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GNSS Based Method of Train Integrity Control

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ABSTRACT

In the paper the original author's concept of train integrity control with the use of signals obtained from satellite systems is presented. The proper identification of train integrity is relevant from the railway transport safety point of view. Nowadays track clear detection systems in the form of axle's counters do not provide sufficient guarantees of fully correct identification of the train integrity on the rail route. Thus, it seems appropriate to use the available, external systems to additional control of the train integrity. Such possibilities are provided among others by satellite systems. These systems are increasingly used for railway tasks. Therefore, the concept of such a system, the algorithm of operation and the possibility of applying the Kalman filter to estimate the measurement results and increase the accuracy is presented in the paper.

KEYWORDS: GNSS, train integrity control, safety

1. Introduction

One of the basic priorities to be implemented in railway transport is to ensure a high level of safety [3, 6, 14, 18]. They are achieved, among others, through continuous improvement of technical systems supported by modern information technologies [11, 12, 14]] as well as increasing requirements in relation to the human factor [13]. This area includes issues related to the train integrity control, which are important for the safety of passengers and transported goods [5]. History shows [1, 4, 8], that in the past years there have been railway incidents and accidents during which the train separation occurred. In Poland the most tragic was the rail crash, which took place on 27 August 1973 at about 2:42 a. m. on the Kielce - Kozłów section of line no. 8 near Radkowice, in which 14 people died and 24 were wounded (Fig. 1).

The cause of this crash was the invasion of the train from Zakopane to Warszawa Wschodnia, driving at a speed of 90km/h on 20 freight wagons that separated themselves from the train going from Jaworzno-Szczakowa towards Skarżysko-Kamienna and remained on the route of the passenger train.

Fig. 1. The train crash near Radkowice on 27th August 1973 [1]

In the described example the train separation occurrence was mentioned. This is a phenomenon that can occur at any time when the train moves along the railway route. The reason for the train separation may be, inter alia, sudden braking and acceleration of train (especially freight train), structural defects of wagons, as well as train formation not in accordance with the instruction [15].

2. The essence of the train integrity control method

The method of train integrity control presented in the paper consists in real-time analysis of satellite signals coming from two navigation receivers [2, 7, 6]. One of them is placed at the front and the other at the end of the train (Fig. 2).

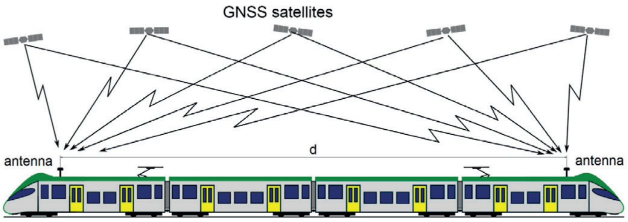

Fig. 2. Determining the train length based on GNSS signals [7]

Signals from the navigation system receivers are transmitted (e.g. using the Wireless LAN) to the processing and logging device (located in the train driver's cab), which determines the current positions of the receivers. The train driver has the possibility to check the train integrity in real-time on the basis of information displayed on the screen. In addition, data from the processing and logging device could be transmitted to the external systems using available transmission media, e.g. to railway operation control centre using GSM-R. The structure of the train integrity control system is shown in Fig. 3.

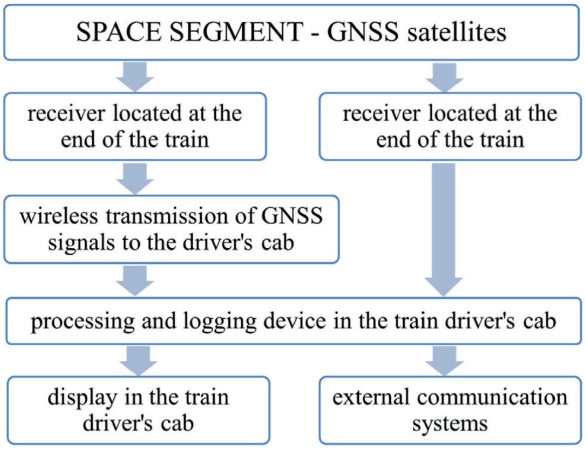

Fig. 3. Structure of the train integrity control system [own study]

On the basis of the determined positions of the receivers, a distance between them (d) is calculated. It is assumed that this distance is constant both during train running and at standstill. Determining the distance between GNSS receivers is subject to an error related to inaccuracy of positioning this receivers. Conducted simulation and field tests allowed to determine the maximum value of GNSS receivers positioning error, which in Fig. 3 was marked with the letter (b). The determined distance between GNSS receivers should not exceed the sum of the original distance between them (d) and the assumed maximum positioning error (b).

In Fig. 4 the moment of the train separation was presented. The task of the proposed system is to generate an alarm signal at the time when distance between GNSS receivers exceeds maximum positioning error (b), which is equivalent to stating the lack of train integrity.

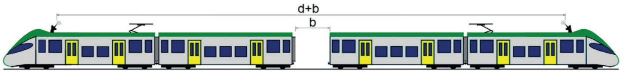

Fig. 4. The moment in which the train separation was detected [own study]

The concept takes into account the case in which distance between GNSS receivers (d) may be reduced while a very long train is running on the track in curve. In such case system does not warn about lack of train integrity.

An important aspect that has been pointed out is the analysis of positioning errors and the use of the Kalman filter for the estimation of measurement results [9]. This approach allows to improve the accuracy of positioning GNSS receivers placed at the front and end of the train, which is the basis of the above mentioned method.

In order to check the method thoroughly, the train integrity control algorithm was analysed (Fig. 5) as well as simulation studies and field tests were carried out.

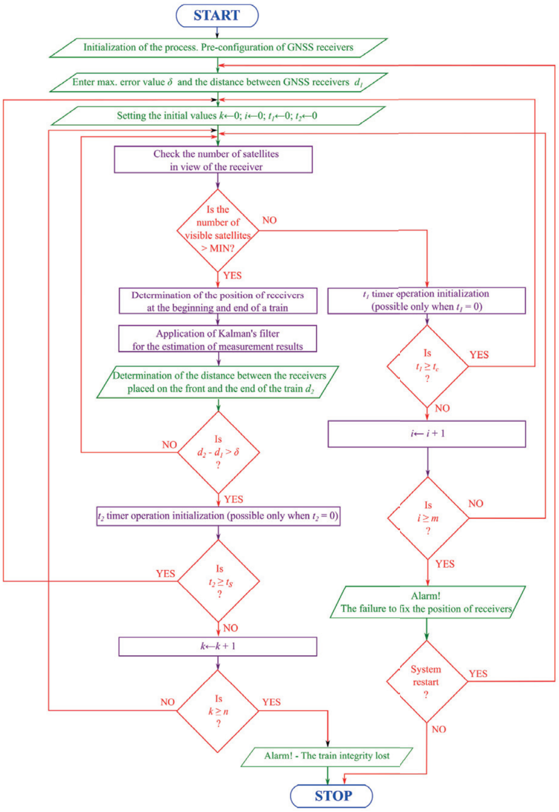

Fig. 5. Train integrity control algorithm [own study]

The above mentioned activities confirmed the effectiveness of proposed approach. The results of these analyses are presented later in the paper.

2.1 Train integrity control algorithm

After the system is started up, the devices are initialized and the GNSS receivers on the front and at the end of the train are pre-configured. The maximum positioning error of the receivers δ as well as the distance d_1 between GNSS receivers are entered into the system. Then the initial values of variables k, i, t_1 and t_2 are set.

In the next step, the number of visible satellites for both GNSS receivers is checked. If this number is greater than the assumed minimum (MIN) then the positions of GNSS receivers are determined (using Kalman filter). On the basis of the designated positions of the GNSS receivers, the distance d_2 between them is determined, which is compared with the value d_1 entered during the process of initialization.

If the distance difference $d_2-d_1>\delta$, then the timer, which allows checked mentioned above difference n times for a set period of time t_c is turned on. If after n subsequent checks the expression $d_2-d_1>\delta$ is still true, then in the driver's cab an alarm, informing about the lack of train integrity is generated. Lack of acknowledgement of exceeds maximum positioning error then the initial settings of the variables are restored and the timer is reset.

The algorithm's authors predicted a case in which, while checking the number of visible satellites this number is less than minimal (in field test 4 was assumed). Then the second timer is started. If during the time t_s (counted from the moment when the timer was started) the system determine (m times) that the number of available satellites is less than minimal, an appropriate information on the monitor in the train driver's cab is displayed. Then it is possible to restart the system or to disable the GNSS based additional train integrity control in case of permanent error. In this case, train's systems work taking into account other available methods of train integrity control.

2.2 System model

The analysis of the mathematical model describing the train integrity control algorithm requires the definition of the train in selected coordinate systems. In the proposed train integrity control method, a system model will be built using Kalman filter.

A movable object such as train is defined in the local coordinate system O'X'Y'Z' (LLF), in relation to the global coordinate system OXYZ. The coordinate system associated with the Earth (ECEF) has been adopted as a global coordinate system. For the train defined in a local coordinate system, it is assumed that the origin of the coordinate system is at the centre of gravity of the train. Train movement also causes movement of the local coordinate system, while the global coordinate system is stationary.

The direction of the train movement (forward-backward) is determined by the OX' axis, while turning the train (left - right) is determined by the OY' axis. Changing the vertical position of the train (when the train is running up or down) is determined by the OZ' axis. The train in the described coordinate systems is shown in Fig. 6.

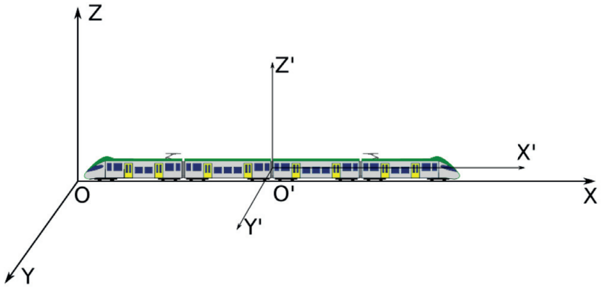

Fig. 6. A train in the local coordinate system O'X'Y'Z' in reference to global coordinate system OXYZ [own study]

During running, the train changes its position from its initial position in reference to the origin of the global coordinate system. Moving along the track, the train may tilt to the left or right (e.g. when driving on the curve track), it can move on slopes causing a change in the angle of the train in relation to the Earth as well as it can change its direction by turning left or right. This is the result of the train's rotation around the vertical axis Z by angle φ, horizontal axis X by angle θ and horizontal axis Y by angle ψ. The graphical interpretation of the train in the local coordinate system with the above-mentioned angles, is shown in Fig. 7, and the interpretation of the angle ψ is shown in Fig. 8.

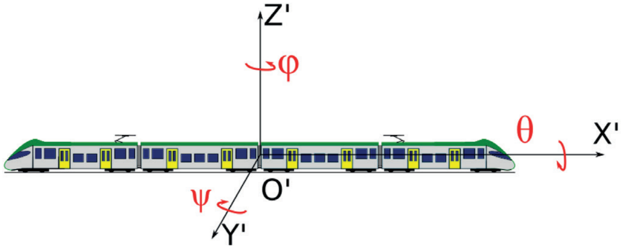

Fig. 7. Train in the coordinate system related to the object (BF) [own study]

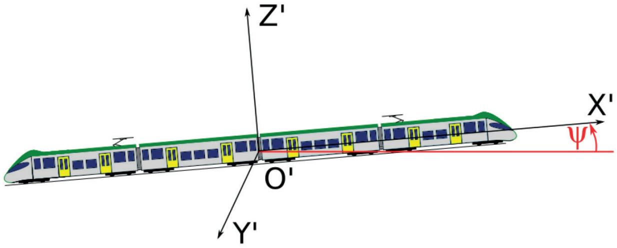

Fig. 8. Graphic representation of the angle ψ (rotation around the Y axis) [own study]

The angle φ (rotation about the Z axis) is related to the lateral movement of the train, which occurs during the train running on the track curve. The graphic interpretation of the rotation angle φ is shown in Fig. 9.

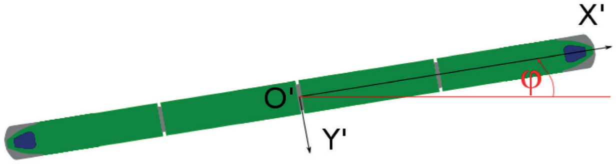

Fig. 9. Graphic representation of the angle φ (rotation around the Z axis) [own study]

The angle θ (rotation around the X axis) is the angle at which the train tilts sideways while running (when compared to the balance position). The interpretation of angle θ is shown in Fig. 10. All these determinants force the train to be placed in the local coordinate system (base frame, BF), which is related to train.

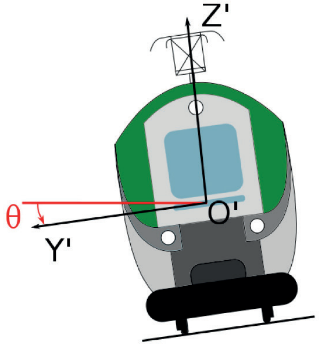

Fig. 10. Graphic representation of the angle θ [own study]

Placing the train in selected coordinate systems and analysing the state vector errors, as well as selecting the appropriate GNSS receiver for the train integrity control method chosen by the authors, allows to choose the appropriate mathematical model built on the basis of the Kalman filter.

The Kalman filter is used for dynamic systems discrete in the time domain. The state of the system is represented by a state vector, which is determined at each step by a linear operator, taking into account the noise associated with imprecise object observations and modelling errors.

The model of the system based on the Kalman filter was presented in Fig. 11. The system is based on the analysis of the process model and measurement system [5, 17]. Process modelling consists in determining the state vector x_k (1) at moment k on the basis of the state vector x_{k-1} at the moment $k-1$ [10, 17].

$$x_k = \Phi x_{k-1} + Bu_{k-1} + w_{k-1} \tag{1}$$

Modelling the measurement at k is based on the determination of z_k – observation of the real state vector x_k (2) [17].

$$z_k = Hx_k + \eta_k \tag{2}$$

Kalman filter is a recursive filter. The advantage of this type of filtration is that the estimation of the state at a given time requires only the knowledge of the previous state and the observation vector. Kalman's filtration is divided into two stages of prediction and correction, which interact with each other. In the first stage - prediction (based on the state vector from the previous step), a priori values are determined, i.e. the estimated value of the state vector and its covariations. In the second stage - correction - the observation data are updated to improve the determined state vector. At this stage, a posteriori values are determined, i.e. the value of the state vector and its covariations.

The presented model of the system leads to the design of the Kalman's filter algorithm to the determine of the train position.

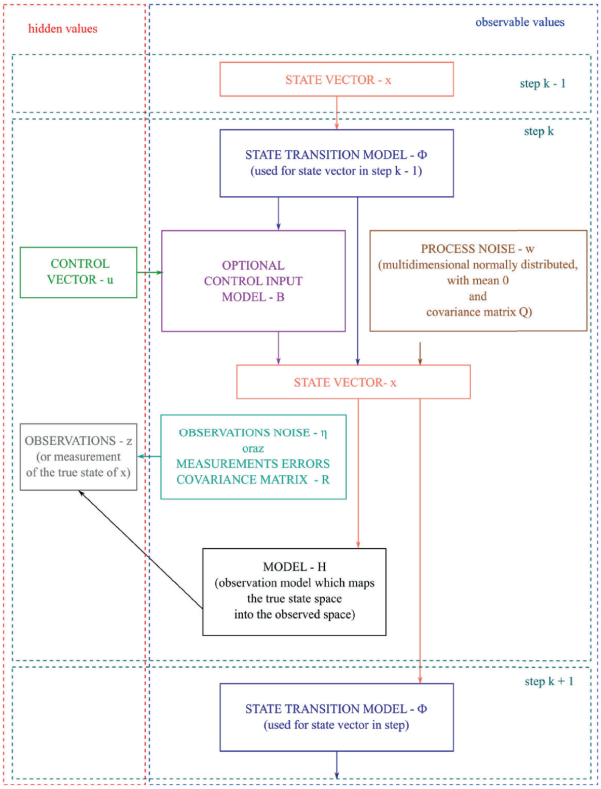

Fig. 11. Model of the system based on Kalman filter [own study]

3. System response to the train separation occurrence

The system response time to the train separation occurrence is inversely proportional to the speed of the train (3).

$$t = \frac{b}{v} \tag{3}$$

Let's assume that the train will move at speeds ranging from V_{min} to V_{max}. The response time of the system will be the lowest if the train is moving at maximum speed. Similarly, the response time of the system will be highest if the train is moving at minimum speed. The method of determining the minimum and maximum response time for the above speed range is presented in equations (4).

$$t_{\min} = \frac{b}{v_{\max}}, \quad t_{\max} = \frac{b}{v_{\min}} \tag{4}$$

If the train will run at low speed, then the response time is less important because the lower the speed, the shorter the braking distance of the train. The system response time dependence in function of train speed is shown in Fig. 12, assuming that the maximum positioning error of the GNSS receivers is 26 m.

The graph shows that the system's response time (from the moment of the train separation to the moment when the system is triggered) is lower the higher the speed of the train is. It can be noticed that at speed above 95km/h, the system's response time is less than 1 second. The risk of unplanned train separation is the higher when the higher the speed of the train is, and then the system will respond more quickly, which is a desirable.

For the purpose of the field test it was assumed that the distance between the receivers placed on the front and the end of the train will be determined with an accuracy of 26m (resulting from the positioning accuracy of the GNSS receivers).

Train running on the track in curve will reduce the distance (*d*) between the GNSS receivers (Fig. 13).

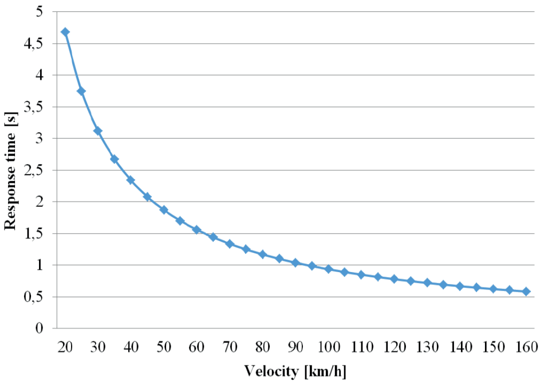

Fig. 12. The system response time dependence in function of train speed [own study]

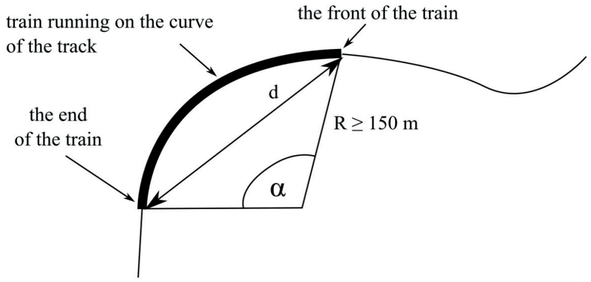

Fig. 13. Train running on the track in curve [own study]

The distance (*d*) between the GNSS receivers located on the front and the end of the train while the train is running on the track in a curve of radius *R* is given by the formula (5).

$$d = R\sqrt{2(1-\cos\alpha)} \tag{5}$$

In this case, the length of the train *l* is defined by formula (6).

$$l = \frac{\alpha}{360°}\cdot 2\pi R \tag{6}$$

The above dependences indicate that a situation where the distance between GNSS receivers will be smaller than the train's length is possible and the train's length change can even exceed maximum acceptable error value (*b*). However, reducing the distance between GNSS receivers does not have a negative impact on the system operation, as in practice it usually does not mean the train separation.

In an extreme case, a very long train set, e.g. a freight train over 300 meters long, can move on a curve with a radius of 150 m (based on [16] the minimum radius of the curves in the mountain area of local importance is 200m, and in the siding tracks, where the shunting of coupled wagons is carried out by locomotive belonging to owner's, manager's or operator's of the siding track, manually or by pullers, it is possible to use curves with a radius greater than or equal to 150m) – Fig. 14.

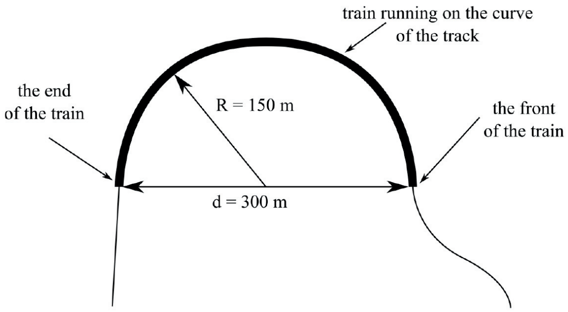

Fig. 14. Running a long train in a curve equal to half a circle [own study]

In this case, the distances between the GNSS receivers placed at the front and the end of the train will be 300m. These distances are smaller than the length of the train and similarly to the previous example will not have a negative impact on the operation of the system, because they do not indicate the train separation.

When considering trains composed of a small number of wagons (e.g. 2 or 3 wagons and an locomotive), the distance between the GNSS receivers will be about 75m-100m. This means that the assumed maximum positioning error of 26m will not negatively affect the operation of a system if train set contains a small number of wagons.

4. Conclusion

On the basis of the analysis presented in this article, it can be said that it is possible to use satellite technology to additional control the train integrity. Of course, according to the authors opinion, this method can only complement the existing methods of train integrity control. Of course, according to the authors opinion, this method can only complement the existing methods of train integrity control. The proposed method does not interfere with the existing railway infrastructure. Equipping trains with such a system entails low costs (costs of installing GNSS receivers and software), which increases the advantages of the proposed method. Due to the existing applications of satellite techniques in railway tasks, the method presented in the article becomes another application element.

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