On-board Train Positioning and Train Integrity Management System by Combination of Tachometer Generators and Inertial Sensors

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An on-board train positioning and train integrity system combining inertial sensors and tachometer generators has been developed to detect train position and presence in a section using a radio train control system. In this system, curves and slopes which are registered as distinctive points on the track in an on-board database are used to detect train position and calculate train length. Additionally, train splitting can also be detected by the difference in acceleration between the head vehicle and the tail vehicle. Running tests using fail-safe processors equipped with these functions have demonstrated the feasibility of this system.

Keywords: inertial sensors, on-board train positioning, train integrity, train length calculation, train split detection

1. Introduction

Recent efforts to decrease wayside equipment and increase train operation flexibility with moving block systems, radio-based train control systems have been introduced [1][2]. In these systems, one of the most important functions is the on-board train positioning function, which is used to control intervals between trains, and is the key difference with traditional signalling systems. The requirements for train integrity defined in ETCS Level 3 [3] are applied for the function of managing the limits of the area occupied by a train. Train integrity needs two functions: train length calculation and train split detection. This paper defines both of these functions, train length calculation and train split detection, as the train integrity.

The on-board positioning and train integrity management system was developed combining an inertial sensor and a tacho-generator. For the new on-board train positioning method, a wheel-slip detection and correction function [4] and an on-board train positioning function using detection of distinctive track points such as curves and slopes were developed [4][5]. For the new train integrity management method, a train length calculation method using distinctive track point detection [4] and train split detection method based on difference in head and tail vehicle acceleration, were developed [6].

In order to confirm the effectiveness and feasibility of these functions, running tests were conducted with these functions installed on fail-safe equipment.

2. On-board train positioning

2.1 Slip detection and correction

In the proposed system, distance calculated by the tacho-generator is used for train positioning. Measured acceleration by the inertial sensor is used for detecting wheel slip and correcting the train position. The section below outlines wheel-slip detection and correction.

When the difference between \( a_p \), calculated using the tacho-generator output, and \( a_m \), measured with the inertial sensor, is greater than the threshold \( T_a \), this is defined as detection of a wheel slip. The slip detection equation is shown in (1).

\[
|a_m - a_p| > T_a
\]

On slopes, acceleration measured with the inertial sensor includes gravitational acceleration. Thus, in order to calculate the acceleration difference correctly, the gravitational acceleration component must be removed from the measured value from the inertial sensor.

Figure 1 shows the relationship between accelerations. The acceleration of the vehicle running direction includes \( g \sin \theta \), which means the running direction component of gravitational acceleration. The slope angle \( \theta \) can be calculated from the difference in head and tail vehicle acceleration, where wheel slip does not occur. When the wheel slip occurs, the wheel-slip detection and correction function corrects the train position.

\[
\text{Fig. 1 Acceleration measured by inertial sensor}
\]
velocity and the distance is calculated with the acceleration of the inertial sensor based on the previous point of the wheel slip.

2.2 Train positioning using detection of distinctive track points, such as curves and vertical curves

2.2.1 Outline

Train position is corrected by detecting distinctive track points such as curves and slopes by combining tacho-generators and inertial sensors. The method was developed to be applied to train control systems or automatic train protection systems. In order to avoid misrecognition, a distinctive track point has multiple matching points, which identify the same distinctive track point. The train position is detected and corrected by comparing the measurement value by inertial sensor and tacho-generator with the matching points registered in the on-board database.

2.2.2 Calculation of curvature

The value of a curvature $\kappa$ [1/m] for detecting the distinctive track point is calculated by the following equation:

$$\kappa = \frac{\omega}{v}$$  \hspace{1cm} (2)

Here, $v$ [m/s] is the velocity calculated by the tacho-generator, and $\omega$ [rad/s] is the angular velocity measured by the inertial sensor.

2.2.3 Distinctive track point detection and train position correction

The procedure of the distinctive track point detection and train position correction is shown in Fig. 2. The train position calculated by tacho-generator and correction method for wheel slip are used.

When train approaches the distinctive track point, the proposed system searches the point from the on-board database. In a curved section, the on-board equipment checks the value of the curve length and the curvature with the values in the on-board database. When the agreement is confirmed, the amount of the position correction is determined by comparing the position recognized on the vehicle with data in the on-board database. After detecting the end of the curve section, the on-board equipment corrects the train position. In order to avoid the misdetection of a distinctive track point, the on-board equipment checks three locations: start of curved section, curved section and end of curved section.

3. Train integrity

3.1 Requirement of train integrity

The train integrity applied, is defined in ETCS Level 3 as “the level of belief in the train being complete and not having left coaches or wagons behind”.

The positions of the head and the tail vehicles must be managed in the system, which uses the on-board train positioning to control train intervals and detects if the train goes through a level crossing. The function of train length calculation is important because the position of the tail vehicle is calculated from the position of the head vehicle and the train length. The detection of the train split is needed, because it can cause the possibility of misrecognizing the area where vehicle exists if a train splits.

A train split must be detected constantly. The train length does not need to be calculated except when detected again: train compositions change for example at the point of entry to a main line or when it is re-composed at a station (Fig. 3).

3.2 System configuration

The train length calculation and train split detection are implemented in the on-board train positioning system using the tacho-generator and inertial sensor for the head and the tail vehicles. Figure 4 shows two configurations which the system has to assume: an electric train configuration and a freight train configuration. In the electric train configuration, the head vehicle and the tail vehicle have tacho-generators, where the two on-board train positioning systems are installed in the head vehicle and the tail vehicle. In the configuration, the procedure for the tail vehicle is the same as for the head vehicle, and the independently processed result of the tail vehicle is transmitted to the head vehicle’s equipment.

In the freight train configuration, the head vehicle has tacho-generator while the tail vehicle has none. In this...
configuration, the on-board train positioning system with an inertial sensor is installed in the head vehicle, and the inertial sensor and transceiver are set at the tail vehicle. The equipment in the head vehicle calculates the measurement data form the inertial sensor in the tail vehicle which is transmitted from the tail vehicle to the head vehicle. It is assumed that wireless communication is used for transmission from the tail vehicle to the head vehicle.

![Fig. 4 System configuration](image1)

### 3.3 Train length calculation

The train length can be calculated by the running distance from where the head vehicle passes a point to where the tail vehicle passes the same point. The train length $L$ is shown as the following equation.

$$L = p(t_h) - p(t) + L_c$$

where, $p(t)$ shows the train position of the head vehicle at the time $t$. The time $t_h$ indicates the time of the head vehicle passing at a point $P$, and the time $t$ shows the time of the tail vehicle passing at the point. The length of the tail vehicle is shown as $L_c$. The vehicle length $L_c$ does not depend on where the sensor of the tail vehicle is set [4].

As the point P for train length calculation, the distinctive track point detected by the tacho-generator and the inertial sensor can be used. Thus, Fig. 5 shows that from the points detected by the head and tail vehicle, the curve can be selected.

The mechanism is as follows: in order to calculate the train length, the information of the distinctive track point detected by the tail vehicle or the measurement angular velocity by the inertial sensor are transmitted with GPS time to the head vehicle. The train length is calculated until the train enters the main running line. However, when the train length cannot be calculated, a preset maximum length for lines is used as the train length.

![Fig. 5 Outline of train length calculation using distinctive track point detection](image2)

### 3.4 Train split detection

The system configuration for train split detection using acceleration monitored by the inertial sensor is shown in Fig. 6. In the method, the differential of acceleration in the running direction of the head vehicle and the tail vehicle measured by the inertial sensor are constantly compared. Normally, the differential of the acceleration does not occur because the train is connected. However, when the train splits, the difference in acceleration due to separation or collision is detected.

In the train split detection method, acceleration by inertial sensor is transmitted with GPS time from the tail vehicle to the head vehicle. When train split is detected, the train must stop quickly. Thus, the train split detection requires the transmission specification equivalent to the transmission specification of the train control systems.

![Fig. 6 Outline of train split detection using inertial sensor](image3)
4. Functional confirmation

4.1 Experimental equipment

In order to confirm the system functions, a prototype of the experimental equipment was made, shown in Fig. 7. Figure 7 (a) is the equipment mounted on the head vehicle or the tail vehicle of the electric train configuration, and Fig. 7 (b) is equipment mounted on the tail vehicle of the freight train configuration. Processing in the equipment shown in Fig. 7(a) is executed by a fail-safe CPU. Both pieces of equipment shown in Fig. 7(a) and (b) have an inertial sensor, a GPS device and a radio transceiver.

![Processing unit and Inertial sensor](image)

(a) Head/tail vehicle

![Tail vehicle of freight train configuration](image)

(b) Tail vehicle of freight train configuration

**Fig. 7** Experimental equipment

4.2 Configuration

The experimental equipment configuration of the running test is shown in Fig. 8. In the case of electrical train configuration, as shown in Fig. 8, the head vehicle and the tail vehicle have processing equipment and an inertial sensor. In this case, the tail vehicle device detects the distinctive track point and transmits the time and the distinctive track point information to the head vehicle.

In the case of the freight train configuration, the device is installed on the left and right side of the tail vehicle, as shown in Fig. 8(b), providing redundancy. The tail vehicle device does not detect the distinctive track point and transmits measurement data with GPS time from the inertial sensor to the head vehicle. The equipment of the head vehicle calculates the train length and detects the train split.

![Configuration of experimental equipment](image)

**Fig. 8** Configuration of experimental equipment

4.3 Running test

4.3.1 On-board positioning

An example of a train position detection and the correction by distinctive track point detection is shown in Fig. 9. Figure 9 shows the results of 4 experiments at the same point.

The total number of the distinctive track point in which the on-board equipment was or was not able to correct the train position is shown in Table 1, over the running tests which carried out at several lines. The equipment was able to correct the train position at 699 points corresponding to 94.3% of the total 741 points. In points where the device was not able to correct the train position, the vehicle’s speed did not reach the speed required for distinctive track point detection or the curvature value exceeded the set threshold for a short period of time.

When the device is unable to correct the train position, safety can be kept by a margin which is set to represent the train presence area.

![An example of train position correction](image)

**Fig. 9** An example of train position correction
4.3.2 Train length calculation

In the running tests, the device was installed both on the electrical train configuration and the freight train configuration. The train length was calculated at every distinctive track point. The result are shown in Fig. 10. Figure 10 shows that the calculated values were distributed in the range of 109 to 129 m around the true value of 120 m. The errors of the calculated values were caused not only by the accuracy of the sensor but also by the errors in the input cycle of the processing device and distinctive track point detection. Table 2 shows the error factors and errors when assuming a maximum of 130 km/h.

From the errors shown in Table 2, the maximum error was ±13 m. This is consistent with the error range in the results of Fig. 10.

| Error factor                      | Error (130 km/h) |
|-----------------------------------|------------------|
| Processing cycle (100 ms)         | ±3.61 m          |
| Processing start time difference   | ±3.61 m          |
| Moving average filter (1.5 sec)   | ±0.78 m          |
| Error in sensor detection         | ±5 m             |
| Total                             | ±13 m            |

4.3.3 Train split detection

The target for the train split detection was the freight train configuration. Figure 11 shows the result of an experiment conducted to simulate a train split by changing the acceleration of the tail vehicle by purposely tilting the equipment while the train was running. The result shows that the train split was detected when the difference in acceleration between the head and tail vehicles exceeded the threshold. Figure 12 shows the acceleration of the head and tail vehicles, difference in acceleration and the results of the train split detection, when the train split occurred.

Figure 12 shows a delay of about 2 seconds until the train split is detected after the acceleration difference exceeds the detection threshold. This delay includes 0.75 seconds, which is half the moving average of 1.5 seconds for the measured value, and transmission and processing delays.

The train split was not detected except where the train split was simulated.

5. Proposing on-board train positioning and train integrity management system

The on-board position detection and train integrity management system combining the inertial sensor with the tacho-generator, allows the performance of four functions shown in Fig. 13. In other words, introducing the proposed on-board position detection and train integrity management system using the inertial sensor with the tacho-generator, it is possible to satisfy the requirements of balise-less train positioning and train integrity. This should enable cost reduction.
6. Conclusion

This paper describes an on-board train positioning and train integrity management system using an inertial sensor with a tacho-generator, in order to adapt to safety systems where the on-board system needs to recognize the train position and train length, such as radio-based train control systems. For the on-board train positioning function, a proposal was made for a wheel slip detection and correction function and a position correction function using distinctive track point detection. For the train integrity management system, a proposal was made for a train length calculation function using the distinctive track point detection and a train split detection function using the difference in acceleration between the head and tail vehicle. The experiments using prototype equipment show the expected performance. Thus, by introducing the proposed equipment, cost reduction and introduction expansion for radio-based train control systems can be expected.

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