Train location with eddy current sensors

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Abstract

A robust train location system with a novel eddy current sensor is proposed. The new system is purely train-based in the sense that no further installations are required on the track beyond the currently existing infrastructure. The eddy current sensor system consists of two identical sensors placed at a distance l in longitudinal direction. Thus, the time delay between the two sensor signals obtained by cross-correlation is a measure for the velocity of the vehicle. In addition, the sensor signals are analysed for characteristical events. The shape of the sensor signals highly depends on the irregularities of the magnetic properties of the rail arising along the track. In particular, it is shown that the characteristic signals of the components in switch areas differ significantly from the signals caused by rail joints along the straight track. This knowledge can be exploited for detection and classification of switches and switch components. Matching the measured position of points with topological position data from a digital route map yields reliable location of the train.

1 Introduction

Due to rather long braking distances of rail vehicles, a reliable train location is a prerequisite for flexible train operation concepts. State-of-the-art systems depend on installations along the track, e. g. balises and axle counters. New systems of operation, e. g. moving block, need a reliable and accurate train location. Therefore, enhancing the track capacity based on a more detailed train location comes along with high investments in infrastructure and high maintenance costs. A train-based location system helps to reduce these costs to a minimum.

The Global Positioning System (GPS) is an existing location system of high accuracy. However, it is not well-suited for railway applications: It does not work

in tunnels and may fail in dense urban environment. Furthermore, it is not possible to distinguish between parallel tracks on multiple-track lines.

In the following, an accurate train location method with eddy current sensors is presented, that overcomes the above mentioned drawbacks. This sensor system is much more robust against weather and enviromental conditions outside a rail vehicle as compared to e. g. optical systems. To explain the measuring principle, some facts of the conference papers [1] and [2], presented at the Comprail 2000 Conference, are summarized in Secs. 2, 3.1 and 4. In addition to the correlation of the sensor signals, a signal processing method to obtain an estimated value of the vehicle velocity is described in Sec. 3.2. The application of an eddy current sensor system to locate a rail vehicle is presented in the following sections. In Sec. 6 some aspects of self-monitoring and redundancy of the location system are discussed.

2 Eddy current sensor system

In addition to nondestructive testing and examination of rails, eddy current sensors are able to detect inhomogeneities in magnetic resistance along the track, e. g. rail clamps or switch components as well as irregularities of the rail. Figure 1 shows the application of a differential eddy current sensor for train-based speed measurement. It consists of one exciting coil E and two pickup coils P1 and P2, depicted in 1(a). For safety reasons, the sensors are placed at a height of about 100 mm above the rail head, such that only significant inhomogeneities can be detected.

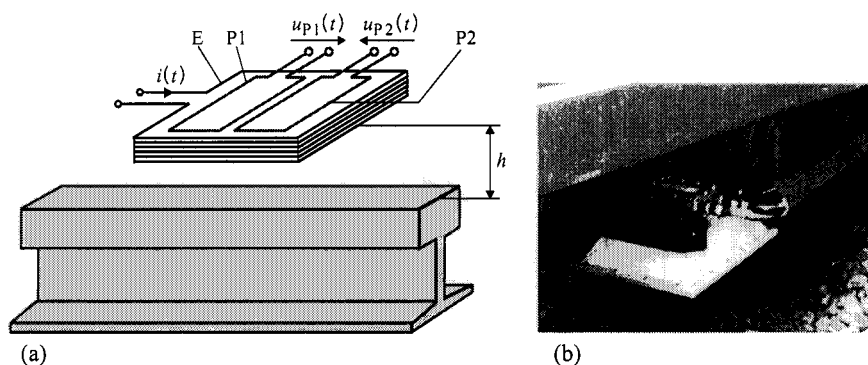(a)   (b)

Figure 1: Differential eddy current sensor: (a) principle drawing; (b) experimental setup with two sensors inside the housing.

Figure 1(b) shows the experimental setup used for field tests at the Albtalbahn, Karlsruhe (Germany). The sensor housing, containing two eddy current sensors, is attached at a bogie of a railcar.

Differential sensors are sensitive only to local fluctuations of conductivity and magnetic permeability along the rail. In contrast, vertical sensor movement and

side movements have almost no effect on the differential output. As an example, the signal caused by a single rail clamp is shown in Fig. 2.
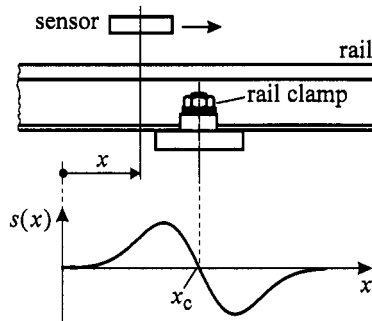

Figure 2: Characteristic signal of a differential eddy current sensor.

Further details concerning the eddy current sensor system and the signal preprocessing are described in Ref. [3].

3 Speed and distance measurement

3.1 Closed-loop correlator

The speed measurement system consists of two identical sensors, arranged at a distance l on a bogie of the rail vehicle. Both sensors capture irregularities along the rail track. Ideally, the sensor signals $s_1(t)$ and $s_2(t)$ are identical beyound a shift by the transit time T, which may be obtained as the position of the maximum of the cross-correlation function

$$\Phi_{12}(\tau) = \lim_{T_A \to \infty} \frac{1}{T_A} \int_0^{T_A} s_1(t - \tau) s_2(t) \, dt. \qquad (1)$$

The train speed is then determined as

$$v = \frac{l}{T}. \qquad (2)$$

The distance x covered by the rail vehicle can be obtained by integrating the measured speed. More details and additional applications concerning the correlator principle can be found in Refs. [3, 4, 5].

The cross-correlation coefficient of the zero-mean sensor signals

$$\varrho_{12}(v\tau) = \frac{\Phi_{12}(v\tau)}{\sqrt{\text{var}\{s_1\} \cdot \text{var}\{s_2\}}} \qquad (\text{var}\{...\} : \text{ variance}) \qquad (3)$$

for typical eddy current sensor signals is depicted in Fig. 3 for an open track and a rail switch, respectively.
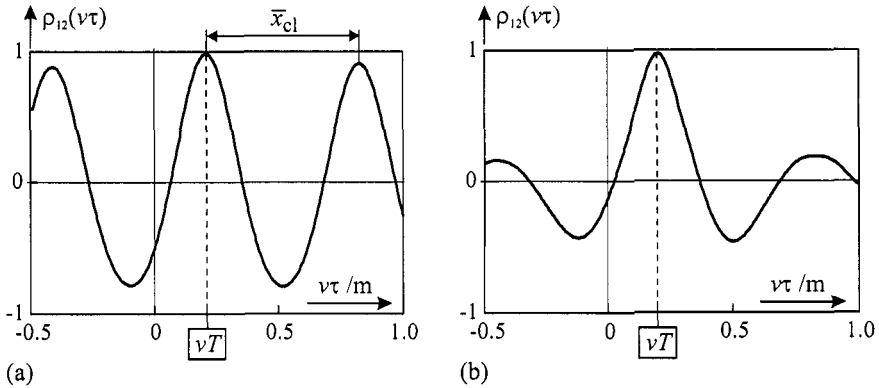

Figure 3: Cross-correlation coefficient $\varrho_{12}(v\tau)$ measured on (a) open track; (b) rail switch.

On open track (a), the sensor detects mainly the equidistant rail clamps. Since the sensor signals are periodic, the cross-correlation function is also periodic. The mean distance $\overline{x}_{cl}$ between two adjacent rail clamps can be derived from the periodic part of $\varrho_{12}(v\tau)$ as illustrated in Fig. 3(a). In contrast, many individual components, such as switch blades or crossings, influence the sensor signals while passing a switch (b). Hence, the resulting cross-correlation function is non-periodic.

The transit time between the sensor signals is obtained as the maximum position of the cross-correlation coefficient (open-loop-correlation). This works very well unless the signals are strictly periodic. In this case it is necessary to track the maximum of the correlation function. This can be done by a closed-loop-correlation, which has the additional advantage of a lower variance of the measured T-values as compared to the open-loop-correlation.

3.2 Analysis of the sensor signals

In addition to the cross-correlation, the sensor signals of each sensor can be analysed individually. On open track, the distance x_{cl} between two rail clamps can be assumed to be constant (usually 60 cm for main lines, for secondary lines often higher). Searching the maximum of the signal spectrum yields the frequency of the rail clamps. Figure 4 shows an example of a typical signal power spectrum.

On open track, the maximum frequency $f_0 = \arg\max\{S^2(f)\}$, i. e. the mean frequency of the rail clamps can be easily found. With the mean distance $\overline{x}_{cl}$ between two adjacent rail clamps, the velocity can be written as
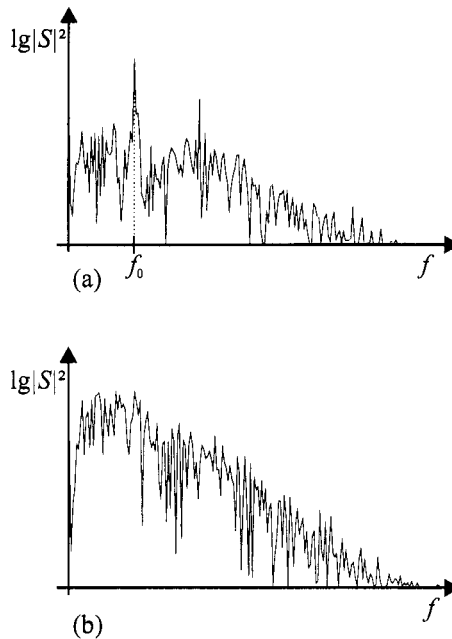
$$v = f_0 \cdot \overline{x}_{cl} . \tag{4}$$

Figure 4: Power spectrum measured on (a) open track; (b) rail switch.

The value of $\overline{x}_{cl}$ can be adapted to local conditions with the exact vehicle velocity calculated by the closed-loop-correlator. This value can be stored in a digital route map for each section of a railway network. A suitable starting value for a track without any reference data is 60 cm.

When passing a switch, the power spectrum as shown in Fig. 4(b) has no significant maximum. Hence, the correlator may deliver an unambiguous value for the vehicle velocity.

4 Switch detection

As can be seen in Figs. 3 and 4, the sensor signals have different shapes depending on the rail components the sensor passes. Therefore, it can be determined whether or not the train is crossing a switch. Furthermore, it is possible to identify particular components, such as switch blades, guard rails or crossings. The sequence of the different events yields the position of points [1].

Samples of sensor signals are depicted in Figs. 5 and 6. The sensor is placed above the right rail in longitudinal direction. In Fig. 5, the switch is set to the left (in this case the main track) and hence the sensor first passes the adjacent switch blade and then the common crossing. This sequence of events yields the conclusion that the vehicle has taken a set of facing points set to the left. It cannot be distiguished whether the train has taken the main line or the branch track.
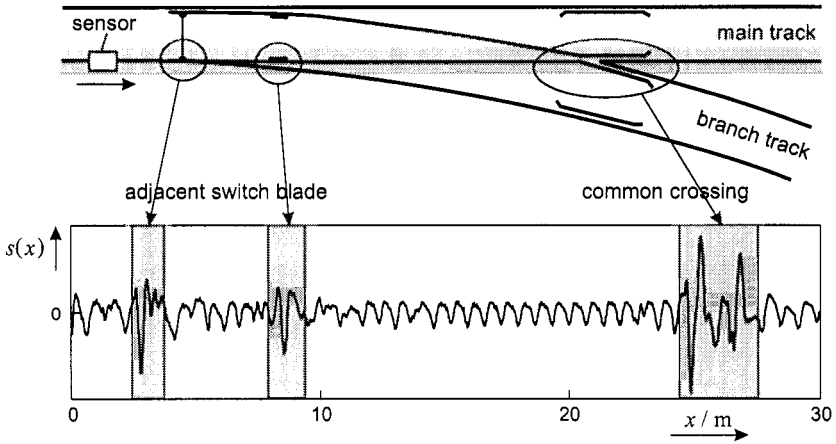
Figure 5: Sensor signal $s(x)$ obtained when passing a set of facing points set to the left.

In Fig. 6, the switch is set to the right and the sensor passes the non-adjacent switch blade followed by the guard rail of the switch. This signal sequence suggests that the vehicle has taken a set of facing points set to the right.
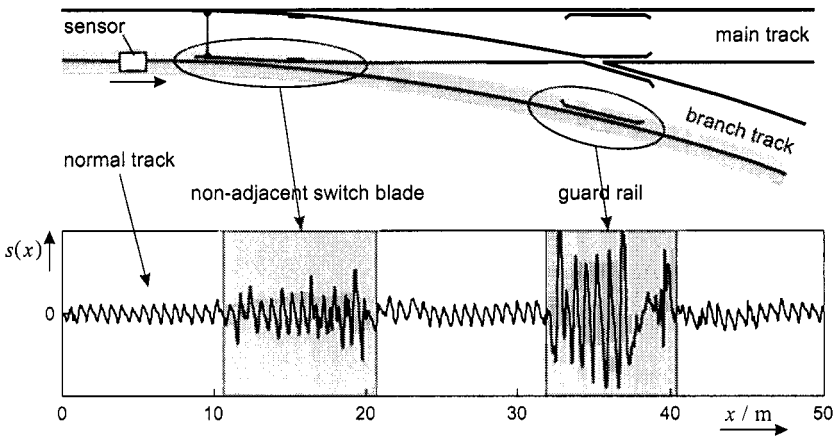

Figure 6: Sensor signal $s(x)$ obtained when passing a set of facing points set to the right.

Since there are only few possibilities of signal sequences, the analysis of track events allows a conclusion about the position of points. It is possible to set up a look-up table with sequences of events to determine the order of switches and their position.

Table 1: Look-up table of switch events (sensor placed above the right rail).

	first event	second event	position of points
1	adjacent switch blade	(common) crossing	facing / set to the left
2	non-adj. switch blade	guard rail	facing / set to the right
3	guard rail	non-adj. switch blade	trailing / set to the left
4	(common) crossing	adjacent switch blade	trailing / set to the right

Only the four combinations shown in Table 1 may occur when passing a switch.
The sensor system detects also e. g. guard rails installed on bridges or in tunnels,
but this will not be recognized as a switch component, because the crossing is miss-
ing. Hence, the proposed sensor system allows to determine what rail components
have been passed and what branch the vehicle has taken.

With a second sensor placed above the opposite rail, the switch detection becomes
even more reliable and allows an additional check for plausibility. In case of pass-
ing a switch, there are always pairs of events appearing at the same time. An adja-
cent switch blade comes along with a non-adjacent switch blade on the other rail.
A common crossing always must face a guard rail. Table 2 shows a look-up table
for the first pair of event the sensor could detect.

Table 2: Look-up table of switch events (one sensor placed above each rail).

	first left sensor event	first right sensor event	position of points
1	adjacent switch blade	non-adj. switch blade	facing / set to the right
2	non-adj. switch blade	adjacent switch blade	facing / set to the left
3	guard rail	(common) crossing	trailing / set to the right
4	(common) crossing	guard rail	trailing / set to the left

In addition to Table 2, the following events must fit the sequences described in
Table 1. That makes a simple test of data integrity possible. This will be discussed
in more detail in Sec. 6.

5 Map matching using topological data

The results of the switch detection explained in Sec. 4 can be mapped onto topo-
logical data of the railway network to exactly locate a vehicle. The data in a digital
route map contains information about the location of switches and the distance
between two neighbouring points. The data includes information on which track

of a multiple-track line a train is travelling on. In addition, the distance measurement of the correlator can be improved by eliminating drift that results from speed integration.

In Fig. 7, an example for mapping measured data with data from a digital route map is shown. Figure 7(a) shows an example of a track travelled by a rail vehicle. The switch recognition yields the information that the train has crossed two set of facing points set to the right and passed one point trailing set to the left, as shown in Fig. 7(b). This information is now mapped onto a digital route map, see Fig. 7(c), and the result of map matching is shown in Fig. 7(d).

(a) travelled track (example)

(b) result of switch detection

(c) stored data (digital rail map)

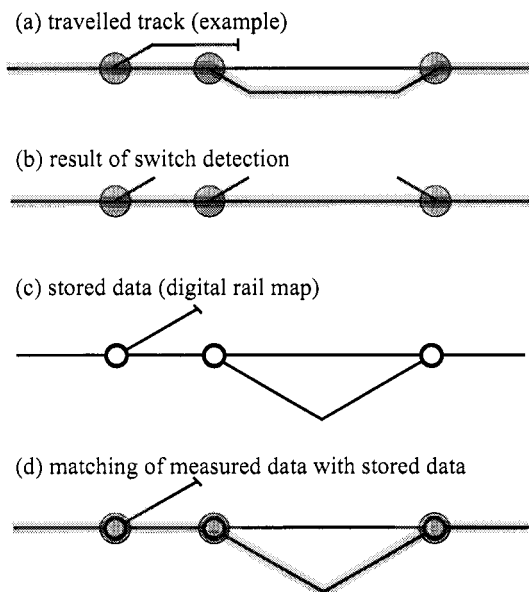(d) matching of measured data with stored data

Figure 7: Matching of sensor signal information onto a digital route map.

By analyzing track events and matching the data with a digital road map, the speed and distance measurement of the correlator becomes more precisely, and the position of the rail vehicle can be determined accurately.

6 Self-monitoring and redundancy

In the following, some considerations about self-monitoring and redundancy of the eddy current sensor system are presented. As outlined in Sec. 4, a fixed sequence of at least two track events is needed to detect a point switch and its position. This allows self-monitoring within the switch detection unit. If one event is missing or a wrong sequence is detected, the switch detection will be able to return an error code. A false identification which is not recognized is unlikely, because at

least two (four with sensors above each rail) independant detection steps must fail simultaineously in this case.

An example of incorrect detection and the resulting implausibility correction is shown in Fig. 8. In the example, the first position of points is not correctly detected. The system assumes that the vehicle has taken the left track. By matching the measured data with the digital route map, the error is detected when the vehicle passes the next switch. This switch should not appear on the branch track.

(a) travelled track (example)

(b) (wrong) result of switch detection

(c) stored data (digital rail map)

(d) discrimination of the detection error,
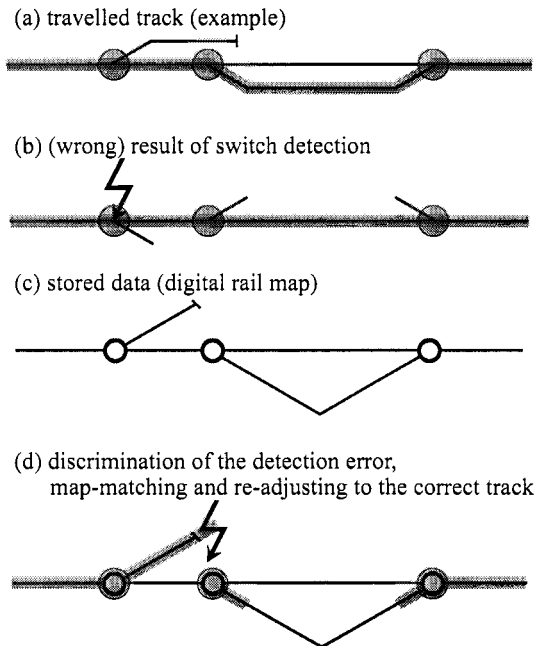   map-matching and re-adjusting to the correct track

Figure 8: Error detection and correction by map matching.

In that case, the two following switches on the main track are detected correctly, the location information will be corrected when passing the third switch as shown in Fig. 8(d).

If one sensor fails completely, correlation measurement will be disabled. When this happens, the vehicle velocity still can be measured by fall-back solution searching the maximum frequency in the signal spectrum of the remaining sensor. The switch detection and identification and the map matching with a digital route map allow to calibrate the distance measurement. This reduces deviations in distance measurement to a minimum, so that the train-based location with only one eddy current sensor is still possible.

7 Conclusion

This contribution has proposed an eddy current sensor system for reliable, slip-free speed and distance measurement. Correlating the sensor signals yields the velocity of a rail vehicle and the travelled distance. Furthermore, analyzing the shape of the sensor signals allows to detect any switches and the position of points the vehicle passes. Matching this data with a digital route map may allow the train to locate itself accurately without any additional infrastructure along the track. Since no additional installation outside the train is needed, this completely autonomous system appears to be highly preferable for future train control applications.

The eddy current sensor system has proved to be a robust system to acquire measurement data from the railway track. First experiments with natural data from field tests indicate the high level of reliability that can be reached with the proposed system.

Acknowledgements

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