TRAIN COMMAND AND CONTROL FOR COMMUTER AND URBAN LINES

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Contribution to the State of the Art

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Abstract: The paper presents the state of the art of command and control and the challenges faced by the Russian Railways (RZD), with a focus on the migration to new paradigms of train separation, train localization and obstacle detection. The authors give an overview of the practical results of some ongoing projects carried out with the direct involvement of NIIAS researchers and developers for the Moscow Central Circle (MCC) railway.

Keywords: RZD; Virtual block; Moving block; Hybrid system; ATO; GOA3/4; Driver assistance system (DAS); Self-driving (autonomous) trains; Artifical Neural Network (ANN); GNSS; Digital route map.

INTRODUCTION

Today, the key task for RZD is to increase the capacity with simultaneous migration to adaptive traffic planning and management.

The importance of this task is due to the surging competition presented by other modes of transport, as well as by the substantial growth of agglomerations that creates an even greater load for railways up to the point of depletion of the design capacity.

Solving the problem most importantly requires further automation of the traffic management systems based on real-time supervision, conflict identification and resolution using artificial intelligence and advanced simulation tools. It also necessitates the development and application of new train spacing models enabling migration from conventional principles based on fixed blocks with trackside signals to virtual blocks with no trackside signals. Such models are especially applicable to high-density commuter or urban lines. The same holds for the migration to self-driving trains.

Implementing the above approach involves such prerequisites as the availability of reliable wireless communication infrastructure, high-precision train localization, advanced trackside train detection and on-board obstacle detection systems. Safety and security considerations are also of great importance [1].

MIGRATION TO NEW TRAIN SPACING MODELS

According to UN data, 55% of the world's population now lives in urban areas, and by 2050 the proportion is expected to rise to 70%. That means that two thirds of the humanity will live in urban agglomerations creating unprecedented pressure on the urban transportation networks, including the railways.

Every year, RZD carries over a billion passengers, and the largest share is carried by suburban lines in large urban agglomerations like Moscow, whose transportation infrastructure is experiencing great pressure.

To address the situation, in September 2016, a new type of urban railway system called the Moscow Central Circle (MCC) was put into revenue operation. The MCC is a 54-km-long above-ground orbital metropolitan passenger railway line that is partially integrated with the metro. Today, the MCC carries over half a million passengers per day. The figures are expected to double by 2030, though the six years of operation show that this will probably happen much earlier.

In many ways, the MCC serves as a site for testing and validating new technologies to be later deployed on mainlines of the network. For instance, at the MCC, the virtual block principle is implemented using short (300 – 400 m) audio frequency track circuits (AFTC) and GLONASS / GPS-enabled ATP units. Audio frequency track circuits enable train separation with no trackside signals and dynamic headway management.

Normally, each virtual block section is composed of 3 or 4 track circuits (TC). The boundaries of the so-called "moving" block sections are not strictly referenced to trackside physical assets like signals or board markers. They rather "follow" the tail of the train to ensure a safe distance between two consecutive trains. The codes of two adjacent track circuits may be different as they are generated according to the distance to the tail of the train ahead or to the entry signals at stations. Thus, the virtual boundary of a block section may fall within any pair of track circuits, and the resolution of train spacing is defined by the length of a track circuit rather than by the length of a block section made up of several track circuits [2].

As of today, the headway at the MCC has been reduced from the original 6 minutes further down to 4 minutes in peak hours using a high-precision coordinate system and a high-precision digital route map with so-called virtual balises, i.e. reference points in the map (see Fig. 1).

The boundaries of track circuits are used as reference points for virtual balises. The positioning errors are corrected at the moment of code changing and travelling over TC boundaries (the number and length of each TC is known and stored in the on-board database). Code changing in TC boundaries is identified by the on-board unit (OBU) with the precision of about 1 m. Reference points in the route map can be also put within a TC for further reduction of the distance between following trains down to the length of a braking distance plus safety overlap [3].

MULTI-LAYER COMMAND AND CONTROL

The above principle can also be implemented as an extended hybrid version of ERTMS Level 3 using Radio Block Centre (RBC) and radio communication over the national signalling system (as a fall-back). That would help reduce the headway down to 2 minutes.

That will represent further evolution for the MCC in the years to come, with the installation of a Russian version of RBC (or route server) communicating with the modified OBU through GSM-R or LTE. Now, radio is used for driver – dispatcher voice communication, as well as for delivering schedule corrections to the on-board driver assistance system, or the on-board automated train operation unit (ATO) while the safe route logic is executed by the automatic block (AB) system that manages the open lines, as well as main tracks within the MCC stations.

The automated traffic management system (TMS) supervises traffic at the MCC and automatically identifies and resolves conflicts by calculating and executing an alternative schedule. Train posi-

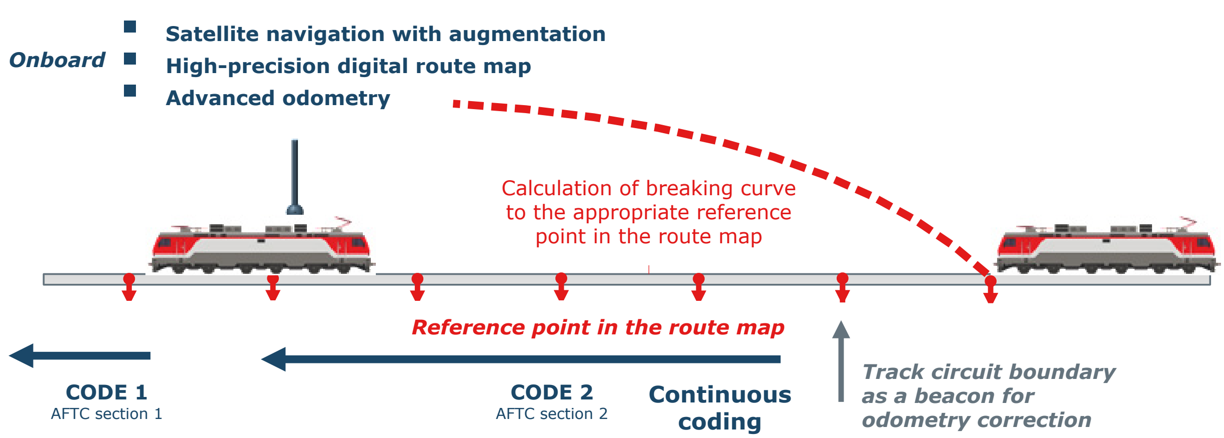

Fig. 1. Virtual block sections at the MCC

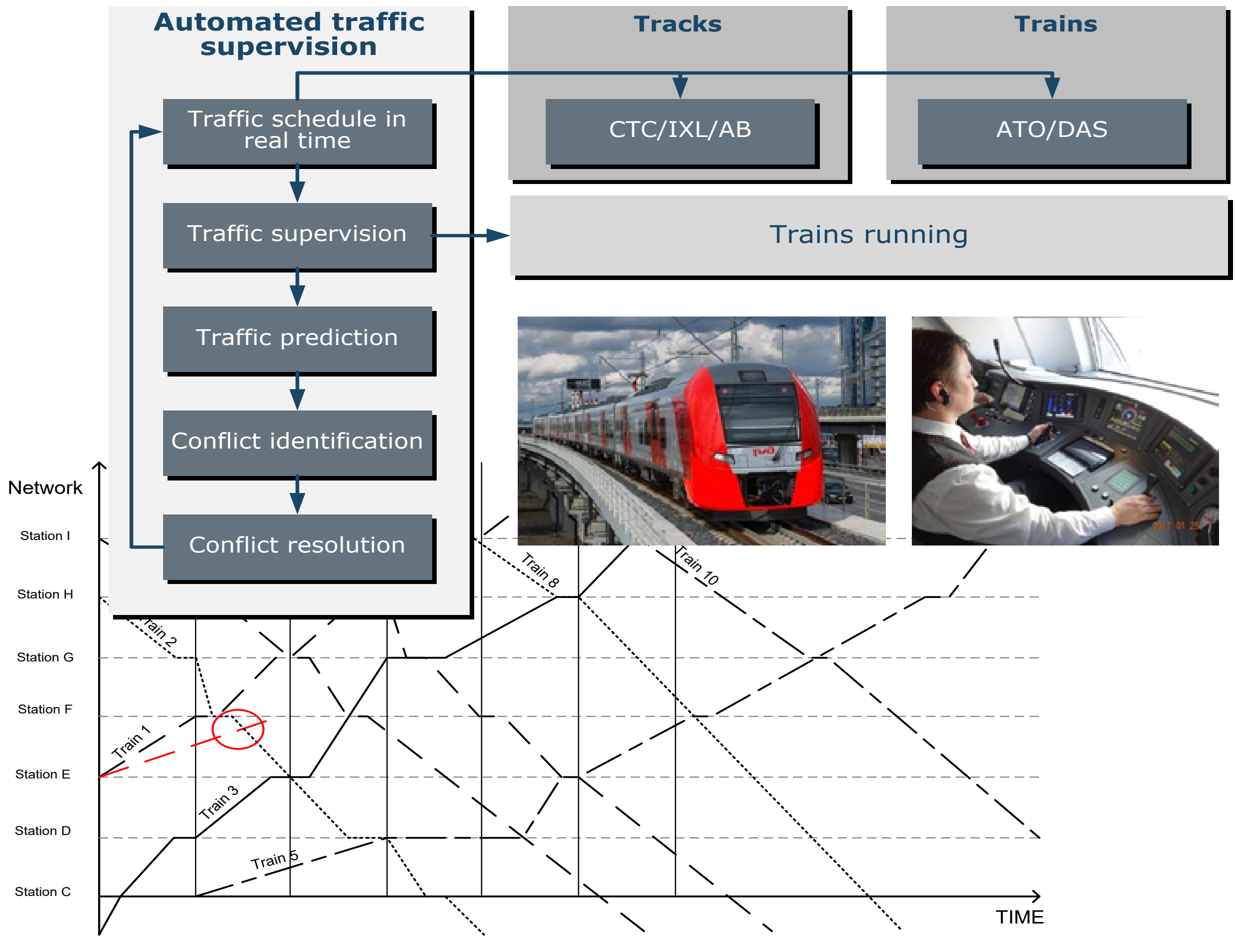

Fig. 2. Key TMS functionality

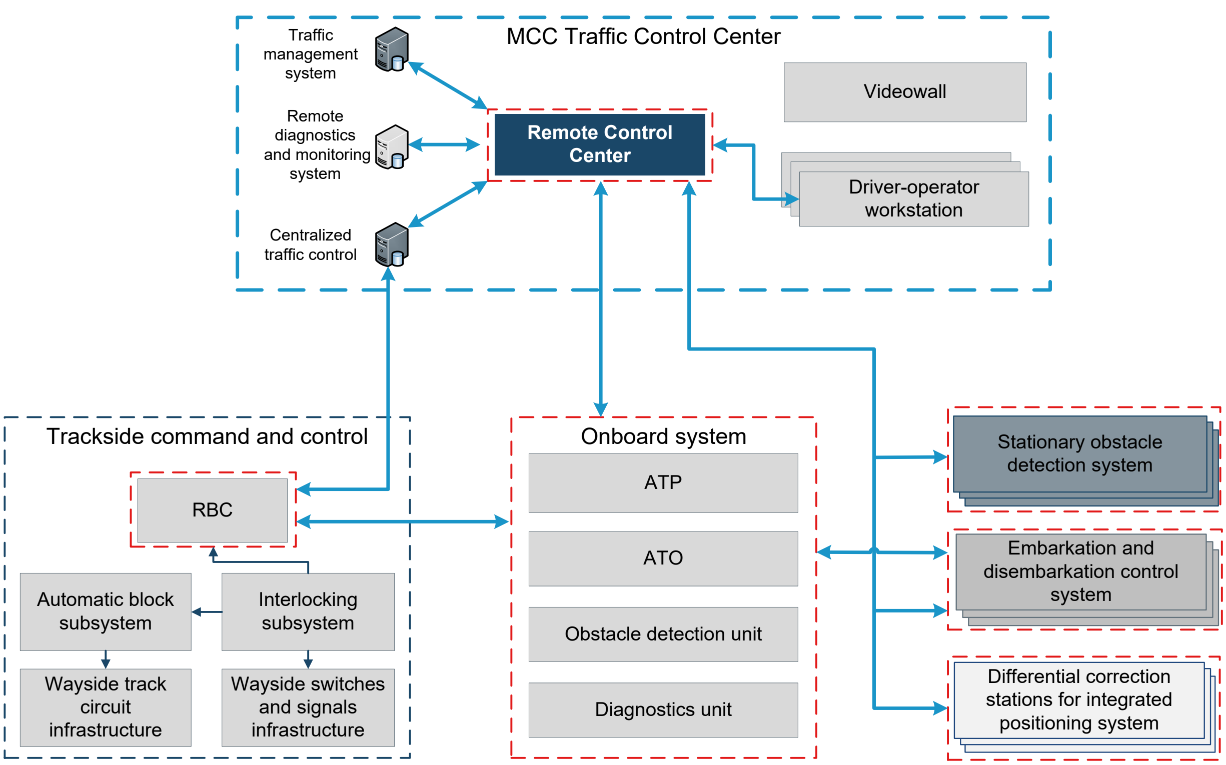

Fig. 3. Multi-layer command and control system with GoA3 / 4 functionality

tion and speed are supervised using GSM-R and an integrated localization system based on satellite navigation as part of the OBU. The TMS operation cycle is shown in Fig. 2.

Compared to subway systems where access to track is restricted and the boarding / alighting process is simplified by platform screen doors, urban railways have to resort to different solutions. Those include CCTV on platforms, trackside and on-board perception (automatic obstacle detection) subsystems used for protecting passengers on platforms, running trains, and people who may appear on the tracks.

Given the plan of putting self-driving EMUs in revenue operation at the MCC by the end of 2022, the general architecture of the MCC command and control is as follows (see Fig. 3):

Evidently, constructing safety models of such complex multi-loop transportation systems requires a comprehensive method. Such method must include systems analysis of unsafe scenarios along with the compilation of scenario library and formalization of a hazard model's description, pertaining to the boundaries of various control loops as well. The systems analysis may further result in the review and modification of the safety model of the transportation system under development and the conclusion regarding the requirement to include additional components into the model to perform the supervision and constraining function, e.g., by implementing a digital twin-based decision-making algorithm.

The introduction of perception (automatic obstacle detection) subsystems that use machine learning into the control loop significantly complicates the already challenging overall task of hazard analysis and safety evaluation of the multi-loop control system associated with the safety of people. The problem cannot be solved by means of the conventional FTA and FMEA hazard analysis methods only and requires a new comprehensive approach [4].

The MCC command and control system is designed as a multi-loop system that implies two control modes, i.e., autonomous and remote. In addition to the conventional track circuit-based train protection system, the control loop also supports radio communication between trackside and on-board train control and protection systems, as well as automatic obstacle detection by means of on-board and trackside perception modules that use ANNs and transmit relevant information to the remote control centre.

MIGRATION TO GOA3/4

Testing of automatic obstacle detection has been under way at the MCC for three years. The LTE network is used as part of remote train control to support the implementation of GoA3/4.

Currently, the Russian Railways is testing two types of trains equipped for GoA3/4. The trains are equipped with obstacle detection sensors and a unit for processing and communication with the remote control centre. The prototype trains are capable of automatic initiation of movement and braking in case of obstacle detection. However, during the testing, a driver is usually present in the cab and is always ready to take control. NIIAS's engineers also supervise the train's movement and monitor its systems in real time.

The first EMU was equipped in 2019 and is now used for data collection only. It is equipped with an infrared camera, LIDARs and eight optical cameras.

Based on the first test results, the second EMU was modified in late 2020 and is now used for testing a wide range of functions. The train is equipped with a new set of optical cameras, a LIDAR and infrared cameras with cleaning systems, short-distance ultrasonic sensors, an improved positioning system, pantograph and catenary monitoring cameras, as well as a boarding and alighting supervision system (Fig. 4).

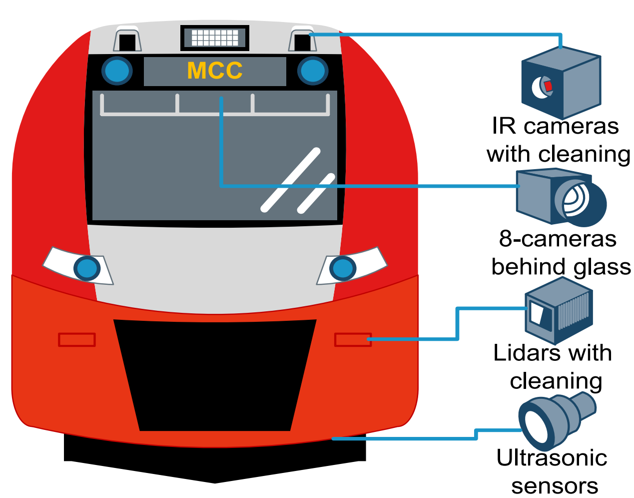

Figure 4. *MCC testing of autonomous EMU*

The trials primarily aim to test the four functions of the driverless system:

- detection of various classes of obstacles in varied weather and lighting conditions and on different infrastructure;
- remote train control;
- high-accuracy train positioning;
- video-based diagnostics of the pantograph and catenary.

Testing of the computer vision system's detection capabilities involves installing various obstacles ahead of the train, including human-like dummies. Up to 100 times a day, the modified EMU automatically detects dummies and stops before them in the morning, afternoon, evening and night lighting conditions, in a varied weather environment (Fig. 5).

The test results suggest promising opportunities of computer vision application. The calculated parameters show the system's superiority over a driver's eyes. For example, in daytime, the system detects a dummy at a distance of up to 600 m, while a person only sees it 400 to 500 m away. In night-time, both the system and the human driver recognize an obstacle from 250 to 300 m away; however, the on-board system has an advantage in the form of the infrared camera. In terms of the time of reaction to an obstacle, the average human performance is 1.3 sec, while the automated system's is 3 to 4 times better [5].

The multiple tests and the analysis of the sensors' efficiency in different conditions shows that there is no single perfect sensor, therefore the only possible solution is to combine data from various sensors using special algorithms, which allows eliminating the shortcomings of each individual sensor and combining their advantages, as well as supplementing them with information from other systems such as odometers, GNSS and on-board digital maps. The principal integrated solution is presented in Fig. 6.

Fig. 5. *Field testing of the prototype driverless train*

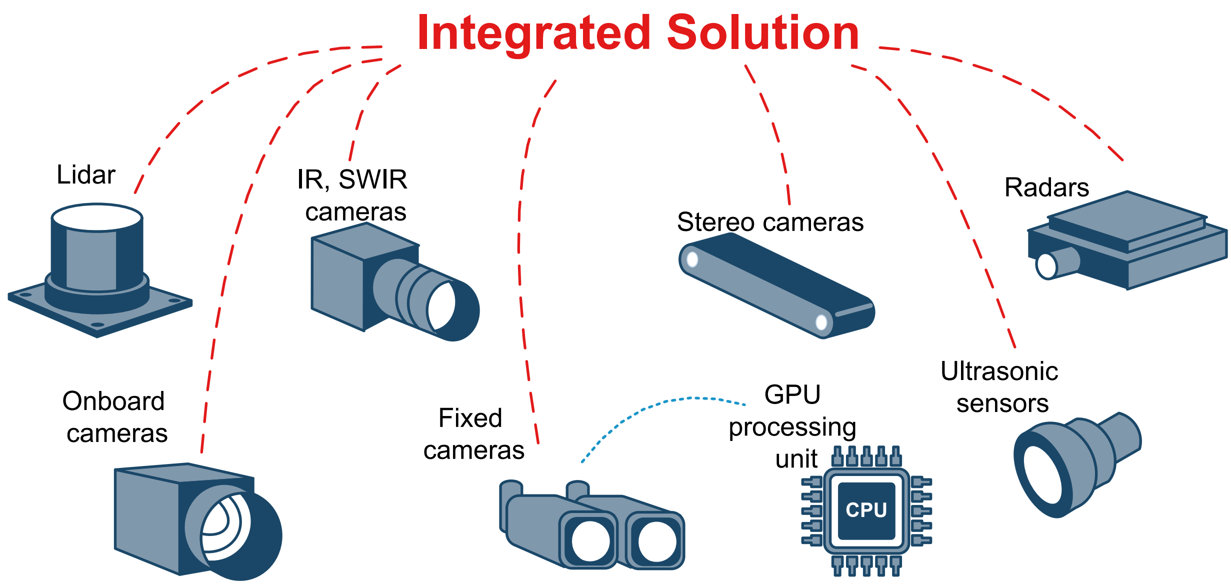

Fig. 6. Integrated solution with different sensor

Detection of obstacles on the track is done by combining signals from several sensors. For each obstacle, a set of features is determined, such as:

- Coordinates of the object,
- Speed of the object,
- Dimensions of the object,
- Object class,
- Probability of object existence.

Objects are classified using neural networks and a signal is to be given if there are people close to the track (less than 5.5 meters from the axis of the track). The speed of objects allows predicting their future positions.

To implement automatic train operation, the obstacle detection system that receives data from sensors must also perform high-level tasks such as recognition, segmentation and identification. Algorithms that use artificial intelligence (AI) to solve these problems are based on machine learning (deep learning in particular), which requires massive labelled datasets.

The usual pipeline for AI data processing includes generation of data, filtering and labelling. The labelled data can then be downloaded into databases for further analysis or be used for different applications like test procedures, AI training or simulation (see Fig. 8) [6].

A typical machine vision dataset is designed for supervised machine learning. In addition to the input data received from the sensors, the dataset contains the target output data. The creation of the correct target output, the so-called annotation or labelling, is usually done by humans.

The typical objects that are labelled on the data for railway applications include:

- people,

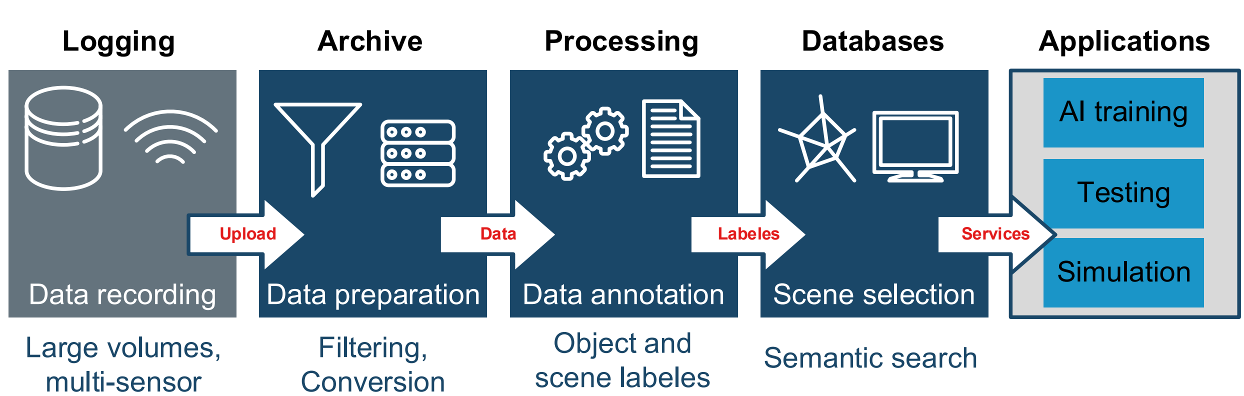

Fig. 8. Artificial intelligence data processing pipeline

- railway workers,
- animals,
- vehicles / machines,
- supports (poles),
- signs and signals (with the status),
- switches.

Data labelling for computer vision can be of several types. The easiest option is to assign a category to the image. Another method involves manually placing image primitives, such as 2D bounding boxes, polygons or 3D regions (cuboids). With semantic annotations (or pixel-wise annotations) each pixel in an image is put in a category usually indicated by a unique colour code [7].

The data annotation process is usually rather costly and laborious since it is done manually. Despite the growing interest in AI-based applications in the last few years and the increased number of public datasets for road traffic applications, the railway industry has been lagging behind. The data used for the obstacle detection evaluation can be of three categories: publicly available data on the Internet, custom made datasets or data from real-world field trials. Relevant public datasets for railways are scarce and the majority of AI-based methods use custom-made and non-public datasets.

Another significant issue is that the initial data usually does not cover all possible cases and conditions. For that reason, augmentation, i.e., the creation of an artificial dataset based on the existing ones, is required. Augmentation mechanisms for railway-related images range from simple linear filters to complex models.

Another class of technical means required for successful operation of ATO systems are satellite positioning systems (GNSS) and platformless inertial navigation systems (PINS) that determine the current coordinates of the train and other railway infrastructure facilities with an accuracy of several metres, in combination with the use of a digital map. This significantly increases the efficiency of automatic control algorithms.

The practical use of an on-board digital map for autonomous driving is closely associated with the implementation of the map-matching algorithm. That is a method based on the image recognition theory that combines a digital map with information on the location of a train to obtain the actual position of rolling stock in the railway network. Map matching can be divided into two relatively independent processes: finding the path of movement of the current train and projecting the current location of the train onto such path.

INTEGRATED SOLUTION FOR TRAIN LOCALIZATION

It is worth mentioning that the Russian Railways was one of the world's first railway companies who started implementing satellite navigation in various railway applications as early as in the 1990s. Since then, all passenger trains and a considerable proportion of freight vehicles have been routinely equipped with GLONASS / GPS-enabled on-board ATP units, with the total number exceeding 20,000.

For the last ten years, all new passenger, freight locomotives and EMUs in Russia were equipped with the BLOK on-board system that combines the functionality of several subsystems and features the most innovative aspects of the OBU family while maintaining the highest safety integrity level (SIL4). BLOK has a modular architecture and can be customized for specific demands.

The design of the BLOK system allows using it both in stand-alone mode and jointly with other locomotive control and diagnostics systems. The system ensures train protection, including the cases when locomotives are operated by a single driver, without an assistant. The key functions of BLOK are as follows:

- receiving and processing of information from cab signalling systems, trackside devices and digital radio conduits (TLC unit),
- continuous speed monitoring and automatic brake application in case of overspeeding,
- prevention of SPADs,
- display of the target and permitted speed to the driver,
- rollaway protection,
- continuous driver vigilance monitoring,
- service and target braking,
- recording of vital train-borne information,
- display of movement parameters to the driver.

The simplified architecture of the BLOK unit is presented in Fig. 7 below.

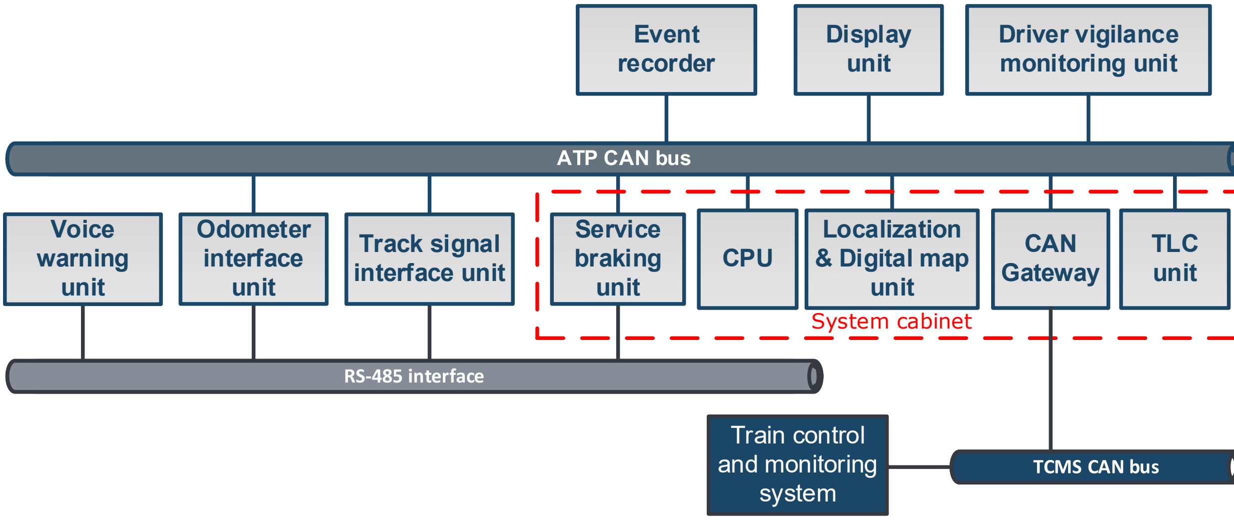

Fig. 7. BLOK simplified structure

A train localization unit in Russian ATP solutions typically uses GNSS positioning data in combination with an on-board digital route map. A standard train localization unit (TLU) with basic input data is presented in a simplified form in Fig. 8.

For the purpose of input data processing, the TLU uses a system of equations based on a Kalman filter to predict the system state evolution and to correct it accordingly. Combining GNSS positioning data with other independent data sources makes TLU outputs more reliable. Map matching helps reduce the search space to the actual route and translate the world coordinates into the linear ones to compute the distances to objects along the route stored in the map.

According to a number of sources [8], standalone GNSS-based positioning is not SIL4-safe. Obviously, it should be cross-checked with other reliable means like odometers, digital route map, track circuits or alternative facilities, and considered as part of some multi-layer railway system where not all of its constituents are to be necessarily SIL4. The safety integrity levels should rather be well balanced between them. In this context, a high-precision on-board digital route map plays an important role providing absolute positioning of authorized tracks, securing the continuity of the trip through previously validated localizations and improving the accuracy of speed profile and braking curve calculation.

A digital route map along with all the information it contains is included in the overall safety loop and acts as a reference, against which GNSS and other measurements are validated (provided that the accuracy of the digital map meets the operational requirements). As part of the navigation unit,

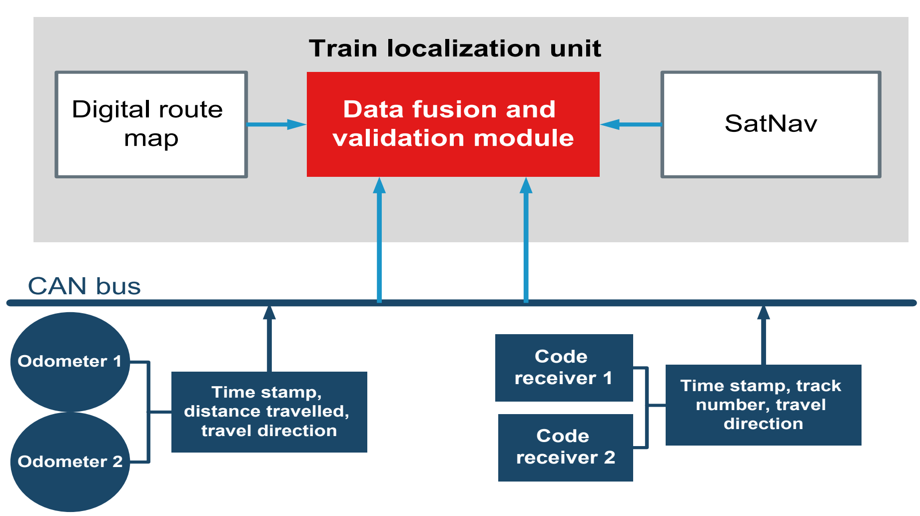

Fig. 8. Simplified structure of TLU

the digital map reduces human factor-related risks and serves as a source of information on trackside assets, the environment, the location of the vehicle even when there is no satellite navigation signal, the visibility is poor, etc.

Certainly, there is still much to be done to provide a more robust on-board train localization solution. Implementing a sound ATO functionality requires a long list of further improvements, including:

- automated generation, verification and updating of digital route map data,
- safe and secure methods of transmission / uploading of updated digital route database,
- standardized route map format and map matching mechanism,
- solutions for time synchronization of data received from different sources and integrated by the on-board data fusion and validation module,
- methods of in-motion verification of satellite navigation data,
- solution for start-of-mission positioning uncertainty,
- better satellite receivers with advanced in-built algorithms and shorter delay times.

Conclusion

The paper covered just a few ongoing developments enabling the migration to new models of train operation. On the face of it, it may seem that the examined issues are not closely related, but in fact, they are. The migration to GoA3/4 is not only about automatic detection of obstacles and replacing drivers with AI-based perception. It is also about absolute train localization and, therefore, safe operation. Ultimately, it is all about increasing capacity and punctuality.

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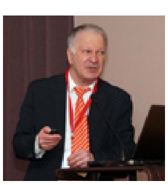

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