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Effects of Sensor Errors on the Performance of Map Matching

Wu Chen, Zhilin Li, Meng Yu, and Yongqi Chen

(*The Hong Kong Polytechnic University*)
(Email: lswuchen@polyu.edu.hk)

Map matching has been widely applied in car navigation systems as an efficient method to display the location of vehicles on maps. Various map-matching algorithms have been proposed. Inevitably, the correctness of the map matching is closely related to the accuracy of positioning sensors, such as GPS or Dead Reckoning (DR), and the complexity of the road network and map, especially in urban areas where the GPS signal may be constantly blocked by buildings and the road network is complicated. The existing map matching algorithms cannot resolve the positioning problems under all circumstances. They sometimes give the wrong position estimates of the car on road; the result is called mismatching. In order to improve the quality of map matching, a deep understand of the accuracy of sensor errors on mismatching is important. This paper analyses various factors that may affect the quality of map matching based on extensive tests in Hong Kong. Suggestions to improve the success rate of map matching are also provided.

KEY WORDS

1. Map Matching. 2. GPS and DR. 3. Navigation System.

1. INTRODUCTION.

Locating a car on road map is an important function of a car navigation system (Fenton and Mayhan, 1991). To achieve such an objective, map-matching techniques have been introduced into the positioning process in car navigation systems (Abbott and Powell, 1999; Bullock and Krakiwsky, 1994). Map matching algorithms are usually heuristic rules by which sensor data and information from the map database are processed to identify the location on that road on which the vehicle is most likely to be travelling (Abbott and Powell, 1999).

Large numbers of map matching algorithms have been developed. Most of the present map matching approaches use a digital map and a positioning system such as GPS, dead reckoning (DR), or their integration, to give car position estimates. Map matching has been proved to be an efficient method to improve the performance of positioning systems while working in an urban environment, because reliable digital road maps are readily available (Bastiaansen, 1996) and the map accuracy is normally higher than that of the positioning sensors. The benefits of map matching come from two aspects. First, it improves the positioning accuracy by constraining the vehicle location to the road. Secondly, it provides controls on sensor errors and therefore the navigation system can be more precise and reliable (Chen, et al., 2003a). However, locating a car precisely and correctly in an urban environment is not a well-resolved problem. The existing map matching algorithms cannot resolve positioning problems under all circumstances. They sometimes give wrong car position estimates or can leave the GPS/DR position unmatched, severely degrading the performance of a navigation system.

The correctness, accuracy and reliability of map matching are affected by many factors, including odometer scale factor, accuracy of car heading measurement, complexity of road network, map accuracy and GPS accuracy. It is important to understand the factors and the ways they affect map matching to enable further improvement on map matching algorithms and greater performance of car navigation systems. This paper presents the performance of an integrated vehicle navigation system (Chen et al, 2003b) in Hong Kong, with extensive road tests (over 3100 km of test roads in urban Hong Kong). The factors that cause mismatching are analysed and suggestions are proposed to improve the performance of car navigation systems, especially in an urban environment. In section 2 of the paper, the configuration and the map matching algorithm used in the car navigation system are briefly summarized. The experimental results and analysis are presented in section 3. Suggestions for further improvement on vehicle navigation systems and conclusions are given in section 4.

2. CONFIGURATION OF EXPERIMENTAL SYSTEM.

The main components of the integrated vehicle navigation system used in the tests are a GPS receiver, DR system, digital map database and a map matching module. The GPS receiver is a ROCKWELL Jupiter OEM receiver. The DR system consists of a MURATA ENV05 gyroscope as a bearing sensor and the odometer of the test car provides the speed sensor. A Kalman filter is designed to integrate GPS position, velocity and DR measurements to provide vehicle position, velocity and heading. The GPS/DR positions are then fed to a map matching module to combine with the map data to estimate the optimal car location on the road.

A hybrid map matching approach is used which applies the topological information of the road network and traffic rules to the integration of geometric and probabilistic approaches. The approach searches the road segments within the vicinity of position measurement. The search area is defined according to the GPS/DR error model. The topological and traffic rules information is used cooperatively with the geometric similarity comparison to select the road segment on which the car is travelling. After determination of the road, the MAP method (Scott, 1994) was adopted to locate the car on the selected road segment. A second Kalman Filter is applied to integrate the map and GPS/DR data to get a better position estimation. The detailed algorithm is described in Yu et al, 2002.

The base digital road map used was released by Hong Kong government in 2000. The reference frame of this map is Hong Kong Grid 1980. It is modified and enhanced for navigation purposes according to the standard of digital navigation map, GDF 3·0 (European Standard CEN, 1995). It provides road shape and position in a form of a multi-centreline road network that consists of arcs, nodes and the basic topological information with a very high accuracy of <1 m. A map sample is shown in figure 1. In addition to the digital road map, the database also contains other useful road information, such as road direction, legal turn information and some other road attributes that have been used in our map matching process.

Figure 1. Sample of Hong Kong map used.

3. PERFORMANCE ANALYSIS ON THE VEHICLE NAVIGATION SYSTEM.

In order to analyse the performance of map matching, we conducted extensive tests in Hong Kong in 2002. The tests covered the most dense and busiest transport areas in Hong Kong. All testing routes have been repeated many times and the total testing distance is over 3,100 km. During the tests, the map matching module processes the map data and GPS/DR data in real-time.

Through the analysis of the experimental data, a total number of 267 cases of mismatching were identified. We examined every case of mismatching to identify the exact causes. This analysis reveals that the main reasons of mismatching, with the percentages are:

- Map errors. (20%).
- GPS position errors. (4%).
- Distance measurement errors. (22%).
- Heading measurement errors. (50%)

It can be noted that 76% of mismatching cases resulted from positioning sensor error, while map errors contribute 20% of mismatching.

3.1. *Map Errors.*

Map errors include missing road features, wrong road attributes and inappropriate representation of road network. Missing road features means that the map database does not contain new-built roads when the map database is used in applying map matching. Therefore the map matching module could not find the road to match GPS/DR positions on the map. Figure 2 shows the mismatching resulting from missing roads.

In our map matching algorithm, we have applied information about legal turning, one-way streets and restricted access as constraint factors. Errors of such information can also cause mismatching. In the tests, most of the mismatching cases were due to incorrect information about legal turns. Whenever the test car turns into a new road segment about which the database contains incorrect turn information the turn is labelled illegal. The map-matching module cannot then find the correct road segment to match GPS/DR position on the map (as shown in Figure 3).

In the digital map used, the representation of road network is multi-centreline based. The complicated road network is represented in the form of multi-centreline in which each lane is represented by a centreline and is considered as an isolated road.

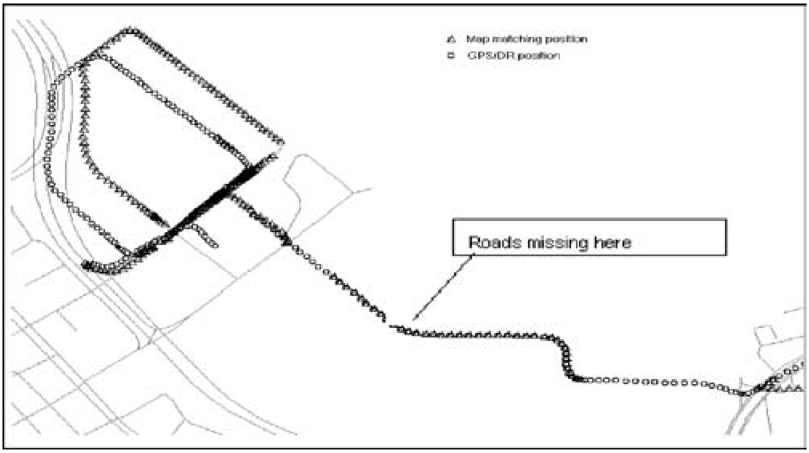

Figure 2. Example of missing road feature.

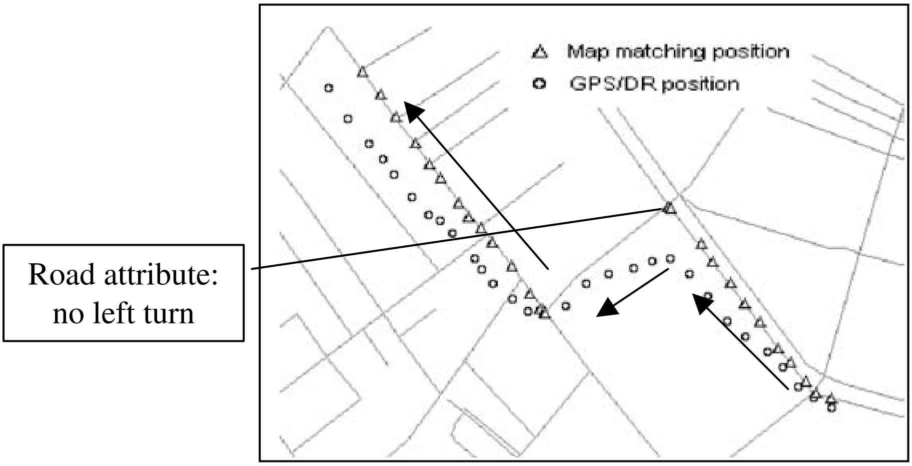

Figure 3. Example of wrong road attributes.

In Hong Kong most of the roads are narrow and the distance between the centrelines of lanes is mostly less than 20 metres so the accuracy of GPS/DR system is not sufficiently high to distinguish lanes. Under these situations the map matching process cannot identify which road segment the car is taking until the car makes a turn to another road. But only one of the multi-centrelines is connected to the new road segment. Therefore if the car is located in one of the unconnected lanes, the new road segment is not connected and the car is forbidden to turn in. One of these cases is shown in Figure 4.

3.2. *GPS Errors*. Over the last two decades, GPS has been widely used in navigation due to its high accuracy, global coverage and low price. GPS positioning accuracy is normally within 10 metres without the Selective Availability (SA) (Satirapod, et al., 2001). However, in an urban environment, the coverage of GPS is severely reduced by buildings. Studies done in Hong Kong show that GPS coverage in central Hong Kong can be less than 20% (Chao et al, 2001). Moreover, the strong

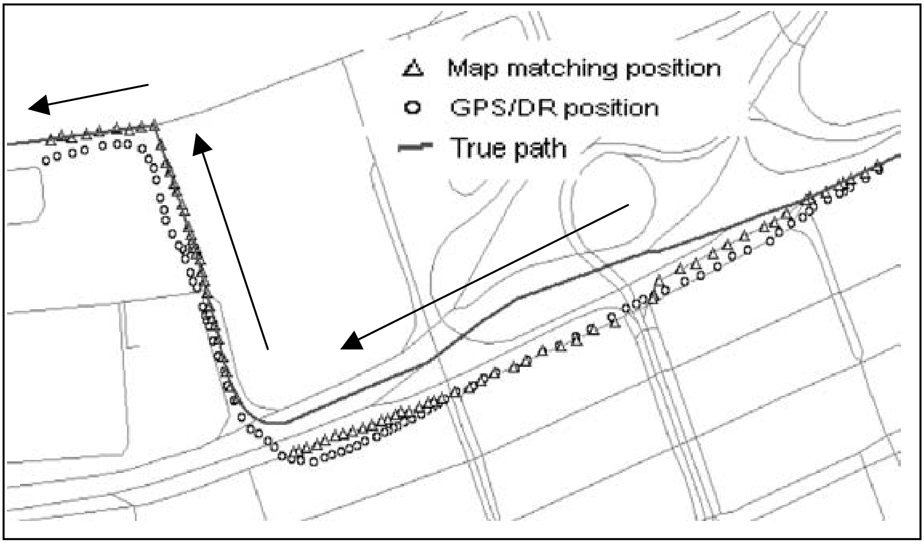

Figure 4. Mismatching caused by multi-centreline representation.

multipath effects and weak satellite geometry in cities make GPS very difficult to use. In our tests, large GPS errors occur in narrow streets, roads along the mountain or with the tall buildings with glass walls. The average GPS error in such environment was 27 metres, and the largest errors were over 100 m. In our navigation system, we have integrated a GPS receiver with a DR unit to overcome these GPS coverage problems. GPS is used to provide the reference points to calibrate DR errors while continuous DR positions are used as position output of the integrated positioning sensor for map matching. In order to avoid the effects of poor GPS positions, we set up stringent criteria to check the quality of GPS positions, these include checking PDOP, SNR, numbers of satellites and agreement of GPS and DR on relative positions. With such methods, most of the poor GPS positions can be eliminated. However, if GPS errors appear as a near constant bias it is difficult to remove them, especially at times when GPS signals have just been recaptured by the receiver after a loss of lock for a significant time. Our tests show that GPS position errors still contribute 4% of mismatching, even after using these checking procedures. Figure 5 shows one of these cases. In the figure there were no GPS positions up to point A, a GPS position was then obtained at point A, but biased with about 110 metres to point B. As the GPS is considered as a reliable position to calibrate DR errors, the position estimate from the integrated system jumped to point B. The GPS signals were lost again and DR system was used to provide positions, with reference to point B. That, inevitably, caused a mismatching, until a new GPS position was available at point C.

3.3. *Distance measurement errors.* Due to insufficient GPS coverage in urban areas, the integrated car navigation system is heavily dependent on the DR system to provide positions. The accuracy of travelling distance measurements strongly affects the map matching process and the experiments show that 22% of mismatching cases are caused by distance errors. Distance errors come mainly from two sources: the speed sensor and the map.

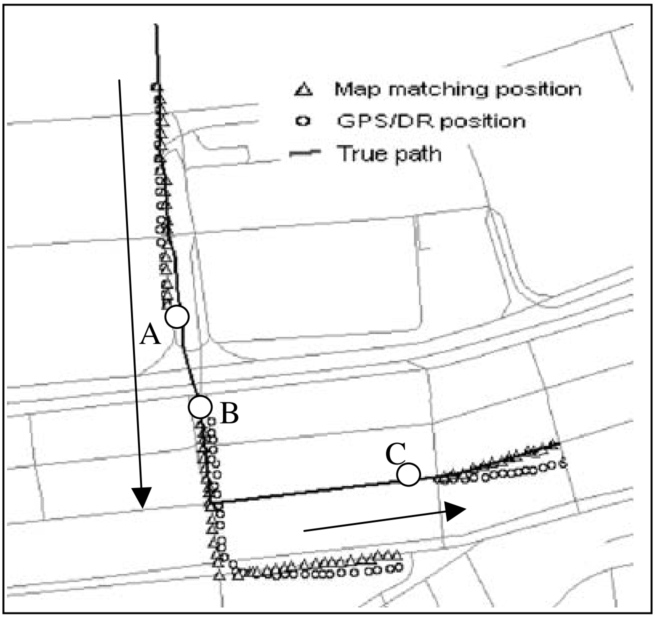

Figure 5. Mismatch caused by GPS multi-path error.

An odometer sensor counts the number of revolution of the vehicle's wheels, which can be converted to a distance travelled by an initial calibration. This conversion is known as the odometer scale-factor determination. One way of determining the scale factor is by driving the vehicle over a known distance. However, the odometer scale factor changes over time due to wheel slippage and skidding, tyre pressure variation, tyre wear and vehicle speed. If left uncompensated, the scale factor error will accumulate rapidly, causing significant positional error. Though we can use GPS positions or corresponding corners between the car trajectory and road to correct the distance error, we may not be able to do so when a car travels along a long, straight road segment. When the distance error has accumulated to be over 20 m, it is difficult to distinguish two or more turns that are close to each other.

There are also two further problems related to distance/road length which may cause mismatching. One is the difference between the actual road length and the road length from the digital map. The digital map is a planar map, so the actual lengths of roads are longer than the length appearing in the map, especially on those roads with slopes. That means the distance measurement is longer than the road segment shown on the map. The other is due to the zigzag movement of the car. A car is not always moving straight forward along the road centreline. In order to reduce the heading error effects, many map-matching algorithms constrain the car movement along the road centreline as a one-dimensional movement to eliminate the cross-track noise. However, we cannot determine whether the shivering car trajectory results from a zigzag motion or from heading measurement noise. Under these conditions determining the car location along a given road will be a problem which can affect the matching processing at road intersections. Figure 6 shows one case of the mismatching caused by inaccurate distance measurements. Figure 6a illustrates the true vehicle

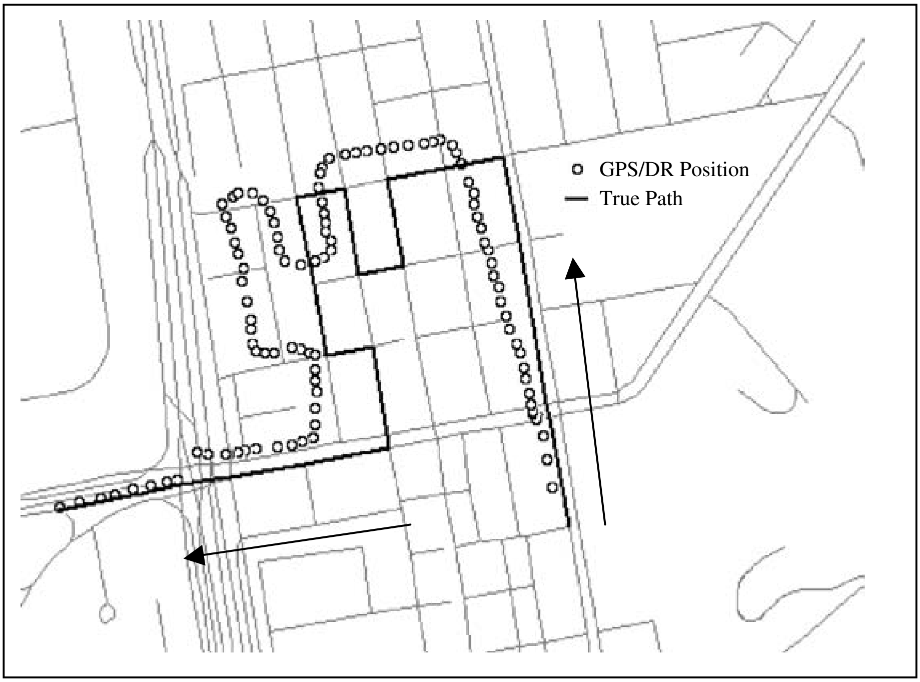

Figure 6a. Mismatching caused by error of distance measurements (GPS/DR positions).

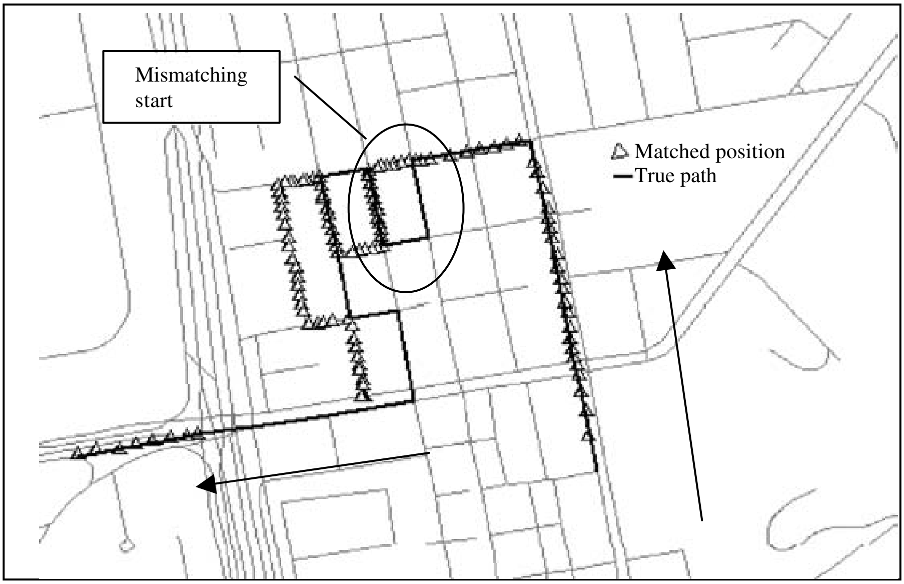

Figure 6b. Mismatching caused by error of distance measurements (matching results).

path and the GPS/DR system output. It can be seen that the road shapes are very similar and the distance error is too large to distinguish between streets close to each other. Consequently the car locations are matched to the wrong roads (Figure 6b).

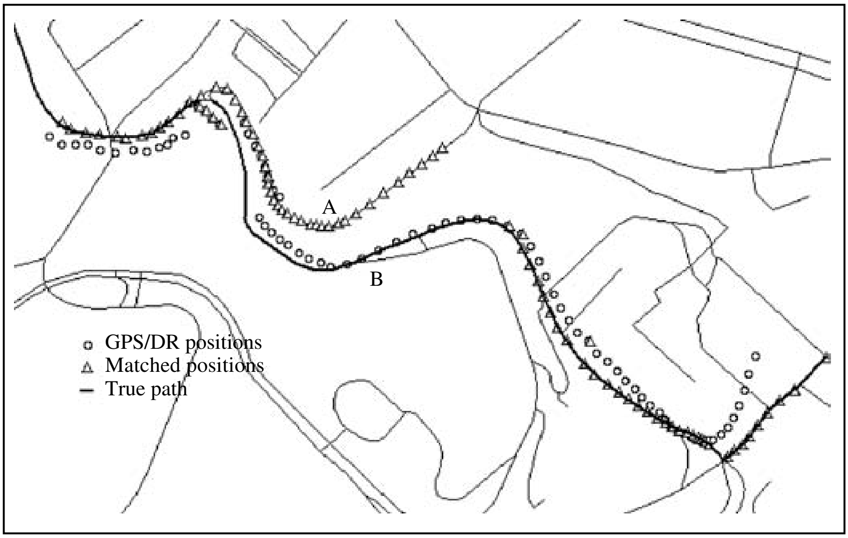

Figure 7. Mismatching at fork-shaped junctions.

3.4. *Heading Measurement Errors.* The vehicle bearing is provided by the gyro and GPS. GPS course is used to give an initial movement direction. The gyro is then used to measure the relative direction changes. If the GPS course is wrong, the DR bearing will definitely go wrong which may cause mismatching. In order to obtain a reliable initial bearing, our experiments show we need to drive the car on a straight road in an open area for at least 50 metres. This may not be available in urban environment. Similar to the odometer sensors, gyroscopes suffer from error accumulation due to gyro bias and scale-factor instability. Due to the cost restriction, low quality gyros are normally used for car navigation systems. The Murata ENV 05 gyro has a reasonably good linearity of output. However, the gyro bias variation is large and temperature-sensitive. We have examined the bearing errors of our experimental system by comparing the gyro output with the turning angles on the map. It is shown that the average accumulated bearing error is 3·56 °, with a standard deviation of 27·34 °. The largest accumulated bearing error can reach up to 50 °. The bearing errors can cause mismatching when there are multiple exits at road intersections, such as fork-shaped roads. As there are large numbers of intersections in cities, bearing errors cause most of mismatching (50% of all cases in our experiments). Figure 7 shows a typical mismatching case at a fork-shaped junction. At the junction, the angle between roads A and B is about 20 ° and the accuracy of gyro cannot distinguish between these two roads and the route is matched to the wrong one. This mismatching error can only be corrected when a new GPS position comes or a significant route feature difference appears between roads A and B.

4. CONCLUSIONS AND DISCUSSIONS.

Based on the extensive tests in Hong Kong, we have identified the major factors that affect the performance of map matching as: map errors, GPS position errors, travelling distance measurement errors and travelling heading measurement errors.

For a map database, the main problems are incorrect information on traffic rules, missing road segments and multiple centreline representations on multiple lanes of the same road segment. The multiple centreline representation is important for vehicle guidance in a city where the vehicle route needs to be in the correct lane in order to turn into the next road segment. However, the positioning system is not able to distinguish between lanes. Therefore, for map matching purposes, the road network needs to be simplified so that each road segment is represented by only a single centreline. The quality of the map database is also an important factor. The database needs to be frequently updated and the quality of data needs to be checked very carefully. Moreover, in cities, the traffic signs may be temporarily changed and such information is difficult to update.

In an urban environment, GPS coverage is low and GPS positioning errors can be very large due to multipath and weak satellite geometry. However, the accuracy of current car navigation-grade DR systems is not sufficient without GPS calibration. If a poor GPS position is used to provide the reference point for DR, the estimated car position will be shifted away and that will cause mismatching. Currently we have applied different criteria to check the quality of GPS position, but we find there are still a number of cases where poor GPS data were not detected.

The DR system with GPS calibration is the main positioning sensor in our system. However, DR position errors drift very quickly if not corrected by GPS. The odometer error is about a few per cent of distance travelled (say 5%). About 400 m travelling distance will cause 20 m distance error and that can cause mismatching in a city environment. Contributions to the distance error come from the odometer, from the map and from car trajectories. Including road slope information in the map database could reduce some of the errors. Most mismatchings are caused by the heading errors, particularly from gyro bias. As the gyro bias is affected by temperature, adding temperature compensation could reduce part of the errors. Another way to monitor the gyro bias change is to examine the gyro output when vehicle is stationary, as the angle velocity of car is zero in this case. Also, as the accuracy of map is much better than DR positions, the map coordinates and headings of road segment can be used to calibrate DR errors; this has been demonstrated to be very successful, especially in city environment (Chen et al, 2003b).

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