Current map-matching algorithms for transport applications: State-of-the art and future research directions

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Abstract

Map-matching algorithms integrate positioning data with spatial road network data (roadway centrelines) to identify the correct link on which a vehicle is travelling and to determine the location of a vehicle on a link. A map-matching algorithm could be used as a key component to improve the performance of systems that support the navigation function of intelligent transport systems (ITS). The required horizontal positioning accuracy of such ITS applications is in the range of 1 m to 40 m (95%) with relatively stringent requirements placed on integrity (quality), continuity and system availability. A number of map-matching algorithms have been developed by researchers around the world using different techniques such as topological analysis of spatial road network data, probabilistic theory, Kalman filter, fuzzy logic, and belief theory. The performances of these algorithms have improved over the years due to the application of advanced techniques in the map matching processes and improvements in the quality of both positioning and spatial road network data. However, these algorithms are not always capable of supporting ITS applications with high required navigation performance, especially in difficult and complex environments such as dense urban areas. This suggests that research should be directed at identifying any constraints and limitations of existing map matching algorithms as a prerequisite for the formulation of algorithm improvements. The objectives of this paper are thus to uncover the constraints and limitations by an in-depth literature review and to recommend ideas to address them. This paper also highlights the potential impacts of the forthcoming European Galileo system and the European Geostationary Overlay Service (EGNOS) on the performance of map matching algorithms. Although not addressed in detail, the paper also presents some ideas for monitoring the integrity of map-matching algorithms. The map-matching algorithms considered in this paper are generic and do not assume knowledge of 'future' information (i.e. based on either cost or time). Clearly, such data would result in relatively simple map-matching algorithms.
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Keywords: Map-matching; Transport applications; Research directions

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1. Introduction

A range of intelligent transport system (ITS) applications and services such as route guidance, fleet management, road user charging, accident and emergency response, bus arrival information, and other location based services (LBS) require location information. For instance, buses equipped with a navigation system can determine their locations and send the information back to a control centre enabling bus operators to predict the arrival of buses at bus stops and hence improve the service level of public transport systems. The horizontal positioning accuracy for such ITS applications is in the range of 1 m to 40 m (95%, i.e. at the 2σ level), with relatively high requirements on integrity, continuity and system availability.

In the last few years, the Global Positioning System (GPS) has established itself as a major positioning technology for providing location data for ITS applications. Zito et al. (1995) provide a good overview of the use of GPS as a tool for intelligent vehicle-highway systems. Deduced Reckoning (commonly referred to as 'Dead' Reckoning or DR) sensors consisting of an odometer and a gyroscope are routinely used to bridge any gaps in GPS positioning (Kubrak et al., 2006). This information is then used with spatial road network data to determine the spatial reference of vehicle location via a process known as map matching.

Map-matching algorithms use inputs generated from positioning technologies (such as GPS or GPS integrated with DR) and supplement this with data from a high resolution spatial road network map to provide an enhanced positioning output. The general purpose of a map-matching algorithm is to identify the correct road segment on which the vehicle is travelling and to determine the vehicle location on that segment (Greenfeld, 2002; Quddus et al., 2003). Map-matching not only enables the physical location of the vehicle to be identified but also improves the positioning accuracy if good spatial road network data are available (Ochieng et al., 2004). This means that the determination of a vehicle location on a particular road identified by a map-matching algorithm depends to a large extent on the quality of the spatial road map used with the algorithm. A poor quality road map could lead to a large error in map-matched solutions.

A map-matching algorithm can be developed generically for all applications or for a specific application. For example, Taylor et al. (2006) developed a map-matching algorithm referred to as Odometer Map Matched GPS (OMMGPS) applicable to services where the most likely path or route is known in advance. In this paper, only generic map-matching algorithms are reviewed. A map-matching algorithm can also be developed for real-time applications or for those where post-processing is sufficient. For instance, Marchal et al. (2005) developed an efficient post-processing map-matching method for large GPS data. In the review presented in this paper, only real-time map-matching algorithms are considered as most ITS services require a map-matching algorithm that can be implemented in real-time.

It is essential that the map-matching algorithm used in any navigation module meet the specified requirements set for that particular service. Although the performance of a map-matching algorithm depends on the characteristics of input data (Chen et al., 2005), the technique used in the algorithm can enhance overall performance. For instance, the performance of a map-matching algorithm based on fuzzy logic theory may be better than that of an algorithm based on the topological analysis of spatial road network data if all else are equal. There are at least 35 map-matching algorithms produced and published in the literature during the period 1989–2006, most of which are recent reflecting the growth in the need for ITS services. The positioning accuracy and quality offered by these algorithms has also improved over the years. This is mainly due to the use of advanced techniques in the algorithms such as Kalman filtering, fuzzy logic, and belief theory, and the improvement in the performance of positioning sensors and the quality and quantity of spatial road network data.

Another important operational consideration is the sampling frequency. Although most ATT services (navigation and road guidance, distance-based road pricing, etc.) require a sample frequency of 1 Hz, some ATT services (such as bus arrival information at bus stops) only require a sample frequency of 0.3 Hz or lower. This can obviously influence the design of an optimal map-matching algorithm, as the performance of some navigation sensors vary, for example with speed. This aspect of the performance of map-matching is measured in part by the required navigation performance parameter of *continuity*.

Different algorithms, however, have different strengths and weaknesses. Some algorithms may perform very well within suburban areas but may not be appropriate for urban areas and *vice versa*. A review of the literature suggests that existing map-matching algorithms are not capable of satisfying the requirements of all ITS

applications and services. For instance, bus priority at junctions requires a 2-D positioning accuracy of 5 m (95%) with integrity. None of the existing algorithms can meet this positioning requirement, especially, within dense urban areas. This implies that apart from other elements including input data sources, further improvements to map-matching algorithms are essential. To accomplish this, it is necessary to identify the constraints and limitations of existing map-matching algorithms for further research. Therefore, the objectives of this paper are to perform an in-depth literature review of existing map-matching algorithms and then to uncover the constraints and limitations of these algorithms. In addition to this, the paper also recommends ideas for future research to overcome these limitations. The potential impacts of the European Geostationary Overlay Service (EGNOS) and the forthcoming Galileo system on the performance of map-matching algorithms are highlighted also. It is important to emphasise that this paper is intended to serve as a key reference for future research and development of map-matching algorithms by bringing together existing knowledge and defining future research directions.

The remainder of the paper is structured as follows. First, an in-depth literature review of map-matching algorithms is presented, followed by a presentation of the performance of some existing map-matching algorithms. The next section describes the constraints and limitations of existing map-matching algorithms. This is followed by a discussion of the potential impacts of Galileo and EGNOS on the performance of map matching algorithms. Conclusions summarise the key constraints and limitations of existing algorithms and provide some thoughts on future research directions.

2. Literature review

As stated above, map-matching algorithms are used to determine the location of a vehicle on a road. Most of the formulated algorithms utilise navigation data from GPS (or GPS integrated with DR sensors) and digital spatial road network data. One of the common assumptions in the literature on map-matching is that the vehicle is essentially constrained to a finite network of roads. While this assumption is valid for most vehicles under most operating conditions, problems may be encountered for off-roadway situations such as car parks or on private land. Most of the studies also report that the digital spatial road network data used for map-matching should be of a large scale in order to generate position outputs with fewer errors (e.g., Zhao, 1997; Quddus et al., 2006a).

Procedures for map-matching vary from those using simple search techniques (Kim et al., 1996), to those using more advanced techniques such as the use of an Extended Kalman Filter, fuzzy logic, and Belief Theory (El Najjar and Bonnifait, 2005; Quddus et al., 2006b). Approaches for map-matching algorithms in the literature can be categorised into four groups: geometric (Bernstein and Kornhauser, 1996), topological (White et al., 2000; Joshi, 2001; Greenfeld, 2002; Chen et al., 2003; Quddus et al., 2003), probabilistic (Zhao, 1997; Ochieng et al., 2004), and other advanced techniques (El Najjar and Bonnifait, 2005; Pyo et al., 2001; Yang et al., 2003; Jagadeesh et al., 2004; Syed and Cannon, 2004; Li and Chen, 2005; Quddus et al., 2006b; Wang et al., 2006). The following sections briefly describe these algorithms.

2.1. Geometric analysis

A geometric map-matching algorithm makes use of the geometric information of the spatial road network data by considering only the shape of the links (Greenfeld, 2002). It does not consider the way links are connected to each other.

The most commonly used geometric map-matching algorithm is a simple search algorithm. In this approach, each of the position fixes are matched to the closest 'node' or 'shape point' of a road segment. This is known as point-to-point matching (Bernstein and Kornhauser, 1996). A number of data structures and algorithms exist in the literature to select the closest node or shape point of a road segment from a given point (e.g., Bentley and Mauer, 1980). This approach is both easy to implement and very fast. However, it is very sensitive to the way in which the spatial road network data were created and hence can have many problems in practice. That is, other things being equal, arcs with more shape points are more likely to be properly matched. In a straight arc with two end nodes, all positioning points above the arc match only to the end nodes of the arc.

Another geometric map-matching approach is point-to-curve matching (Bernstein and Kornhauser, 1996; White et al., 2000). In this approach, the position fix obtained from the navigation system is matched onto the closest curve in the network. Each of the curves comprises line segments which are piecewise linear. Distance is calculated from the position fix to each of the line segments. The line segment that gives the smallest distance is selected as the one on which the vehicle is apparently travelling. Although this approach gives better results than point-to-point matching, it has several shortcomings that make it inappropriate in practice. For example, it gives very unstable results in urban networks due to high road density. Moreover, the closest link may not always be the correct link.

The other geometric approach is to compare the vehicle's trajectory against known roads. This is also known as curve-to-curve matching (Bernstein and Kornhauser, 1996; White et al., 2000; Phuyal, 2002). This approach firstly identifies the candidate nodes using point-to-point matching. Then, given a candidate node, it constructs piecewise linear curves from the paths that originate from that node. Secondly, it constructs piecewise linear curves using the vehicle's trajectory, and determines the distance between this curve and the curve corresponding to the road network. The road arc which is closest to the curve formed from positioning points is taken as the one on which the vehicle is apparently travelling. This approach is quite sensitive to outliers and depends on point-to-point matching, with the consequence of sometimes giving unexpected results (Quddus, 2006).

Taylor et al. (2001) propose a novel method of map-matching referred to as the road reduction filter (RRF) algorithm, which uses GPS, height-aiding[1] from the digital spatial road data and virtual differential GPS (VDGPS) corrections. Due to the use of height-aiding, they report that one less GPS satellite is required for the computation of the vehicle position (i.e., height-aiding removes one of the unknown parameters). The initial matching process of this algorithm is based on the geometric curve-to-curve matching proposed by White et al. (2000) which is quite sensitive to outliers.

2.2. Topological analysis

In GIS, *topology* refers to the relationship between entities (points, lines, and polygons). The relationship can be defined as adjacency (in the case of polygons), connectivity (in the case of lines), or containment (in the case of points in polygons). Therefore, a map-matching algorithm which makes use of the geometry of the links as well as the connectivity and contiguity of the links is known as a topological map-matching algorithm (e.g., Greenfeld, 2002; Chen et al., 2003; Quddus et al., 2003; Yin and Wolfson, 2004; Blazquez and Vonderohe, 2005; Meng, 2006).

Greenfeld (2002) reviews several approaches for solving the map-matching problem and proposes a weighted topological algorithm. This is based on a topological analysis of a road network and uses only coordinate information on observed positions of the user. It does not consider any heading or speed information determined from GPS. This method is very sensitive to outliers as these can lead to the calculated vehicle heading being inaccurate. Care must be taken, however, in the use of vehicle headings calculated from the coordinates of the vehicle, as GPS position fixes are less reliable at speeds of less than 3.0 m/s (Taylor et al., 2001; Ochieng et al., 2004). At low speed, the uncertainty in the vehicle position could contaminate the derivation of heading based on displacement, over several epochs depending on the frequency of matching.

Meng (2006) also uses a topological analysis of the road network to develop a simplified map-matching algorithm. This algorithm is based on the correlation between the trajectory of the vehicle and the topological features of the road (road turn, road curvature, and road connection). A number of conditional tests are applied to eliminate road segments that do not fulfil some pre-defined thresholds. The thresholds are obtained from statistical analysis of field-test data. The algorithm is implemented using navigation data from GPS/DR and spatial road network data including information on turn restrictions at junctions to improve performance. The algorithm does not work well at junctions where the bearings of the connecting roads are not similar. In these circumstances, the algorithm switches to a post-processing mode to identify the correct link, making it

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[1] Height data obtained from a Digital Elevation Model (DEM) are used as a forcing function in the navigation differential equations to generate position, speed and heading.

unsuitable for real-time applications. However, a qualitative decision making process based on the speed of the vehicle, the direction of the vehicle from a turn-rate gyro, the distance travelled by the vehicle, the quality of the digital map, and the errors associated with the navigation sensors could be utilised to correctly identify the correct link in real-time applications for such circumstances.

Quddus et al. (2003) developed an enhanced topological map-matching algorithm based on various similarity criteria between the road network geometry and derived navigation data. However, the objectives of the research are to use fewer inputs and to make the algorithm as simple and as fast as possible. The similarity criteria developed by Greenfeld (2002) are applied also. To improve the performance of the algorithm, the weighting scheme is enhanced by introducing additional criteria and other parameters including vehicle speed, the position of the vehicle relative to candidate links, and heading information directly from the GPS data string or the integrated GPS/DR system. Different weighting factors are used to control for the importance of each of these criteria in determining the best map-matching procedure.

2.3. Probabilistic map-matching algorithms

The probabilistic algorithm requires the definition of an elliptical or rectangular confidence region around a position fix obtained from a navigation sensor. This technique was first introduced by Honey et al. (1989) in order to match positions from a DR sensor to a map. Zhao (1997) discusses this technique in the case of GPS and suggests that the error region can be derived from the error variances associated with the GPS position solution. The error region is then superimposed on the road network to identify a road segment on which the vehicle is travelling. If an error region contains a number of segments, then the evaluation of candidate segments are carried out using heading, connectivity, and closeness criteria. While such criteria are conceptually beneficial, Zhao (1997) does not go into the details of their implementation. Indeed, there are many other parameters such as speed of the vehicle and distance to the downstream junction that can be used to further improve the map-matching process.

Ochieng et al. (2004) developed an enhanced probabilistic map-matching algorithm. In this algorithm, the elliptical error region is only constructed when the vehicle travels through a junction (in contrast to constructing it for each position fix as suggested by Zhao (1997) and there is no need to create the error region when the vehicle travels along a link. This makes the algorithm faster as there are a number of processes involved in the creation of the error region and hence the identification of the correct link. This method is more reliable as the construction of an error region at each epoch may lead to incorrect link identification if other links are close to the link on which the vehicle is travelling. Ochieng et al. also developed a number of criteria based on empirical studies to detect a turning manoeuvre of the vehicle at a junction. This helps to effectively identify the switching of the vehicle from one link to another. This enhanced probabilistic algorithm also takes into account the inaccuracy of the heading from the navigation sensor when the vehicle travels at low speeds. This effectively assists the algorithm to correctly match the position fixes at low speed, especially in urban areas where there are frequent stops. Moreover, an optimal estimation for the determination of vehicle location on a link is developed. This technique takes into account various error sources associated with the navigation sensor and the spatial road network data quality.

2.4. Advanced map-matching algorithms

Advanced map-matching algorithms are referred to as those algorithms that use more refined concepts such as a Kalmam Filter or an Extended Kalman Filter (e.g., Krakiwsky et al., 1988; Tanaka et al., 1990; Jo et al., 1996; Kim et al., 2000; Li et al., 2005; Obradovic et al., 2006), Dempster–Shafer's mathematical theory of evidence[2] (e.g., Yang et al., 2003; El Najjar and Bonnifait, 2005), a flexible state-space model and a particle filter (Gustafsson et al., 2002), an interacting multiple model (Cui and Ge, 2003), a fuzzy logic model (e.g., Zhao, 1997; Kim et al., 1998; Kim and Kim, 2001; Syed and Cannon, 2004; Quddus et al., 2006b; Obradovic et al.,

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[2] See Dempster (1968) and Shafer (1976) for details.

2006), or the application of Bayesian inference (Pyo et al., 2001). Some of these algorithms are described briefly below.

Kim et al. (2000) developed an integrated navigation system consisting of GPS, DR, and a map-matching technique for ITS applications. Their study assumes that several ITS services require 2-D horizontal positioning accuracy of 5–10 m (95%). They attempt to achieve this accuracy by the efficient use of digital road maps. First, a simple point-to-curve matching approach is used to identify the correct link. Then an orthogonal projection of the position fix onto the link is used to obtain the location of the vehicle. Due to the projection, the cross-track error (i.e., the error across the width of the road) is reduced significantly. However, the along-track error remains a key issue. An extended Kalman filter (EKF) is then used to re-estimate the vehicle position with the objective of minimising the along-track error. The inputs to the EKF come from GPS position fixes. The performance of such a filter may depend on the quality of spatial road network data, specifically how road curvature is represented. As stated earlier, the point-to-curve method is not sufficient to select the correct link especially in dense urban road networks. If the identification of the link is incorrect, then the inputs to the Kalman filter will also be inaccurate which inevitably leads to further positioning errors. The method can be improved using a more efficient technique for the selection of the correct link taking into account the heading and speed of the vehicle as well as a topological analysis of the road network.

Gustafsson et al. (2002) developed a framework for positioning, navigation and tracking problems using particle filters (a Recursive Bayesian Estimation). One of the applications of their method is vehicle positioning by map-matching in which a digital map is used to constrain the possible vehicle positions. The only other input to the algorithm is wheel speed. The paper suggests that an erroneous initial position (on the order of km's) is improved to one metre accuracy by the use of particle filters. Their method could be used to supplement or replace GPS. In this method, the initial position of the vehicle is marked by the driver or obtained from a different source such as a terrestrial wireless communications system or GPS. The initial area should also cover a region not extending more than a couple of kilometers to limit the number of particles to a realizable number. With infinite memory and computation time, no initialization of the algorithm is necessary. The performance of this algorithm is evaluated against the performance of GPS. In open-space, both provide similar results, but in urban areas the particle filters provide better results. However, it is unclear how the performance in urban areas is measured.

Cui and Ge (2003) propose a constrained solution to tackle the problem associated with GPS in urban canyon environments where GPS signals are often blocked by high-rise buildings and trees. Their study solves this problem by approximately modelling the path of the vehicle as pieces of curves such as straight lines, arcs, and polynomials. The vehicle path is assumed to be constrained to a known segment of road as the vehicle enters an urban area. With this constraint only two GPS satellites are necessary to obtain the positioning information. To identify the correct road segment after entering a junction, their method then uses a probabilistic algorithm which is further integrated with an EKF to estimate the location of a vehicle at junctions and to identify the correct road from all the roads meeting at a particular junction. Since this algorithm only requires two satellites, the availability of position fixes within an urban area increases. The algorithm fails in the case where either one or no satellite is available. Further testing of this algorithm is essential to evaluate its performance.

Yang et al. (2003) developed an improved map-matching algorithm based on Dempster–Shafer's (D–S) theory of evidence using rule based logical inference systems. The inputs to the algorithm (i.e., vehicle positions from GPS) are smoothed with a Kalman filter (KF). The distance between a GPS position fix and the surrounding road segments is obtained using the point-to-curve matching concept. Weights are then given to segments based on the calculated distances. Their results suggest that the algorithm identifies 96% of the road segments correctly (based on 1075 position fixes). However, this may not always be the case in urban areas, as the point-to-curve method does not fully consider the topology of the road network.

Najjar and Bonnifait (2003) developed a novel road-matching algorithm to support real-time car navigation systems. The study first describes the integration of DGPS with ABS (Anti-lock Braking System) sensors for continuous positioning information. The vehicle, in this case is not equipped with any additional extra sensors such as a gyroscope. Their map-matching method is based on several criteria using Belief Theory. These are the proximity criterion (based on the distance between the position fix and the link) and the heading criterion (based on the difference between the heading of the vehicle and the direction of the candidate segment). Based on each criterion, a degree of Belief (*yes, perhaps, no*) is assigned to each link. These criteria are then combined

using Demspter–Shafer's rule. If a link is associated with a large Belief to the *yes* hypothesis from both criteria, then it is selected as the correct link. The method however, can give inaccurate results in parallel streets, as it does not consider the topology of the road network. The algorithm does not take into account the errors associated with the navigation sensors and the digital spatial road network data. Therefore, the location of the vehicle estimated by the algorithm may not be robust as it will be adversely affected by these errors.

Syed and Cannon (2004) also describe a map-matching algorithm based on a fuzzy logic model. The algorithm consists of two sub-algorithms: (1) first fix mode, and (2) tracking mode. In the first sub-algorithm, a fuzzy inference system (FIS[3]) is used to identify the correct link for the initial position fix. Following the identification of the first link and the location of the vehicle on it, the algorithm then goes into the second sub-algorithm. Another FIS is used to see whether the subsequent position fixes can be matched to the link identified in the first fix mode. The inputs are proximity, orientation and distance travelled by the vehicle along the link. The algorithm normally takes about 30 s in order to complete the first fix mode. This is too long for some services such as en-route guidance where the vehicle can travel through several junctions within this time period. In addition the map matching algorithm does not take into account the error sources associated with the navigation sensors and the digital maps when estimating the location of the vehicle on the identified road segment.

Fu et al. (2004) propose a hybrid map-matching algorithm by analysing the geometry of the road network. A fuzzy logic model is used to identify the correct link among the candidate links. Two inputs used in the FIS are: (1) the minimum distance between the position fix and the link, and (2) the difference between the vehicle direction and the link direction. The single output of the fuzzy inference system is the possibility of matching the position fix to a link. This simple fuzzy logic model is sensitive to measurement noise. Moreover, the vehicle heading obtained from GPS is inaccurate at low speed. This has not been taken into account. As the algorithm selects a link for each position fix with no reference to historical trajectory, there is a high possibility of selecting a wrong link, especially at junctions.

Pyo et al. (2001) developed a map-matching algorithm using the Multiple Hypothesis Technique (MHT). The MHT, which uses measurements from a validation region, is re-formulated as a single target problem to develop the map-matching method. Pseudo-measurements are generated for all links within the validation region as defined using the error ellipse derived from the navigation sensors (GPS/DR). Pseudo-measurements (position and heading) are defined as the projected points of the GPS/DR positions on the links. The topological analysis of the road network (connectivity, orientation, and road design parameters) together with the pseudo-measurements are used to derive a set of hypotheses and their probabilities for each GPS/DR sensor output. The main disadvantage of this map-matching algorithm is that it does not have a method for initial map-matching. The performance of the subsequent matching largely depends on the initial matching and thus potential mismatches are likely.

Quddus et al. (2006b) developed a fuzzy logic map-matching algorithm that attempts to overcome some of the limitations of the existing map matching algorithms described above. The algorithm uses a number of new input variables (at no extra cost). These are: (1) the speed of the vehicle, (2) the connectivity among road links, (3) the quality of position solution, and (4) the position of a fix relative to a candidate link. These inputs are incorporated into the fuzzy rules in order to improve the performance of the algorithm. Three sets of knowledge-based fuzzy rules are formulated when the navigation solution comes from either stand-alone GPS or GPS/DR. The first set (six rules) is for an initial map-matching process (IMP), the second set (thirteen rules) is for subsequent map-matching on a link (SMP-Link), and the third set (four additional rules) is for subsequent map-matching at a junction (SMP-Junction). Zhao (1997) developed a total of eight rules in the case of a navigation solution obtained from a DR sensor. These eight rules do not represent completely the stand-alone GPS or the integrated GPS/DR scenarios.

2.5. Performance of existing map-matching algorithms

The formulations of most of the existing map-matching algorithms are not accompanied by methodologies for performance assessment. The few performances reported are captured in Table 1.

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[3] A fuzzy inference system (FIS) is the process of formulating the mapping from a given input to an output using fuzzy logic.

Table 1
The performance of some existing map-matching algorithms

Authors and year of publication	Navigation sensors	Test Environments	Correct Link Identification (%)	Horizontal Accuracy (m)
Kim et al. (2000)	GPS	Suburban	–	10.6 (100%)
Kim and Kim (2001)	GPS/DR	Urban and suburban	–	15m (100%)
White et al. (2000)	GPS	Suburban	85.8	–
Pyo et al. (2001)	GPS/DR	Urban and suburban	88.8	–
Taylor et al. (2001)	GPS + Height	Suburban	–	11.6 (95%)
Bouju et al. (2002)	GPS	Suburban	91.7	–
Yang et al. (2003)	GPS	Suburban	96	–
Quddus et al. (2003)	GPS/DR Map scale – 1:2500	Urban and suburban	88.6	18.1 (95%)
Syed and Cannon (2004)	GPS/DR	Urban and suburban	92.8	–
Ochieng et al. (2004)	GPS/DR Map scale – 1:2500	Urban and suburban	98.1	9.1 (95%)
Quddus et al. (2006b)	GPS/DR Map scale – 1:2500	Urban and suburban	99.2	5.5 (95%)

The navigation sensors used in the algorithms, the test environments, the percentage of correct link iden-
tification, and the 2-D horizontal accuracy are shown in columns two, three, four, and five respectively. The
most frequently used navigation sensors are either GPS or GPS/DR. The percentage of correct link detection
ranges from 86 (White et al., 2000) to 99 (Quddus et al., 2006b). The 2-D horizontal positioning accuracy
ranges from 18 m to 5.5 m (95%). Very few studies state the scale of the digital spatial road network data used
to estimate performance. As shown in Zhang et al. (2003) and Quddus et al. (2006a), the quality of spatial data
can have a large impact on map-matching performance.

3. Constraints and limitations

Some of the map-matching algorithms discussed in the previous sections possess the capability to support
the navigation module of many ITS applications and services. For example, a positioning accuracy up to 5.5 m
(95%) is achievable within suburban areas using some algorithms. Among these algorithms, the fuzzy logic
map-matching algorithm provides the best performance both in urban and suburban areas. However, as
reviewed in the previous sections, there are a number of issues that hinder the maximum exploitation of
the current map-matching algorithms. These are discussed in the following sections.

3.1. Problems with initial map-matching processes

Most of the map-matching algorithms start with an initial matching process. The purpose of this process is
to select road segments that fall within an error ellipse[4] based on the errors associated with the navigation
device. The initial matching process first selects all nodes (i.e., road junctions) or shape points (i.e., road topol-
ogy) that are within the error ellipse. The segments that originate from (or are destined to) these nodes or
shape points are considered to be candidate segments. Although this process normally identifies the correct
segment near a junction or a shape point, there may be some circumstances in which the initial matching pro-
cess needs to start on a road segment which is further from the junctions or shape points. The error ellipse then
does not contain any junctions or shape points (see Fig. 1). Consequently, the initial matching process com-
monly used in the literature would identify no road segments and would assume that the vehicle is off the
known road network. This is incorrect as the vehicle can be on link AB in the case of Fig. 1. This type of sce-

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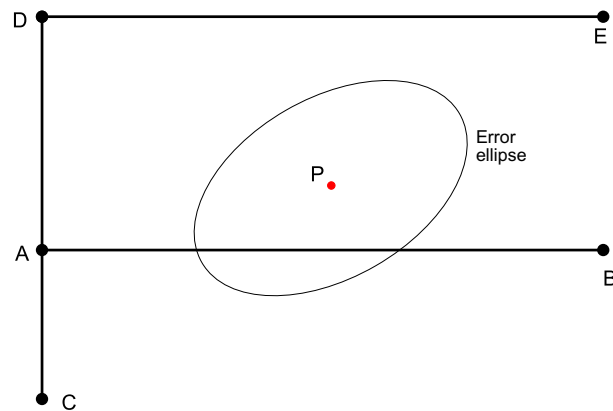[4] An error ellipse is determined based on the assumption that the error has a Gaussian distribution.

Fig. 1. No nodes within an error ellipse.

nario can occur if the map-matching process needs to be re-initialised between the middle of two junctions (e.g., on a motorway) and if there is no historical information available. This type of ambiguity needs to be resolved.

A possible solution would be to consider an error circle with a radius equal to the semi-major axis of the error ellipse. This gives an assurance that the error circle selects all segments that would have been selected by the error ellipse. Moreover, the error circle is relatively easy to formulate compared to an error ellipse. Alternatively, a 99% or more positioning probability circle which is equal to the 3-drms (distance root mean square error) or the $2.6 \cdot$ CEP (circular error probable[5]) could be used to formulate the error circle. A straight line representing the road segment can then be formed using the coordinates of the starting node and end node. This is a one-off offline process that could be performed for all road segments within the spatial digital map data. Therefore, the problem of identifying road segments within an error ellipse then transforms to the problem of identifying whether a line intersects a circle or not. This is known as a circle-line intersection problem and should eliminate the issues related to the initial map-matching processes discussed above.

3.2. Problems with threshold values

A variety of thresholds are used to make the correct decision during various decision-making processes within host map-matching algorithms. For instance, the threshold for the minimum speed at which the heading of the vehicle from stand-alone GPS is incorrect is taken as 3 m/s by Taylor et al. (2001) and Quddus et al. (2003). The threshold values are commonly derived empirically from a series of field observations. A more analytical approach may be needed to improve this value. Moreover, the values of various weighting parameters used in map-matching algorithms can vary based on different operational environments. For example, the values of a and b (the weighting parameters for heading and relative position respectively) used in the algorithm developed by Quddus et al. (2003) are based on using data from London. These values may be different when they are derived using data from another city and may also be dependent on the type of sensor equipment used. The transferability of the method to determine weighting parameters for map matching in different operational scenarios is a key research issue.

3.3. Problems at Y-junctions

The techniques used in existing map-matching algorithms may fail to identify the correct road segment at or near a Y-junction as shown in Fig. 2. Given that a map-matching algorithm identifies the correct link, AB, for the position fixes P1 and P2, the identification of the correct link for the fix P3 may be incorrect if the perpen-
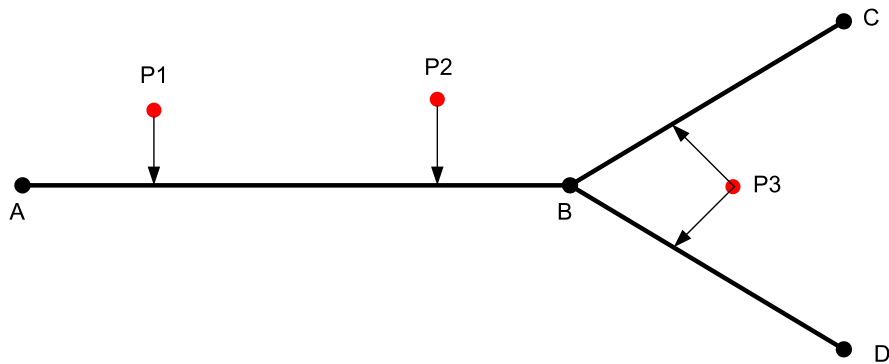
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[5] 1 CEP = 1.17 · (1-sigma standard error).

Fig. 2. A hypothetical road network.

dicular distance from P3 to link BC and BD is almost *equal*, and the heading of the vehicle from the navigation sensor is 90°.

This type of hypothetical road network may be observed in motorway diverging scenarios. Further improvements of map-matching algorithms should focus on this type of scenario. One possible suggestion is to consider the sign of the difference in heading between fixes P3 and P2 as an additional input to the map-matching algorithm. For instance, a positive heading change between fixes P3 and P2 implies that the vehicle is on link BD and a negative heading change implies that the vehicle is on link BC.

3.4. Consideration of road design parameters in map-matching

Road design parameters such as turn restrictions at junctions, roadway classification (such as one-way, two-way), width of the carriageway, number of lanes, and overpass and underpass information are normally not included as inputs to existing map-matching algorithms as the data have not been readily available. The availability of such attribute data could potentially improve the performance of map-matching algorithms especially at junctions.

3.5. Height data from the navigation sensors

Map-matching algorithms normally do not make use of height data from a navigation sensor.[6] This height data together with the data from a 3-D digital road network map can effectively identify the correct road segment at a section of roadway with fly-overs. However, this will largely depend on the accuracy of height data and the availability of a high-quality 3-D road map.

3.6. Spatial road network data quality

The review of the literature suggests that spatial road network data have both geometric and topological errors (Noronha and Goodchild, 2000; Kim et al., 2000; Zhang et al., 2003). It is envisaged that the position fixes from a stand-alone GPS, specifically in an open-space environment, could be better than the map-matched positions if a poor quality map is employed in the map-matching algorithm. Therefore, the quality of the spatial road map data that is used may affect the performance of a map matching method. Quddus et al. (2006a) demonstrated this to an extent by evaluating the effects of the digital spatial road network data on the performance of map-matching algorithms using map scales[7] of 1:1250, 1:2500, and 1:50000. Further research

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[6] Note that height data from GPS are not as accurate as horizontal positioning data.

[7] Map scale can be defined as the ratio of distance on a map over the corresponding distance on the ground, represented as 1:M where M is the scale denominator. Map scale is an issue because as scale becomes larger the amount of detail that can be presented in a map is also increased.

is required to characterise the link between spatial data quality and the performance of map-matching algorithms. For example, in addition to the work in Quddus et al. (2006a), other scales should be studied, e.g. 1:5000, 1:10,000, and 1:25,000.

Topological errors due to features which are omitted or simplified in some road maps are typically ignored by many of the algorithms. These features can include roundabouts, junctions, medians, and curves, amongst others. For example, large roundabouts might be represented by a single node (i.e. a point). Before implementing a map-matching algorithm, a thorough check needs to be carried out to identify such flaws in any spatial road network data. The error budget associated with spatial road network data can be derived from field experiments and can be incorporated into the map-matching process. In addition to this, it would be interesting to see how other topological features of road maps such as a multi-centreline representation of a carriageway and a representation of a roundabout by a node, affect the performance of a map-matching algorithm. Initial results by Meng (2006) suggest that spatial road network data that represent a carriageway by multiple centrelines (i.e., a centreline for each lane) provide incorrect results for identifying road segments. Further research is essential to quantify such errors in terms of the estimation of the location of a vehicle on a link.

3.7. Techniques used in the map-matching processes

The methods used in the map-matching algorithms vary greatly from using simple search techniques to highly mathematical approaches. The performance and speed of the algorithms in turn largely depend on the technique used in the algorithm. For instance, it has been found that the fuzzy logic based map-matching algorithms provide better performance compared with other methods for the same inputs. Other potential techniques would be to employ a pattern recognition approach, or a hierarchical fuzzy inference system optimised by a genetic algorithm (GA), or a hybrid method. Currently, map-matching algorithms generate outputs exactly on the centreline of a road segment. This may be desirable for many ITS applications. However, some ITS applications require more accurate positioning information. Therefore, the current methods introduce large errors in the location estimation, especially in the case of low resolution spatial road network data. A method should be developed so that the final positioning outputs from the map-matching algorithm can optimally be determined anywhere within the edges of the carriageway.

3.8. Validation issues

Validation of a map-matching algorithm is essential to derive statistics on its performance in terms of correct link identification and vehicle location determination. A precise vehicle reference (true) trajectory is required in order to assess performance. Very few existing map-matching algorithms provide a meaningful validation technique. Although some studies report on the accuracy of map-matching algorithms, it is unclear how this is determined. Kim et al. (2000) use code-based DGPS to obtain reference vehicle positions. However, the performance of DGPS is strongly affected by signal multipath, among other factors, and varies according to the surrounding environments. The typical accuracy of DGPS is of the order of 0.5–5 m (95%) (US DoA, 2003). Consequently, the vehicle positions obtained from DGPS may not be suitable to derive the reference trajectory of the vehicle. Quddus et al. (2004) employ high accuracy GPS carrier phase observations in order to validate the performance of a map-matching algorithm. However, it is not always possible to obtain GPS carrier phase observations in dense urban areas due to inherent problems associated with GPS signal masking and multipath error. A *tightly coupled* integrated navigation system employing GPS and a high-grade Inertial Navigation System (INS) could be used to obtain reference vehicle trajectories in urban areas at the centimetre level. This is a key area for further research to validate new and existing algorithms. Currently the carrier phase measurements are differenced across receivers and satellites (double differences) in order to mitigate the effects of some of the error sources. In future, there is the possibility of using the undifferenced measurements made by a single receiver to realise centimetric positioning accuracy. This is refereed to as real-time precise point positioning (PPP).

The PPP concept is based on the (near) real-time availability of precise GPS satellite orbit and clock data (Heroux et al., 2001; Shen and Gao, 2002). This is a relatively new area of research in the field of positioning and navigation and is based on the processing of un-differenced pseudo-range and carrier phase observations

from a single GPS receiver. It has the potential to provide global position accuracy at the level of decimetres to centimetres in stand-alone kinematic and static modes. A number of researchers and institutions around the world are developing models for predicting ephemeris and satellite clock corrections, which would help to make real-time PPP possible.

The effectiveness of the use of a carrier phased based reference trajectory for the measurement of the performance of map-matching algorithms should be evaluated for the two components of map-matching: link identification and accuracy of map-matched position. The first is affected directly by the quality of the spatial database in addition to other factors. Hence, even if a GPS/High-grade INS is used, there is the real possibility of error in link identification. One way of dealing with this is to use the carrier phase based trajectory together with the calibration of the spatial database by the concept of 'way points' or the adoption of human generated second-by-second link data. Note that the latter may have problems of both spatial and temporal referencing to the map-matched data. The second (i.e., accuracy) can be measured effectively by the use of the 'truth' from an integrated GPS/High-grade INS. Note also that this approach (carrier phase based validation) has the flexibility to operate with the expected improvement in the quality of digital spatial data.

3.9. Integrity (level of confidence)

The integrity of a map-matching algorithm directly reflects the level of confidence that can be placed in the map-matched position. Integrity measures can be used to detect a failure in the map-matching process. The detection capability can be utilised to provide a timely warning to the driver that the position solution should not be used for navigation or positioning, and to aid the algorithms in recovery from the failure mode. Quddus (2006) describes a simple empirical method to derive the *integrity* of a map-matching algorithm. Yu et al. (2004) developed a technique to detect wrong map-matched solutions and recover from such circumstances. Although the performance of these integrity methods are good for the test route used, it is essential to further investigate their performance with other test routes, especially in urban areas. An alternative to the empirical approach would be to consider more rigorous statistical approaches similar to that used in autonomous integrity monitoring systems such as Receiver Autonomous Integrity Monitoring (RAIM) which would be based on consistency checking and redundancy measurements (outlier detection capability) within a sensors/data integration architecture.

3.10. Implementation issues

Map-matching algorithms can be implemented in two ways depending on the application: (1) within an in-vehicle unit; and, (2) within a central station (i.e., a central server). In the case of the former (e.g., for route guidance), each vehicle must have a map-matching processor along with other navigation devices and spatial road network data. A communication link with the central server is only required if other information (such as roadway traffic conditions) is essential for the application. In the case of implementing the algorithm in a central server (e.g., for fleet management), each vehicle contains the navigation sensors. The positioning data (easting, northing, speed, and heading) computed by these sensors are then sent to the central server to improve the accuracy of the vehicle position, and to obtain data on physical location (i.e., addresses) and road related information using a suitable map-matching algorithm. In this case, communication between the vehicle and the central server is essential. Clearly, there is the potential that the type of implementation including the available functionality will influence not only the performance of the map matching algorithms but also the service as a whole. Therefore, a careful trade-off is required to consider a number of issues including communications requirements and bandwidth, computation load, data management including storage, security, cost, etc.

3.11. Summary

The areas listed above are the ten primary topics where further enhancement of map-matching algorithms is necessary. It is expected that future map-matching algorithms that account for all of these shortcomings will be able to make a significant contribution to the realisation of a system that supports the navigation require-

ments of many ITS services with a high degree of accuracy, integrity, continuity and availability in different operational environments.

4. Impacts of Galileo and EGNOS

The Galileo System will be an independent, global, European-controlled, satellite-based navigation system that will provide a number of services to users equipped with Galileo-compatible receivers. Galileo will also provide a number of navigation and search and rescue (SAR) services globally (ESA, 2002). The most relevant services to surface transport are: the Open Service (OS) which will provide positioning, navigation and timing services, free of charge, for mass market navigation applications (such as GPS–SPS), and the Commercial Service (CS) which will generate revenue by providing added value over the *OS* including dissemination of encrypted navigation related data (1 KBPS), and ranging and timing for professional use with service guarantees. The additional data provided by Galileo may improve the accuracy of map matching with existing algorithms.

Although GPS provides users with their locations and other derivatives in real-time, limitations on system performance and potential political considerations suggest that stand-alone GPS cannot always meet all the requirements of a range of ITS services and other safety-of-life (SOL) applications. Moreover, the US DoD, which operates GPS, does not guarantee the Standard Positioning Service (SPS). One solution to this is to develop an augmentation to GPS to improve accuracy, integrity, continuity, and availability (Ledinghen and Auroy, 2001). Therefore, Europe is developing a satellite-based regional augmentation system, known as the European Geostationary Overlay Service (EGNOS). The development of EGNOS began in the early 1990's initiated by the Tripartite Group (ETG), comprising the European Space Agency (ESA), European Community (EC), and EUROCONTROL. The initial operation of EGNOS began in July 2005 (http://www.essp.be), with full operational capability expected in 2007.

The following sections examine the potential impacts of the forthcoming European Galileo and EGNOS systems on the performance of map matching algorithms and whether this will further improve the capability to support the navigation module of ITS services. Note that although the other current and potential satellite-based navigation systems such as (Kaplan and Hegarty, 2006) Russia's GLONASS, China's Bei-Dou, India's GAGAN (GPS and Geo-Augmented Navigation) system and IRNSS (Indian Regional Navigation Satellite System), and Japan's GZSS (Quasi-Zenith Satellite System), have not been addressed here due to a lack of maturity and/or uncertainty (as a result of economic and institutional concerns), they should result in even higher navigation performance particularly with respect to integrity, continuity and availability with limited improvement in accuracy. Such an improvement in navigation performance should improve further the performance of map-matching algorithms.

4.1. The impact of Galileo

Most ITS services will be supported by the combination of Galileo Open Service (OS) and the commercial service (CS) which will provide a horizontal positioning accuracy of 4 m 95% of the time when a dual frequency Galileo receiver is used. According to US DoD (2001), stand-alone GPS provides an accuracy of 13 m (95%).[8] Hence, the integration of Galileo with DR will provide better positioning fixes than GPS/DR, thereby improving the performance of map matching algorithms if map quality allows.

The United States and the European Union (EU) signed an agreement to harmonize their respective satellite navigation systems: the existing US GPS system and the planned European Galileo system during the US-EU summit in Ireland (http://www.useu.be/Galileo). As a result, this opened the door for future navigation receivers that use both systems. This will provide the capability of computing the receiver location using a significantly increased number of satellites. Therefore, the deployment of Galileo and the modernization of GPS over the next few years will have a profound impact on future GNSS receiver design. Currently, ITS applications use single frequency GPS receivers. In the future it will be possible to have affordable multi-frequency

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[8] Although higher accuracy is generally achieved in practice particularly in open areas.

receivers. Such receivers will provide higher positioning accuracy and will be able to acquire and track lower strength signals compared to the current single frequency GPS receivers. Furthermore, the impact of RF interference could be reduced using techniques including the use of special antennas (e.g. beam steering) and/or redundant sensors. In general, the cost of a future integrated GNSS receiver (GPS + Galileo) will be on the order of 10–20% more than a single-system receiver (Rizos, 2005).

However, the navigation module of any ITS services will still require the support of a robust map-matching algorithm. This is because the positioning fixes obtained from an integrated GNSS receiver will still need to be placed on a known-road network where a spatial digital map is used as a physical reference for the vehicle. Although the availability of satellites from a particular point on the earth will be increased, the effect of multipath and satellite blockage (including weak satellite configurations) on the performance of the quality of navigation solutions will remain a critical issue, especially in urban areas. The implication of this will be that augmentation with other sensors such as DR will still be required. A good example of this is the urban canyon where although more satellites will be visible, the geometry of the satellites with respect to the receiver will still be relatively weak. In such cases, a map-matching algorithm will be required not only to identify the physical location of the vehicle but also to improve accuracy and availability of the positioning service.

4.2. The impact of EGNOS

EGNOS was designed to provide potential users with the following services (Sauer, 2004).

- *GEO ranging*: Under this service, 3 GEO satellites transmit GPS-like L1 band signals which improve the availability.
- *Integrity channel*: GPS/EGNOS integrity information is available in this service. This is expected to satisfy the integrity requirement for civil aviation up to Category I (*CAT I*)*Precision Approach*.
- *Wide area differential*: This service includes the broadcast of differential correction data to users. This enhances the accuracy of GPS/EGNOS.

Ledinghen and Auroy (2001) provide an overview of how Europe-wide civil aviation can benefit from EGNOS. Other transport sectors, especially land transport can also benefit from the use of EGNOS. The following scenarios are considered to discuss the potential impact of EGNOS on the performance of map-matching algorithms.

Scenario 1 (GPS + DR + Map Matching): This is the basic scenario on which current map-matching research is based. In this scenario, a map matching algorithm takes inputs from an integrated GPS/DR and a road map. The quality of the position solution from the GPS/DR depends among other things on the duration of GPS outage. In such cases, the performance of a map-matching algorithm depends on the performance of DR sensors, especially in a dense urban area where the visibility of GPS satellites is poor.

Scenario 2 (GPS + EGNOS + DR + Map Matching): In this scenario, a GPS receiver will be capable of receiving data as transmitted by the different services provided by EGNOS. This will facilitate obtaining good quality GPS data due to the availability of differential corrections and marginally better geometry due to the additional signal (GEO L1) for some instances where the EGNOS GEO satellites will be visible. This will lead to a marginally better positioning accuracy. Therefore, the improvement in the performance of map-matching algorithms is expected to be marginal, especially in urban areas.

Scenario 3 (GPS + EGNOS(SISNet) + DR + Map Matching): In this scenario, the problem of the unavailability of GEO satellites in urban areas (scenario 2) is addressed to some extent by the development of an internet solution called SISNeT[9] which provides wide-area differential correction data via the internet. SISNeT gives access to the corrections and the integrity information of EGNOS. Any user with access to the internet (usually through wireless networks e.g., GSM or GPRS) can access EGNOS through SISNeT. This will provide EGNOS differential correction data continuously. Therefore, it will be possible to have better quality GPS data for visible satellites at all times. This will always lead to better quality positioning data. With

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[9] http://esamultimedia.esa.int/docs/egnos/estb/sisnet/sisnet.htm

SISNet, visibility of a GEO satellite will not be required, therefore, the GEO L1 data is effectively lost, and there will be no improvement in satellite geometry. However, there will be significant improvement in positioning accuracy when the geometry allows. Consequently, the improvement in the performance of the map-matching algorithm will be significant and only constrained by the spatial road network data quality.

Scenario 4 (GPS + EGNOS (conventional + SISNet) + DR + Map Matching): This is the combination of scenarios 2 and 3. In this scenario, a GPS receiver will be capable of receiving both differential correction data via SISNet and the additional data (GEO L1) directly from EGNOS. This will lead to better positioning data at all times and a marginal improvement in geometry for some instances. The performance of map matching algorithms will be improved if the spatial road network data quality allows.

Clearly further research is required to quantify the impact of each of the scenarios above not only on the geometric positioning capability (as inputs to the map-matching process) but also on the overall performance.

On the issue of integrity, the EGNOS integrity service monitors GPS satellite signals to generate integrity information. The latter is broadcast to the users in terms of use/don't use and other parameters that are used by the user receiver to carry out failure detection. This requires not only the required navigation performance parameters, but also the computation of the protection levels. The drawback of this approach of external integrity monitoring is that it does not account for errors local to the user. The other relevant issue is that of the combined use of data from GPS and other sensors such as DR and digital spatial databases. Clearly, a good approach to monitoring the integrity of map-matching algorithms could account for these issues. Therefore, the autonomous integrity monitoring concept (as highlighted in Section 3.9) applied at the user receiver level is appropriate in this case. This process should include methods to determine the test statistic(s), threshold(s) and protection levels.

5. Conclusions

The navigation function of an intelligent transport system can be supported by a map-matching algorithm that integrates positioning data with spatial road network data. This paper has presented an in-depth literature review of map-matching algorithms. A number of different techniques are used in the map-matching processes such as simple search techniques (e.g., point-to-point matching, point-to-curve matching) and complex ones including the applications of probability theory, fuzzy logic theory, and belief theory. These algorithms are not always capable of supporting the navigation module of some ITS applications such as bus priority at junctions, especially in dense urban areas. Therefore, to achieve the required navigation performance for some ITS services, further research and improvements to map-matching algorithms are essential. This paper has identified a number of constraints and limitations of existing map-matching algorithms and has suggested key areas for further research. The key constraints and limitations are the problems associated with initial identification of vehicle positions, the problem of matching positioning fixes in complex road lay-outs (such as Y-junctions and fly-overs), performance evaluation, especially in dense urban areas, and development of confidence indicators. These algorithm enhancements will be aided by enhanced and new systems including EGNOS and Galileo to offer a significantly improved performance capable of supporting a wide variety of ITS services in different operational scenarios.

In terms of implementation, most of the map-matching algorithms reviewed here have been developed in recent years with details on their actual implementation (for example in commercial applications of advanced traveller information systems) not being available in the public domain. However, the recent increase in collaboration between industry and research establishments in this area is indicative of a strong interest from industry in advanced map matching algorithms.

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