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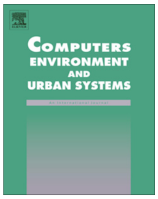

Review

A critical review of real-time map-matching algorithms: Current issues and future directions

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ABSTRACT

Current navigation systems/services allow drivers to keep track of their precise whereabouts and provide optimal routes to reach specified locations. A reliable map-matching algorithm is an indispensable and integral part of any land-based navigation system/service. This paper reviews existing map-matching algorithms with the aim of highlighting their qualities as well as unfolding their unresolved issues as a means to provide directions for future studies in this field. Existing map-matching algorithms are compared and contrasted with respect to positioning sensors, map qualities, assumptions and accuracies. The results of these comparisons provide interesting insights into the workings of existing algorithms and the issues they must address for improving their performance. Example findings are: (a) not all map-matching algorithms pay sufficient attention to topology of networks, directionality of roads or turn-restrictions; (b) most map-matching algorithms make an unbalanced trade-off between performance and accuracy; and (c) weight-based map-matching algorithms balance simplicity and accuracy and advanced map-matching algorithms provide high accuracy but with low performance. Based on the findings, suggestions are made to improve existing algorithms.

Contents

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1. Introduction

Today, navigation systems/services are available in automobiles, cell-phones and other mobile devices. Coordinates of the device, obtained through positioning sensors, are used along with the road network database of the area to estimate user's location on a road segment (Zhang, Wang, & Wan, 2003). The process of continually estimating a user's position on a road segment is known as map matching (Greenfeld, 2002; Karimi, Conahan, & Roongpiboonsopit, 2006; Quddus, 2006). Matching position obtained through GPS, or other positioning sensors, on road segments can be performed either in real-time mode (Velaga, Quddus, & Bristow, 2009; Li, Quddus, & Zhao, 2013; Quddus, Noland, & Ochieng, 2006; Syed & Cannon, 2004) or post-processing mode (Yuan et al., 2010a; Ebendt, Sohr, Tcheumadjeu, & Wagner, 2010; Kuehne et al., 2003; Miwa, Kiuchi, Yamamoto, & Morikawa, 2012). Real-time map matching must address challenges such as finding the road segment on which the user is traveling and snapping or projecting updated GPS points on that segment in real time (White, Bernstein, & Kornhauser, 2000). In real-time mode, all GPS points up to the current one can be used to match the current GPS point. In contrast, in post-processing mode, map matching is performed after all or a large part of GPS points are collected (Bierlaire, Chen, & Newman, 2013; Lou et al., 2009; Miwa et al., 2012; Rahmani & Koutsopoulos, 2013; Yang, Kang, & Chon, 2005). This necessitates the access to all GPS points in post-processing mode in order to find the best matching path in the road network for the entire trip (Marchal, Hackney, & Axhausen, 2005). In other words, the problem in post-processing map matching is finding a path on a road network which closely matches a raw GPS trajectory (Lou et al., 2009). Some studies refer to post-processing map-matching algorithms as global algorithms (Brakatsoulas, Pfoser, Salas, & Wenk, 2005; Lou et al., 2009; Rahmani & Koutsopoulos, 2013; Yuan, Zheng, Zhang, Xie, & Sun, 2010b). Furthermore, incremental or local map-matching algorithms, which do not require all GPS points but a considerable part of them to match a path (Yuan et al., 2010b), are also categorized under post-processing algorithms. In general, real-time algorithms provide position estimates faster but post-processing algorithms are more accurate (Brakatsoulas et al., 2005). While continuity on the path during the entire trip is not guaranteed in real-time map matching, it is a condition for post-processing map matching (Brakatsoulas et al., 2005). Table 1 summarizes the main differences between real-time and post-processing map-matching algorithms.

Post-processing map matching is for applications where knowledge on the actual path for the entire trip is more important than on the instantaneous position of the user and where large data processing and intensive computation are allowed (Bierlaire & Frejinger, 2008; Rahmani & Koutsopoulos, 2013). Example applications of post-processing map matching are mining historical trajectories of a large number of experienced taxi drivers to find shortest routes between different origin–destination pairs at different times of day (Yuan et al., 2010a) and estimating travel time (Ebendt et al., 2010) or traffic (Kuehne et al., 2003; Li, Zhang, & Yu, 2011; Miwa et al., 2012) along a road segment by crowd-sourcing. Considering that post-processing map-matching algorithms potentially have to deal with large amounts of data and computationally intensive tasks, two approaches are taken to mitigate these issues. One approach is decreasing the number of points for post-processing by increasing the polling time interval (Lou et al., 2009; Miwa et al., 2012; Rahmani & Koutsopoulos, 2013; Yang et al., 2005) and another approach is recording only the position and timestamp for each point ignoring other data items such as heading and speed (Lou et al., 2009; Miwa et al., 2012; Rahmani & Koutsopoulos, 2013; Yang et al., 2005). When the time interval between two consecutive positions is long, it cannot be guaranteed that they both belong to the same road segment. If the time interval is too long, the two road segments may not even be connected, which may mean that the user has passed a few road segments between two position estimates. Due to all these possibilities, finding the correct path between consecutive GPS positions with long time intervals is a challenge in post-processing map-matching algorithms. While real-time map-matching algorithms access high frequency position data with many recorded data items such as position, speed and heading, post-processing map-matching algorithms must map match a massive amount of low frequency position data with only the latitude and longitude coordinates recorded. Consequently, real-time map-matching algorithms cannot directly be used in place of post-processing map-matching algorithms as they have to resolve different challenges (Chen et al., 2014).

Bierlaire et al. (2013) developed a post-processing map-matching algorithm for GPS-enabled smartphones only for driving. Position, speed and heading data from GPS are used to assign a probability to each candidate path based on horizontal accuracy of GPS data and the road network. Inaccurate and low-frequency positioning data are two challenges in their study. Miwa et al. (2012), Rahmani and Koutsopoulos (2013), Yang et al. (2005) and Lou et al. (2009) developed a similar algorithm specifically for vehicles with lower positioning data frequency and only position coordinates and timestamp. Sparse positioning data, with gaps up to 1.5, 3, 5 and 5 min with latitude, longitude and timestamp, were used. Chen et al. (2014) proposed a map-matching algorithm for large-scale low-frequency floating car data. They used a multi-criteria dynamic programming technique to minimize the number of candidate routes for each GPS point. Lou et al. (2009) considered two important points in their post-processing algorithm: (a) true paths tend to be straight, rather than roundabout and (b) true paths tend to follow posted speed limits on roads. Yang et al. (2005) proposed to project GPS points within 20 m from intersection nodes onto the intersection node itself, postponing resolution of the problem to the next point. Yuan et al., 2010b used Tobler's first law of geography that "everything is related to everything else, but near things are more related than distant things" to develop an interesting approach of assigning a segment to a GPS point in their post-processing map-matching algorithm. First, all segments within a constant distance from the GPS point are

Table 1
Comparing real-time and post-processing map-matching algorithms.

Criteria	Real-time	Post-processing
Problem	Assigning a road segment to current GPS point	Finding the real path through all points
Purpose	Navigation and real-time applications	Mapping large-scale floating cars data, fleet monitoring, traffic surveillance
Required data	Position, timestamp, heading, speed, accuracy	Position and timestamp
Next points	Not needed	Needed
Polling time interval	1–10 s	1–5 min
Result	Fast	Accurate
Continuous tracking	Not guaranteed	A condition