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Evaluating the performance of map matching algorithms for navigation systems: an empirical study

Jaiteg Singh[1] · Saravjeet Singh[2] · Sukhjit Singh[3] · Hardeep Singh[4]

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Abstract Navigation systems are extensively used for location identification and route finding. The efficiency of navigation systems is highly affected by map matching algorithms. This paper provides a review of major map matching algorithms. The performance of reviewed algorithms was further evaluated with the help of an empirical study. A dataset of forty seven kilometers was collected to deploy various map matching algorithms so as to measure their performance. A comparison of geometric, topological and Kalman filter based map matching algorithms was performed on the same dataset. It was concluded that performance of Kalman filter algorithm provide better results in comparison to geometrical and topological algorithms.

Keywords GPS · Geometric · Topological · Kalman filter · Road network

✉ Jaiteg Singh
jaitegkhaira@gmail.com

[1] Department of Computer Applications, CUIET, Chitkara University, Punjab 140401, India

[2] Department of Computer Science Engineering, CUIET, Chitkara University, Punjab 140401, India

[3] Department of CSE, Guru Nanak Dev Engineering College, Ludhiana, India

[4] Department of Civil Engineering, Guru Nanak Dev Engineering College, Ludhiana, India

1 Introduction

Map-matching techniques can greatly affect the performance of any navigation system. Map-matching refers to the method of using spatial information and Geo Positioning satellite signals for locating an entity onto a digital map [1, 2]. Contemporary navigation systems are equipped with intelligent software applications and are widely used for finding best route, navigation, location sharing, transport management, traffic control and other location based services. For instance, a vehicle or user equipped with a navigation system is not only aware of its current location but can also share it with other systems to navigate towards an intended destination. The expansion of the United States Global Positioning System (GPS) and the Russian Federation's Global Orbiting Navigation Satellite System (GLONASS) has resulted in a robust and reliable Global Navigation Satellite System (GNSS) for providing location information to navigation equipment. Latitudinal and longitudinal information from GNSS consortia is taken as input by map matching algorithms for providing route guidance and temporal information regarding location. Map-matching techniques have to deal with some inherent issues like multi-lane environments, limited or inaccurate mapping of rural areas, low frequency of GNSS signals and low precision GPS/GNSS receivers. Such issues may result in inaccurate fixing of geographical location or may even result in wrong navigation instructions. In reference to aforesaid issues, it becomes mandatory to logically rectify such erroneous location fixes with the help of map-matching algorithms. Navigation systems primarily rely upon vector maps for deciding geo-position of a vehicle, hence map-matching algorithms also make use of vector maps for integrating sensor positioning data to estimate best position of any vehicle. Numerous studies have individually investigated map-matching algorithms and have proposed amendments for the same, yet to the best of our knowledge, concurrent empirical evaluation of map-matching algorithms is still not available. [3–9]. This paper evaluates the performance of map matching algorithm for road based navigation systems. A typical navigation system is an amalgamation of spatial database, geo location information, map-matching algorithms and route assistance modules as shown in Fig. 1.

The working of the navigation system depends on five main components, these include GNSS receiver, map matching algorithm, spatial database, addition guidance procedures, and user interface. The input from the GNSS receiver, the spatial database is processed by the map matching algorithm to provide the nearest possible GNSS fix on the digital road network. This processed output is visualized and displayed to the user, using a GUI interface. Additional guidance procedures enhance and improvise the user output to inculcate the more user-friendly behavior.

Navigation systems are widely used in intelligent transport systems to provide real time tracking of vehicles. Accuracy of vehicle tracking depends on the mapping of GPS data on electronic map. Measurement errors imbued by GPS receivers are to be rectified through map matching algorithms for ensuring accurate maneuvering instructions. To minimize falsification within mapping process, many map-matching algorithms have been developed. Due to high involvement of map matching algorithm in navigation system, there is always a scope of improvement in the performance of navigation system. In this study we evaluate the performance of map matching algorithm for road based navigation system.

Though every map matching algorithm has its own pros and cons yet they have been studied and deployed by the research community in a diversified manner. This paper tries to empirically evaluate the performance of a few prominent map matching algorithms through an empirical study. Section 2 presents a briefing about major studies done to develop and enhance the performance of map matching algorithms. Section 3 provides the methodology and Sect. 4 provides results of the experiment. Section 5 includes conclusion and discussion about future scope.

2 Literature review

2.1 Overview of map matching algorithms

Map-matching algorithms, consider road network as graph, $G(V, E)$ where V is a set of spatial nodes and E is the edge (link) between two nodes. The path covered by any moving object is denoted by $O = O_1 \ldots O_t$ where O_t is a position of an object at time t, whereas the spatial coordinates calculated by GNSS are denoted with $P = P_0 \ldots P_n$. The goal of map-matching algorithms is to determine the actual position O_t of the vehicle on a graph G by using GNSS point P. The output of any map-matching algorithm is to define O_t in terms of P_n such that $O_t \epsilon O$ and $P_n \epsilon P$. The map matching algorithms are broadly divided into three main categories namely, Geometric, Topological and Advanced map

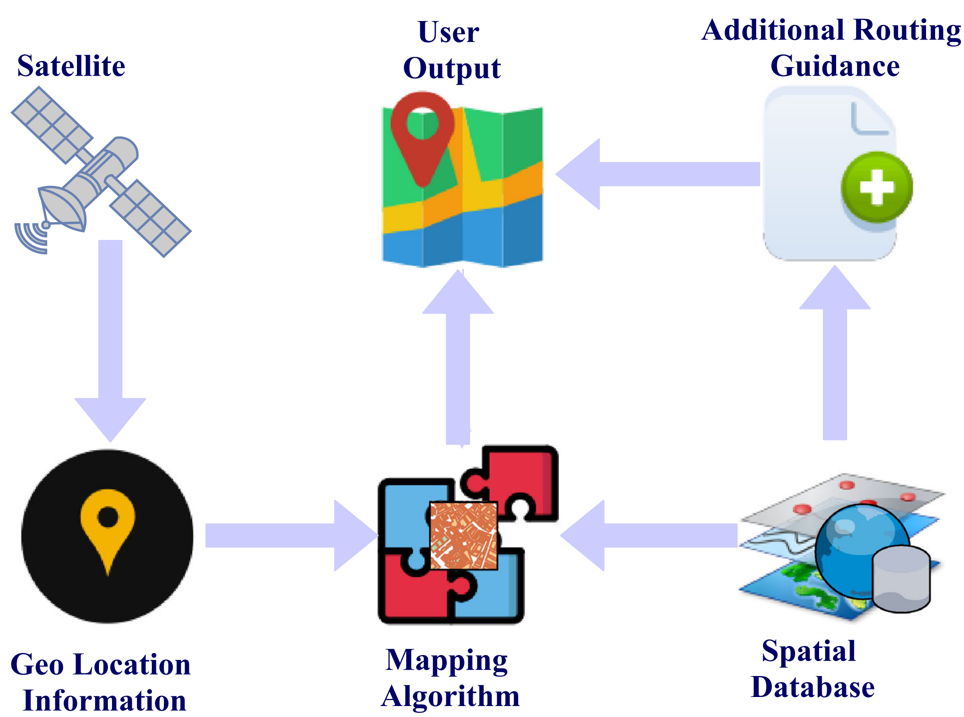

Fig. 1 Components of navigation system

matching algorithms. Methods used within aforesaid algorithms are shown in Table 1 [5–7, 10–18].

2.1.1 Geometric map matching algorithm

Geometric map-matching algorithms use geometric information of the road network by considering only the shape of the vector features or links. Geometric algorithms are quite simple to deploy. They work well with straight roads, yet their efficiency is greatly affected by junctions, roundabouts and parallel roads. Geometric map matching algorithms can be classified into three types as discussed below.

Point to point (P2P) The most commonly used geometric map-matching algorithm is a simple search algorithm. In this approach, each of the geo positioning fixes is matched to the closest 'node' of a road segment within the electronic map [10]. Line L1 is a point to point map matching approach for a vehicle traveling on a road network consisting of ten nodes (A to J) (Fig. 2). The geo position fixes from the navigation system using P2P are indicated by P1 till P7. The actual links on which the vehicle is traveling during this period are AC and CD. However, the results from the point to point map matching show that the vehicle travels on AC, then CF, FG and finally GD. Hence, the routes produced by this method are mostly long and incorrect.

Point to curve (P2C) In this technique, the positions acquired from the navigation system are matched onto the closest curve in the network. Each curve made up of segment of linear lines. Distance is calculated from the GPS position fix to each of the line segments. The line segment which gives the smallest distance is selected as the one on which the vehicle is apparently travelling. Results obtained from this approach are better than point to point matching [10]. The result of the point to curve map-matching algorithm for the same road network configuration is shown in Fig. 2. It can be seen that the algorithm selects AC, CF and FD as the correct links when the vehicle actually travels on AC and then CD. The result of the point to curve map-matching algorithm for the same road network configuration is shown in Fig. 2. It can be seen that the algorithm selects AC, CF and FD as the correct links when the vehicle actually travels on AC and then CD.

Curve to curve (C2C) This approach is based on a bi-curve approach and works on vehicle trajectory. Trajectory

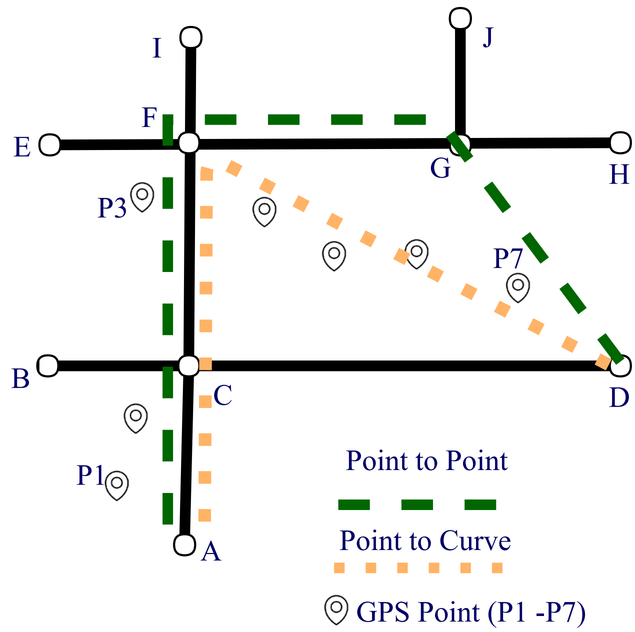

Fig. 2 Point to point and point to curve map-matching algorithm for the same road network configuration. Where **a–j** alphabet represents node in the road network and P1–P7 points represents the GPS receiver output. Output of the point to point and point to curve approach are show by two different line named as Lines l1 and l2 respectively

Table 1 Summary of prominent literature associated with map matching algorithms

Algorithm	Methods	Uses
Geometric	Point to point	GPS fix (longitude, latitude)
	Point to curve	GPS fix (longitude, latitude) and junction information
	Curve to curve	GPS fix (longitude, latitude) and junction information
Topological	Basic topological	GPS receiver fix, information of roads and junctions, connectivity and containment information of roads
	Weighted topological	GPS receiver fix, information of roads and junctions, connectivity and containment information of roads, weight factor associated with each input
Advanced	Kalman filter	Kalman filter model, error calculation technique, GPS receiver fix, road information
	Fuzzy logic	GPS receiver fix, fuzzy inference system, speed of vehicle, perpendicular distance between position fix and road
	Dead Reckoning sensor	GPS receiver fix, inertial sensor, micro-electro-mechanical sensor, previous position of vehicle, Dead Reckoning device

is the path covered by a moving object in finite space and finite time. The current travelling curve of the vehicle is matched with network curves obtained from the spatial database. The curve to curve approach provides high outlier sensitivity but is slower compared to the other two processes [13, 19, 20].

2.1.2 Topological map matching

Topology refers to the relationship between entities. Entities can be points, lines and polygons. The relationship between entities can be defined by metrics like adjacency, connectivity or containment. A topological map-matching algorithm uses geometry, connectivity and contiguity matrices for the calculation of user location and to give navigation information towards the destination. Historical GPS data along with geometrical and topological information of the road network are used to enhance an algorithms performance [6, 12]. In topological map-matching, the vehicle's trajectory and topological features of the road (e.g., road turn, road curvature, and road connection) are matched. Figure 3 explains the working of geometric and topological algorithms. Line l1 gives the navigation path of the vehicle using the geometric algorithm and line l2 gives the routing direction calculated using the topological algorithm. In addition to nodes and edges, topological map matching algorithms consider the face attribute of the digital map. Face is a closed area like a polygon, which is formed by connecting edges. The geometric algorithm only considers the nodes and links between them whereas the topological algorithm considers the nodes, edges, faces and

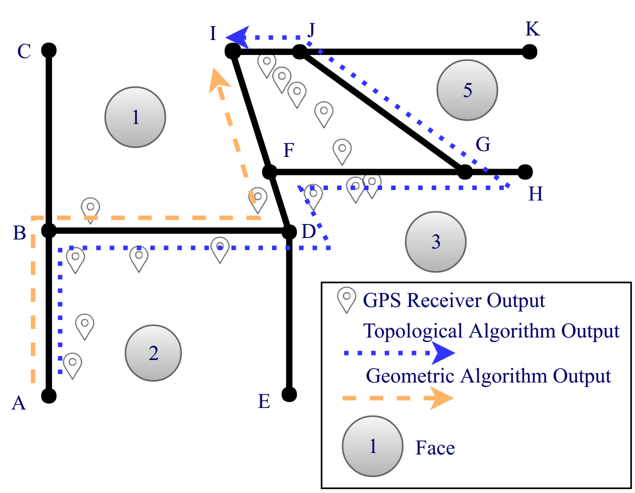

Fig. 3 Diagrammatic representation of geometric and topological map matching algorithm on same example set. Where e1 to e11 are the edges in the road network. **a**–**k** Are the nodes in the network. Two nodes are connected by edge. For example edge e1 is formed by connecting node B and C

their relationship. Topological information of Fig. 3 is shown in Tables 2 and 3 respectively.

Apart from the geometric information, topological algorithm uses matrices having information about direction, area and referral point. In Fig. 3 vehicle movement is shown by 15 GPS points (balloon), on the basis of points, route calculated by the geometric algorithm is correct till node F, after node F, route is incorrect. But by considering the topological matrix, the topological algorithm gives the correct path starting from A and passing through B, D, F, G, J and I.

2.1.3 Advanced map-matching

Advanced map-matching algorithms are based on both geometrical and topological map-matching algorithms with some additional models to improve the accuracy. Kalman filter, extended Kalman filter, state-space, particle filter, fuzzy logic, inertial sensor and multi sensor are the models used in advanced map matching algorithms.

Kalman filter Kalman filtering is a quadratic estimation technique that works on linear systems. This algorithm estimates the precise value of variables that are initially observed under uncertainties. The first step of Kalman filtering is to produce an estimate of noisy and uncertain current state variables. This step is known as the Prediction step. In the second step, next measurement is taken and again estimation is done with the weighted average and higher certainty. This process is recursive and continues until a refined result is found [21].

Inertial sensor Inertial sensors have extensive utilization for determining the motion of moving objects and their attitude. Micro electro mechanical systems (MEMS) sensors are a type of low cost and power saving sensor used in smart devices for navigation calculations. GPS and multiple inertial sensors provide good results in error prone inputs [6].

Fuzzy logic based map-matching algorithm Fuzzy logic methods allows a variables to take any value between 0 and 1, while using Boolean logic a variable can only take a value either 0 or 1. Fuzzy logic provides a partial result

Table 2 Topological element relationship

Face	Edge	Node
1	e1, e3, e5, e8	B, C, D, F, I
2	e2, e3, e4	A, B, D, E
3	e4, e5, e6, e7	E, D, F, G, H
4	e6, e8, e9, e10	F, G, I, J
5	e7, e9, e11	G, H, J, K

Table 3 Topological edge direction matrix

Edge	Left face (LF)	Right face (RF)	From node (FN)	To node (TN)
e1	–	1	B	C
e2	–	2	A	B
e3	1	2	B	D
e4	2	3	E	D
e5	1	3	D	F
e6	4	3	F	G
e7	5	3	G	H
e8	1	4	F	I
e9	4	5	G	J
e10	–	4	I	J
e11	–	5	J	K

according to the percentage of success and failure. Fuzzy logic can indicate ways to improve the performance of map-matching algorithms by handling uncertain and ambiguous data. It provides precise output to uncertain data generated in an environment having low GPS signal strength or frequent signal disconnect [6, 7].

Dead reckoning Dead reckoning is a process to estimate the position of entities based on previously calculated position, speed and direction information. This method uses the heading, speed and elapsed time of the vehicle to determine the output of the navigation system [17, 22, 23].

2.2 Recent developments in map matching algorithms

As discussed above, map-matching algorithms are used to precisely fix the location of vehicle on the spatial road network. The algorithms introduced above use GPS and a spatial data base for the route finding process. One of the common assumptions in the literature on map-matching is that the vehicle is essentially constrained to a finite network of roads. Map matching algorithms vary from those using simple search techniques, to those using more advanced techniques such as the use of an Extended Kalman Filter, fuzzy logic. This section explains the research done in map-matching techniques and analysis based on the literature studied.

2.2.1 Geometric map matching

The concept of in-vehicle navigation started in 1990's to find the exact location of the vehicle. Bernstein and Kornhauser [10] explained the concept of a geometric algorithm. Their research gave the detail and use of three basic geometric map-matching techniques namely, point to point, point to curve and curve to curve and gave two conclusions about these algorithms: (1) point to point and point to curve matching does not work well in ambiguous environment (2) Performance can be improved by incorporating topological information in the algorithm [10]. Greenfeld [12] explained geometric map-matching approaches and implemented a map-matching algorithm based on the geometric information of the road [12]. Kim et al. [9] developed an advance map-matching algorithm that combined GPS receiver output with a dead reckoning model and Kalman Filter. This algorithm attempted to achieve adequate efficiency for intelligent transport systems by the use of an electronic road map. This algorithm used a point to curve geometric algorithm and orthogonal projection to identify the vehicle position. Error correction and effectiveness of the algorithm was improved using the Extended Kalman filter approach. In case the correct link is not identified in the first step then a point to curve approach is combined with topological analysis to improve the accuracy [9]. Taylor et al. [19] proposed a map-matching method which used virtual differential GPS with a height-aiding component of spatial road data. The basic matching process of this algorithm was based on a curve to curve map-matching process [19]. Bouju et al. [13] reviewed the point to point and point to curve algorithms for map-matching processes in rural and urban areas and suggested three important factors to improve the performance of geographical algorithms [13]. These factors include use of historical information, speed information obtained from GPS and road design parameters such as turn restrictions and roadway classification.

Srinivasan et al. [20] presented improvements to the point to curve algorithm based on two types of additional checks in their paper Development of an improved ERP system using GPS and AI techniques". In this paper the first check was executed between the immediate vehicle direction obtained from GPS and location on the road segment. The second check was performed to verify that the direction difference of two successive position fixes obtained from GPS are approximately equal to the turn calculated from the topology of the road network [20]. Ochieng et al. [6] identified the limitations of the [20] algorithm in rural areas and proposed an improved version. This algorithm incorporated the concept of a geographical information system with GPS to handle the frequent GPS disconnection and to detect outliers in positioning accuracy [6].

2.2.2 Topological map matching

Greenfeld [12] proposed a weighted topological algorithm centered on topological analysis of a road and coordinate information. This algorithm emphasized topological analysis with coordinates showing inaccurate results in the presence of outliers [12]. To improve the performance of topological algorithm, Meng et al. [24] proposed an algorithm called Simplified map-matching (SMM). The general approach used for improvements in SMM was based on a qualitative decision making process, that used correlation between the vehicle trajectory and topological features of the road. In contrast to the weighted topological algorithm, this algorithm provided information about direction and speed of the vehicle in the mapping process. Topological features of the road were effectively extracted by combining GPS signals with dead reckoning methods. Dead reckoning is the process to fix the position of a moving entity, based upon its previous position, direction information and speed. The prime limitation of this algorithm is its inability to fix vehicle position on parallel roads [24]. Xu et al. [25] designed a prototype for an urban area car navigation system. This algorithm took into account any error that occurred during road turns or curves. To reduce turn error, the algorithm used GPS fix, Kalman filter, dead reckoning and turn topological information of the road [25]. To utilize and improve the performance of the topological algorithm, Fu et al. [26] worked on route planning and map-matching in vehicle navigation. Their study provided an integrated navigation system based upon GPS, dead reckoning and electronic map. This integrated topological algorithm combined the concept of the point to curve approach with topological information of the vehicle. According to this algorithm, the final decision was a combination of GPS output and three step topological analysis. These three steps include basic topological analysis, point to curve analysis and trajectory information [26]. Velaga et al. [27] developed an Enhanced Topological map-matching algorithm" to augment the performance of the weighted topological algorithm, by adding two additional weight parameters. These new parameters were turn restriction and link connectivity at the junction. This algorithm gave fast and simple results by using the minimum possible inputs. This algorithm showed 97% accuracy urban and sub urban areas [27].

2.2.3 *Advanced map matching*

Kim and Kim [28] presented a fuzzy Q-factor algorithm. This algorithm used the concept of fuzzy logic along with topological information of road and orthogonal projection to measure the exact path for the navigation system. This was the first map-matching algorithm based on fuzzy logic with topological information; however it does not work well on complex roads [28]. To evaluate the performance of fuzzy logic based map matching algorithm, Syed and Cannon [7] implemented fuzzy map matching in urban canyon conditions. This algorithm targeted canyon conditions within urban areas. A canyon area is an area where streets are covered by tall buildings. In such conditions GPS signals cannot be correctly received by low sampling rate GPS receivers. To handle canyon conditions, a high strength receiver with low gyro were used [7]. Fu et al. [26] used a fuzzy model with geometric and topological analysis of the road network. This algorithm considered position, speed, direction information, historical trajectory, data link connectivity, shape points and positioning sensors for navigation purposes. This algorithm improved the performance at junction points and urban areas [7]. Yang et al. [21] developed an improved map-matching algorithm by introducing Kalman filter and Dempster Shafer theory with point to curve geometric analysis. This algorithm provided 96% efficiency in less dense areas. Due to the absence of topological information, this algorithm does not provide good efficiency in dense urban areas [21]. The concept of Kalman filtering was carried forward by Najjar and Bonnifait [29] to develop a road map-matching method using Belief Theory and Kalman filtering. This algorithm used deferential GPS with ABS (Anti-Lock Braking) sensors to improve system performance in urban environments. This algorithm did not work well on parallel roads [29]. Pereira et al. [8] used topological analysis in offline mode and combined the functionality of Marchal's algorithm and GEMMA algorithm [8]. Yanagisawa [30] presented the concept of map-matching algorithms for offline applications using integer programming. Instead of working with online maps this method worked with offline map coordinates. Integer programming with the point to edge method gave less error and an optimal solution. According to the authors this was first method for offline map-matching that is based on the concept of optimal objective function [31]. Sakic [32] developed score based map matching algorithm that used spatial, temporal and topological information for fixing GPS positions. This algorithm targeted incorrect results due to the GPS signal interference. To improve the accuracy of input, Wi-Fi data was used along with GPS information. As a result, this technique provided effective results but was still unable to provide correct output at intersection points [32]. Newson and Krumm [33] gave a map-matching algorithm based on a hidden markov model (HMM). This model worked with GPS data and gave better performance than traditional algorithms but did not overcome the selection bias problem. The selection bias problem arises when the input sampling data has very low frequency [33]. Mohamed et al. [34] presented the SnapNet system for map matching in a cellular GPS environment. This system was based on the incremental hidden markov model and topological features of the road network. This system was designed for the situation when the user is driving on major roads instead of minor roads with many turns. With HMM, this system used filters to reduce the input noise. These filters were speed filter, trimmed filter and direction filter [35]. Yang et al. [21] enhanced the performance of topological algorithms in urban environments by combining the road information as weighted parameters [25]. Miler et al. [36] gave the concept of string matching technique to predict the location of a vehicle in a high traffic area. The motive of this research was to match the location in the map where chances for accidents are high. This method uses two techniques Jaro Winkler String Matching Technique" and the Inverse Distance Weighting Method". This method used topological analysis in an online environment and claimed that the errors were minimized to the extent of 15% [36]. Based on literature studied, research in map matching algorithms is categorized into Geometric, Topological, Advanced, Topological advanced and Geometric advanced [3, 5, 6, 9, 14, 16, 22, 27, 28, 31, 35–39] shown in Table 4. From the literature we observed a few points. First, map matching is a continuous process due to the presence of some unsolvable issues like map matching in multi lane environments, poor performance of navigation systems in rural area, difficulty in handling low frequency signal with low cost devices etc.

Figure 4 shows a time line graph of map-matching algorithms that started in 1996 with research still continuing for improvement of these algorithms. Secondly, map matching algorithms have evolved from geometric analysis, and the advancement of technology has resulted in much more accurate algorithms based on advanced mathematical models as shown in Fig. 4. The motive for advanced algorithms is to improve the accuracy of the navigation system. The literature reports that recent work is on multi-lane crowded areas and off-line map-matching techniques, but due to advances in crowd sourced navigation systems, there is a lot of scope for the improvement of map matching procedures. Figure 4 also indicates there is recent work on topological analysis based advanced map-matching algorithm. As perceived from the literature, topological data with advanced string matching and error

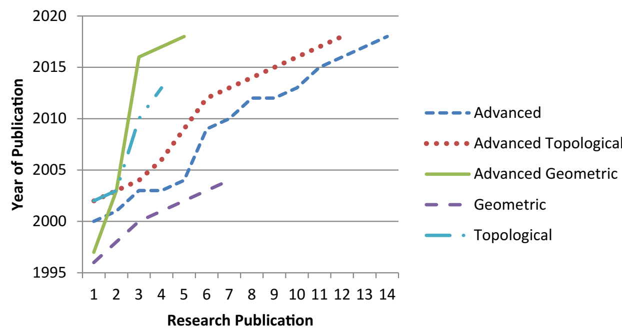

Fig. 4 Time series diagram of map matching algorithms

handing techniques provides an effective solution with minimum errors. From the literature studied and to the best of our knowledge, no study has offered any consolidated empirical evaluation of map matching algorithms, This motivated us to pursue with the experiment detailed in section 3. [36] (Fig. 5).

3 Methodology

To review the performance of techniques discussed in the literature review, an experiment was designed and a few of the algorithms from each category were implemented. For the experimental study we used geometric, topological and Kalman filter techniques due to maximum publications suggesting their use. Experiments were undertaken into two phases, the first phase includes data collection and the second phase includes results and analysis as described below.

3.1 Data collection

For reviewing and implementing map-matching algorithms discussed in previous sections, real time data were collected using a GPS receiver. The GPS receiver (Quectel L86 GPS with GLONASS Module) had maximum sensitivity 160 dBm and tracking 149 dBm. A total of 3830

Table 4 Concluded Categories of map matching algorithms

Algorithm	Procedures
Geometric	Basic geometric information includes point and curve accumulation
Topological	Basic topological data includes trajectory, geometric entities and their relationship
Advanced	Dead reckoning, Kalman filter, probability theory, spatial and temporal analysis, Belief theory, sensor data, offline map
Geometric advanced	Geometric data with error correction by using orthogonal projection, Damper Shafer's theory
Topological advanced	Topological analysis with error correction techniques like fuzzy logic, heading information, neuro logic, incremental hidden markov model

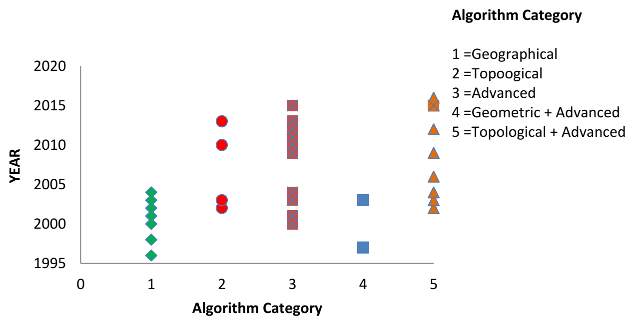

Fig. 5 Based on the publication and technique used, category wise algorithm generation (each symbol represents one paper)

points were collected for bounding box (30.28167834, 76.83468928) to (30.51628095, 76.65953611). The points were collected for a road distance of 47 km (Fig. 6). The collected data included National highway, urban, sub urban and rural areas. The speed during the collection of data varied in the range of 5–80 km/h.

3.2 Comparison matrices

To compare the performance of map matching algorithms, we considered two matrices named Root Mean Square Error (RMSE) and count of matched and unmatched node. RMSE calculates the prediction error of two datasets. It measures the difference between data points of observed output with the actual standard output. If we have two data series S (standard data series) and O (Observed data series) then RMSE can be calculate following equation:

$$\mathrm{RMSE} = \sqrt{\frac{1}{n}\sum_{i=1}^{n}(S_i - O_i)^2}$$

where N is total input size and S_i and O_i are the ith input.

Matched and Unmatched node count represent the total number of node of observed data series is exactly matched with the standard data series. S_i and O_i are the ith point in both the data series then if $S_i = O_i$ then point is matched else not. In our experiment we considered the road node point as the standard data series and output of map matching algorithm as observed data series. These two data series were analyzed by using above mentioned matrices.

4 Results

The collected GPS data were mapped to the both off-line and on-line maps. To map the data, geometric and topological map-matching algorithms and Kalman filter approaches with topological mapping were used. The Kalman filter was implemented using a python library available for Kalman filter [40]. Output of the matching process showed the geometric map-matching technique works faster on straight roads. Topological algorithm considers all minor turn as compare to geometrical algorithm. The performance of these two algorithms in rural and suburban area is shown in Fig. 7. The Geometric algorithm performance is poor when speed is less and GPS points to be mapped are comparatively large as shown in Fig. 8. Topological map-matching techniques work comparatively better in dense areas and provide more accurate

Fig. 6 Bounding box coordinates track recorded during experimental study (imaginary used OSM)

mapping in curved areas. Figure 7 shows the mapping output of the geometric and topological algorithms. Output of Kalman filter based map matching algorithm is showm in Fig. 9

The Kalman filter model is added to the map matching process to approximate the erroneous input. Kalman filter techniques avoid nearby points with negligible difference and generate approximate generalized data. To check the efficiency of map-matching algorithms, in terms of the number of nodes matched or not matched, a subset of the complete path was taken due to computing and hardware limitation. The sub path is from a rural area and has length of 9 km with 670 points of interest. After applying map-matching algorithms, matched and unmatched points were calculated (Table 5). The comparison shown in Fig. 10, explains the Kalman filter gives much better results compared to Geometric and topological map-matching. Similarly Root Mean Square Error were calculated based upon the considered road network and output of the map matching algorithms. The RMSE values are shown in the Table 6. According to RMSE it is also considered that Kalman filter based map matching algorithm gives better output in comparison to topological and geometrical algorithm.

The RMSE are calculated for each algorithm. Actual road points are collected from OSM dataset and this data set is treated as standard dataset for the RSME calculation. GPS dataset received from GPS receiver is processed using map matching algorithm. Their output is compared with standard data set and RSME are calculated and are shown in Table 6. According to these values Kalman filter based algorithms have less error in comparison to other two

Fig. 7 Geometric and topological map-matching output rural and sub urban area

Fig. 8 Geometric and topological map-matching algorithm performance at slow speed

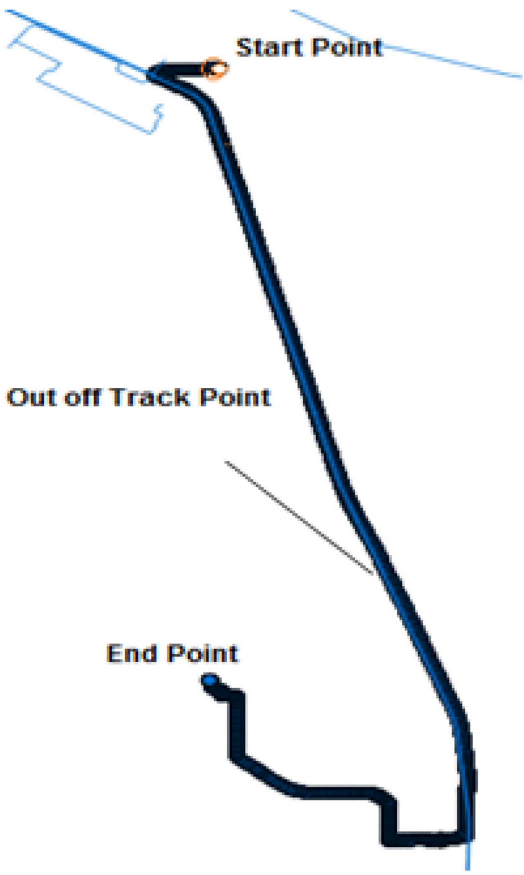

Fig. 9 Path for matched node calculation (Kalman filter approach)

Table 5 Count of matched and unmatched nodes of considered map matching algorithms

Algorithm	Geometric	Topological	Kalman filter
Matched	423	507	590
Un-matched	247	163	80

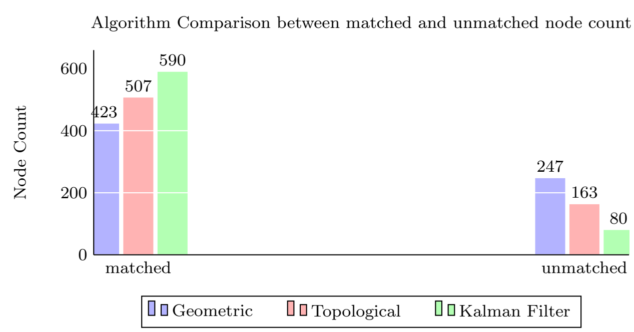

Fig. 10 Comparison of geometric, topological and Kalman fitter based map matching algorithms

Table 6 Root mean square error for considered map matching algorithm

Algorithm	Geometric	Topological	Kalman filter
RMSE	0.78	0.57	0.36

algorithms. Similarly geometric algorithm has much more error rate in comparison to topological and Kalman filter based map matching algorithm. Higher the RSME value means less the accuracy of the algorithm. The Kalman filter based algorithm has more accuracy due to 2 step processing. First step involves the preprocessing of data using Kalman filter based approach and then second step is mapping process using topological algorithm.

5 Conclusion and future scope

From the experimental results, it can be concluded that the performance of a navigation system is completely dependent on the map-matching algorithms employed. The experimental study evaluated the performance of topological, geometrical and Kalman filter based topological map-matching algorithms on the same data set. From the results, it has been observed that topological map-matching algorithms perform better in comparison to geometric Algorithms. Geometric Algorithms consider only longitude and latitude of the moving entity, whereas topological algorithms consider speed, direction, bearing difference, Euclidean distance, previous position of vehicle and other sensor data of navigable device. It is also observed that when we collect data at low speed then geometric algorithms gave worse performance compared to topological algorithms. The performance of topological map-matching with Kalman filter approach gave much better results with the dataset, which comprised urban, rural, sub urban roads and a national highway. Therefore, to achieve good performance for a navigation system, especially in areas where GPS signals are weak or frequently disconnected, topological algorithms and its variation with advanced technologies are best suited. Further improvements to map-matching algorithms are essential to provide accurate results in multilane and canyon regions. In the current era, non proprietary data sets like open street map are being used in navigation systems, so much attention is required on the mapping process for these systems as they rely on crowd sourced information, which at times is not precise. It was concluded that a combination of topological analysis with advanced mathematical models can take the present scenario of navigation systems to the next level. From the study it is also concluded that navigation systems still require upgrading, so as to achieve better accuracy and this can only be achieved by improving the map-matching process.

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