A Simplified Map-Matching Algorithm for In-Vehicle Navigation Unit

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Abstract

GPS has been widely used for land, sea and air navigation. However, due to signal blockage and severe multipath environments in urban areas, GPS alone cannot satisfy most land vehicle navigation requirements. Dead Reckoning (DR) systems have been widely used to bridge the gaps of GPS and to smooth GPS position errors. However, the DR drift errors increase with time rapidly and frequent calibrations are required.

As land vehicles have to be on roads, digital map can be used to constrain the locations of vehicles, known as map-matching, which is an efficient way to improve the performance of positioning systems while working under urban environment. In this paper, a simplified map-matching algorithm is proposed for an in-vehicle navigation unit, as the processing power of in-vehicle processor is limited. Extensive field tests have been conducted in Hong Kong and Macau. The results reveal this map-matching algorithm can improve the performance of the vehicle navigation unit significantly.

I. INTRODUCTION

Land vehicle navigation systems have been widely applied for vehicle tracking, fleet management and many other applications. In last two decades, satellite navigation technology, especially the Global Positioning System (GPS), has been rapidly developed as a major positioning technology in land vehicle navigation. However, as GPS requires clear sky view, it is difficult to positioning in urban areas, such as in Hong Kong. Tests have shown that the availability of GPS is only about 30% in high dense population areas of Hong Kong (Chao et al, 2001). Even when GPS position is available, it may suffer from poor positioning accuracy due to the canyon effect, caused by the severe multipath and bad satellite geometry. Without the Selective Availability (SA), GPS positioning accuracy is normally within 10 meters (Satirapod et al, 2001). However, our field tests in Hong Kong showed that the GPS positioning errors could offset from the true position by more than 80 meters. Obviously, GPS alone cannot satisfy most land vehicle navigation requirements in highly built urban environment, such as Hong Kong.

Dead Reckoning (DR) systems have been widely used to bridge the gaps of GPS and to smooth GPS position errors (Abbott and Powel, 1999). A basic DR system consists of an odometer to measure the travel distance of a vehicle and a gyro or compass to provide moving direction. Then the position of the vehicle can be calculated by giving an initial position. The main advantage of the DR system is that it is a self-contained system and can provide position information continuously. However, the DR drift errors increase with time rapidly and frequent calibrations are required. We have tested two types of low-cost DR units in Hong Kong and the results show that without calibration, the DR units can only maintain positioning accuracy of 10 meters within 200 meters of traveling distance. Integration of GPS and DR provides a better solution as the DR unit gives us continuous positioning capability with short-term high positioning accuracy, while GPS is used to constrain the growth of DR drift errors. In urban areas, however, GPS may not be available for quite long periods and DR has to provide the positioning function alone during the periods. In Hong Kong, for example, it is not uncommon that GPS may not available for more than 20 minutes and DR drift errors may reach hundreds of meters during the period. Thus, it is strongly demanded to develop a technique/system that can complement GPS/DR system in highly built urban areas.

As land vehicles have to be on roads, digital map can be used to constrain the locations of vehicles, known as map-matching techniques (Scott, 1996). As reliable digital road maps are readily available (Bastiaansen, 1996), and the map accuracy is normally higher than that of the positioning sensors, map-matching is an efficient way to improve the performance of positioning systems while working under urban environment. The benefits of map-matching come from two aspects. Firstly it improves the positioning accuracy by constraining the vehicle location on the roads. Secondly it provides the controls for the DR drift errors and therefore the navigation system can be used for longer period when GPS is not available. Map-matching technique is basically a pattern recognition and matching process (Zhao, 1997). The map-matching algorithms can be classified into two categories in general. One is geometric approach that considers point-to-arc and arc-to-arc matching. The other is to use conditional probability approach (Kim and Kim, 2001). The former tries to match the position measurement to the nearest point of the nearest road, or make

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use of the feature point of the vehicle trajectory and road network to find the corresponding point. However, in the geometric matching, the nearest road is not always the right one, and the corresponding point requires case-by-case calculations. The later is more robust than the former and the chance of false positioning is less, but it requires more computation time and memory to store the vehicle trajectory.

For in-vehicle unit, another constrain is the processing power. With the development of computer technology, the processing speed of in-vehicle processors is not a problem. For practical consideration, on the other hand, it would have advantages to use cheap processors for wider applications. This paper proposes a simplified map-matching algorithm that preserves the advantages of both geometric and statistical approaches. Meanwhile, the algorithm can be implemented into low speed in-vehicle processors to give a workable and cost-effective solution.

II. MAP REQUIREMENTS FOR THE PROPOSED MAP-MATCHING ALGORITHM

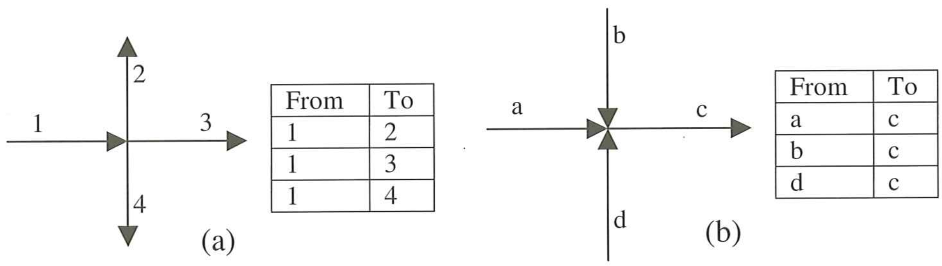
Map-matching is a software algorithm that is used to integrate various positioning sensor data with digital road map data to give a better position estimate of vehicle (Zhao, 1997). It plays an important role in the positioning system as it employs digital road map database to improve the accuracy and reliability of positioning system. Commonly, map-matching methods firstly determine the section of road by comparing the trajectory with the road network to find out the most similarity. Then the position of vehicle can be located on the road (Zhao, 1997; Takashi and Miki, 1996). The basic assumption of map-matching is that vehicle is on the road most of time (French, 1989). After given an initial position and direction, the map-matching process keeps asking that if the vehicle is still on the road network, and which road it is on. The matching process selects all possible roads around the vehicle position derived from a positioning unit, and then applies conditional tests to determine road the vehicle is traveling on. The road intersections or shape feature points are very important for road section determination. The conditional tests consider not only the correspondence between the geometric attributes, such as turn at road intersections, road azimuth, road length, and road curvature, but also the road rules because the vehicle should conform to certain traffic rules while driving on the road networks.

Actually, digital road map is adopted as a pseudo-sensor to improve the overall positioning system performance includes the positioning accuracy, reliability and continuity. To meet the map-matching requirements, the essential content of the digital road map is the accurate position and shape of the road network. And the correctly, completely, and clearly defined topology of road network is also very useful to the map-matching process (Bullock and Krakiwsky, 1994). With regard to positional accuracy, it is generally considered to be acceptable for vehicle navigation if the digital road map is accurate to within 15m of 'ground truth' (Zhao, 1997; Bullock and Krakiwsky, 1994). However, if a digital road map is to be used for DR calibration, a better accuracy of a few meter level is desirable.

The base digital road network map released by HK government provides the road shape and position in the form of a road network that consists of the basic topological information, such as road centerline and intersections, with very high accuracy (<1m). For map-matching, on the other hand, other road information, such as road direction, turn restriction, and road slopes, are also very helpful. The navigation database for Hong Kong has been recently established (Chao et al, 2001). It includes not only the road geometry, but also road attributes and road traffic information. It provides much detailed information of Hong Kong road network, with the size of more than 30Mb. However, it contains many other details that do not benefit the map-matching process but degrade the map-matching processing efficiency.

For the purposes of simplicity, the vehicle position is assumed to be a point on the road and the road is represented by its centerline that consists of nodes and arcs. Several essential components of digital road data representation are: geometric shape of roads, topological connectivity, and explicit turn restriction representation of road junction, which is a sub-set of the Hong Kong navigation database.

The turn restriction, for example, can be stored in the following forms in Figure 1. In Figure 1(a), from arc 1, the vehicle can turns to either arc 2, 3 or 4, and all the possibilities can be stored in the corresponding table. However, in Figure 1(b), it is not allowed to turn from arc a to arcs b and d.



From	To
1	2
1	3
1	4

From	To
a	c
b	c
d	c

Figure 1. Turn restriction model

The road topological connectivity is constructed based on a non-planar network concept as flyover that does not have an intersection with the road underneath (Figure 2). Therefore, the flyover and the road underneath are modeled separately as two unconnected line segments. The benefit of such a model is to eliminate the case in which the roads will be shown as intersected in planar graph while the actual roads do not intersect.

III. MAP-MATCHING ALGORITHM

Basic features of the algorithm

The proposed algorithm not only considers the similarity or correlation between the trajectory of vehicle and the road network is carried out, that takes error estimates of sensors and map into account. It is different from the conventional map matching, which calculates the correlation between the trajectory of vehicle and the road network, case by case, based on the probabilistic theory. In our algorithm, we use thresholds to perform conditional tests to find out the maximum similarity. The thresholds were obtained from the statistical analysis of field-testing data

As described previously, the map database is enriched with attribute information. Therefore such a map database would be of great help in the positioning of vehicles. That is, the location of a vehicle could be confined to only a limited number of road segments, with the aids of information in map database.

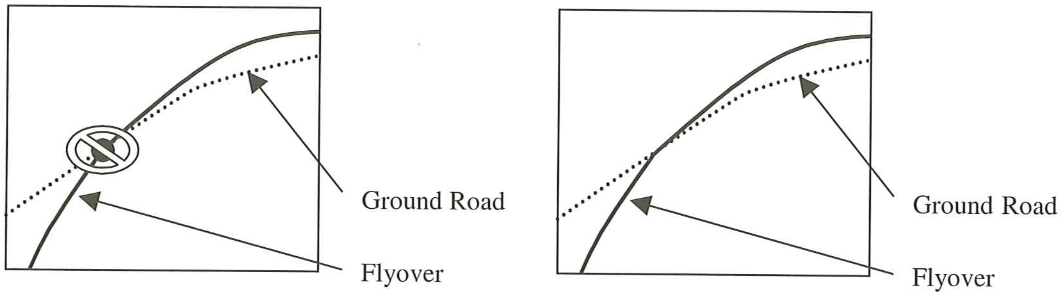


Figure 2. Example of road connectivity representation

In this way, the processing is more efficient.

The proposed map-matching algorithm can be divided into four key operations:

- Road identification
- Road feature detection
- Road following
- Reliability and integrity

Road identification is a procedure of finding the road vehicle is currently traveling on. Road feature detection is a procedure of detecting geometric and topologic feature of roads, such as road turn, road curvature, and road connection. After a road is identified, the vehicle position is relocated on the proper position relative to the identified road. This procedure is called road following. It would be serious problems if a vehicle were matching to a wrong road without notice. If that were the case, the positioning function would be totally lost unless GPS is available. Therefore, special algorithms have designed for the reliability and integrity checks for map-matching.

The basic flowchart of the proposed algorithm is illustrated in Figure 3.

Road identification

Road identification is a process of finding a road segment that a vehicle is currently travelling on. To start map-matching, an

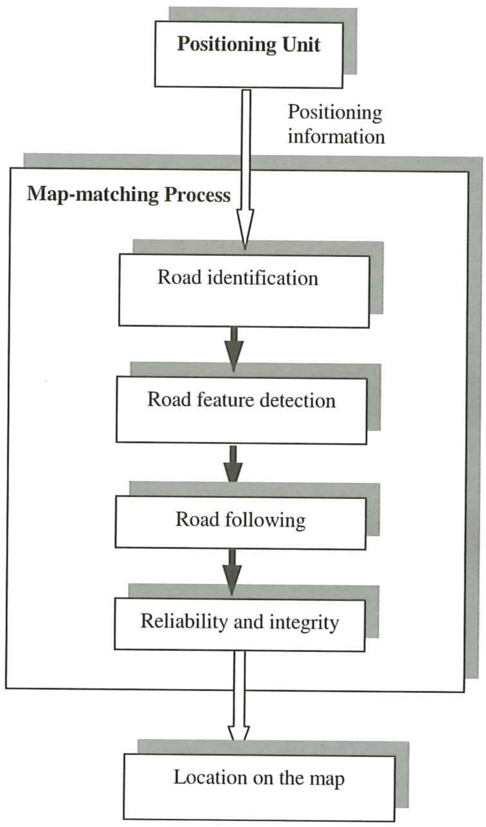


Figure 3. The processing flowchart of proposed map-matching algorithm

accurate and absolute position measurement defined in the map reference frame and the accurate vehicle bearing are needed. Also at junctions, a new road segment needs to be identified before matching process can be applied. In real-time application, the initial position and direction are normally given by GPS when it is available. However, in urban environment, GPS may not be available at the time. Two alternative methods can be applied in this situation. The first method records the last measurements of position and direction in the memory. When a vehicle start to move again, this store information can be used for initialization. The second method tries to find the maximum similarity (such as similar azimuth, length, curvature) between the vehicle trajectory derived from a positioning unit and the road network. In our algorithm, when determining the road candidate, we take into account not only the shape of the road but also the distance from between the road and sensor-derived position.

As road identification tries to match the road network with the measured positions, both map and position measurement sensors errors have to be considered. Firstly, all road segment candidates within a given confidence interval are selected from

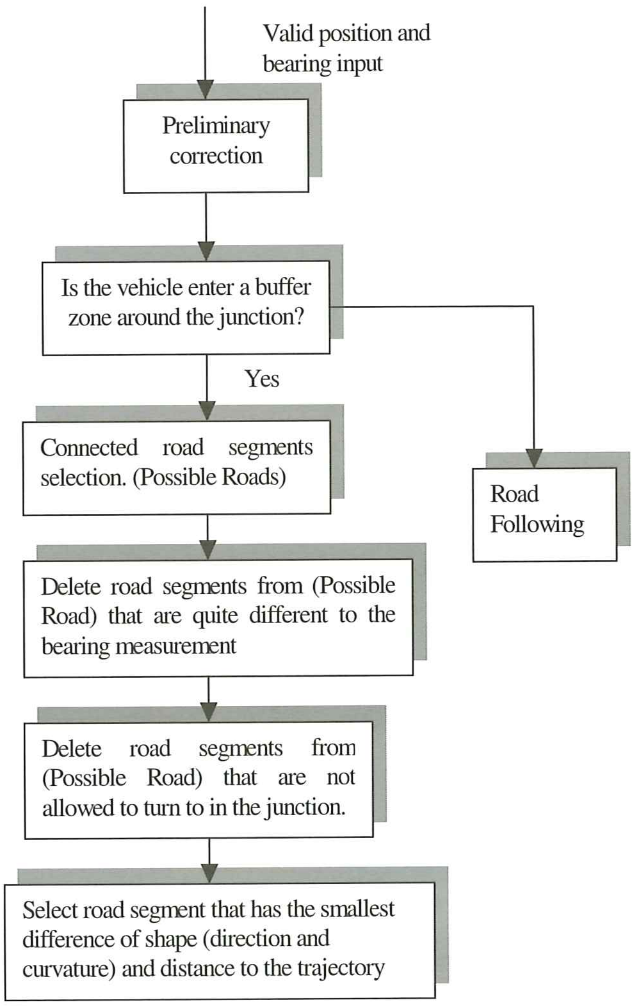


Figure 4. Road Identification

the map database. Then a number of conditional tests are applied to eliminate those segments that do not satisfy the defined tests. For example, the road segment that has the similar bearing as the measured one from the positioning unit is considered as the road segment the vehicle is currently traveling on. One-way road segments have only one direction q while bi-way road segments have two possible directions, q and q±180. If more than one road segment meet the criteria been set, the vehicle trajectory obtained from the positioning unit is compared with all possible candidate road segments until the correct one can be identified by using the one 'closest' to the trajectory. The vehicle position then can be relocated to the road by project the measured position to the determined road segment by distance measurement. After successful initialization, the map-matching process is continuously to match the vehicle location on the identified road segment whenever new positioning information is received. Figure 4 illustrates the road identification process.

Road features detection

When a road segment is determined, we can extract the related information of the road, such as the road azimuth, road length, road connectivity, turn restriction of its junction. The information can then be used for next road identification and calibrate measurements (distance, bearing, and position) of the positioning unit. Moreover, such information is important for the reliability and integrity checks in data processing.

Road azimuth can be used to correct the bearing measurements. As we determine the road segment, we can calculate the azimuth of the road segment. Because we know that the vehicle is now traveling on the road, we can use the road azimuth to calibrate gyro or compass measurements. The difference between the last relocated position and the last measured position can also be used to correct the current position measurement. Whenever a feature point of road segment such as the largest curvature point is detected, it can be used to correct the accumulated distance error.

Road following

Road following is a process to determine the location of the vehicle on an identified road segment. After a road candidate is determined, a new position can be obtained from two sources. One is the predicted based on the vehcile velocity and the road azimuth and another from positioning sensors. The final position is obtained by the weighted average of the two solutions, as showed in the following equation:

$$\hat{X} = C_1^{-1}(C_1 + C_2)^{-1} X_1 + C_2^{-1}(C_1 + C_2)^{-1} X_2$$

where X_1 is the projected position measurement and X_2 predicted position. C_1 and C_2 are the corresponding covariance matrices.

Reliability and Integrity

The reliability check is the procedure that makes sure the vehicle location is correctly matching to the map road network, while integrity check tries to identify any wrong matching. As the reliability and integrity requirements for land vehicle navigation is lower than civil aviation requirements, it is not a severe problem if GPS is available. However, this is very important for urban environment navigation because GPS may not be available for very long period, and position of vehicle is provided by the DR unit. Even when GPS is available (>4 satellites in view), the positioning error may still too large due to bad geometry and multipath. If a vehicle location is wrongly matched on the road network, the following process will be completely wrong as DR uses this location to derive the next position unless reliable GPS is obtained again.

In our algorithm, the reliability and integrity checks can be divided into three levels. The first level checks the quality of measurements. The GPS/DR unit outputs not only the position estimates from the integrated sensors, but also sensor measurements and quality indicators, such as distance, bearing, GPS positions, HDOP, signal to noise ratio, and etc.. Only the positions can agree with each other will be updated for map-matching. The second level checks the agreement between the sensor output and road network. For example, the sensor measurements indicates a turns, there should be a corresponding turns in the road network. If a vehicle enters areas where no road information, the matching algorithm has to stop. The third level examines if the matching is correct. This process basically compares the feature points between road network and vehicle trajectory. If they don't agree with each other, a re-initialization process will start to identify the road segment where the vehicle is on.

In practical, the wrong matching mostly occurs under the situation that more than one road segments can pass the conditional tests and they are very similar to the measured trajectory with some degree. In this case, we will not eliminate any candidates but match to all candidates separately until the correct one can be identified.

IV. FIELD TESTS AND RESULT ANALYSIS

To evaluate the performance of the proposed map-matching algorithm, extensive field tests have been conducted covering most of roads in Hong Kong and Macau. The test results show that map-matching have greatly improved positioning in terms of continuous vehicle positioning and positioning accuracy (Chen et al, 2002). The following are a few examples to demonstrate the performance of the proposed algorithm. These tests were conducted in the downtown of Hong Kong. The narrow streets surrounded by dense residential and commercial skyscrapers constitute a complicate road network. In such areas, GPS signals are almost completely not available and therefore the position estimates are mostly from the DR sensors.

Figure 5 shows the road identification at the junction A and B. This is a simple case with sharp turning at junction B. In Figure 5, the circle sign represents the position from the DR and the triangle sign for the matched position. Before the vehicle is approaching the junction A, the position error is getting larger. It can be seen from Figure 5 that actually the positions from the DR are even closed to road b. However, as the vehicle was identified on road c between junction A and junction B, the matched results only follow road c. When the vehicle is approaching junction B, three connected road segments are found at the junction after checking the road connectivity. A further searching of the database indicates U turn is not permitted at junction B on road c. Now, only 2 road segment candidate arcs left to opt. By checking the azimuth change of the bearing measurements. The new road, i.e. road a, can be easily identified. That is, when the bearing change reaches nearly 90 degrees, the azimuth of road a is matched to the vehicle bearing. On the other hand, the point at which there is a bearing change of nearly 45 degrees can be matched to junction B.

Figure 6 shows the positioning accuracy improvement due to road following process. Figure 6 gives a case when the vehicle passes a tunnel. After the tunnel is verified being taken by vehicle, the map-matching process relocates the vehicle positions along the tunnel. It can been see from Figure 6 that although the DR position is drifted away from road, the matched position is always on the road as there are no other alternative roads to follow, and thus the across-track error is significantly reduced.

The road feature is useful information that can be used for next road identification and for the correction of the positioning errors. The feature points of road segment such as the largest curvature point and the sharp turn between road segments can be used to correct the accumulated distance error and to

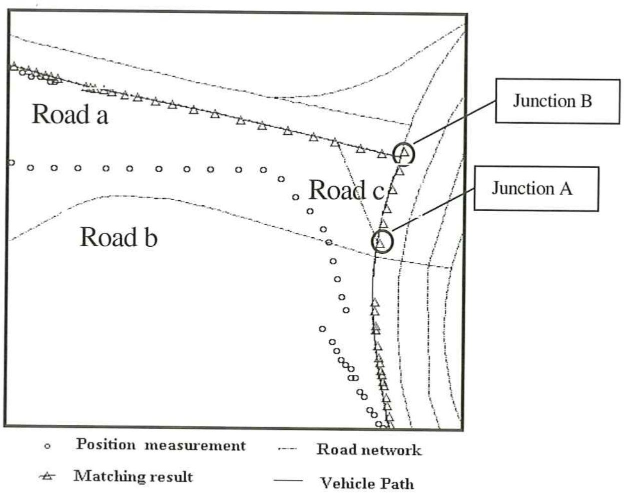


Figure 5. Example of road identification

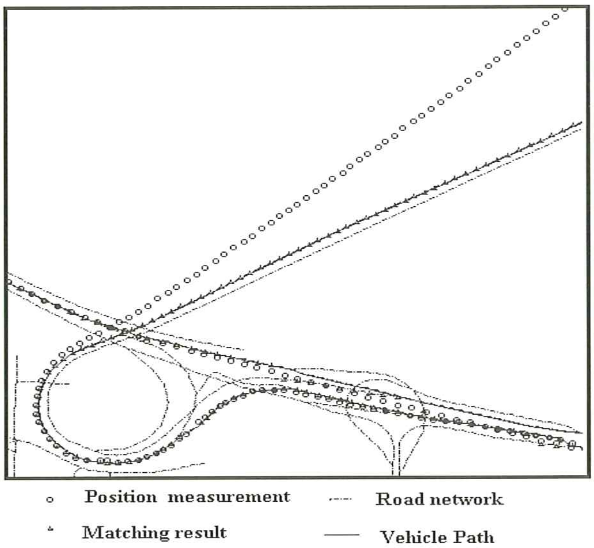


Figure 6. Examples of road following

help to identify road segments. Figures 7 and 8 demonstrate the use of feature points for map-matching. In Figure 7, it is clear to see that although the position estimates from the DR are significantly biased, the trajectory of the vehicle can be easily matched back to the road network by comparing the shape trajectory. In Figure 8, the position estimate from DR is much closed to junction B. Because the position error is estimated at junction A and the consequent positions are corrected, the correct turning junction C can be identified.

The final example is given in Figure 9. This is in an area where there are a lot of high buildings surrounding the narrow streets. During seven minutes of the travel, no GPS position can be obtained and the vehicle is positioning by DR only. It can be seen in Figure 9 that the vehicle positions derived from DR were becoming increasingly poor along with the distance traveled. With the map-matching method proposed in this paper, the vehicle locations can be accurately matched with the road network.

V. CONCLUSIONS

The proposed map-matching algorithm preserves the advantages of both geometric and probabilistic approaches while simplifies the process. The keys of the map-matching algorithm are: 1) Initialization of the map-matching process; 2) Identification of the road segments that vehicle is traveling on; 3) Finding out the corresponding feature points between the measured trajectory and the road network; 4) Following the identified road to relocate the vehicle position to match on the road segment; 5) Matching reliability and integrity checks.

As the results of field tests shown, map-matching can significantly improve the vehicle positioning in reliability, continuity and accuracy. With map-matching, the cross-track position error can be reduced to half of road width, and the along-track position error can be corrected whenever a feature is detected. In most cases, the along-track error can be constrained in 10 m. And the proposed algorithm is capable of maintaining the reliability and accuracy by performing continuous integrity checking and frequently sensor error correction.

It must be noted that the algorithm has been simplified to suit the given threshold obtained from existing data sets and therefore it may not be able to work well in those areas of uncertainty where there are similar patterns, see Figure 10. In such a case, when vehicle travels passing junction A, it is hard to determine whether the vehicle is traveling on road A or road B. The road identification will be delayed until a significant difference between these roads occurs. Further development is underway to find more robust thresholds.

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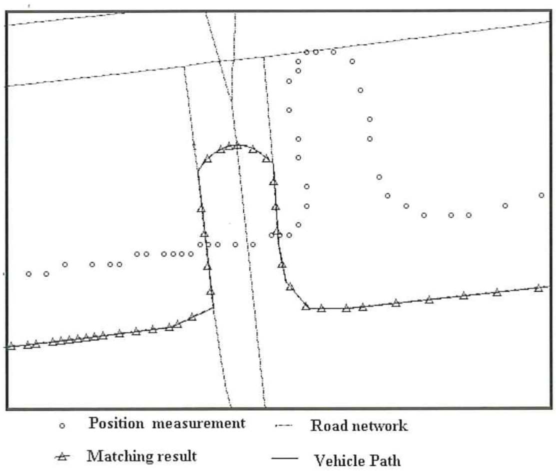

Figure 7. Example of road feature detection

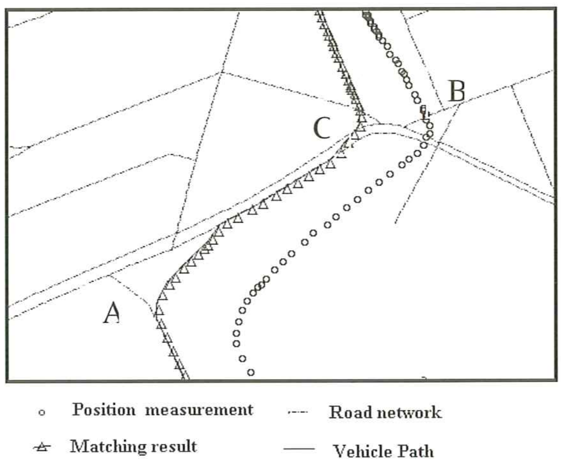

Figure 8. Example of sharp turn

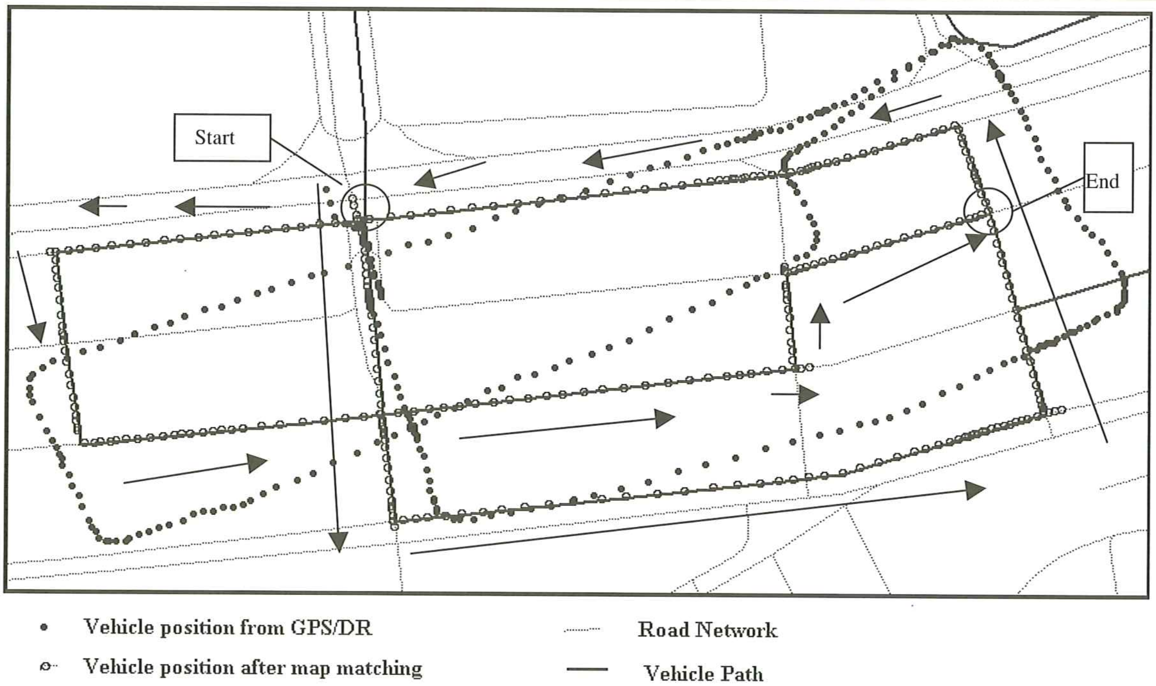

Figure 9. Example of long period without GPS (Wan Chai, Hong Kong)

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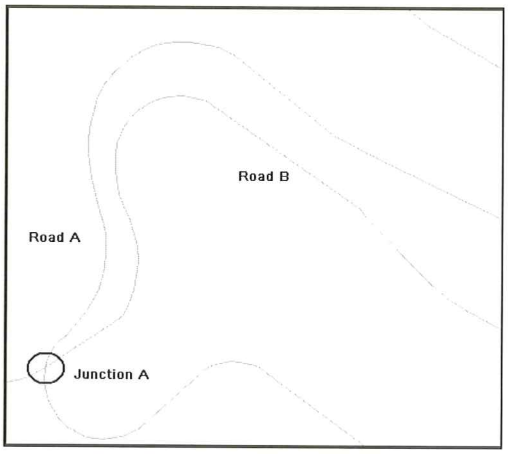

Figure 10. The fork-shape roads