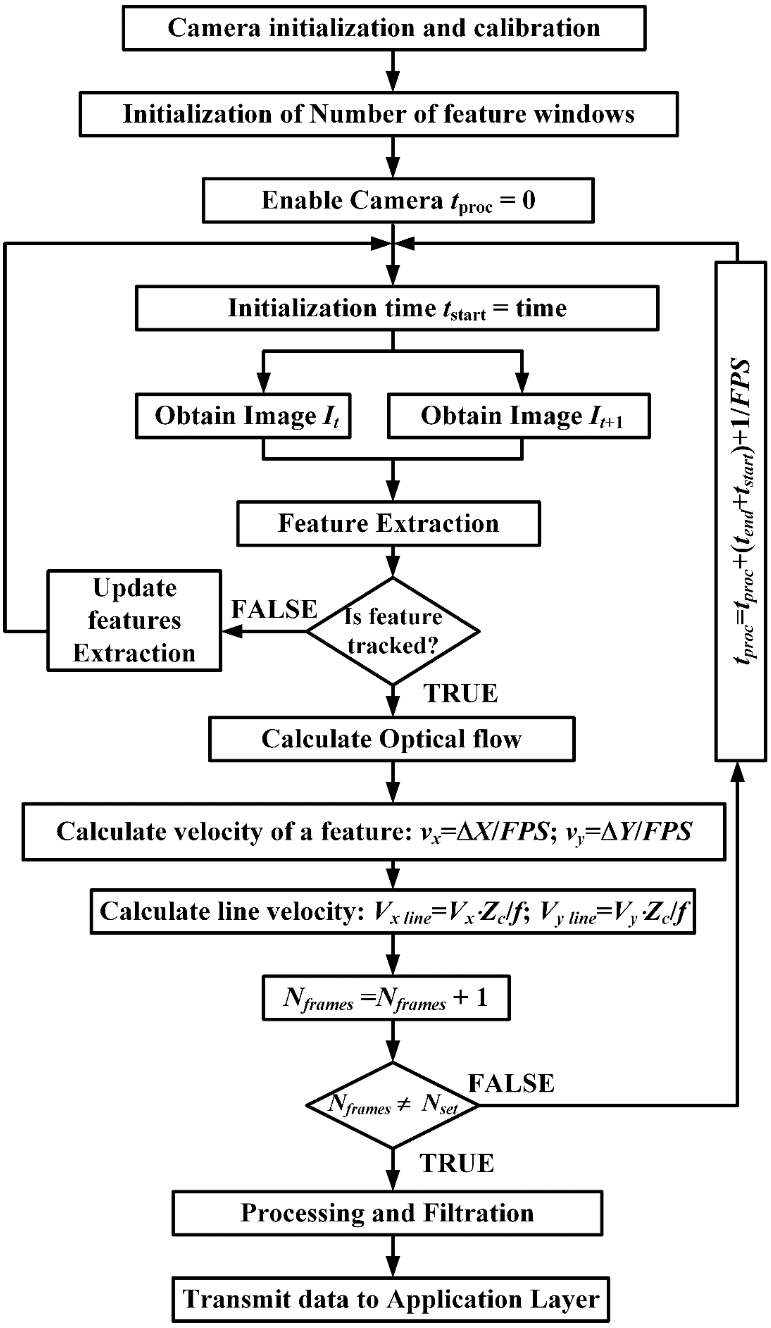


Figure 18 *Flowchart of optical flow-based speed calculation method*

Table 1 *Linear velocity values obtained by calculation and experiment*

No.	V, m/s	V_{cv}, m/s	Δ , %
1	0.15319	0.15097	1.449180756
2	0.19673	0.19399	1.392771819
3	0.24127	0.23854	1.131512413
4	0.28583	0.28163	1.469404891
5	0.32791	0.3238	1.253392699
6	0.37158	0.3664	1.394047042
7	0.41483	0.40811	1.619940699
8	0.45992	0.45188	1.74813011
9	0.50211	0.491	2.212662564

degree of automation and traffic safety of the rail vehicles.

Measuring the low linear speeds of rail vehicles, with an error not exceeding 2% makes it possible to determine the speed of excess sliding, and thereby develop a system for realizing the maximum traction force under adhesion conditions.

The current state of research is the fundamental base for integration to control system. During the conducted the experiments, the optimal hardware was chosen and the software was implemented. It combines a part the line speed measurements and the computer vision module of curvature estimation and defects detections.

In the future studies, the plan is to explore this platform using a stereo camera, which, in turn, will help improve the accuracy of measurements and expand the scope of application of this platform.

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Conflicts of interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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