3rd International Conference on Through-life Engineering Services

Precise vehicle location as a fundamental parameter for intelligent self-aware rail-track maintenance systems

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Abstract

The rail industry in the UK is undergoing substantial changes in response to a modernisation vision for 2040. Development and implementation of these will lead to a highly automated and safe railway. Real-time regulation of traffic will optimise the performance of the network, with trains running in succession within an adjacent movable safety zone. Critically, maintenance will use intelligent trainborne and track-based systems. These will provide accurate and timely information for condition based intervention at precise track locations, reducing possession downtime and minimising the presence of workers in operating railways. Clearly, precise knowledge of trains' real-time location is of paramount importance.

The positional accuracy demand of the future railway is less than 2m. A critical consideration of this requirement is the capability to resolve train occupancy in adjacent tracks, with the highest degree of confidence. A finer resolution is required for locating faults such as damage or missing parts, precisely.

Location of trains currently relies on track signalling technology. However, these systems mostly provide an indication of the presence of trains within discrete track sections. The standard Global Navigation Satellite Systems (GNSS), cannot precisely and reliably resolve location as required either.

Within the context of the needs of the future railway, state of the art location technologies and systems were reviewed and critiqued. It was found that no current technology is able to resolve location as required. Uncertainty is a significant factor. A new integrated approach employing complimentary technologies and more efficient data fusion process, can potentially offer a more accurate and robust solution. Data fusion architectures enabling intelligent self-aware rail-track maintenance systems are proposed.

Keywords: vehicle location; uncertainty; data fusion architecture

1. Introduction

The rail industry in the UK is undergoing substantial changes in response to a modernisation vision for 2040. Gradual development and implementation of these changes will lead to a highly automated and safe railway. Real-time regulation of traffic will optimise the performance of the network. In this scenario, trains will run in succession within an adjacent movable safety zone. Enhanced protocols will communicate the location of each train to control centre. Control centre will then command optimised energy and network capacity travel speed. Future rail maintenance will use intelligent trainborne and track based systems. These will provide accurate and timely information for condition based intervention at precise locations, reducing possession downtime and minimising the presence of workers in operating railways. Clearly, the precise knowledge of trains' real-time location is of paramount importance.

The positional accuracy target of the UK future rail is < 2m [1]. In the USA 3.5m has been specified [2]. However, a finer resolution is required for locating faults such as damage or missing parts. A critical consideration of these requirements has been the capability to resolve train occupancy in adjacent tracks, with a high degree of confidence.
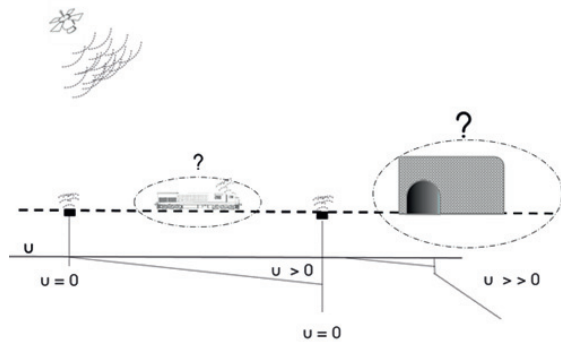
Fig. 1. Train location scenario and illustration of its uncertainty (U).

Currently track circuits, axle counters and balise transponders are the primary technologies employed for train location [1, 3]. However, these systems only provide location within discrete track sections. Although they can be accurate at the point of register, location uncertainty of moving trains rapidly escalates. Resolution is even poorer in rural sections of the track, where the length of track between these wayside systems can be of several km.

A relatively small number of trains are currently fitted with standard Global Navigation Satellite Systems (GNSS), primarily employed for basic fleet management and passenger information purposes. However, standard GNSS is not capable of precisely and reliably resolving the demanding location requirements of the future train [4]. Figure 1 illustrates the location case scenario studied.

This work starts by reviewing technologies currently used for train location, in the context of the needs of the future rail. While a number of reviews have been published before [5, 6]; these either are out of date or not consider the demands of the future rail. Location uncertainty sources are discussed. Previous literature integrated location systems and their data fusion architectures are discussed. Finally data fusion architectures are proposed to assist the decision making process in intelligent self-aware rail-track maintenance systems that use location as a fundamental parameter.

2. Technologies for rail track vehicle location systems

Future rail-vehicle track location systems have stringent requirements resulting from enhanced safety, increased network capacity requirements and optimized traffic control. Traditionally, signaling systems have been used to broadly estimate the position of trains [5]. Because track coverage varies largely from urban to rural areas, location and occupancy certainty cannot always be reliably resolved. Location systems are generally classed as follows [7, 8]:

2.1. Global Navigation Satellite System (GNSS).

GNSS uses a constellation of orbital satellites that transmit positional data to a vehicle receiver. A very accurate time-stamp and a trilateration algorithm permit precise computation of its location, usually within a few meters. Standard GNNS alone, however, does not provide enough accuracy [4] for the location needs of the train of the future.

Augmented GNSS, most commonly in the form of differential global positioning system (DGPS), is used to enhance rail positional accuracy, usually to within 2-3 m [9, 10]. DGPS employs accurately positioned fixed point receivers that provide a correction factor for the computation of location [7]. A higher grade DGPS train-location system with < 20 cm resolution has been recently investigated in the USA [11].

Convenience and the ability to provide the highest-accuracy currently available have resulted in GNSS technology rapidly becoming commonplace for rail track applications. However, GNSS main shortcoming for this application lies in its reliability. Ingress to tunnels, dense forests, tall buildings and passage through deep and narrow track openings significantly degrade or even prevent reception temporarily [12]. Given the speed at which trains run, even a few seconds signal blackout adds to substantial uncertainty.

An increasing number of railway applications using GNSS as part of an integrated location system have been investigated in recent years. These include route mapping for railway asset management [13], rail track profiling [10], train navigation [14] and automated train control [11]. Naturally, the number of patents issued related to GNSS train applications shows a steady growth [15].

2.2. Radiolocation

Radiolocation methods locate vehicles by directly measuring time of radio signals traveling between the vehicle and a number of fixed stations. As with GNSS, trilateration can be used to compute the vehicle's position [8]. The nominal accuracy of radiolocation is in the order of 30 m. However, interference and atmospheric conditions often increase uncertainty up to 400 m [7]. Asset management of trains based on the global system for mobile communication (GSM) using an integrated location system has been demonstrated in Portugal [16].

2.3. Proximity

In proximity systems, location of a vehicle is given by the relationship between the vehicle and fixed location devices strategically positioned throughout the route. They are extremely accurate at point of register, but uncertainty rapidly increases shortly after. Positional accuracy can be enhanced by the use of an increasing number of devices. This, however, makes it inevitably expensive.

Block occupancy and broad location of trains largely rely on wayside track signalling equipment, such as track circuits and axle counters; which can be classed as proximity devices. Track circuits typically use a low voltage current applied to electrically isolated sections of the track rails. Current flow interruption by train wheels provides indication of train presence [17]. Axle counters are electro-magnetic devices capable of registering the presence of rail vehicles. They are typically used in pairs, and by counting the number of axle sets in-and-out of track sections, are also capable of

determining travel direction [18]. In general, signalling systems are susceptible to failure by either inherent or external factors, which can result in costly disruptions. A typical example is the failure of track-circuit systems due to tree-leaves, flakes, etc.; which degrade their conductivity [18].

Balise transponders [6] are a principal wayside component of modern signalling and control rail platforms [19]. Balises are placed along the track, at suitable intervals and also at some key locations. They can be passive or active devices. Typically, balises transmit a signal that includes some basic information to a train-borne receiver.

Other proximity technologies used in railway track applications include Radio Frequency Identification (RFID) and Doppler radar. Typical tag reading RFID systems use an antenna attached to a signal processing unit. The processing unit transmit an RF signal and monitors the signal returning from the antenna. Precise positioning of RFID tags using a phased array antenna has been investigated [20]. A number of rail applications involving traffic management and tolling have been reported in Hong Kong [21, 22] and the USA [22], respectively. Advanced applications include the use of RFID tags interfaced with rail-vehicle axle temperature sensors, enabling quasi real time condition monitoring (CM) of bearings [23].

Early command and communication systems integrated train-borne Doppler radar systems to estimate moving-trains position, based on frequency shift measurements [24]. However, Doppler systems can also be greatly affected by interference, among other disadvantages [6]. Similarly, other researchers [25, 26] have used differential eddy current devices to compute velocity of trains, based on localised conductivity and magnetic permeability track fluctuations.

2.4. Dead reckoning

Localization of a vehicle by dead reckoning involves computing of its distance and direction of travel from a known fixed point. Typically, several devices such as odometers, tachometers, accelerometers, clocks, computers and communication systems might be used in conjunction to measure, record and update travel data [26].

Linear accelerometers are used to measure acceleration in different dimensions. Position can be then computed by integration [6, 27]. Gyroscopes are used to measure angular rotation of the vehicle. Odometers and pulse counters are relatively simple components used to estimate distance travelled by wheel rotation [13].

Uncertainty of dead reckoning systems builds up over long track distances due to inherent cumulative errors typically caused by wheel slippage, wear of wheels and mechanical parts, bias, hysteresis, etc. [6, 27]. In addition, deviation from the originally planned route or track can lead to considerable errors. However, dead reckoning can be a useful complement when navigating through GNSS "dark areas" [28] i.e. tunnels, etc. Table 1 summarizes advantages and disadvantages of location techniques currently used for train location

Table 1. Advantages and disadvantages of current location techniques used in rail applications

Location technique	Advantages	Disadvantages
GNSS	Accurate to within a few meters, high quality systems are accurate to < 20 cm	Signal unavailability through "dark areas" i.e. tunnels, dense vegetation, etc.
	Non-invasive	Affected by poor weather conditions and other sources of interference
	Relative low cost, no major infrastructure investment	
	Wide coverage available	Dependency on external signal providers
		May require accuracy enhancement to achieve the demands of the future rail
Radiolocation	Established automatic vehicle location (AVL) technique	Susceptible to interference and signal "dark areas"
		Less accurate than GNSS
		Requires infrastructure investment
Proximity	Highly accurate at point of register	Fixed wayside technology
		Maintenance costs
	Established technology, major component of rail signaling systems	Reliability (false signals)
	Generally less affected by interference	
Dead reckoning	Able to operate in "dark areas" and poor weather conditions	Cumulative errors lead to large uncertainty
	Accurate over short track distances	Deviation from planned route adds to substantial errors
	Train-based, self-contained systems	

3. Location uncertainty

In addition to illustrating the train location scenario, figure 1 also illustrates its some of the currently known inherent sources of uncertainty (U). As seen in this figure, uncertainty of location based on signaling systems rapidly escalates between track signaling elements, only being certain at point of register. Inconsistent length of signaling blocks makes calibration extremely challenging.

GNSS based location of trains typically resolves the position of a train within a surrounding uncertainty zone of a few meters. Several factors are involved, such as satellite signal quality and others that are inherent to the GNSS system such as: clock errors, availability of differential calibration signals, etc. Also of great significance for rail systems is the uncertainty resulting from vehicle navigation through GNSS dark zones, particularly tunnels. Unavailability of satellite signals results in rapidly escalating uncertainty. Once out of the tunnels, GNSS systems take time to reacquire signals from a sufficient number of satellites, which amounts to further uncertainty. Supporting dead reckoning systems can also become largely uncertain due to cumulative errors. A number of algorithms and parameters may be used to compute position; and these also may have some inherent uncertainty.

Table 2. Previous integrated location systems summary

Application	Accuracy target (m)	Sensor technology employed	Position estimation approach	Author reference # year of publication
Control, command & com.	--	Odometer Balises Doppler radar	Kalman filter	Anon. [24], 1990
Measurement of railway profiles & train simulator	± 10	GNSS Tilt meter axle pulse generator Gyroscope	Unspecified algorithm	Leahy, et. al. [10], 1993
Navigation through GNSS dark areas	--	Odometer Accelerometer GNSS	Integration of acceleration	Mazl, et. Al. [12], 2003
General train location	--	Eddy current GNSS	Extended Kalman filter	Bohringer [25], 2003
Navigation through GNSS dark areas	--	Accelerometer Odometer GNSS	Kalman filter	Ernest et al. [28], 2004
Route mapping for asset management	1m	GNSS Gyroscopes Tilt meter Pulse counter Cameras	Kalman filter	Judd et al. [13], 2005
Train collision system	30m	Accelerometer Odometer GNSS	Kalman filter	Acharya et. al. [29], 2010
Train positioning system simulation	--	GNSS Balise Odometer Accelerometer Gyroscope	Gaussian particle filter and Kalman filter	Bai-Gen & Liu et. al. [30, 31], 2011, 2012
Map train navigation system	--	Mapping Accelerometer Gyroscope	Bayesian filter	Heirich et. al. [32]

4. Overview of integrated rail location systems research

Precise and reliable estimation of train-vehicle location in real-time is not a new challenge. A number of previous global studies attempt to resolve location more accurately using a combination of complimentary location techniques and data fusion algorithms (see table 2). Typically, accuracy demands of the proposed systems have been largely defined by particular functionality requirements e.g. general location and navigation, collision systems, etc. However, the authors have found no previous publication attempting to accurately estimate rail vehicle location of the UK's future rail systems supported by intelligent maintenance systems.

Listed in chronological order, table 2 details on some of the attributes of previously published integrated train-location solutions. As clearly illustrated, most location systems so far investigated use a combination of technologies that are heavily reliant on GNSS. Kalman filter appears to be the preferred mathematical algorithm employed for location.

Commercial integrated solutions currently offered do not disclose enough of their technical details or their approaches

to sensor fusion and estimation algorithms. Therefore these are not included in our analysis.

5. Intelligent rail-track maintenance: data to information to decision transitions using precise location

It is envisioned that future trains will possess track inspection capabilities (e.g. ultrasound and cameras) [3]. For intelligent localised track condition-based maintenance, precise location knowledge of damage entities or missing parts is of paramount importance. Enhanced intelligent maintenance architectures can then allow for integration of optimised scheduling and planning of these activities.

Integration of data from different sources to enable tangible interpretation and decision making is formally achieved through data fusion principles. Data fusion models/architectures can be used to structure high level transitions from data typically from sensors, to information; and subsequently to assist decision making.

Within the context of intelligent maintenance, integrated systems should automate the retrieval of information that decision makers require to make sound judgments [33]. Data fusion establishes links between data sources and closes the loop from the minutiae of data collection to strategic decision making. Distinctively, it maximises the useful information content, for improved reliability or discriminant capability whilst minimising the quality of data ultimately retained.

Clearly, data fusion not only implies fusion from data sources (i.e. sensors) but it goes further by inferring states and ultimately prompt decision making. Depending on the data and information types, the lower level fusion processes employ a variety of analytical or statistical algorithms for collecting and reporting the data and information.

5.1. Intelligent localized self-aware rail-track maintenance: application of the JDL model

The data to information and information to decision transitions using location knowledge for intelligent self-aware maintenance have been illustrated using the JDL model. This model was standardised by the US military joint directors of laboratories (JDL) [34]. The model considers combination of data and information for decision process at every step from the measured data to performance appraisal. Science and engineering disciplines have adapted the JDL model approach since. Figure 2 shows a simple schematic of the JDL model. Figure 3 shows the JDL model adaptation for intelligent localized self-aware rail-track maintenance. The model hierarchy can be explained as follows:

- *Sources*: 2 principal sensor sources are proposed. One is a set of entities associated with accurate positioning of the train. A second one is associated with the health condition of the track. These are continuously supported by database and tacit knowledge inputs. The sensing technologies likely to be associated with these are in one hand the location estimation sources such as GNSS, odometer, gyroscope, accelerometer, rail-track digital mapping, signalling, etc. and in the other hand the condition based maintenance sources, which are in line with UK's Network Rail

preferred monitoring technologies: Ultrasound, 3D profile, linescan and thermal cameras.

- *Level 0* processing: source processing specific to location and condition of the track, to address process estimation and processor computational and scheduling requirements by normalising, formatting, ordering batching and compressing input data.
- *Level 1* object refinement: locates and identifies objects. A global picture of the situation is reported by fusing the attributes of an object from the multiple sources. In this particular scenario, this level can be broken into lower fusion levels. At the lowest level (level 1.2, not shown). Both the location of the train and in-service track deterioration are resolved/inferred by concurrent processes. The outputs of this sublevel are input to the model's next intermediate level (level 1.1, figure 4), where a further fusion process integrates positional coordinates and damage condition; thereby defining them as localised damage objects.
- *Level-2* situation assessment: localised damage condition instances detected in the track are identified and analysed. Consequences of track deterioration e.g. derailment, its location, remaining useful life and eventually failure are evaluated.
- *Level-3* Threat assessment: results from level 2 in terms of possible opportunities for operation are interpreted. Is immediate intervention required? What is the risk level? Can maintenance be postponed? What is the costs trade-offs?
- *Level-4* process refinement: achieves improved results by continuously refining estimates and assessments by subsequent train borne inspections.
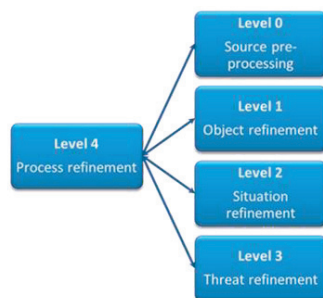

Fig. 2. JDL data fusion model schematic refs [34]

6. Discussion: Towards location enabled intelligent self-aware rail track maintenance systems

Precise location is a fundamental parameter for intelligent self-aware maintenance practices of the future UK rail-track, enabling most effective decision making. It is generally envisioned that an array of highly effective positioning systems will need to be employed to meet these stringent location demands [3], whilst supporting optimized track usage too.

From the analysis of the literature, it is clear that current location technologies and approaches cannot resolve location with enough accuracy and robustness. GNSS (DGPS) is likely to be a key component of this future array, due to its high accuracy potential at low cost. DGPS is capable of resolving location in wide open sections of the track, with relatively low uncertainty. At present, however, navigation satellite signals are largely under American control, which means that signals can be degraded or even be made unavailable when American national security is at risk. Due to delays to the European Galileo program, full availability of alternative satellite signals has been postponed [35].

Previous integrated approaches, have so far failed to mitigate uncertainty sufficiently to enable the estimation of location as required. Uncertainty mitigation strategies and the evaluation of estimation algorithms are part of our current research.

In the future, location architectures will be supported by accurate landmark digital maps. DGPS will be complemented by dead reckoning systems that will compute location thorough GNSS dark zones. Modern European Rail Traffic Management System (ERTMS-level 2) signaling balises will act as milestones and correct distance measurement errors and route changes, ensuring robustness even when navigating through GNSS dark-zones. Integration of balise and GNSS systems is currently under investigation [36]. In the UK, ERTMS level-2 will be gradually implemented on a number of the main lines over the next 6 years [37].

A great advantage of high-level data-fusion architectures is their flexibility. Figure 3 can be adapted to the current or future sensing technology and thus remain valid.

7. Conclusion

Intelligent self-aware rail-track maintenance systems supporting effective decision making, are key systems to support the needs of the future UK rail. A fundamental parameter to their success is the knowledge of the damage or missing parts location for their effective monitoring. However, no current technology is able to resolve the location demands of the future rail accurately and reliably on its own.

While GNSS provides the highest accuracy and is nominally capable to meet the accuracy demands of the future rail; it can also be affected by signal availability and degradation, interference, and adverse weather. Proximity and dead reckoning systems can help resolving location in these GNSS adverse conditions.
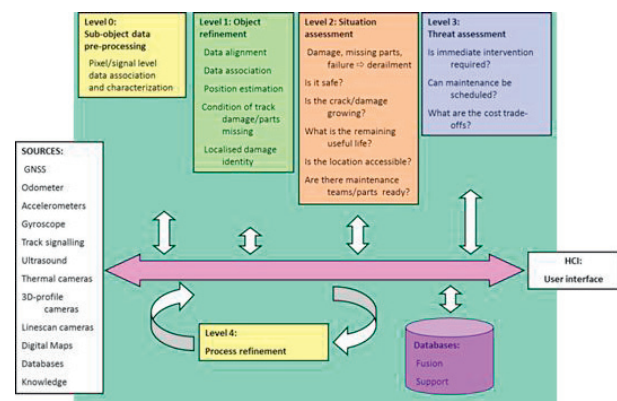

Fig. 3. JDL model adaptation for intelligent rail-track maintenance

An integrated array of complimentary sensor technology can provide a viable robust-approach to compute location as required enabling intelligent self-aware rail-track maintenance systems. This necessarily requires source integration, development of functional data fusion architectures and implementation of highly efficient low-uncertainty estimation algorithms.
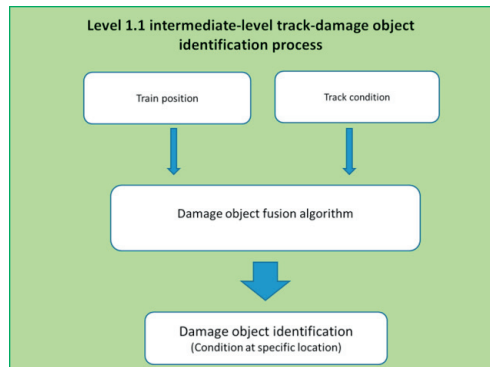

Fig. 4. JDL model illustration level 1.1.

Acknowledgements

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