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Multisensor Integration Methods in the Development of a Fault-Tolerant Train Navigation System

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Onboard train positioning (navigation) plays a vital and safety critical role in advanced Automatic Train Control (ATC) and Automatic Train Protection (ATP) systems. Such onboard systems are also essential for moving block signalling and control systems for railways. The application of multi-sensor fusion algorithms to the vehicle navigation field has made it possible to create inexpensive and accurate positioning systems, which will satisfy the railways' requirements. The state estimation methods involved in Kalman filtering have proved to be some of the most effective techniques in multi-sensor data fusion. A multisensor navigation system is introduced in this paper to address the shortcomings of the existing train positioning systems. The proposed system utilizes the Global Positioning System (GPS), Doppler radar, gyroscopes, tachometers, digital maps and balises. In order to provide fault detection and isolation capabilities, a hierarchical structure is proposed for the multi-sensor integration system in which different combinations of navigation systems would function. Several data integration nodes, including DR/GPS, DR/Balise, and DR/GPS/Balise, are studied in more detail and their performances are evaluated.

KEY WORDS

1. Multisensor Fusion. 2. Kalman Filter. 3. Train Navigation.

1. INTRODUCTION. The development of onboard navigation systems is one of the most important areas of current research in improving railway control systems. Existing train positioning systems suffer from a lack of accuracy, continuity and reliability, but advances in multisensor fusion techniques have made it possible to build inexpensive, accurate and reliable positioning systems that will satisfy the stringent requirements of future railway operators [1].

Traditionally a train's speed and distance travelled can be determined onboard by the use of odometers and track-based facilities, such as balises, for the initialization of the odometer systems. Wheel slip and slide contributes to the low accuracy of the odometer systems and the high cost of the balises (for a fine accuracy achievement) provides the motivation to discover other methods that can provide highly accurate positioning information with a reasonable reliability at low cost.

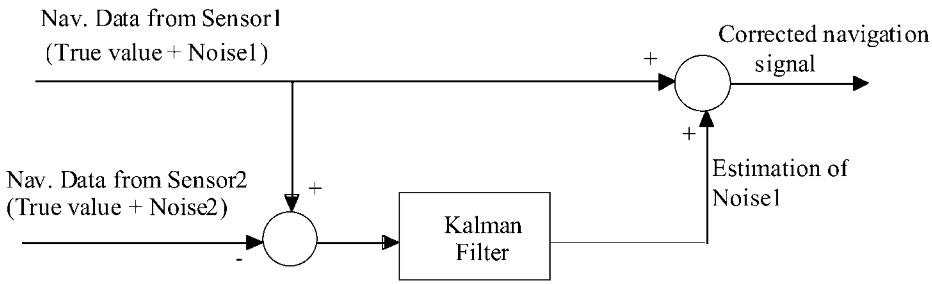

Figure 1. Integration of two navigation sensors using Kalman filtering.

Inertial navigation system (INS), GPS, Doppler radar, digital map and radio navigation systems are widely used in other positioning and navigation systems and, with some modifications, can be used for railway applications. Use of any one of these systems to provide high reliability and accuracy as a stand-alone positioning sensor raises costs dramatically. Use of a proper combination of sensors to form a multisensor navigation system, makes it possible to achieve the same or higher level of accuracy and reliability at a lower cost. In addition one of the main advantages of a multisensor fusion approach is to achieve a fault tolerant system at minimal additional cost. The Kalman filtering approach is the means of data integration used throughout this paper.

2. KALMAN FILTERING FOR MULTISENSOR NAVIGATION APPLICATIONS.

The Kalman filter is a technique that combines, in an optimum manner, the noisy measurements of a dynamic system with all the other information known about that system to obtain the best possible estimate of the variables or states in that system [3]. There is extensive information on Kalman filtering theory in literature including references [2] and [3]. Kalman filtering has been used in vehicle navigation as one of its earliest applications. Figure 1 represents the integration of two navigation sensors in its simplest form. After synchronisation and transformation to a common coordinate frame, the differences between two sets of sensor data are used as filter observations. The observation vector will include the error of the two sensors since the data from each sensor includes the true value of the measured variable and the sensor error (noise).

The filter design is based on the system error model and the state vector of this model includes various errors which may affect the navigation accuracy. In a multisensor integration navigation system, different redundant and/or complementary sensors providing acceleration, velocity, and position data, can be integrated in order to derive the navigation solution. The reliability and performance of a multisensor navigation system is affected by parameters such as the number of sensors used in the system (in terms of the level of redundancy which can be provided), the accuracy and reliability of the individual sensors, the integration method being implemented and the types of sensors that are used. Positioning sensors such as GPS and balises play an important role in bounding the drift error of dead reckoning systems and, because of its higher frequency of data update, GPS can be more effective in this role.

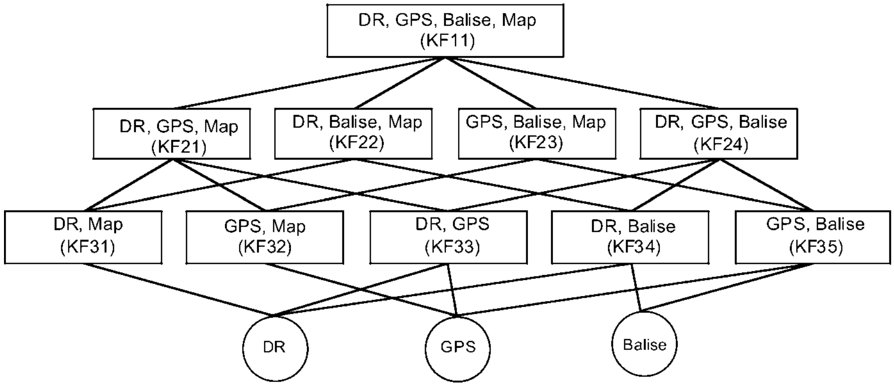

Figure 2. Multisensor integration design using hierarchical structure approach.

2.1. *Hierarchical Structure of Kalman Filters.* There is considerable information on centralized, decentralized and federated Kalman filtering approaches in the literature. The centralized (standard) Kalman filtering approach suffers from lack of fault tolerance, an important aim in the design of multisensor systems, whilst the main shortcoming of the decentralized approach is sub-optimality in the estimations. Also in a decentralized filtering approach, where several local and one master filter are functioning, there is a possibility of losing valuable measurement information that cannot be recovered by the master filter. There is also a lack of tolerance in the case of failure in the master filter. The federated Kalman filtering method is sometimes recognised as a special case of the decentralised Kalman filtering. It employs the principle of information sharing among the local Kalman filters and between the local and the master filters to improve the fault tolerance performance of the system in addition to providing more optimality of the estimations. References [4 and 5] provide extensive information on this approach.

Figure 2 shows a proposed hierarchical architecture for the integration of several navigation sensors. This approach, using centralized Kalman filters at each node, benefits from the optimality of centralised integration and, at the same time, the fault tolerance of the decentralised approach. This approach processes the data from all sensors in a hierarchy of filters using different combinations of sensors and different levels. As the figure shows, the hierarchical architecture forms a tree of filters where a set of filters emerges from each filter in a particular level.

For the proposed combination of sensors for the train navigation system, the hierarchy can be defined as a block diagram (see Figure 3) where each block represents one of the Kalman filters. In this design, the Kalman filters are not passing the information but rather are running in parallel with each other. At each instant of time, the system will consider the solution of the filter at the highest level which has a proper solution.

Obviously this design will result in a high computation load if all the combinations of sensors and filters are to be considered. The number of filters and combinations of sensors can be limited to a small number by considering the characteristics of the sensors and ignoring combinations which do not satisfy the overall requirements of the system (e.g. GPS/Balise and DR/Map). This design also provides a modular and flexible software design environment. Updating the lower level filters with the

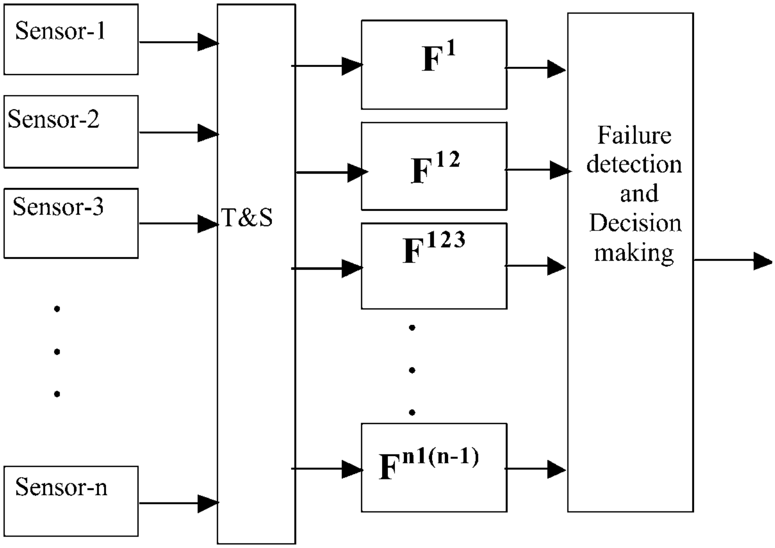

Figure 3. Parallel operation of filters in hierarchical design.

solutions from the upper level filters improves their performance. In this architecture all the integration nodes provide a navigation solution, with the more accurate solutions provided by higher levels. In case of a failure in one of the sensors or filters in the higher level, the system will use the solution from a lower level. Reference [6] provides detailed information on this integration architecture.

3. MULTISENSOR INTEGRATION MODULES.

The hierarchy approach to integration of the navigation sensors shown in Figure 3 includes several different integration modules, in which various combinations of the sensors are integrated. The GPS/DR, GPS/DR/Balise and Balise/DR integration modules are introduced in this section.

3.1. *GPS/DR Integration.* Speed sensors such as Doppler radar or tachometers in conjunction with heading and tilt data obtained from gyroscopes can provide train position and velocity information using the dead reckoning principle. For the train navigation application the following sensors provide the required navigational information in three dimensions with reasonable accuracy:

- Velocity sensor (giving the linear speed of the train in longitudinal direction)
- Heading Gyro (giving the heading angle of train)
- Tilt Gyro (providing the pitch angle of the train, due to line gradients).

Doppler radar is the preferred velocity sensor due to its better overall accuracy when compared with a tachometer which is subject to errors such as slip and slide. The Doppler sensor error can be considered as a low amplitude white noise.

In train navigation the pitch or inclination angle, which is the gradient of the line, can be measured accurately, stored in the system database and utilized on a "look-up" basis.

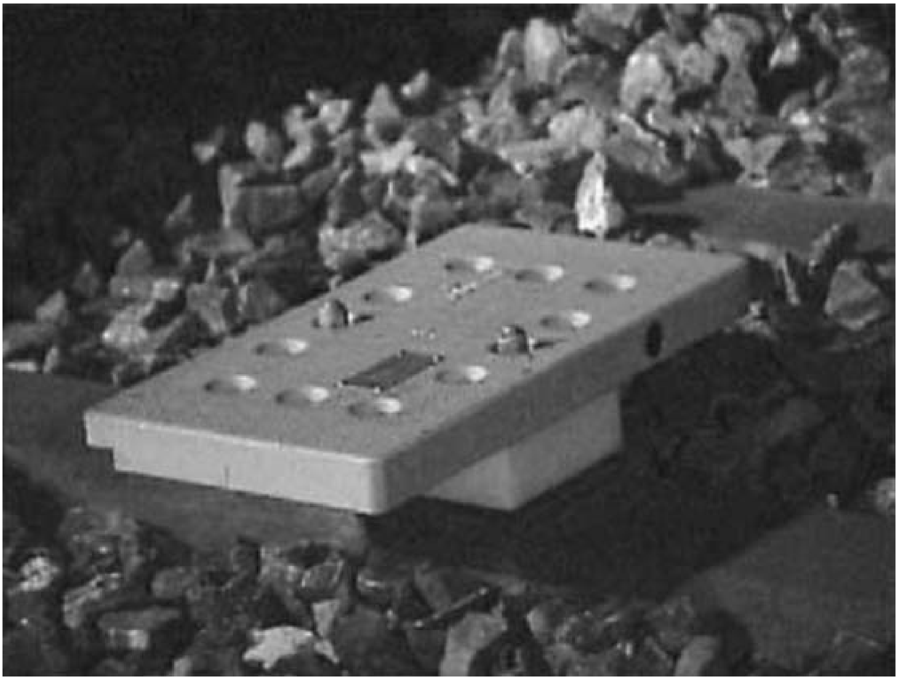

Figure 4. Typical balise installation.

A dead reckoning system can be modelled using different approaches known as Position Velocity (PV) and Position, Velocity, Acceleration (PVA) models [7]. Note that for a two dimensional PV model at least 4 (and for a PVA model 6) states are required to describe the system. Additional states such as gyro bias, random walk errors and Doppler scale factors can increase the accuracy of the model. The heading and tilt gyro errors can be modelled as first or second order Gauss-Markov processes.

There are two approaches to integration of the GPS and other navigation systems, cascaded and embedded; in this paper the cascaded approach has been used and tested. More detail on these approaches will be found in references [7] and [4].

The integrated navigation system error model can be expressed in state space form as:

$$X_{K+1} = \Phi X_K + w_K,$$

$$Z_k = HX_k + v_k,$$

where X_K is the state vector, Φ is the state transition matrix, and v_k and w_K define the process and measurement noises respectively.

3.2. *DR/Balise Integration.* Balises are used to pass information from track to train and also for train detection as a part of a railway signalling system. A balise is a track mounted transponder which is normally powered up by a passing train (e.g. with a 100 kHz inductively coupled power source), enabling it to provide data about its position, the location of the next balise(s) and, in the case of ATP systems, about the limit of movement authority available to a train. An inductive balise, shown in

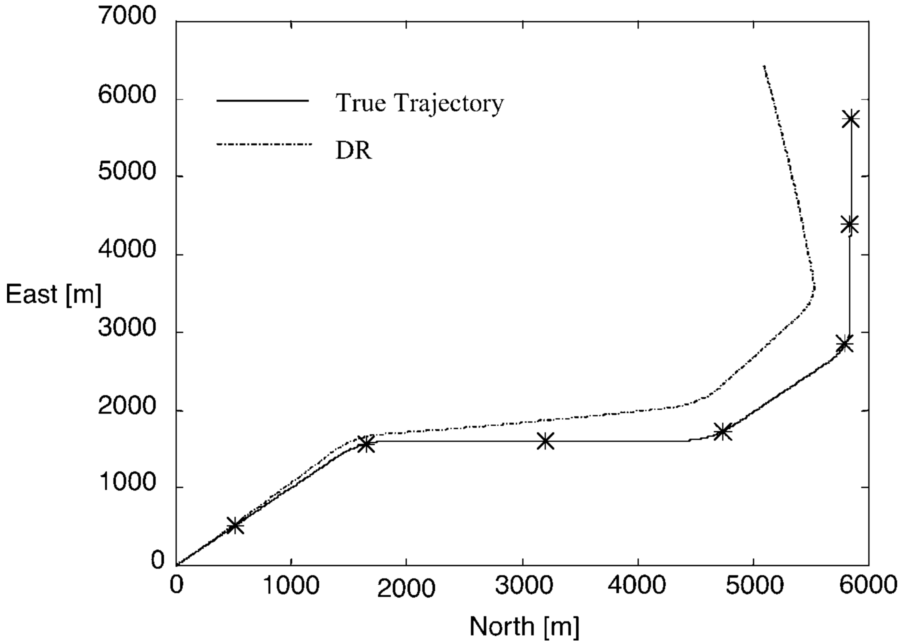

Figure 5. Simulated true and DR derived trajectory of the train.

Figure 4, comprises two basic components, the transponder itself and the interrogator. Transponders are usually passive and track mounted whilst interrogators are active and train mounted. The position of the balise can be expressed in terms of the distance from some initial point such as a station or, in a 3D format, as latitude, longitude and height in ECEF coordinate frame, or eastings, northings and height in a local navigation coordinate frame. In navigation applications, the balise position data can be used to re-calibrate the DR system with a high level of confidence. The balise positioning error can be modelled as zero mean Gaussian white noise. The variance of this error is very low since off-line highly accurate positioning is possible.

3.3. *DR/GPS/Balise Integration.* In this approach the system works in the DR/GPS integration mode until the balise data becomes available. The role of the balise in this integration system is to increase the reliability and availability of the navigation system by providing accurate positioning data, since GPS data is not always available. The loss of a balise on the line, an event which must be expected, or a shortage of DR data due to mechanical or electrical problems in the system, can be compensated by using GPS data. Balises can be used to providing accurate positioning data when GPS data is unavailable.

4. SIMULATION RESULTS.

Having discussed the various combinations of navigation systems, we can investigate the relative merits of each by simulation. As an example, we use the trajectory shown in Figure 5. The actual trajectory is shown with a solid line and the trajectory determined by DR alone is shown with dotted line. It is assumed that balises are placed at intervals of 1000 m and are shown

Table 1. Error budget for different sensors.

Error source	Heading Gyro	Doppler Radar
	σ	σ
Random walk	20 deg/hour	0.1 m/sec
Bias	0.02 deg/sec	-
Scale factor	0.05	0.02

Table 2. Standard deviation and time constants of the GPS errors.

Error Type	**Standard deviation** σ **[m]**	**Time Constant** $1/\beta$ **[s]**
Ionospheric refraction	5	1800
Tropospheric refraction	2	3600
Multipath error	5	600
Satellite Broadcast Parameter error	30	3600
Selective Availability	30	180

Table 3. Positioning error for different navigation modes.

Integration Mode	*Position Error SD, m*	
	North	East
GPS	23.6	14.6
DR	243.2	248.6
DR/GPS (PV model)	11.05	10.4
DR/GPS (PVA model)	6.01	9.01
DR/DGPS (PV model)	3.4	2.7
DR/DGPS (PVA model)	3.3	2.6
DR/Balises	10.1	11.3

in the figure as star symbols along the actual trajectory. Table 1 lists the error budget of the DR system used in this experiment.

The GPS data was generated using simulated trajectories for 8 satellites in orbit in conjunction with the simulated train trajectory. The position data from the GPS has been estimated using a local Kalman filter. The GPS errors have been modelled with a second order Gauss-Markov process for the selective availability (SA) error and with first order Gauss-Markov processes for other errors, including ionospheric refraction, tropospheric refraction, multipath and also satellite broadcast parameters errors. The standard deviation and time constants of the errors used in this experiment are listed in Table 2.

Table 3 represents the standard deviation of the positioning error for the different stand-alone and integration modes of the navigation system. As expected use of a

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Table 4. The effect of increasing the balise distance on positioning error.

Balise Interval(m)	*North direction*	*East direction*
500	3.8	2.6
600	4.7	3.8
700	5.2	3.6
800	6.1	6.7
900	11.1	12.1
1000	10.1	11.3
1100	9.1	9.6

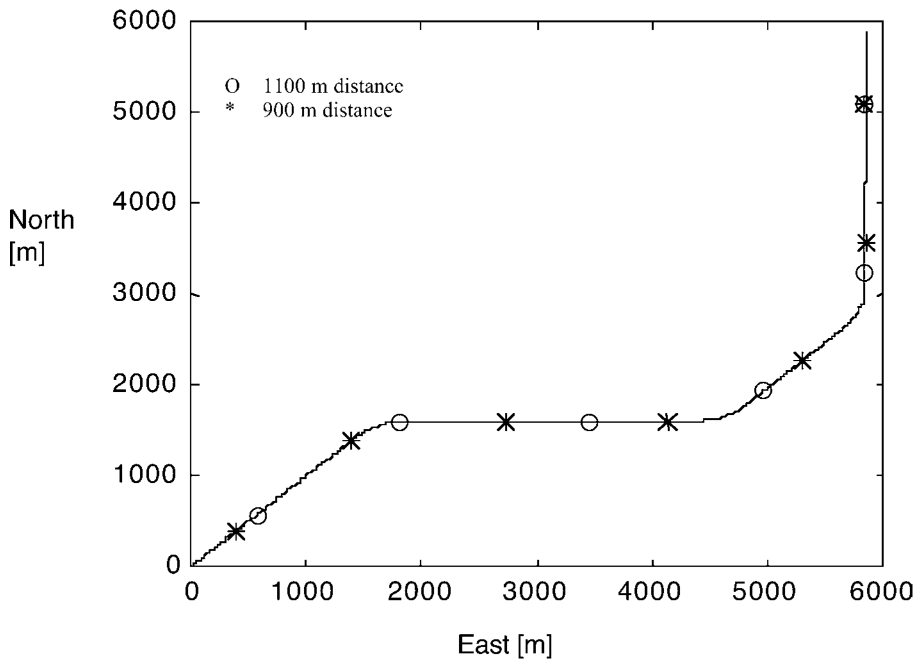

Figure 6. Balises location for 1100 and 900 distance intervals.

differential GPS could improve the performance of the system considerably, however, it may reduce the availability of the system due to the low coverage of the differential signal on the railway line. Table 3 shows the improvement achieved by the DR/Balise integration system compared to the stand-alone DR system. In this example, balises are considered to be spread at 1000 metre intervals. The position error of the DR/Balise integration system is a function of the distance between balises.

Table 4 represents the effect on the positioning error of the DR/Balise integration system by varying the distances between balises. In this table balise separation from 500 to 1100 metre has been examined. An important point highlighted by these results, is that the positioning error in this method is not just related to the distance between balises, but also to their location with respect to the geographical characteristics of the line. Installing balises after every curve in the line would be efficient

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Figure 7. Trial Section of the Sheffield Supertram Line.

in bounding this error, which results from the scale factor or other gyro system errors which exhibit their effects mainly after deviation from a straight trajectory.

This point is demonstrated in Table 4 where the error of the integrated system with the balises spaced at 900 metres is higher than when they are 1100 metres apart. Figure 6 shows that when the balises are spaced at 900 metre intervals, they are almost all located before the turns, whilst with 1100 metre spacing they are after the turns. On single line railways, it will therefore be necessary to consider the effect on the navigation system performance of the balise positions in both directions.

5. REAL DATA INTEGRATION.

The approach developed for the integration of the navigation sensors was tested with real data using the Sheffield Supertram line. Figure 7 shows the map of a section of the Supertram line on which the test was carried out. The section includes 11 stations which together with some arbitrary points along the track, were defined as the control points for the research work.

The trial was conducted by recording the navigational data from a selection of navigation systems installed on one of the trains. The systems were a Motorola GPS system from Oncore Ltd, a Doppler radar speedometer developed specifically for vehicle navigation by Ferranti Technology Ltd, a Fibre Optic heading Gyro (FOG), manufactured by Andrew Corporation (now KVH Industries Inc.), and the train's tachometers.

5.1. *Performance Evaluation.* The evaluation of the system performance required knowledge of the true train trajectory and two options were available to provide this. The first option was to use as a reference a more sophisticated navigation system with data more accurate than that of the systems being studied. The second was to make use of accurately positioned control points along the track. The

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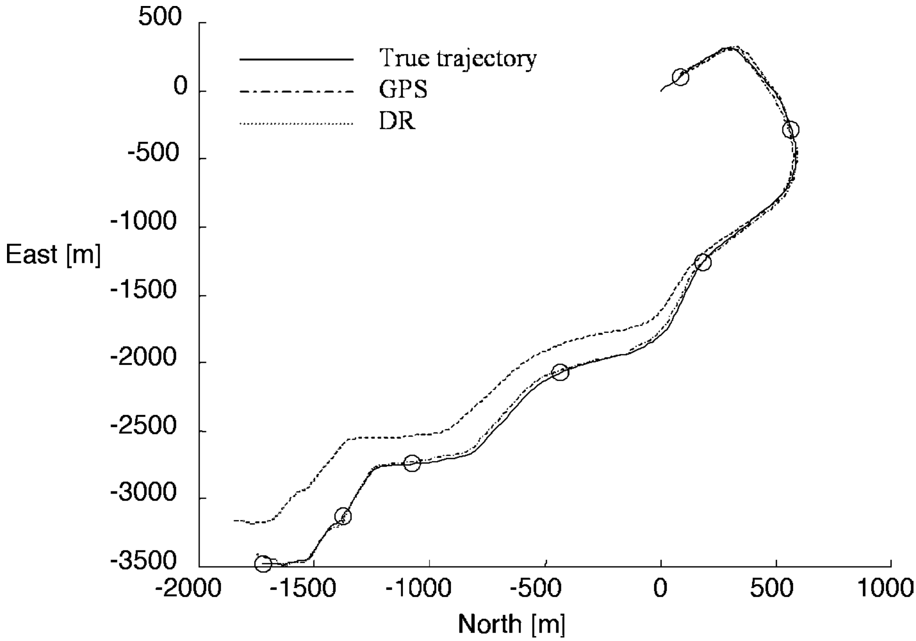

Figure 8. Trial section of the Supertram line trajectory.

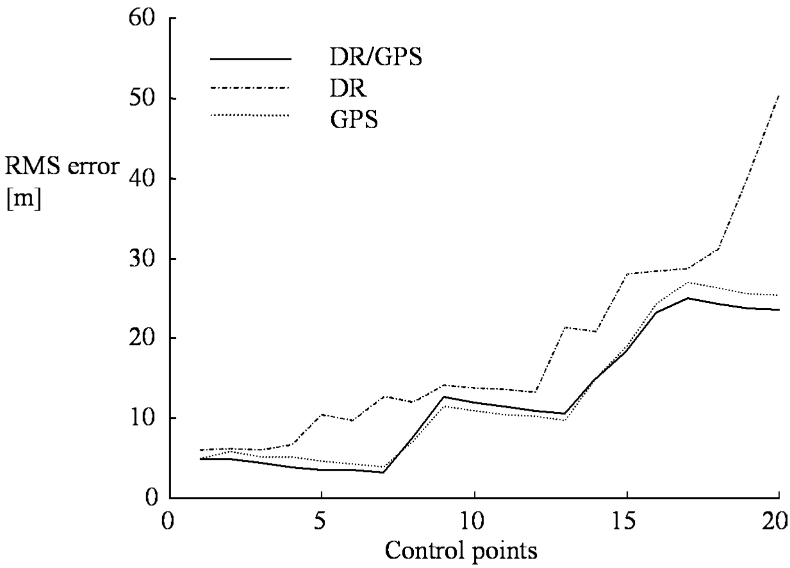

Figure 9. GPS, DR and DR/GPS integration northerly positioning error.

navigation solution from the system under test is then compared with the control point position whenever a control point is reached. The first option can provide the opportunity of a continuous evaluation of the system, while the second facilitates a discrete evaluation. The second approach was used in this trial using several real and

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Table 5. Standard Deviation of the positioning error for different integration modules.

Integration Mode	Position Error SD, m	
	North	East
GPS	22.48	32.03
DR	42.3	106.2
DR/GPS (PVA model)	21.05	30.2
DR/Balises (Position update)	22.8	51.6
DR/Balises (Position and heading update)	14.5	36.1
DR/GPS/Balise	9.8	12

virtual control points whose positions were selected from the ordnance survey map of the line.

5.2. *Integrated Navigation Systems.* Using the navigation sensors detailed above, the multisensor navigation system was tested in three different integration modes, DR/GPS, DR/Balise, and DR/GPS/Balise. In all these modes, the DR system was used as the reference system. Figure 8 represents the normalized GPS and DR data in comparison with the Geographical Information System (GIS) data for the Sheffield Supertram line. In this figure the station positions are marked with an "O" sign. The DR data from the gyroscope, Doppler radar, and tachometer were recorded at a frequency of 10 Hz, while the GPS data was recorded at its standard update frequency of 1 Hz.

5.2.1. *DR/GPS Integration.* In this mode the integration of the DR and the GPS data was implemented in a cascaded filter approach. Data integration was applied at a lower frequency (0·1 Hz) in order to consider the time correlation of the GPS data. Figure 9 shows the RMS northerly errors of the GPS, DR, and DR/GPS integration and Table 5 presents the standard deviation of these errors in a quantitative form. As the results show, a considerable improvement has been achieved when compared with the DR use only.

5.2.2. *DR/Balise Integration.* Use of the balises in a multisensor navigation system may ensure the availability of accurate positioning data in the absence of GPS data. Balises can provide highly accurate positioning data to reinitialise the system frequently and to bound the DR error if there is a GPS failure. The effects of balise data were studied in the DR/Balise integration mode. Figure 10 shows the RMS of the northerly positioning error, and Table 5 presents the standard deviation of the

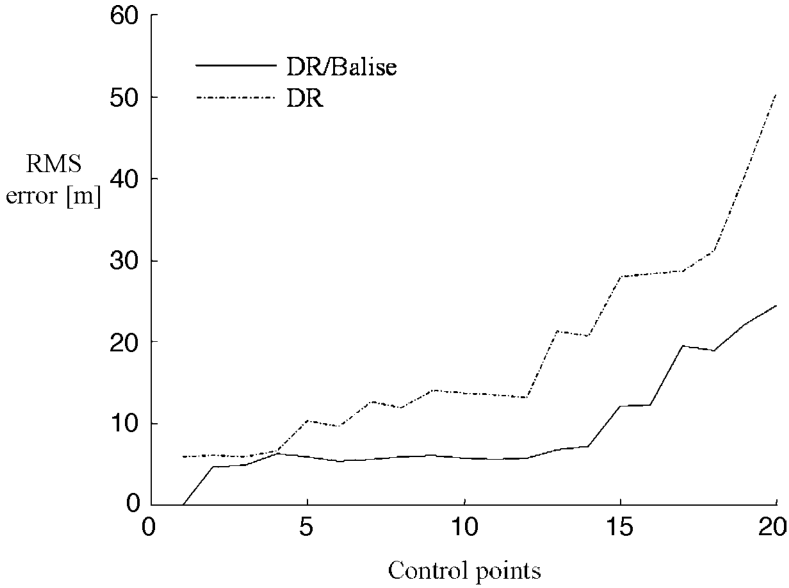

Figure 10. DR and DR/Balise integration northerly positioning error.

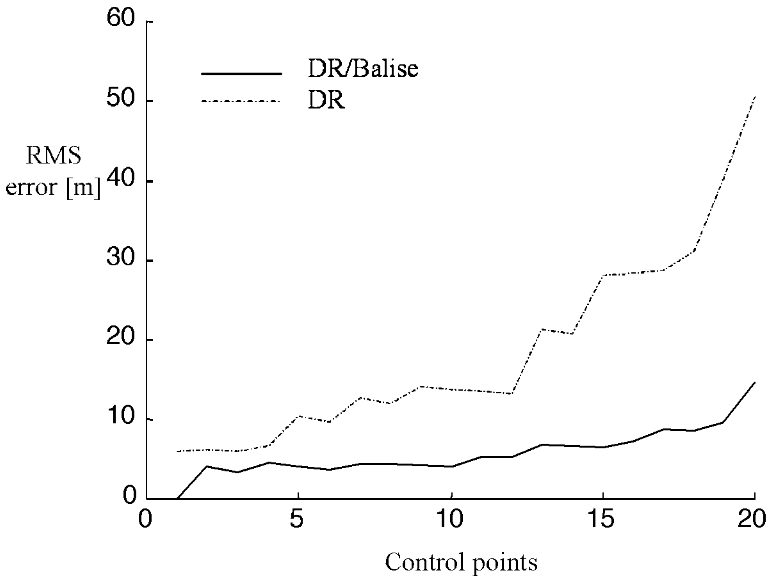

Figure 11. DR and DR/Balise integration northerly positioning error with heading update.

northerly and easterly positioning errors. This integration mode was studied using two different approaches. In the first series, only the positioning data of the balises were used to update the estimation algorithm, while in the second approach the heading angle of the balise was used in addition to the positioning data.

Figure 10 corresponds to the first and Figure 11, to the second approach. These results show that the heading data can improve the positioning accuracy considerably.

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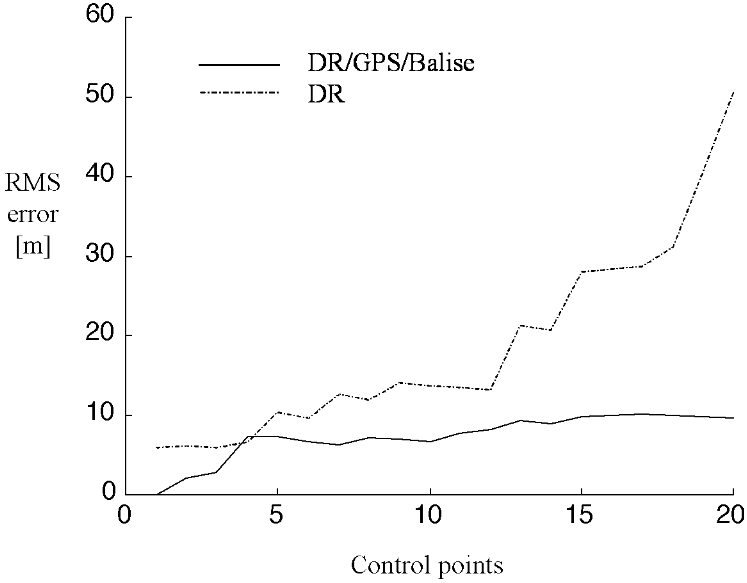

Figure 12. DR and DR/GPS/Balise integration northerly position error.

Different parameters, such as the distance between balises, the speed of the train, and the geographical location of the balises may affect the performance of DR/Balise integration system. The best positions to install balises on uni-directional lines are after each curve and, on bi-directional lines, before and after each curve. In addition to these locations, the installation of balises in stations may provide the opportunity for system re-calibration whilst the train is stationary.

5.2.3. *DR/GPS/Balise Integration.* In the last section, the results of the integration of dead reckoning data with balises was studied. In the DR/Balise system the integration algorithm estimates the dead reckoning position and velocity errors. DR/Balise integration is applied whenever the balise data become available (i.e. when the position of a balise is reached). For the period of transit between two balises, the stand-alone DR system is used to derive the navigation solution. In a DR/GPS/Balise integration system, the DR/GPS integration mode is used for the distance between two balises. When the balise data becomes available, the system uses the DR/GPS/Balise integration mode, from which the GPS and dead reckoning errors can be estimated.

Another important point of note relates to the accuracy of the positioning data provided by the balises that are, potentially, much more accurate than the GPS data, hence giving more accurate error estimations when the system is updated with the balise data. This is particularly true when the GPS data is derived from a moving receiver, as is the case here. Given this fact, switching from a DR/GPS/Balise integration mode, which provides accurate estimations, to the DR/GPS integration mode shortly after passing a balise, may nullify any positive effects of the balise update on the navigation accuracy. The GPS data should therefore be suppressed until a predefined time limit is reached or a failure of the DR system is detected.

The results presented in Table 5 show an improvement in the standard deviation of the northerly and easterly positioning data to 9·8 and 12 metres respectively.

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Figure 12 shows the northerly RMS error of the DR/GPS/Balise integration system. In this mode of integration DGPS data would improve the results and provide more accuracy in the positioning data.

6. CONCLUSION. The work described in this paper has attempted to demonstrate that tangible benefits can be gained by integrating different sensor information in a train navigation application. A high level of fault tolerance and reasonable accuracy are the characteristics of this system which can then satisfy the requirements of train protection systems in both fixed block and moving block approaches to train control. Each of the sensors used in this trial have their shortfalls but a combination of sensors may overcome the shortcomings of each individual sensor. By use of a multisensor integration approach (i.e. multisensor fusion) in train navigation, an improved positioning system can be obtained. In the proposed hierarchical architecture presented, the optimality of the solutions of the centralized approach and fault tolerance of the decentralized approach can be achieved.

REFERENCES

[1] Mirabadi, A., Mort, N., Schmid, F. (1996). Application of Sensor Fusion to Railway Systems. *Proceedings of the 1996 IEEE/SICE/RSJ international conference on multisensor fusion and integration for intelligent systems*, Washington DC, USA, pp. 185–192.

[2] Brown, R. G. (1997). *Introduction to Random Signal Analysis and Kalman Filtering*. John Wiley & Sons.

[3] Maybeck, P. S. (1979). *Stochastic models, estimation and control*, Vol. 1. Academic Press.

[4] Gao, Y., Krakiwsky, J., Abousalem, M. A. (1993). A Comparison and Analysis of Centralized, Decentralized, and Federated Filters. *Journal of Institute of Navigation*, **40**, 69–86.

[5] Carlson, N. A., Berarducci, M. P. (1994). Federated Kalman filter simulation results. *Navigation*, **41**, 297–321.

[6] Mirabadi, A., Mort, N., Schmid, F. (1999). Design of Fault Tolerant Train Navigation Systems. *Proceedings of the American Control Conference, ACC*, San Diego, USA.

[7] Schwarz, K. P., *et al*. (1994). Aided versus embedded a comparison of two approaches to GPS/INS integration. *Proceedings of the IEEE Position Location and Navigation Symposium*, Las Vegas, NV, USA.