THE HONG KONG POLYTECHNIC UNIVERSITY
DEPARTMENT OF LAND SURVEYING
& GEO-INFORMATICS

IMPROVED POSITIONING OF LAND VEHICLE IN ITS USING DIGITAL MAP AND OTHER ACCESSORY INFORMATION

Prepared by

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for the Degree of Doctor of Philosophy

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CERTIFICATE OF ORIGINALITY

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Abstract

Without accurate vehicle position measurements, many ITS applications, such as vehicle navigation, fleet management, emergency dispatching and automatic crush avoidance, are not possible. Most of the existing GPS based vehicle navigation systems do not provide sufficient coverage and accuracy in high density urban areas, such as Hong Kong, to satisfy the requirements of ITS applications.

This thesis develops various algorithms that integrate information from various positioning sensors, digital maps, and other accessory information to provide a better solution for vehicle navigation in urban areas. Based on the analysis of the errors and uncertainties of GPS, DR, and digital road maps, an optimal integration framework of GPS, DR and digital road maps is proposed. A task-oriented map-matching algorithm using multiple criteria decision is developed. This method makes the map-matching process concise and easy to implement, and also provides an integrating framework to combine various information sources. A method that tightly integrates positioning sensors and digital map databases to control DR drift errors under a situation where GPS is not available has been proposed to improve the performance of vehicle positioning in urban areas. The issues of system integrity and reliability have also been addressed in the study.

The system design and map-matching algorithms developed in this study have been implemented in a prototype vehicle navigation system that integrates GPS, DR, radio beacon, and a digital map database. Extensive tests carried out in Hong Kong illustrated that the new integration framework and map-matching algorithms significantly improved the performance of vehicle positioning to meet the requirements of various ITS applications in terms of accuracy, availability, coverage, integrity and reliability. The system has also been used in Macau to investigate the feasibility of GNSS applications in the city.

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List of Abbreviation

ABS - Anti-Breaking System

ALI - Autofahrer Leit-und Information system

ANFIS - Adaptive Neuro Fuzzy Inference System

AOA - Angle-of-Arrival

ARCS - Automatic Route Control System

ATIS - Advanced Transportation Information Systems

ATMS - Advanced Traffic/Transportation Management Systems

CACS - Comprehensive Automobile Traffic Control System

CCIII - Third Generation Command and Control Communications System

CGI-TA - Cell Global Identity with Timing Advance

CVO - Commercial Vehicle Operations

DGPS - Differential GPS

DOD - US Department of Defense

DOP - Dilution of Position

DOT - US Department of Transportation

DR - Dead Reckoning

EGNOS - European Geostationary Navigation Overlay Service

EOTD - Enhanced Observed Time Difference

ERGS - Electronic Route Guidance System

FCC - Federal Communications Commission

FHWA - Federal Highway Administration

FIS - Fuzzy Inference System

FLAIR - Fleet Location and Information Reporting System

FM - Frequency Modulation

GEO - Geostationary Earth Orbit

GNSS - Global Navigation Satellite Systems

GPS - Global Positioning System

GPS/DR – GPS and DR integrated system

GPS/DR/MM – GPS, DR and map matching integrated system

GSM - the Global System for Mobile Communications

HKFSD - Hong Kong Fire Service Department

HKPF - Hong Kong Police Force

INS - Inertial Navigation System

ITS - Intelligent Transport System

LANDFALL - Links and Nodes Database for Automatic Land vehicle Location

LMU - Location Measurement Unit

MAP - Map Aided Positioning

MHT - Multiple Hypotheses Technique

MM – Map Matching

MSAS - Multi-Functional Satellite Augmentation System

PDOP - Position Dilution of Precision

PPS - Precise Positioning Service

RAIM - Receiver Autonomous Integrity Monitoring

RMS – Root Mean Square

RRF - Road Reduction Filter

RSS - Received Signal Strength

RTK - Real-Time Kinematic

SA - Selective Availability

SPS - Standard Positioning Service

SRKF - Spatially Reduced Kalman Filter

TDOA - Time-Difference-of-Arrival

TCC - Traffic Control Centre

TGMS - Third Generation Mobilizing System

TIS - Transport Information System

TOA - Time-of-Arrival

UF - Ultrasonic Frequency

UMTS - Universal Mobile Telecommunications System

VPS – Vehicle Positioning System

VNS - Vehicle Navigation System

WAAS - Wide Area Augmentation System

WADGPS - Wide Area Differential GPS

Chapter 1 Introduction

1.1 Background

Intelligent Transport System (ITS) is a complex system of information and computer technologies applied to transport infrastructure and vehicles to improve transport efficiency and safety [Stough, 2001]. Due to a great increase in human activities over the last few decades, some of the existing transportation networks have become more and more congested and building new roads is no longer the only solution to the problem. Using advanced information and computer technologies to improve the efficiency and safety of existing road networks provides a new solution to the problem. In recent years, the development of ITS has led to the enabling of road network optimization and support decision making.

Vehicle position information is a key element to many ITS applications, e.g. Advanced Traffic/Transportation Management Systems(ATMS), Advanced Transportation Information Systems(ATIS), Commercial Vehicle Operations(CVO), and especially such applications as fleet management, emergency dispatching, and automatic road guidance. The development of ITS places a new emphasis on the requirement of vehicle positioning technology in terms of navigation accuracy, availability and integrity. For example, as documented in the February 2000 Air Force Command Operational Requirements Document (ORD) AFSPC/ACC 003-92-I/II/III for Global Positioning System (U), the accuracy requirement of land vehicle navigation and route guidance is 5-20 meters with 95% confidence level, the integrity values range between 1 to 15 seconds, and the availability for highways and transit is estimated as 99.7% [DoD and DoT, 2002]. When it comes to ITS applications, both the absolute vehicle position, and the vehicle location relative to the road network are of interest. This has led to the development of map-matching techniques, which attempt to place a vehicle location on a map.

A large number of vehicle positioning systems are currently available in the market and most of them are based on Global Navigation Satellite Systems (GNSS). The GNSS technologies have been progressively developed over the last few years, especially the US Global Positioning System (GPS). GPS provides a practical and affordable means of determining the accurate position, velocity and time anywhere in the world and at all times. Due to its accuracy and moderate cost, GPS has become the “first choice” among the positioning systems for ITS applications [Drane and Rizos, 1998]. However, GNSS technologies can be difficult to use in urban areas due to satellite signal blockage and multipath caused by surrounding buildings. A large number of experiments have demonstrated this problem [Nee, 1992; Braasch, 1996]. In urban areas, GPS positioning coverage can be less than 30% [Chao, et al., 2001], with the positioning errors larger than 100 m [Chen, et al., 2003; Yu, et al., 2002;].

Dead Reckoning (DR) systems, which involve an odometer to measure the travel distance and a direction sensor to measure the bearing of the vehicle, have been widely used to perform the positioning function when GPS is not available.

The first commercial in-vehicle navigation system utilizing DR and map-matching, called Navigator, was introduced in the US by Etak in 1985 [Sweeney, 1993]. When using low-cost DR sensors, the DR positioning errors increase dramatically with time. For example, our field experiment shows the DR positioning errors can reach more than 100 m within 20 minutes, with a vehicle speed of 50km/hr, if no other systems are used to calibrate the DR errors. Thus, the integration of GPS and DR cannot provide an accurate vehicle positioning system for many ITS applications, especially in urban environments where GPS are frequently unavailable.

Map-matching is a technique of trying to locate a vehicle on the road which it is driven on. Many map-matching algorithms have been developed [French, 1995; Zhao, 1997; White, et al, 2000] and widely incorporated into GPS/DR vehicle navigation systems to produce experimental hybrid systems [Bullock and Krakiwsky, 1994; French, 1995; Zhao, 1997; Hofmann-wellenhof, et al., 2003; Young and Kealy, 2002; Yu, et al., 2002]. However, these systems still do not work well in urban areas because the vehicle position may be matched to a wrong road segment since large vehicle positioning errors occur frequently in urban areas. This incorrect location match is called mismatch [Chen, et al., 2005; Yu, et al., 2004].

In recent years, the Hong Kong government has engaged in the development of ITS to improve traffic flow in the city. The Transport Department initiated an ITS strategy review for Hong Kong in 2001. As a result, a Transport Information System (TIS) and a Traffic Control Centre (TCC) were established. The construction of the TCC was completed at the end of 2003 and the centre has been in operation since 2004. The TIS is scheduled for completion in 2006 [Transport Department of Hong Kong SAR, 2001].

The other two important systems initiated by the Hong Kong government are the Third Generation Mobilizing System **(**TGMS) for the fire department and the Third Generation Command and Control Communications System (CCIII) for the Hong Kong Police Force (HKPF). The TGMS was fully commissioned in June 2005, and the CCIII is also being implemented in three phases (between the end of 2004 and early 2006). The general requirements for vehicle positioning systems for these applications are 10 m accuracy, with 95% coverage on Hong Kong roads [FSDHK, 2000]. The speed of a vehicle is normally from 10 to 30 meters per second. Therefore, 10 meters accuracy requirement is suitable to describe the movement of a vehicle. At the moment, the commercially available low-end GPS/DR systems cannot satisfy the requirements. Thus this study has been conceived to improve vehicle positioning performance cost-effectively to meet the requirements of vehicle navigation in urban areas.

1.2 Objectives

This study is to improve vehicle positioning performance using digital map and other accessory information with the aim of developing a cost-effective prototype vehicle positioning system for land vehicle navigation, particularly for urban applications, with performance of 10 meter accuracy and 95% positioning coverage.

The overall objective of this study is to improve the accuracy, coverage and integrity of land vehicle positioning systems to meet the requirements of land vehicle navigation and route guidance. In particular, the following issues are addressed in this thesis:

- Developing methods to improve input data quality
- Overcoming the problems of GPS long-term unavailability
- Investigating new methods to calibrate DR drifting error
- Tightly integrating map matching process with positioning sensors
- Improving map-matching performance and system integrity through mismatch automatic detection

1.3 Thesis Structure

This thesis firstly reviews the development of land vehicle positioning systems, and briefly introduces commonly used techniques and their integration in chapter 2. In addition the advantages and disadvantages of these systems and techniques are addressed. The positioning sensors and their integration used in this study are also presented in this chapter.

In chapter 3, different map-matching methods are reviewed. Many of them focus on road identification, which is to find the maximum similarity between candidate roads and the vehicle trajectory. The main difference between these algorithms is the adoption of different parameters to define the maximum similarity. Some critical issues, such as the mismatch problem, are also discussed in the chapter.

For the purpose of developing an integrated positioning system that optimally combines the available positioning related data, the quality of the data is assessed in chapter 4. The data include GPS measurements, DR measurements, data from a radio beacon, and information from a digital road map database. The nature of each error and the uncertainty of each data set are analyzed, especially the comprehensive analysis of GPS performance based on extensive field tests in urban areas (i.e. Hong Kong and Macau). Based on the error analysis and the discussion of existing map matching methods, an integrated framework of map matching is proposed for positioning data integration, particularly for applications in urban areas.

A task-oriented map-matching method using multiple criteria is introduced in chapter 5. It provides an integrated framework for the implementation of map matching. In the method, the map-matching process is divided into four basic tasks which are feature extraction, road identification, road following and system reliability and integrity maintenance. A simplified real-time algorithm based on multiple criteria threshold checks is introduced and implemented in the chapter.

Mismatch is a serious problem in map-matching, especially in urban environments such as Hong Kong, where GPS positioning is hardly available in some areas. In chapter 6, the causes of mismatch are analyzed in detail, based on the extensive tests of the implemented algorithm carried out in Hong Kong. Suggestions to improve the success rate of map-matching are given at the end of this chapter.

New techniques are proposed based on the analysis presented in chapter 6. The techniques are for improving the performance of map-matching through using map matching results for the sensor calibration (especially DR sensors) and the mismatches automatic detection and recovery. A curve pattern matching algorithm is adopted to detect mismatches automatically. A feedback filter is designed to control the sensor calibration after the map matching results pass the process of mismatch detection. These improvement methods are presented in chapter 7.

The performance of the integrated vehicle positioning system developed in this thesis is analyzed in chapter 8. The analysis mainly focuses on the accuracy, coverage of the system and mismatch detection rate which forms part of system integrity. The analysis demonstrates that the performance of the vehicle positioning system developed in this study satisfied the requirements of land vehicle positioning and navigation in urban areas and is significantly improved compared with other low-end GPS/DR systems.

The research is summarized and suggestions for further developments in future vehicle positioning systems are made in the concluding chapter of the thesis.

Chapter 2 Vehicle Positioning Systems

One important component of ITS is a precise vehicle positioning system (VPS) which locates the position of a vehicle [Drane and Rizos, 1998; French, 1996]. Many of the advanced functions of ITS systems are not possible without positioning systems. For example, an automatic vehicle navigation system needs vehicle locations to predict the subsequent maneuvers of the vehicle and to give instructions to the driver; an emergency dispatching system needs them to assign the vehicle nearest to a site; a transportation information system needs them to calculate traffic flow. There are many types of vehicle positioning technologies on the market. Examples include DR systems, the GPS, mobile phone systems, electronic benchmarks, and image-based systems [Hofmann-wellenhof et al., 2003]. Owing to the great variety of applications, there is no 'perfect' single positioning system that can serve all ITS applications. Each technology used for vehicle navigation has its own problems that affect the system performance. System integration provides a way of overcoming the problems existing in a single positioning system [Zhao, 1997; Drane and Rizos, 1998]. In practice, there are still a lot of problems in developing an accurate and reliable land vehicle positioning system to be used in urban areas such as Hong Kong.

In this chapter, the development of various vehicle positioning systems is reviewed. The working principles and the characteristics of various positioning systems are then discussed. Finally, an integration of positioning sensors developed in this research is described.

2.1 Development of Vehicle Positioning System

The basic location and navigation technologies such as odometer, differential odometer, and magnetic compass were invented about 2000 years ago and are still in use in modern automobile navigation [Zhao, 1997]. After the first automotive road map was published in the U.S. in 1895, many mechanical vehicle route guidance devices were developed between 1910 and 1920 to provide explicit real-time route instruction automatically. During World War II, the U.S. developed an electronic VNS for jeeps and other military vehicles, which was the first vehicular navigation system to incorporate electronics [French, 1995]. In the late 1960s, the Electronic Route Guidance System (ERGS) project was initiated by The Federal Highway Administration (FHWA). This provides in-vehicle route guidance to the driver by using a proximity-beacon type vehicle navigation system, although it was never fully implemented [Rosen, et al, 1970]. Systems with an approach similar to ERGS were further developed and tested in projects such as the Comprehensive Automobile Traffic Control System (CACS) in Japan and Autofahrer Leit-und Information system (ALI) in Germany during the 1970s [Peeta, 1994; French, 1995; Zhao, 1997].

In the early 1970s, an autonomous navigation system named ARCS (Automatic Route Control System), the first system using the DR technique assisted by a map-matching technique to locate the vehicle, was introduced in the U.S. [French and Lang, 1973]. Similar systems were also developed by other groups in the United States and the United Kingdom, such as the LANDFALL system (Links and Nodes Database for Automatic Land vehicle Location) and the FLAIR system (Fleet Location and Information Reporting System) [French, 1989]. The practical in-vehicle navigation system utilizing DR and map-matching, called Navigator, was commercially introduced in the U.S. by Etak in 1985 [Sweeney, 1993]. In the early 1980s, Japanese automobile companies such as Honda, Nissan, and Toyota started introducing first-generation navigation systems using DR and digital maps into their domestic market. Europe, autonomous navigation systems were developed including Philips' CARIN and Bosch's EVA which used DR, map-matching and a colour monitor for map display. The EVA system also provided drivers with voice guidance in addition to visual display [French, 1995]. The DR system is simple, inexpensive, and easy to implement in real-time. However, its accumulated errors greatly degrade its performance when it is used without supplementary position measurements. Earlier practical DR based positioning systems, even if assisted by map matching, eventually lost the vehicle track due to growing drift error.

Since the 1980s, great improvements have been achieved in the GPS. It provides a practical and affordable means of determining position, velocity and time globally and has become the “first choice” among the positioning systems for ITS applications [Drane & Rizos, 1998]. As a result, a number of GPS-based vehicle navigation systems, either GPS alone or GPS combined with other sensors have been developed in different countries such as Japan, Europe, the U.S., etc. In the 1990s, Hybrid systems were introduced which combine DR with GPS-based positioning and a map-matching technique, such as Toyota Electro-Multivision [French, 1995], Bosch Travelpilot [Buxton, J.L. et. Al., 1991], Guidestar [Collier, 1990], Oldsmobile Guidestar [Collier and Weiland, 1994], and BMW 1994 model CARIN [French, 1995]. As summarized by Krakiwsky (1993) out of 136 vehicle navigation systems identified up to 1993, 76% were based on GPS. However, it is well-known that GPS suffers from signal blockage and multi-path effects when used in urban areas. For this reason, it is difficult to rely on GPS-alone systems for vehicle positioning in urban areas. Even GPS-based hybrid systems, e.g. GPS/DR, work well only if the GPS outage are not frequent and long. However, in the case of a metropolis, e.g. Hong Kong, GPS signals in densely built-up areas are usually unavailable, and may result in a positioning failure.

The mobile communication market has grown rapidly in recent years and provides another way for vehicle positioning. The U.S. government has already required that mobile phone manufacturers provide positioning functions for emergency services, E911 [FCC, 1996]. In Europe, member states, regulators and consumer groups voted in favor of a requirement for caller location for emergency calls (including the European Emergency Number 112) to be imposed from 1 January 2003 [Commission of the European Communities, 2000]. Many companies, such as Ericsson, SnapTrack and CellPoint, have introduced mobile phone based positioning systems. However, mobile phone network based positioning systems provided as a commercial service have presented a challenge to mobile operators and are still not generally available, and the positioning accuracy with the mobile communication systems depends on the density of cell stations. Current research [Hein et al., 2001] reports that with the time-difference-of-arrival (TDOA) technique, which presents the most promising approach for positioning in cellular networks, the positioning error budget of GSM and UMTS are 270-380m and 19-26m respectively.

Image-based navigation systems provide vehicle location by processing a series of images captured by digital cameras or laser scanners. As a result of the interaction of the sensor with its surroundings, sophisticated techniques may be developed to help vehicles navigate even within unknown surroundings and to complement the traditional navigation with specialized tasks like collision avoidance. Current applications often refer to robot technology [Haubecker and Spies, 2000]. In order to obtain absolute location, an image-based system requires geo-referenced images or landmarks stored in a database in advance. However, such a database is not generally available. Consequently, image-based technology will not be discussed further in this thesis.

All positioning technologies introduced so far have some inherent limitations related either to system design or to application environment. Integrating different technologies seems to be a good and effective solution for vehicle positioning in urban areas and should be considered, in addition to developing new sensors and technologies.

Various integrated positioning systems are being studied by researchers and organizations. Typical and commonly used integrated systems are GPS/DR or GPS/INS (Inertial Navigation System) aided with a map [Abbott and Powell, 1995; Greenspan, 1996; Drane and Rizos, 1998; Farrell and Barth, 1999; Grewal, et al.,2001; Young and Kealy, 2002]. However, to improve the positioning performance in urban areas by using low-end positioning sensors is still a problem. The integrated low-end GPS/DR systems still fail in high density urban area where long GPS outage frequently occurs.

More effective system integration is needed for vehicle positioning in urban areas. To choose and integrate the positioning technologies properly, it is necessary to understand the working principles of commonly used positioning techniques. The following sections will introduce these technologies in detail.

2.2 Global Positioning System (GPS)

GPS is a satellite-based radio navigation system developed by the United States Department of Defense (DoD). It offers highly accurate, instantaneous, absolute positioning on a world-wide scale and, with suitable techniques, relative positioning at the centimeter level or higher [Parkinson and Spilker, 1996; Hofmann-Wellenhof et al., 1997; Misra and Enge, 2001; DoD, 2001].

The GPS consists of three segments: the space segment, the control segment and the user segment. A constellation of 24 GPS satellites ensures that a minimum of four satellites, which are well distributed in the sky to give the necessary geometric strength, are visible at all times anywhere in the world. There are no limits on the number of users because user receivers are passive (i.e. they only receive signals from GPS satellites).

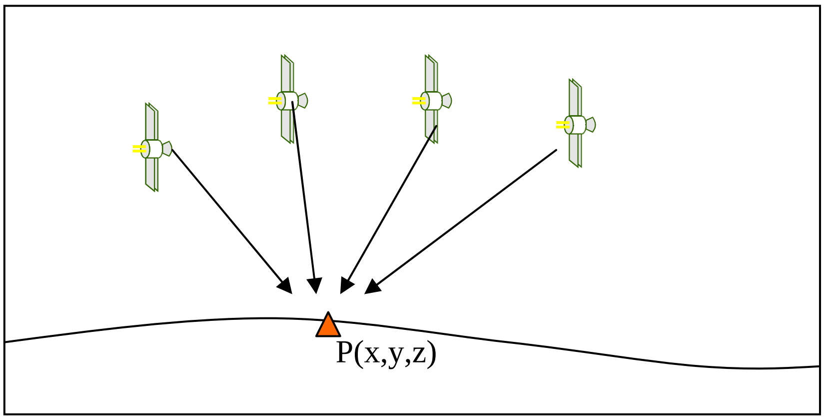


Figure 2-1 Principle of GPS positioning

The principle of GPS positioning is based on the time-of-arrival ranging method. A GPS receiver determines travel times of ranging signals transmitted from a number of GPS satellites. All satellite clocks are synchronized very precisely to the GPS time by the control segment. The receiver's clock error needs to be determined together with the receiver position. The basic observation equation can then be written as Equation 2.1, in which there are four unknowns including three position coordinates and receiver clock error. By collecting data from at least four satellites at the same time, the four unknowns can be solved (as shown in Equation 2-1).

$$\rho = d + cdt_r = \sqrt{(x^s - x)^2 + (y^s - y) + (z^s - z)} + cdt_r \qquad \text{(Eq. 2-1)}$$

where, x, y, and z are receiver coordinates; x^s, y^s, and z^s are satellite coordinates; dt_r is receiver clock error, and c is the speed of light.

For navigation, two basic services are provided by GPS, namely the Standard Positioning Service, SPS and the Precise Positioning Service, PPS. The SPS is for civil users, employing the C/A code pseudo-range on L1 frequency. The PPS service is mainly for military users, employing the dual frequency P code pseudo-range. In the GPS modernization program another two civilian signals will be added to the L2 and L5 frequency bands. Prior to May 2000, the main error source in GPS was due to Selective Availability (SA). After the switch off of SA, the SPS position accuracies have been improved significantly, i.e. around 10 meters [Satirapod, Razos, and Wang, 2001; DoD, 2001; Misra and Enge, 2001; El-Sheimy, 2002], although the SPS service still suffers from the effects of the ionosphere, multipath and larger measurement noise.

As many GPS errors are spatially correlated, the use of differential techniques can efficiently reduce them and significantly improve the positioning accuracy, typically to the level of 1 to 5 meters [Parkinson and Enge, 1996; Hofmann-Wellenhof et al, 1997]. Such Differential GPS (DGPS) techniques are based on the use of at least two GPS receivers, one as a reference and one as a user. The reference receiver is located at a known point, and thus the corrections can be calculated. These corrections can then be transmitted via telemetry to a user receiver to achieve accuracies higher than those achieved by a single-point position mode. Various broadcasting methods have been used to transmit the DGPS corrections, including terrestrial Ultrasonic Frequency (UF) radio link, Frequency Modulation (FM) side-band, and communication satellites. In Hong Kong, the Marine Department is currently operating a marine beacon system for transmitting DGPS corrections. Although the main purpose of this system is to provide a DGPS service for marine users, the system covers most of the land in Hong Kong as well. Anyone with a beacon receiver is able to obtain the broadcast pseudo-range corrections free of charge.

For higher precision, the measurements of the phase of the carrier wave, which have a precision of a few millimeters, routinely yield relative positioning accuracy in the order of 1 part per million or higher. In recent years, the Real-Time Kinematic (RTK) techniques have been rapidly developed, which enable users to position themselves with accuracy to the centimeter level in real time [Hofmann-Wellenhof et al., 1997； McDonald, 2002； DoA, 2003]. Currently the Lands Department of the Hong Kong government is developing an active GPS network, which will provide RTK services within the next few years.

It is generally accepted that GPS itself cannot satisfy all performance requirements for civil navigation, such as integrity, availability and continuity [Drane and Rizos, 1998]. In recent years, a number of wide area augmentation systems have been established, including US FAA’s Wide Area Augmentation System (WAAS), the European

Geostationary Navigation Overlay Service (EGNOS), and the Japanese Multi-Functional Satellite Augmentation System (MSAS) [McDonald, 2002]. A wide area augmentation system consists of a ground network and a number of Geostationary Earth Orbit (GEO) satellites. The ground network is used to monitor the integrity of GPS. It also generates the Wide Area Differential GPS (WADGPS) corrections to improve positioning accuracy for users. The GEO satellites are used to transmit integrity and WADGPS corrections to users. In order to minimize the changes to existing GPS receivers, the GEO satellites also transmit in the L band, with a similar signal structure as GPS. Therefore, users can also measure extra ranges from those GEO satellites to improve the availability and continuity of GPS. The fundamental concept of WADGPS is similar to that of DGPS. A set of reference stations are located at known positions; therefore, they can be used to detect errors in GPS measurements, such as orbit, clock and atmospheric delay errors. Conventional DGPS usually has an accuracy to 2 to 5 meters within 100 kilometers of the stationary calibration receiver. To implement DGPS on a large scale, the total number of monitor stations needed to cover the United States Continent to this accuracy would exceed 500. WADGPS is a system that can limit the number of necessary monitor stations to 15 while achieving the same accuracy. WADGPS can reduce the installation cost and the operational cost of the system dramatically.

GPS has revolutionized the concept of navigation. With a single system, it provides navigation services for air, sea and land users. The standard positioning accuracy reaches 10 to 20 meters (2DRMS, 95%). With a DGPS service, positioning accuracy of a few meter levels (1m - 5m, 95%) can be achieved. However, there are some major problems associated with GPS. Firstly, it requires observing at least four satellites simultaneously in order to determine position. This restricts the applications of GPS, especially in urban areas, where satellite signals are frequently blocked by high-rise buildings. Furthermore, positioning accuracy of GPS can be significantly reduced by other error sources, such as multipath, a phenomenon which occurs when the satellite signals are not transmitted to the receiver directly, and reduction in the strength of satellite geometry. The positioning error with multipath alone can reach more than 100 m with the C/A code [Nee, 1992; Braasch, 1996; Yu, et al., 2004].

Additionally, GPS SPS does not promise a real time integrity service. Integrity is the ability to detect position errors when they exceed a predefined threshold within a given time period. GPS may produce large position errors for a number of reasons, such as satellite and receiver problems, severe multipath effects and other forms of interference. For reliable navigation, these errors must be detected within a specified time interval. The situation is even more serious for land vehicle navigation, as the cost of in-car navigation systems is a crucial issue for widespread applications. For in-car systems, OEM GPS cards are commonly used, with a price ranging from $100 to $500 US dollars. Integrity functions are not included in this type of GPS receiver.

Consequently, GPS is afar from the “ideal” positioning system for ITS applications in urban or heavily foliated environments where a GPS receiver may be unable to provide a position for long periods of time. For this reason, a land-vehicle navigation system in general cannot continuously position a vehicle solely by using a GPS receiver [Abbott and Powell, 1999]. Supplemental sensors/positioning systems should be integrated with GPS.

2.3 Dead Reckoning

The rather primitive positioning technique, DR system, the process of determining a vehicle’s position by integrating measured distance increments and directions of travel relative to an initial position, is used in many vehicle tracking systems [French, 1986]. It mainly includes the use of direction sensors and velocity sensors normally, odometers, compasses and gyroscopes, and Inertial Navigation Systems (INS). As Dead reckoning is a self-contained positioning technique, it is not subject to the line-of-sight problem inherent in many radio navigation systems, e.g. GPS. It works continuously anytime, anywhere with high short-term stability. One typical example of DR systems is Navigator developed by Etak which utilizes DR and map matching [Sweeney, et al., 1993].

Odometers are devices which measure distance traveled based on counting wheel turns or Doppler shift against the ground. For a land vehicle, the simplest way is to measure the number of turns of the wheels. This type of data can be easily extracted from the gearbox or the Anti-Breaking System (ABS) of the vehicle, which generates a series of pulses associated with the number of wheel revolutions. A simple pulse counter can then be used to obtain the total distance traveled from a starting point. The main advantages of such a system are that it is cheap and that no extra instruments are required. However, the accuracy of such a system is relatively low and is affected by many factors, such as tyre slippage and tyre diameter variations due to speed and pressure changes. In general, their accuracy is typically of the order of 0.3-2% of the distance traveled [Drane and Rizos, 1998].

Direction is normally measured by magnetic compasses or gyroscopes. It may also be obtained by measuring the turning of the car steering wheel. Magnetic compasses measure the vehicle bearing but suffer from external magnetic influences such as bridges, large buildings and any other structures that contain a large amount of magnetic materials. Although the resolution of magnetic compasses can be 0.5 degrees, the accuracy is normally not more than a few degrees or even less [Drane and Rizos, 1998; Stephen and Lachapelle, 2000]. Gyroscopes are used to measure the rate of change of vehicle bearing. The drift and scale errors are their major sources of error.

The accuracy of gyroscopes varies significantly with different types, and also the price. With low quality gyroscopes used for general-purpose car navigation, e.g. vibrating rate gyros, the accuracy range from 0.1to 1°/s [Stephen and Lachapelle, 2000; Chao, 2001].

The position of a vehicle can then be calculated by using the distance and bearing measurements (see Figure 2-2 and Equation 2-2).

$$\begin{pmatrix} X_2 \\ Y_2 \end{pmatrix} = \begin{pmatrix} X_1 \\ Y_1 \end{pmatrix} + D \times \begin{pmatrix} \sin\theta \\ \cos\theta \end{pmatrix} \quad \text{(Eq. 2-2)}$$

where, D and θ are measured distance and bearing, (X_1, Y_1) are the coordinates of a start point, and (X_2, Y_2) the coordinates of a new point.

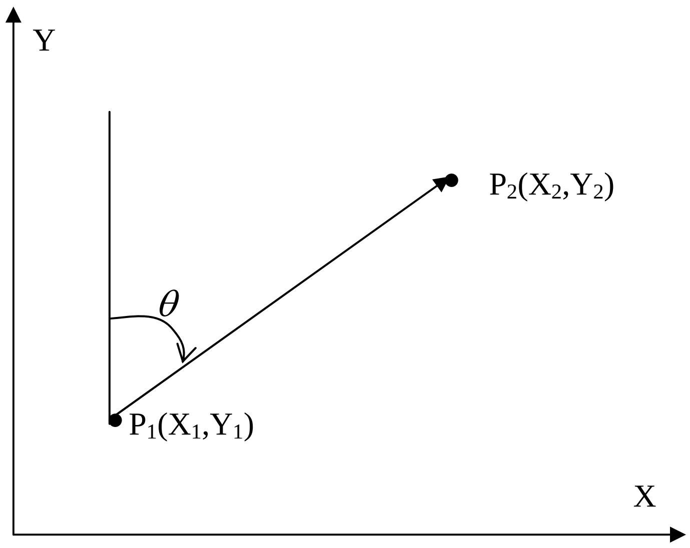


Figure 2-2 Dead Reckoning technique

As both distance and angle measurement errors (with a gyroscope) increase with time, the position error with a DR system grows very quickly. Thus dead-reckoning sensors are normally used as a sub-system of an integrated navigation system.

Inertial Navigation Systems (INSs) consist of a set of accelerometers and gyroscopes. The gyroscopes are used to maintain a reference frame while the accelerometers measure the acceleration along the specific directions. The change in the position can then be obtained by integrating the acceleration twice along the specific direction over time. As the accelerometers cannot separate the vehicle acceleration and gravity of the earth, if the direction on movement is not precisely known, the contribution of Earth's gravity cannot be removed. To precisely determine the direction on movement, the accuracy requirements for the gyroscopes are very high. As an INS is very expensive compared with other sensors, it will not be considered further in this research.

2.4 Proximity Beacons

Proximity Beacon techniques, which are also known as signpost techniques, locate a vehicle by detecting by detecting the presence of the vehicle at a beacon using a range of media including inductive loops, infra-red waves, and microwaves [French, 1986; Krakiwsky 1993]. This positioning technique is useful for various applications such as Automatic Toll Collection System [Hills and Blythe, 1994; Tetsusaki, 1994], Vehicle Tracking [Tsubaki and Sugimoto, 1999], Traffic Management [Fischer, 1991;

Sugimoto et al., 2000], Dynamic Route Guidance [Sugimoto et al., 1994] and other systems.

Proximity Beacon systems are robust and the in-vehicle subsystem is inexpensive. However they do not measure the absolute position of a vehicle, but its presence at a specific point. As a positioning technology for navigation, this is not very effective as the position is known only when the vehicle is in the vicinity of a beacon. However when proximity beacons are used in addition to another source of position data such as dead reckoning and GPS, they can form an effective positioning system. The localization of the beacon means that the position, when available, is accurate. This feature can be used as a mechanism for correcting dead reckoning drift errors [Iwaki, Kakihara, and Sasaki 1989].

One drawback of beacon technology is the cost of construction and maintenance. The widespread coverage requires substantial infrastructure and an ongoing need to expand the infrastructure as the road network expands.

2.5 Mobile Phone Positioning System

A mobile communication network is a radio-based signal transmitting system that has many base stations to transmit or receive signals from mobile phones. It is therefore possible to carry out positioning using a mobile phone communication system, for example, wireless E911 services. The U.S. FCC required that from October 1, 2001 the location of the mobile unit be identified within three dimensions and within a radius of no more than 125 meters [FCC, 1996]. The required accuracy of the system was redefined in 1999. For network-based technologies, the required accuracy is 100 meters for 67% of cases and 300 meters for 95% of cases. For handset-based technologies, it is 50 meters for 67% of cases and 150 meters for 95% of cases [FCC, 1999]. Currently, the deadline for the national deployment of E-911 wireless location systems is set for the end of 2005 [FCC, 2002].

The positioning technology is similar to GPS but with the additional capability of determining location inside buildings, parking garages and other shielded areas such as inside a pocket or briefcase, that are inaccessible to GPS systems. There are several ways in which the position can be derived by using a mobile phone positioning system. Commonly studied techniques are angle-of-arrival (AOA), time-of-arrival (TOA), and time-difference-of-arrival (TDOA) [Zhao, 2000; Caffery, 2000].

The AOA method determines the location of a handset by combining the observations of the signal arrival angle of at least two base stations. The user’s location is the intersection of two radials from the base stations to the handset (Figure 2-3). However, this technique has disadvantages. First, AOA requires directional antennas or antenna arrays to estimate the angle-of-arrival of received signal. This increases the amount of modification required on the base stations. AOA based systems also perform slightly worse than TOA based ones in a multipath environment and the accuracy of AOA systems tends to degrade as the distance to the mobile increases.

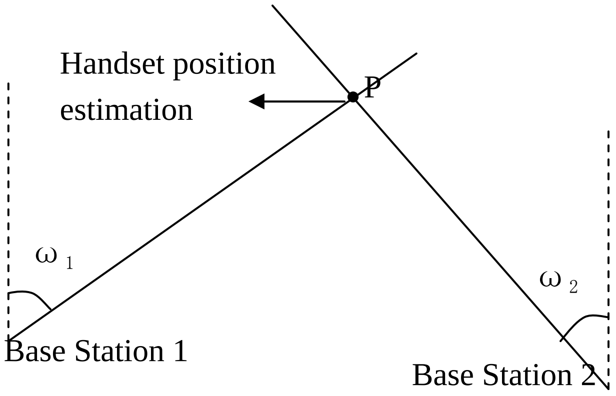


Figure 2-3 Positioning by AOA

The TOA method determines the mobile phone position by measuring propagation time of a signal traveling from the mobile to several base stations or vice versa. The distance can be obtained by multiplying the speed of light by the propagation time. The position of the mobile phone can then be determined by using the range-range method (Figure 2-4). The TOA method requires a precisely synchronized base station network and a time-tagged transmitted signal to enable pseudo-range measurement. Also, the non-line-of-sight propagation caused by signal reflection has a significant influence on the accuracy of the measurement.

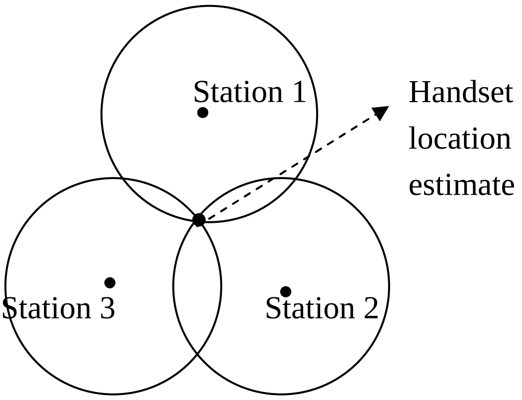


Figure 2-4 Positioning by TOA

The TDOA system determines the position of a mobile phone by means of time difference rather than by absolute TOA measurements. This is done in a hyperbolic mode because the time difference is converted to a constant distance difference to two base stations that defines a hyperbolic curve. The intersection of two hyperbolas determines the position, as shown in Figure 2-5. The accuracy is affected by the relative base station geometric locations. At least three base stations are required for two dimensional positioning.

A special case of TDOA is the enhanced observed time difference (EOTD) method. In this method, additional location measurement units (LMUs) are placed at known positions to determine the clock offset between each pair of base stations. The mobile station observes the time differences of the TOA of the signal from the base stations to the mobile station. That time difference is then used to calculate where the user is located relative to the base stations. The calculation can be done either in the mobile phone or the network. The accuracy is expected to be around 125m (RMS), and unlike GPS, the technique is not reliant on a clear sky view [Andersson, 2002].

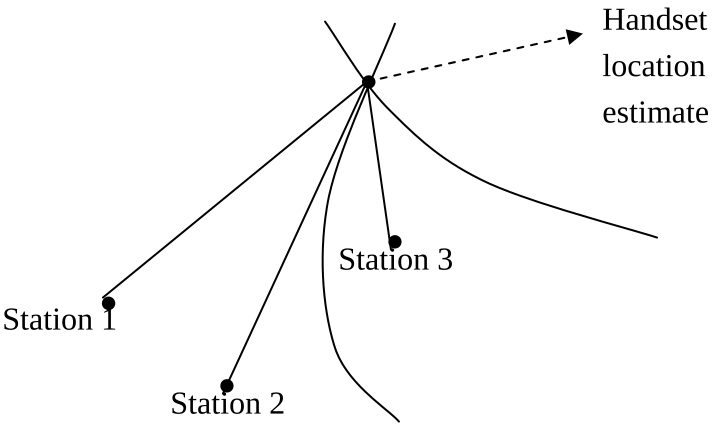


Figure 2-5 Positioning by TDOA

There are also some other mobile phone network positioning methods such as Cell Global Identity with Timing Advance (CGI-TA), Received Signal Strength (RSS) and methods based on measuring the characteristic pattern of the signal. The CGI-TA method uses the identity that each cell (coverage area of a base station) to locate the user within the cell assisted with TA information which provides the time between the start of a radio frame and the data burst. The accuracy of the CGI-TA method is limited to the size of the cell. RSS employs a mathematical model describing the loss of signal strength as a function of the distance between the mobile phone and the base station. The location of the mobile phone can then be calculated. The signal pattern methods locate mobile phones by comparing the pattern of signal measurements with patterns stored in a central database.

The main advantage of such a system is that it integrates positioning and communication functions. Secondly, as on mobile phone radio bands, the signal can be received both inside and outside a building, therefore a single system can be used anywhere as long as a mobile phone can be used. As mobile communication has been widely accepted by society, this extra positioning function will benefit many users by providing different applications. It is beyond doubt that the positioning accuracy will be further improved as the technology developed. However, a well-distributed network is required to achieve high accuracy for navigation purposes. This may not be a problem in urban areas. Meanwhile, the positioning accuracy may be reduced significantly in areas which do not have enough cell stations, such as rural areas. Multipath effects may also reduce the positioning accuracy. According to Hein et al. [2001], the TDOA method represents the most promising approach for positioning in mobile phone networks. With the system architecture optimized for positioning, GSM-based TDOA techniques typically accumulate a total error of 270-380m (RMS), and UMTS-based TDOA positioning will be in the range of 20-27 meters (RMS). However, mobile phone networks are optimized for communication purposes, which means interference may result from the existing marginal overlaps of cells.

Furthermore, the network geometry does not provide an acceptable coverage for self-positioning using TDOA techniques. Therefore, it would be better to include other navigation technologies, e.g. GPS, in the mobile phone positioning technology.

At present, there are two mobile positioning service providers in Hong Kong. However, there are still concerns regarding accuracy and reliability of the mobile positioning services. Current mobile positioning services available in Hong Kong generally provide better than 200 meters (RMS) accuracy in urban area, but the positioning error can be as large as 1 kilometer in rural areas [Mok et al., 2004].

2.6 Integrated Positioning System

As discussed in previous sections, the commonly used navigation technologies have some inherent limitations related to system design or application environments. Consequently, no single existing technique can provide complete positioning data with a continuously high performance and accuracy. One way to improve navigation system performance is to integrate different existing sensors into what is called an integrated positioning system. The integrated systems can provide redundant, complementary measurements to each other to build a more positioning system.

GPS provides 24-hour global coverage positioning. As a result of continuous innovations in GPS and a significant drop in price, GPS has become the first choice for most vehicle navigation systems. Recently, most integrated systems are GPS-based combining GPS receivers with other sensors such as DR, INS, Loren-C, digital camera, Laser Scanner, beacon, mobile-phone [Krakiswsky, et al., 1988; Watanabe et al., 1994; Mattos, 1994; Schwarz and Wei, 1994; Abbott and Powell, 1995; Mar and Leu, 1996; Greenspan, 1996; Enge and Graas, 1996; Drane and Rizos, 1998; Krakiswsky et al., 1998; El-Sheimy and Schwarz, 1999; Farrell and Barth, 1999; Brown, and Silva, 1999; Kealy, et al., 1999; Brown and Olson, 2000; Hafskjold et al., 2000; Wang et al., 2000; Bonnifait et al., 2001 ; Tiano, et al., 2001; Chen and Grejner-Brzezinska,2001; Grejner-Brzezinska, 2001; Grewal, et al., 2001; Stephen and. Lachapelle, 2001; Young and Kealy, 2002; El-Sheimy, 2002]. In all these systems, GPS contributes its global coverage, high accuracy, absolute geo-reference and a long-term stability. Other supplementary sensors are used to bridge GPS outages, to support ambiguity resolution after loss of lock, and to provide redundant data to ensure the system integrity, reliability and availability. The choice of the sensors usually depends on the criteria set up by the nature of the application and financial constraints. Generally the system developer’s goal is to maximize the system’s performance while minimizing its total cost.

Typical and commonly used integrated systems are GPS/DR or GPS/INS. In fact, integration of these two systems is often the only way to maintain a specified level of navigation during GPS outages, provide a higher update rate than conventional GPS and reduce random errors of GPS [Greenspan, 1996; El-Sheimy, 2002]. Basically these systems augment GPS by using a specified dead-reckoning (DR) system to maintain navigation accuracy during GPS outage. DR sensors are utilized because they can accurately measure changes in a vehicle's position over a short time period. The error natures of GPS and DR are different and complementary, so a proper integration of GPS and DR can produce a better system performance. The DR smoothes the short-term GPS errors and bridges the GPS gaps, while the GPS positioning calibrates the long-term DR sensor drifts.

There are two approaches to integrating GPS and DR, loosely coupled and tightly coupled. In a loosely coupled approach, GPS and DR are cascaded by feeding the DR with GPS derived position and velocity. In a tightly coupled approach, the raw data from GPS and DR are used directly in a Kalman integration filter. Recent research has investigated the error budget of DR sensors and GPS receivers, and different algorithms for integrated data processing using simulated and field data were presented [Gao et al., 1993; Abbott and Powell, 1995; Mar and Leu, 1996; Greenspan, 1996; Zhao, 1997; Farrell and Barth, 1999; Bonnifait et al., 2001; Grewal, et al. 2001].

A low cost DR prototype has been integrated with GPS/DGPS and tested in Hong Kong. Results obtained from various tests in Hong Kong reveal that the feasibility and reliability of positioning is improved [Chao, et al., 2001]. However, if GPS signal is unavailable for a long period (i.e. 10 minutes), the system was not able to provide accurate positioning because DR errors will accumulate to an unacceptable level. With map-matching (MM) introduced into the GPS/DR integrated system. In such a system, positioning performance was improved as well. However, the system still failed to operate in the metropolis as the DR sensors still needed frequent calibration using GPS.

2.7 Integration of GPS/DR/Bluetooth sensors for This Study

A metropolis, such as Hong Kong, has a complicated transportation system that consists of a complex transport network and narrow streets surrounded by dense residential areas and skyscrapers. These cause GPS signal blockage and multipath. The positioning accuracy is also affected by poor satellite geometry for the same reasons. Thus, many land-vehicle positioning systems utilize other positioning systems to assist GPS and to enhance overall system performance.

Based on the analysis of the different positioning techniques presented above, GPS, low-cost DR sensors, and a Bluetooth beacon receiver are used in this research. The configuration of sensor is illustrated in Figure 2-6. The sensor fusion process has been done by Sun (2003). GPS and DR are integrated in a loosely-coupled way. When reliable GPS positioning is available after GPS signal pre-processing, GPS positions and DR measurements are fused by applying an adaptive Kalman filter and the optimal positioning result will be fed to a map-matching process for further processing which will be described in chapter 5. When GPS is not available, the system provides only DR measurement to map-matching process. A Bluetooth beacon is used directly to update the GPS/DR position if the position of road-side beacon is available.

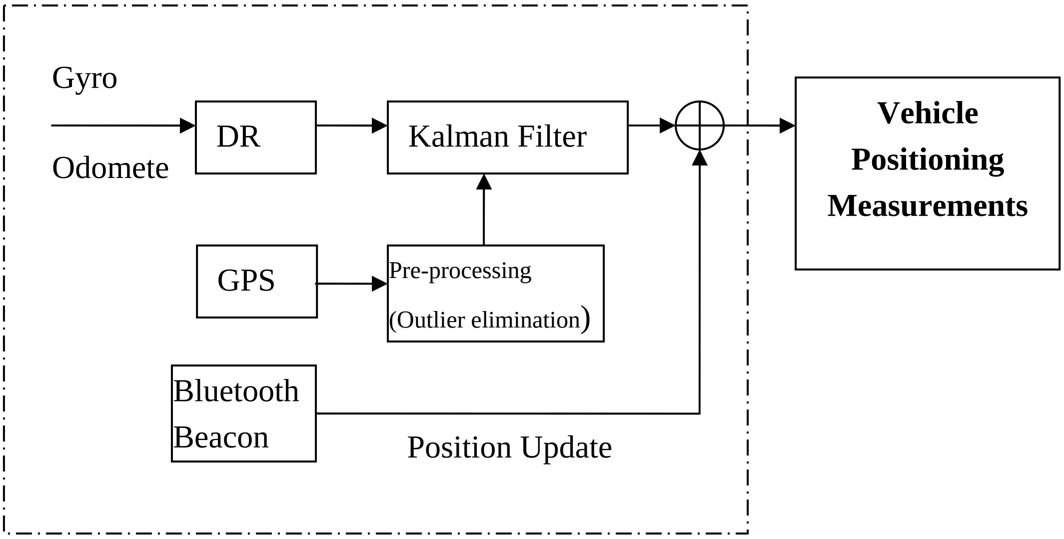


Figure 2-6 Configuration of positioning sensors

The fusion of GPS and DR measurements within a Kalman filter requires sophisticated stochastic modeling techniques to accurately model highly dynamic land vehicle trajectory and a recursive processing of noisy measurement data. In our experimental system, the following states are selected:

$$X = [x, v_x, a_x, y, v_{y,} a_y]^T \qquad \text{(Eq. 2-3)}$$

where x and y are easting and northing coordinates respectively, v is the speed of a vehicle and a is the acceleration of a vehicle. The dynamic equations can be written as:

$$\begin{bmatrix} \dot{x} \\ \dot{v}_x \\ \dot{a}_x \\ \dot{y} \\ \dot{v}_y \\ \dot{a}_y \end{bmatrix} = \begin{bmatrix} 0 & 1 & 0 & 0 & 0 & 0 \\ 0 & 0 & 1 & 0 & 0 & 0 \\ 0 & 0 & -1/\tau_{a_x} & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 0 & 0 & 1 \\ 0 & 0 & 0 & 0 & 0 & -1/\tau_{a_y} \end{bmatrix} \begin{bmatrix} x \\ v_x \\ a_x \\ y \\ v_y \\ a_y \end{bmatrix} + \begin{bmatrix} 0 \\ 0 \\ \bar{a}_x/\tau_{a_x} \\ 0 \\ 0 \\ \bar{a}_y/\tau_{a_y} \end{bmatrix} + \begin{bmatrix} 0 \\ 0 \\ \omega_{a_x} \\ 0 \\ 0 \\ \omega_{a_y} \end{bmatrix} \qquad \text{(Eq. 2-4)}$$

where, τ is the time constant, $\bar{a}$ is the mean value of the acceleration, and ω_a is the white noise (0， $2\sigma_a^2/\tau_a$). The matrix form of Equations 2-4 is:

$$X(k+1) = \Phi(k+1,k)X(k) + U(k+1,k)\bar{a} + \Gamma(k+1,k)W(k) \qquad \text{(Eq. 2-5)}$$

The measurements are chosen as:

$$Z = [d, w, x, y]^T \qquad \text{(Eq. 2-6)}$$

where, d is the vehicle travelling distance; w is the rate of change of bearing; (x, y) is the vehicle position measurement from GPS.

Then the measurement equation is:

$$Z = \begin{bmatrix} d \\ w \\ x \\ y \end{bmatrix} = \begin{bmatrix} \varphi T \sqrt{v_x^2 + v_y^2} \\ \dfrac{v_y a_x - v_x a_y}{v_x^2 + v_y^2} \\ x \\ y \end{bmatrix} + \begin{bmatrix} \varepsilon_d \\ \varepsilon_w \\ s_1 \\ s_2 \end{bmatrix} \qquad \text{(Eq. 2-7)}$$

where φ is the scale factor for the odometer; T is the sampling period; ε_d and ε_ω are the measurement errors of the odometer and gyro respectively; s_1 and s_2 are the GPS easting and northing measurement errors respectively. These equations can be rewritten in a matrix form as:

$$\mathbf{Z}(t) = \mathbf{h}[t, X(t)] + \mathbf{V}(t) \qquad \text{(Eq. 2-8)}$$

The Kalman filter equations can be written as:

$$\begin{aligned} &\hat{\mathbf{X}}(k) = \hat{\mathbf{X}}(k/k-1) + \mathbf{K}(k)[\mathbf{Z}(k) - H(k)\hat{\mathbf{X}}(k/k-1)]] \\ &\hat{\mathbf{X}}(k/k-1) = \mathbf{\Phi}(k/k-1)\hat{\mathbf{X}}(k-1) + U(k/k-1)\bar{a}(k-1) \\ &\mathbf{P}(k/k-1) = \mathbf{\Phi}(k/k-1)\mathbf{P}(k-1)\mathbf{\Phi}^t(k/k-1) + \mathbf{Q}(k-1) \qquad \text{(Eq. 2-9)} \\ &\mathbf{K}(k) = \mathbf{P}(k/k-1)\mathbf{H}^T(k)[\mathbf{H}(k)\mathbf{P}(k/k-1)\mathbf{H}^T(k) + \mathbf{R}(k)]^{-1} \\ &\mathbf{P}(k) = [\mathbf{I} - \mathbf{K}(k)\mathbf{H}(k)]\mathbf{P}(k/k-1) \end{aligned}$$

The Kalman filter can be used to produce optimal estimates of the state vector only when suitable statistical properties of errors are assigned to the models. In this system, an adaptive algorithm is used to update the mean acceleration and their associated error variances. The mean acceleration ($\overline{a}$) is adopted as the prediction of acceleration ($\hat{a}(k,k-1)$).

$$\begin{aligned} \overline{a_x} &= \hat{a}_x(k/k-1) \\ \overline{a_y} &= \hat{a}_y(k/k-1) \end{aligned} \qquad \text{(Eq. 2-10)}$$

The variance of the acceleration is modeled using the following empirical functions which are derived from testing data:

$$\begin{aligned} &\text{1) when } a > 0, \sigma_a^2 = \frac{4-\pi}{\pi}\left[a_{\max} - a(k)\right]^2 \\ &\text{2) when } a < 0, \sigma_a^2 = \frac{4-\pi}{\pi}\left[a_{-\max} - a(k)\right]^2 \\ &\text{3) when } a = 0, \sigma_a^2 = \frac{4-\pi}{\pi}\left[a_{-\max}\right]^2 \end{aligned} \qquad \text{(Eq. 2-11)}$$

where $a_{\max}$ and $a_{-\max}$ are absolute values of upper limit and lower limit of the acceleration.

A Bluetooth beacon, if available, can be used to update the vehicle position. This technique is adopted because of its global technology specification, universal radio interface in the 2.4 GHz ISM frequency band, small size, low power requirements and cost. If the position data from a Bluetooth beacon is available, it can be used directly to adjust the GPS/DR positioning result. However, in this study, the Bluetooth beacon positioning is only an optional component and not fully tested because the roadside beacons are generally unavailable.

Generally, for the system to start working, the initial step needs at least one accurate absolute position and direction measurement is needed. That means either available good GPS signal or other initial method such as manual input of accurate position and direction for the very first time initialization of GPS/DR system. To avoid the loss of vehicle location, the GPS/DR unit is designed to record the latest position and bearing in memory when the vehicle stops.

Chapter 3 Map-matching Techniques

A digital road map is a valuable positioning information source which can be used to improve the positioning performance of navigation systems. Accurately locating a car on the map is also one of the important functions of a car navigation system [Fenton and Mayhan, 1991; Iwaki, et al., 1989]. The integration of positioning sensors and digital road maps is called map-matching (MM). Many map-matching methods have been developed and have significantly improved the performance of vehicle navigation systems [Bullock and Krakiwsky, 1994; French, 1989; White et al, 2000; Zhao, 1997]. The simplest map-matching approach presumes that both the sensor and map are free from errors. Thus, the matching process becomes simply a matter of displaying the vehicle location on the background map. However, the error-free assumption does not hold in the real world. There are a number of different ways to approach the map match problem, each of which has advantages and disadvantages and will be reviewed in this chapter. This chapter aims to point out the common problems of existing map matching methods instead of focussing on the comparison between them.

Though the map-matching process in general should improve the performance of vehicle navigation systems, existing map-matching algorithms do not operate successfully in all conditions. With the accuracy requirement of land vehicle navigation and route guidance (5-20 meters with the 95% confidence level) [DoD and DoT, 2002], none of the existing map-matching algorithms used with GPS/DR has been tested extensively in the field and reported to satisfy the requirement in urban areas in which long-period GPS outages occur frequently. Moreover, the existing map-matching algorithms lack integrity, the ability to identify and exclude mismatches.

3.1 Concepts of Map-matching

As Zhao (1997) points out, the basic idea of conventional map-matching is to compare the vehicle's trajectory against known roads close to previously matched positions. The road whose shape most closely resembles the current trajectory and its previously matched road is selected as the one on which the vehicle is traveling. Abbott and Powell (1999) give a definition which seems more suitable to the current map-matching algorithms used in land vehicle positioning. A map-matching algorithm can be considered as consisting of heuristic rules by which sensor data and information from the map database are processed to identify the location on the road on which a vehicle is most likely to be traveling. Other formal definitions of map-matching can be found in Bernstein and Kornhauser (1996), White et al. (2000).

The map-matching problem can thus be described as follows. Within a digital map, a road is a curve consisting of many arcs, and the intersection of roads is a node. Roads are divided into many road segments (arcs) by nodes, and within any road segment there are many vertices along the road segment to describe the shape of the road segment. These vertices are called shape points. With a vehicle moving along finite sections of roads (arcs) N, its actual location at time t_i (i=1, 2, …, n) is P_i and the estimate of P_i provided from the positioning systems is denoted by $P_i^{'}$. Then the goal of map-matching is:

(a). to determine the road segment in N that contains P_i ; and then

(b). to locate the vehicle position on the determined road segment.

The former is called Road Identification and the latter can be called Position Match. The road segment determined in the road identification process is called identified road and the vehicle position located on the identified road is called matched position.

The early conventional map-matching algorithm was developed in the 1970s independently by two U.S. groups and one U.K. group [French, 1989]. It is known as semi-deterministic map-matching employing the DR and constraining vehicle on a predefined route or a particular network. As time passed, many other map-matching algorithms were developed employing the digital map and a positioning system such as GPS, dead reckoning (DR), or their integration, thereby to give better car position estimates. They vary from those using simple search methods [Bernstein and

Kornhauser, 1996; kim et al., 1996; White et al, 2000], to those using more complex mathematical techniques such as the Kalman filter and fuzzy logic [Jo et al., 1996;Kao and Huang, 1994; Kim and Kim, 2001; Krakiwsky, et al., 1988; Najjar and Bonnifait, 2002; Scott, 1996]. Most map matching algorithms focus on road identification, and they can be generally classified as follows:

1). Geometric methods: these use only geometric information including road shape, spatial location and road connectivity.

2). Conditional probability based methods: these involve probabilistic estimation and take into account the history of vehicle motion.

3). Fuzzy logic based methods: based on fuzzy logic, or Bayesian belief theory.

3.2 Road Identification

3.2.1 Geometric Map-matching Methods

Geometric map-matching methods use only the geometric shape of road and vehicle trajectory, and road network connectivity. Geometric methods include point-to-point, point-to-arc and arc-to-arc matching. They are reviewed in Bernstein and Kornhauser (1996), White et al. (2000).

The simplest geometric map-matching method is point-to-point matching. The vehicle location is snapped to the nearest node or shape point [Bernstein and Kornhauser, 1996; Kim et al., 1996; White et al., 2000]. The advantages of point-to-point matching are ease of implementation and low computational load. However, it is very sensitive to the way that the road network was digitized. Road segments with more shape points are more likely to be matched. This can cause significant error and instability.

Another simple geometric map-matching method is point-to-arc matching [Bernstein and Kornhauser, 1996; White et al., 2000]. This method projects the vehicle location onto the nearest road segments rather than onto the nearest node or shape point. ‘Nearest’ is defined as the minimum perpendicular distance between the vehicle position and the road. It is more accurate than the point-to-point method. However, this method can be quite unstable, especially if there are parallel, space-closely road segments as shown in Figure 3-1. Points P1 – P4 should all be located in road segment CD. However, P3 is closer to road segment AB. Then the matching results jump from road segment CD to AB and then back to road segment CD. Another problem of the simple point-to-arc method occurs near road intersections. As shown in Figure 3-2. Points P1 – P6 should be matched to road segment CD. However, near the intersection of road segments CD and AB, points P5 and P6 are closer to road segment AB. Therefore, these two points will be mismatched to road segment AB instead of road segment CD.

Neither point-to-point matching or point-to-arc matching reflect the fact that the vehicle trajectory actually constitutes arcs which represent road segments. Bernstein and Kornhauser (1996) proposed that it is more important to perform some kind of curve-to-curve matching and to incorporate topological information. Bernstein and Kornhauser (1996) and White et al. (2000) have suggested an arc-to-arc matching algorithm referred to as the piece-wise matching method. It firstly searches for candidate nodes within a range which is defined by the measurement error. Piece-wise linear curves are then constructed from the set of paths that originated from that node. At the same time, another piece-wise linear curve is constructed by using GPS determined positions. The distances between GPS determined curve and the curves corresponding to the network are computed. The closest curve derived from road network is selected and the GPS-determined points are projected on to that curve. Joshi (2001) also proposed a piece-wise map-matching method based on rotational variation metric (RVM). RVM consists of a series of angles between corresponding pairs of tangent vectors to the two curves, positioning measurements derived curve and road network derived curve. The variance of the angles, called the Rotational Variation Coefficient (RVC), quantifies the degree of similarity between the two curves. Thus, for the curve forms from positioning measurement, calculating the RVC with each candidate road, and then the one with minimum value is confirmed as the right road. This is a pure geometrical approach and assumes an outlier-free navigation solution. However, arc-to-arc matching methods are more complicated compared with point-to-point and point-to-arc methods. This proposed piece-wise arc-to-arc matching is complex to implement. Moreover, the piece-wise matching method, proposed by Bernstein and Kornhauser (1996) and tested by White et al. (2000), does not consistently perform better than other algorithms in a real world experiment. White et al. (2000) also comments that more attention needs to be paid to the problems that arise at the intersection of roads.

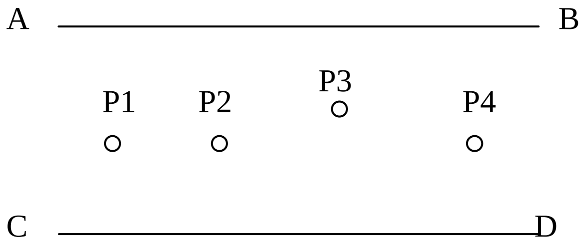


Figure 3-1 Problem example of point-to-arc matching – parallel roads

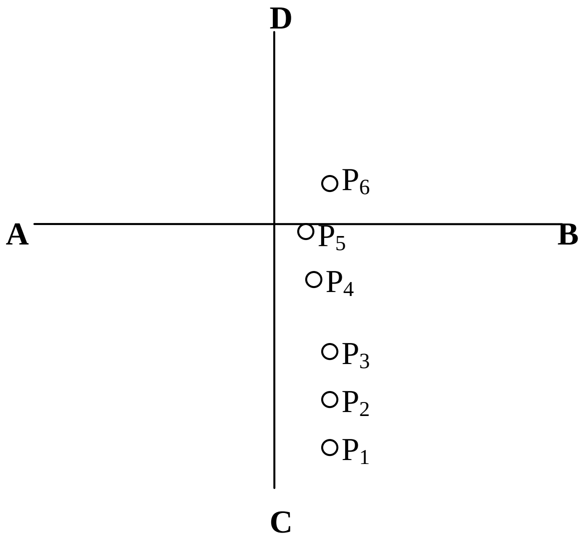


Figure 3-2 Problem example of point-to-arc matching – intersections

Many measurements can be incorporated to provide better selection criteria for road identification. For example, in addition to distance measurement, there are also differences in bearing, road connectivity, rotational variation [Greenfeld, 2002; Joshi, 2001], road separation space [Honey et al., 1989], GPS position relative to the road link [Quddus et al., 2003], and other road rules such as road type, speed limit [Scott, 1996]. These expand the decision space from one-dimensional (distance) to multi-dimensional.

According to the expansion of decision dimension, the simple point-to-arc and arc-to-arc methods can be improved by adding directional information, road network topology and other supplementary information such as drive restriction as suggested by Bernstein and Kornhauser (1996), and tested by White et al. (2000). Obviously, the parallel road problem shown in Figure 3-1 can be overcome by using road network topology, and the intersection problem shown in Figure 3-2 can be solved by using directional information.

For example, Taylor and Blewitt (1999) propose a road reduction filter (RRF) based on distance relationship which is improved by applying road network connectivity information along with drive restrictions [Taylor et al., 2001]. These additional conditions help to filter out any incorrect road segment. Etak, Inc. also develops an improved point-to-arc matching which sequentially applies conditional tests to find out the road on which a vehicle is travelling. [French, 1989; Honey et al., 1989]. The conditional tests are based on parameters such as directional information, distance between roads, distance between sensors measured position and the road, and road network connectivity. Each parameter is linked with a predefined threshold. For all candidate road segments, the one which passes all tests is selected as the identified road. For the identified road, a correlation coefficient based on RMS error of the bearing between sensors measured vehicle trajectory and the identified road is calculated. If the correlation coefficient passes a threshold, the identified road is confirmed and then the vehicle location will be updated on this road. However, this improved point-to-arc method is sensitive to the threshold used for road identification. Also, one mismatch can lead to a sequence of mismatches [Quddus et al., 2003].

Intuitively, applying more measurements can better help avoiding matching errors than single measurement. However, this would also result in conflicting matching conclusions and therefore, cause more confusion. To remove confusion, multiple criteria need to be fused for road identification. There are different ways to combine the multiple criteria decisions. One simple way is to combine the criteria by means of a weighting scheme and the weight factors can be derived empirically from data testing [Zhao et al., 2002; Quddus et al., 2003] or from adaptive fuzzy network based training [kim and kim, 2001]. Another complicated way is to use Bayesian Belief

Theory and Dempster-Shafter’s rule for deriving the unique non-ambiguous selection [Najjar and Bonnifait, 2002]. The Bayesian Belief Theory, Dempster-Shafter’s rule and adaptive fuzzy network based training will be discussed in later sections which focus on fuzzy logic based map-matching methods.

Greenfeld (2002) proposed a weighted topological arc-to-arc matching algorithm. Based on criteria such as the difference of bearing measurement, the difference of distance, and the rotational variance between the line formed by the two consecutive GPS points and the road, likelihood scores are computed for every candidate road to find the best match. The study states that the algorithm works well even with inferior GPS data. However, the study also suggests that further research is required to verify the accurate performance of the algorithm and to make an accurate position determination on a given road segment. Quddus et al. (2003) improves the weighted topological algorithm by adding more measurement information such as “GPS position relative to the road link”, and by taking into account vehicle speed information to determine the position of the vehicle on the selected road link. Field tests suggest that the weighting score for heading should be given more importance than that of relative position. Furthermore, the weighting score for relative position should be given more importance than that of distance difference. After determination of the relation between the weighting score based on the knowledge of a priori statistical performance of sensors and the topology of the network, any given positive value of weighting parameter of distance difference can provide good results.

Algorithms based on purely geometric approach work well in the absence of large positioning system errors and high noise. They tend to fail when there are outliers in the positioning sensor output and/or there is an array of similar road segments in close vicinity which is typically found in urban areas. Therefore, algorithms based on conditional probability are developed due to the fact that the position measurements both from sensors and the digital road network contain errors and uncertainties.

3.2.2 Conditional Probability Based Map-matching Methods

A variety of more advanced statistical methods have been proposed to perform the map-matching process. The conditional probability based map-matching methods attempt to improve the quality of map-matching through better accounting for some of the uncertainty in position estimates. This kind of methods includes simple probabilistic techniques, and other more complicate methods such as Kalman filtering, multiple hypothesis filtering and Markov modelling.

With a simple probabilistic method, known error characteristics of a location estimate can be used to restrict the candidate set of road segments for map-matching. The error characteristics can be used to determine an error elliptical or rectangular area which limits the search area for road identification. After finding candidate road segments in the area, other methods can be applied to further determine the identified road. The simple probabilistic method can be used as an additional filter on top of many map-matching methods, e.g. the geometric methods described in the last section [Taylor and Blewitt, 1999].

Kalman filtering, taking into account uncertainties via covariance matrices, is an optimal estimation method that can be used to integrate position estimates from positioning sensors and digital road maps [Krakiwsky et al., 1988; Tanaka et al, 1990; Jo, Haseyama, and Kitajima, 1996]. Choosing different state vectors to model the dynamic process and giving proper error estimates can achieve optimal vehicle location estimations. Krakiwsky et al. (1988) proposed a Kalman filter to integrate position estimates obtained from digital map and position measurement from GPS and DR. Another good example of a map-matching algorithm with innovation of Kalman filter was proposed by Jo et al. (1996). The direction of travel is taken as the state vector and it is assumed that the target vehicle does not change its direction suddenly; this means that the direction in time epoch k is equal to time epoch k+1. The direction measurement should be consistent with the path direction. Therefore, the road that has high linear correlation with vehicle direction measurements is the identified road. Although these kind of methods work well for simple trajectories, it is very difficult to model real-life trajectories, which are governed by complex road networks.

There is always ambiguity in determining the identified road. Therefore, a multiple hypotheses technique (MHT) is applied. It firstly identifies roads by using the simple probabilistic method. The probability of a vehicle being matched to a road segment is determined through a series of recursive equations that incorporates the network topology along with their differences in position and bearing. These equations are used to develop a series of hypothetical paths for a particular vehicle. As new position estimates are generated, the hypotheses are updated and a likelihood score for each hypothesis is computed. The hypotheses with likelihood scores below a particular threshold are eliminated. For example, Scott (1996) proposed a multi-hypotheses map-matching method incorporated within a spatially reduced Kalman filter (SRKF) and a map aided positioning (MAP) estimator to determine the location of vehicle on a road network. The MAP estimates are generated for each candidate road. Validation gates are set up based on the error characteristics of the position measurement and SRKF associated confidence interval of prediction. Only those MAP estimates that pass through both validation gates are taken as inputs to SRKF for updating the hypotheses which are the estimated position measurements on the candidate road segments. These hypotheses are subsequently evaluated. Two metrics are used to evaluate hypotheses. The first is the likelihood that the sequence of MAP estimates would have generated the observed position measurement. The second is the goodness of fit of the MAP estimates to the SRKF as measured by the innovations sequence.

With the best hypothesis defining the current position and velocity, poor hypotheses are deleted, and the remaining hypotheses are maintained in case the best hypothesis is not the correct one. Pyo et al. (2001) also proposed another MHT method. The likelihood used to evaluate the hypotheses is a recursive conditional probability function of the following factors: probability of existing road facility (e.g. underpass), probability of link direction, probability of position and bearing difference, and probability of connectivity. In addition, a Kalman filter is used to estimate bias of position and bearing to improve map-matching performance.

A Markov model has also been introduced into the map-matching process to model the vehicle movement between road segments. Lamb and Threbaux (2000) proposed a MHT map-matching method by using a Markov model and Kalman filter. The Markov model is used to handle the topological aspects of the road map, maintaining a set of hypothetical roads and their respective probabilities. The Kalman filter handles the metric component of the location problem, providing least-squares optimal estimates of the vehicle location on each of the hypothesized roads. The statistics from the Kalman filter are used to update the Markov belief state at each time step and the Markov model provides a probability distribution over the Kalman filter. Enescu and Sahli (2002) proposed a multiple model estimation scheme for map-matching which is actually a Markov model based MHT method. These kinds of methods rely heavily on the assumption that the initial positioning measurement is accurate, and fail if the previous few epochs have consistent blunders.

Compared with the pure geometric methods, the conditional probability based methods are more robust. However, they require more computation time and more memory to store vehicle trajectory. Also, it is difficult to model vehicle motion dictated by a complex road network.

3.2.3 Fuzzy Logic Based Map-matching Methods

The fuzzy logic based map-matching methods are methods based on fuzzy logic [Driankov, 2001; Nguyen and Walker, 2000]. Clearly, because map-matching is a qualitative decision-making process involving a degree of ambiguity, it is suggested to develop fuzzy-logic-based map-matching algorithms [Zhao, 1997]. Many fuzzy logic based map matching algorithms use the concept of degree of membership. The membership functions define the degree to which an input belongs to a fuzzy set. These membership functions are chosen empirically and optimized using a sample input/output data. Fuzzy membership functions can be optimized using an Adaptive Neuro Fuzzy Inference System (ANFIS). ANFIS uses techniques like least squares or back propagation algorithms to determine the membership functions for a given input/output data sets. A set of *If-then* rules are used to define a Fuzzy Inference

System (FIS) by connecting the antecedent to the consequent (i.e. input to output). These rules are given weights based on their criticality.

Kao et al. (1994) developed a map-matching algorithm based on the approximate reasoning in fuzzy logic. It uses fuzzy logic to assign truth values from 0 to 1 for each of the sensor signals and road segments and then make decisions based on the assigned truth value. Syed and Cannon (2004) also developed a similar map matching algorithm. The fuzzy sets used in this algorithm are proximity of position solution (to the road segment), small bearing change, average distance travelled on current road segment, large distance travelled on current road segment, small bearing difference (which is defined as the difference between bearing change and the angle between the current and concurrent road segment).

Kim and Kim (2001) proposed an adaptive fuzzy-network-based C-measure map-matching method. C-measure is defined to represent the certainty of the car's existence on the corresponding road. It is associated with factor (D) which is a function of distance between the position of the car obtained from a positioning system and its projected position on the road, and factor (V) which is a function of the angle between the bearing of the car and the direction of the road. Because a car can only change to another road by going through a junction, C-measure should be designed to represent this property as well as D and V. Therefore, C-measure is defined as $C(k+1)= aD+bV+rC(k)$, where $a>0$, $b>0$ and $0<r<1$. The adaptation of parameters a and b can be obtained by applying adaptive fuzzy network.

Najjar and Bonnifait, (2002) developed a method to locate a vehicle by using Bayesian Belief Theory and Dempster-Shafter’s rule for deriving a unique non-ambiguous selection. The parameters they used to represent the similarity are also the distance between the position of the car obtained from a positioning system and its projected position on the road, and the difference between the bearing of the car and the direction of the road.

However, compared with probabilistic methods, they are essentially the same process except that the probabilistic methods describe the sensor error models relative to the candidate road segment in probabilistic terms, while the fuzzy-logic-based method use membership function [Zhao, 1997]. The fuzzy logic based method has similar performance compared with probability-based methods.

3.3 Methods for Position Match of Map-matching

When the correct road segment has been identified, the next step is to determine the position of the vehicle on the road segment. This is called position matching.

First, let us consider a situation where the map used for map matching is free of errors. Figure 3-3 shows a section of road segment and an error ellipse of a position sensor.

For convenience, we choose the coordinate frame according to the direction of the road, where the X-axis is in the along-track direction and the Y-axis is in the across-track direction. The coordinates of a point determined by the positioning sensor in the reference frame are denoted as x_p and y_p . The true coordinates of the point are x_t and 0, as the location must be on the road.

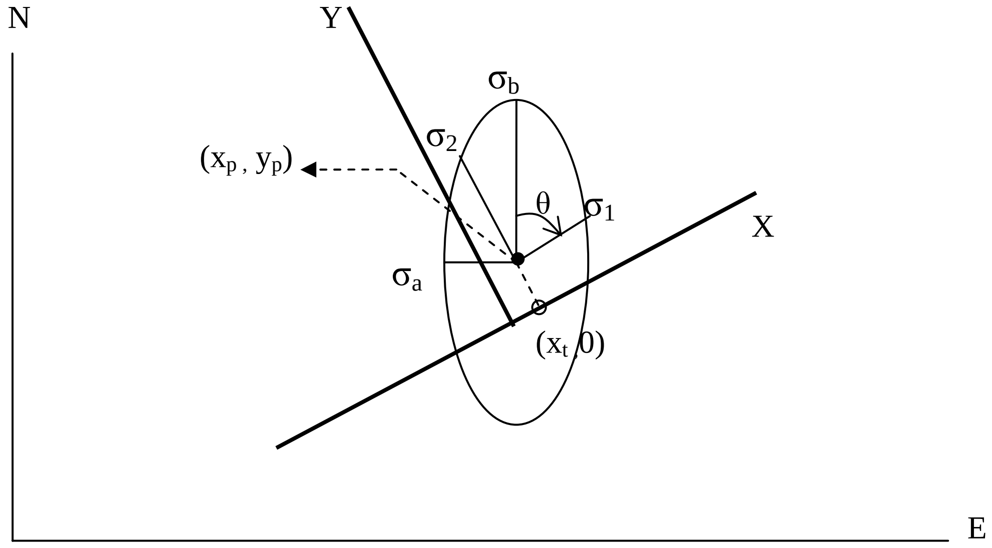


Figure 3-3 Position error ellipse and road reference frame

Without map-matching, the position estimates represent the coordinates as shown in Equation 3-1, and the position error variance can be calculated by using Equation 3-2.

$$\hat{x}_t = x_p$$
$$\hat{y}_t = y_p \qquad \text{(Eq. 3-1)}$$

$$\sigma^2 = \sigma_a^2 + \sigma_b^2 \qquad \text{(Eq. 3-2)}$$

where, $\hat{x}_t$ and $\hat{y}_t$ are the coordinate estimation, and σ_a and σ_b are minor and major axes of the error ellipse respectively.

The simplest position matching method is the so-called Nearest Point (NP) method. This method is to find the point on the road segment which has smallest distance to the point determined by positioning sensor.

$$\begin{aligned} \hat{x}_t &= x_p \\ \hat{y}_t &= 0 \end{aligned} \qquad \text{(Eq. 3-3)}$$

The variance with NP can then be calculated as

$$\sigma^2 = \sigma_a^2 \cos^2\theta + \sigma_b^2 \sin^2\theta \qquad \text{(Eq. 3-4)}$$

Where, θ is the angle between the X axis and the major axis of the ellipse.

Comparing equation Eq.3-2 and Eq.3-4, it can be seen that the variance with NP algorithm is smaller than the original position estimates from the positioning sensor directly. However, with the NP algorithm, the orientation of the error ellipse is not considered in the coordinate estimation.

Another improved method is called MAP -- the Maximum a posterior Probability (MAP) [Scott, 1996]. The MAP estimation with map constraint $y_t = 0$ can be expressed as

$$\begin{aligned} \hat{x}_t &= x_p - \frac{\sigma_1}{\sigma_2} r y_p \\ \hat{y}_t &= 0 \end{aligned} \qquad \text{(Eq. 3-5)}$$

where,

$$\begin{aligned} \sigma_1^2 &= \sigma_a^2 \cos^2\theta + \sigma_b^2 \sin^2\theta \\ \sigma_2^2 &= \sigma_a^2 \sin^2\theta + \sigma_b^2 \cos^2\theta \\ \sigma_{12} &= \sin\theta\cos\theta(\sigma_b^2 - \sigma_a^2) \\ r &= \frac{\sigma_{12}}{\sigma_1\sigma_2} \end{aligned}$$

The variance of MAP estimation is

$$\sigma^2 = \sigma_a^2\sigma_b^2 / (\sigma_a^2 \cos^2\theta + \sigma_b^2 \sin^2\theta\ ) \quad \text{(Eq. 3-6)}$$

In a more general case both position and map errors are considered. Figure 3-4 shows the error ellipses of both systems. The position estimates can be written as the weight average of both systems:

$$\begin{aligned} \hat{X} &= C_1^{-1}(C_1 + C_2)^{-1} X_1 + C_2^{-1}(C_1 + C_2)^{-1} X_2 \\ &= A_1 X_1 + A_2 X_2 \end{aligned} \qquad \text{(Eq. 3-7)}$$

With the covariance matrix

$$C = A_1 C_1^{-1} A_1^T + A_2 C_2^{-1} A_2^T\ \ ) \qquad \text{(Eq. 3-8)}$$

where, X_1 and X_2 are the position vectors from the positioning sensor and map respectively, and C_1 and C_2 the corresponding covariance matrices.

It is clearly shown in Figure 3-4 that the position uncertainty with this method is in the common area of both ellipses, which is smaller than that of either of the original two. This method requires the position estimates from both positioning sensor and map, together with their covariance matrices. The position estimates from the map can be obtained from the velocity (or distance) along a road section. However, the variance of the position is difficult to determine, as it is the combination of velocity error and map error. In general, the error in along-track direction is larger than that in across-track direction.

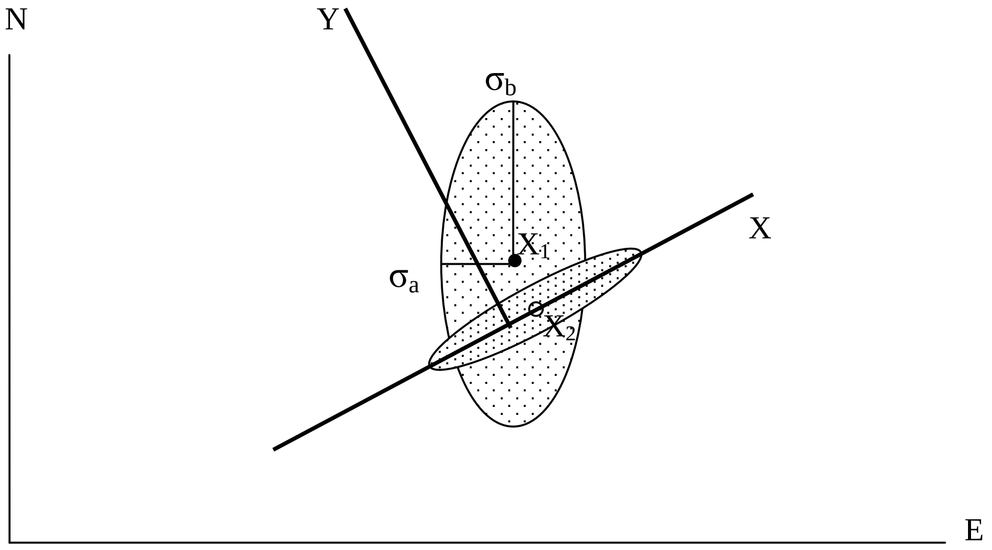


Figure 3-4 MAP method: both position and map errors considered

3.4 Discussions on the Existing Map-matching Methods

Digital road maps are readily available, and they are normally more accurate than the low-end positioning sensors being discussed in this study [Ad Bastiaansen, 1996; Bullock and Krakiwsky; 1994]. Thus, map-matching not only relates the coordinates obtained from positioning sensor data with a geographic object, but also improves positioning accuracy. The two benefits of map-matching are firstly that it improves positioning accuracy and secondly it provides controls for positioning sensor errors by constraining vehicle location on the roads and therefore the navigation system can be more precise and reliable [Chen, et al., 2003]. Generally, the conditional probability based methods have better performance than the pure geometric method in terms of the number of correctly identified road segments and accuracy. They are more robust and can recover from false positioning more quickly. The fuzzy logic based methods have similar performance compared with the conditional probability based methods.

Although most of the GPS/DR based map-matching algorithms work well in open area conditions with sparse road networks, none of them are specifically designed to face the challenges of navigation in urban areas with complicated road networks. As previously stated, none of the existing map-matching algorithms used with GPS/DR has been extensively tested in the field and reported to satisfy navigation and route guidance requirements in urban areas in which long-period GPS outages occur frequently.

Most of the map-matching algorithms discussed above are isolated processes and are loosely integrated with GPS/DR sensors; that is these map-matching processes just take the positioning measurements from an external GPS/DR system without improving it with map information. Because of GPS blockage and multipath issues, the accuracy of GPS/DR system can be very poor in urban canyons. This corrupted positioning measurement introduces many errors into the map-matching processing and can lead to mismatches.

The existing map-matching algorithms also lack robustness in identifying correct road segments. Many of them sometimes give the wrong position estimates of the car or just leave the GPS/DR position unmatched; that would strongly degrade the performance of navigation systems. Eventually the map-matching process loses track of the correct road segment when the sensor noise increases. Moreover, none of the map-matching approaches has navigational integrity monitoring to ensure the reliability of the navigation system. Firstly, for successful vehicle navigation, especially in urban areas, measurement outliers need to be removed before position data integration. This can be achieved by using pseudo-measurements from the digital map to monitor the GPS solution and DR sensor measurements. Secondly, the correctness and accuracy of the position estimate obtained by map-matching processing need to be validated. Without integrity monitoring of the map-matching process, the system is not aware of mismatches and is not able to recover from them. Consequently, the reliability of the system cannot be guaranteed and results in significant degradation of system performance.

Clearly, an optimal integration of positioning sensors and digital maps, which means a more robust and effective map-matching method, needs to be developed. By doing so, the land vehicle positioning can be improved to meet the requirements of various ITS applications, especially in urban areas.

Chapter 4 Quality Assessments of Positioning Related Data in Urban Environments

As discussed in chapters 2 and 3, the positioning sensors used in this research include a GPS receiver, a DR system, and a navigation database that includes a digital road network and other supplementary information, i.e. road rules. In most existing vehicle positioning systems, GPS has become the ‘first choice’ for performing the positioning function, due to its cost effectiveness and high accuracy. The DR system is commonly used to supplement GPS, i.e. to fill short gaps when GPS is not available, while a digital road map is used to confine the vehicle position to the road network. However, such simplified integration philosophy does not work in dense urban areas such as Hong Kong [Chao et al., 2001].

The development of GPS and other satellite navigation systems has revolutionized navigation concepts over the last twenty years but one of the major drawbacks of satellite navigation systems is that they do not work in narrow streets and indoor environments, although there have been developments in low signal reception and multipath mitigation techniques in recent years [Cho et al., 2004; Nayak et al., 2000; Peterson et al., 2001, Satirapod et al., 2001]. For example in dense urban areas of Hong Kong, less than 30% of the test areas are able to receive 3 or more satellites [Chao et al., 2001]. Thus, in such environments, a DR system is the dominant system for positioning, while GPS, a beacon system and digital maps are used to calibrate or correct DR errors. Unfortunately, the positioning errors of a DR system used for vehicle navigation drift away very rapidly due to cost restraints. Therefore, to improve the performance of a land vehicle navigation system in such a situation, we need to understand the quality of the data collected from each subsystem and to develop a map-matching algorithm that optimally combines the position data from all positioning sensors and from the digital road map.

In this chapter, field tests of different types of positioning units, including GPS, DR, GPS/DR integration, and GPS/DR/MM integration have been carried out in Hong Kong and Macau. Based on the testing results, the quality of data from each positioning units and the navigation database are assessed.

4.1 Description of Field Experiments

Macau and Hong Kong are located in the south of China. They are two of the most modern cities in Asia with international airports, harbours, and a sophisticated road network.

In order to have a clear picture of the environmental restriction on vehicle positioning, the road network in Macau is divided into two parts: primary roads (44%) which are main roads essential to land vehicle transportation and secondary roads (56%) which are mostly narrow streets., and the testing area of Hong Kong is divided into different regions such as new town (Sha Tin, Junk Bay), urban areas (Central, Wan Chai) and old developed urban areas (Mong Kok; Kwung Tong) (see Figure 4-1). The classification of the areas is based on the population density provided by Hong Kong SAR government information center (http://www.gov.info.hk). The road network of Macau is shown in Figure 4-2 where the red lines represent primary roads. The testing in Macau covers all of the primary roads and more than 90% of the secondary roads and the testing in Hong Kong covers different regions and most of the road network, with repeat coverage in different time periods.

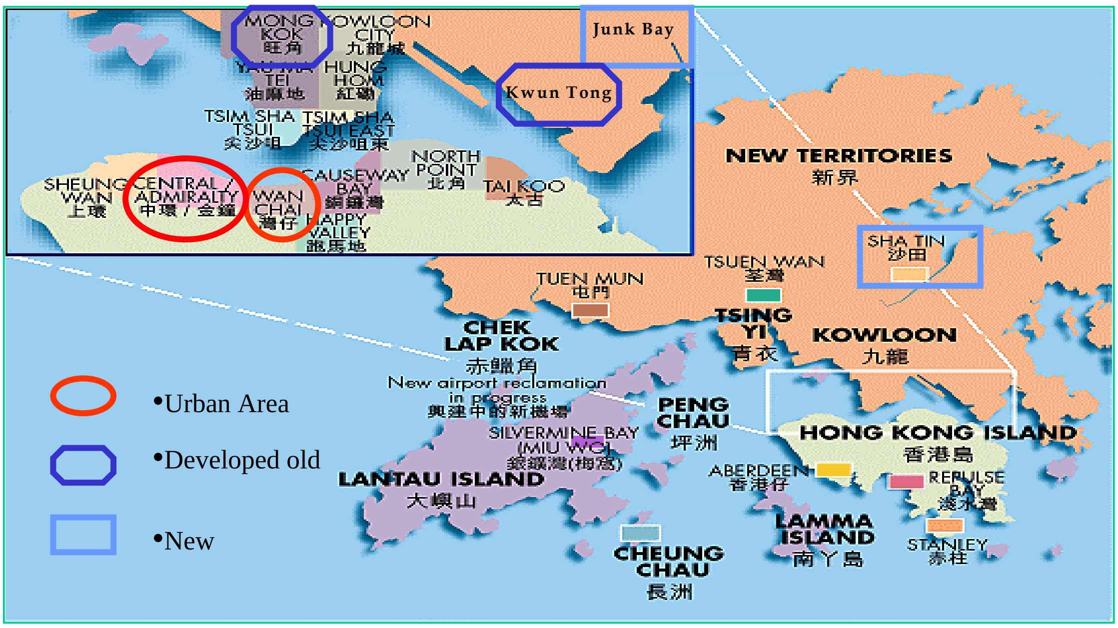


Figure 4-1　　Test areas in Hong Kong

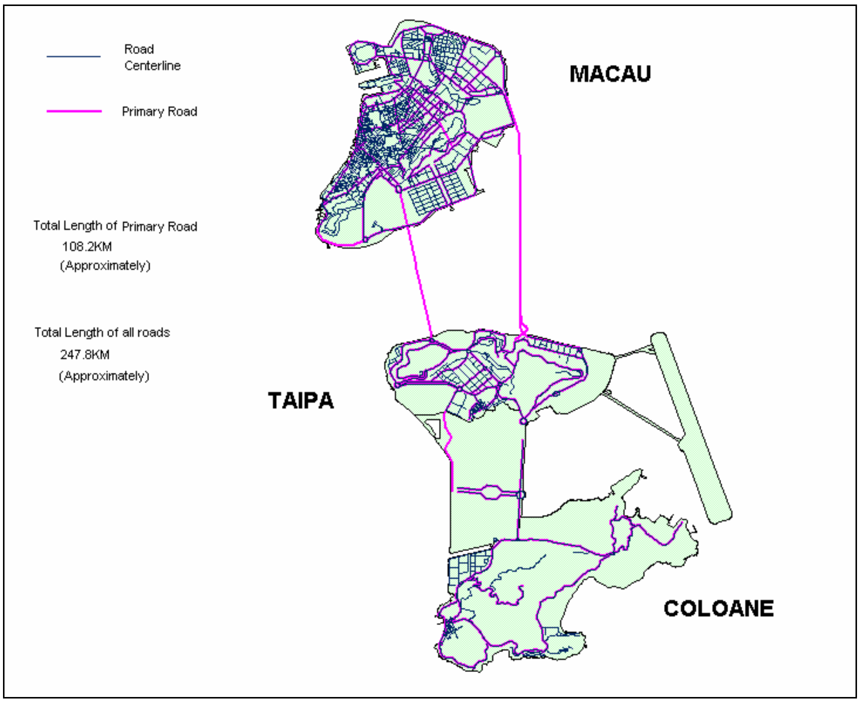


Figure 4-2 Macau road network

Different navigation systems were used in the experiments carried in Macau and Hong Kong, including GPS receivers, a DR system, GPS/DR integration, and digital maps. Therefore, we can examine the performance of different commonly used land vehicle navigation technologies in urban areas.

During the tests, all data collected were stored in computers for further analysis. Ideally, the true trajectories of testing vehicles should be determined by using a highly accurate and reliable system. However, it is difficult to determine the true coordinates of the testing vehicle, as the testing vehicle moved on roads at high speed. In our experiments, a high quality digital map was used for map-matching purpose.

Therefore, the centrelines of roads on which the testing vehicle is travelling are considered as the true trajectory of the vehicle.

4.2 Dead Reckoning

Dead reckoning (DR), though a very primitive positioning technique, is used in this research as the dominant sub-system in the integrated positioning system due to the poor GPS visibility in Hong Kong and Macau [Chao et al., 2001; Chen, et al., 2002]. DR is a relative positioning system, which means that it determines the vehicle position relative to a reference point. It normally consists of direction and velocity sensors. When given the coordinates of an initial point, it calculates the vehicle position by incrementally integrating the distance travelled along a given direction.

The DR accuracy depends on the quality of components used. In a vehicle positioning system, a low cost rate gyro or a digital compass are commonly used to measure the change of vehicle bearing and an odometer is used to measure the distance travelled. The typical accuracy levels of low-cost DR sensors are summarized in Table 4-1 [Bullock, 1995; Chao et al., 2001; Drane and Rizos, 1998; Stephen and Lachapelle, 2000]. The errors associated with distance and direction sensors are continuously increasing and then result in a large position drift error if the sensor errors are not properly compensated for.

Type	**Accuracy**	**Comments**
Bearing sensor		
Vibratory Gyro	0.1-1 deg/sec	Temperature sensitive
Fiber-optic Gyro	0.001 deg/sec	Expensive
Fluxgate compass	2 - 4deg	Sensitive to iron
Distance sensor		
Odometer	0.3-2% of distance	Sensitive to wheel slippage and radius change of wheel
Doppler Radar	1% of distance	Sensitive to road irregularities
Acceleration type	1-10 mg	Sensitive to gravity effect

Table 4-1 Accuracy of DR components

In our experimental system, the bearing sensor is a MURATA ENV05 gyroscope. This type of gyroscope suffers from large error accumulation due to gyro bias and scale-factor instability. In DR systems, the bearing error increases with periods of travel when no correct data is provided to calibrate the gyro. That, combined with the distance error, results in a large positional error. A gyro bias is a temperature-sensitive variable error, which implies that a gyro will display a non-zero value even if the angular velocity is zero. The gyro scale-factor error, on the other hand, affects the gyro measurements when the vehicle changes its bearing. After examining about 110 samples of 90-degree turns, it is found that the errors caused by scale-factor can reach up to 10 degrees after a 90-degree turning. Though clockwise and anticlockwise turns can compensate for the angle error caused by scale-factor, the position error resulting from the angle error can not be eliminated.

An odometer measures the travelling distance of a vehicle. Various odometers can be used in a DR system and the typical accuracy is 0.3-2% of the distance. In our experimental system, an odometer installed in the test vehicle was used. This odometer measures the revolutions of a wheel by sending out a number of pulses when the wheel is rolling. The number of pulses is then converted to distance travelled by a scale factor. The pulse output of the odometer contains random errors. The scale factor is not a constant, and depends on the radius of the vehicle's wheel. The radius of the vehicle's wheel varies with tyre pressure, temperature, tyre wear condition and the vehicle's speed. For example, the calculated scale-factor of one of our experimental cars is 1.543 with a standard deviation of 0.1516. If the odometer scale-factor error is left uncompensated for, it can cause an accumulated distance error and result in a significant positional error combined with an angle error. As seen in Figure 4-3, DR position measurements start drifting from Point A. Without error control, the position errors grow larger with increase in the distance travelled. After travelling 2.2 kilometres (about 15 minutes), the DR position error is about 150 meters.

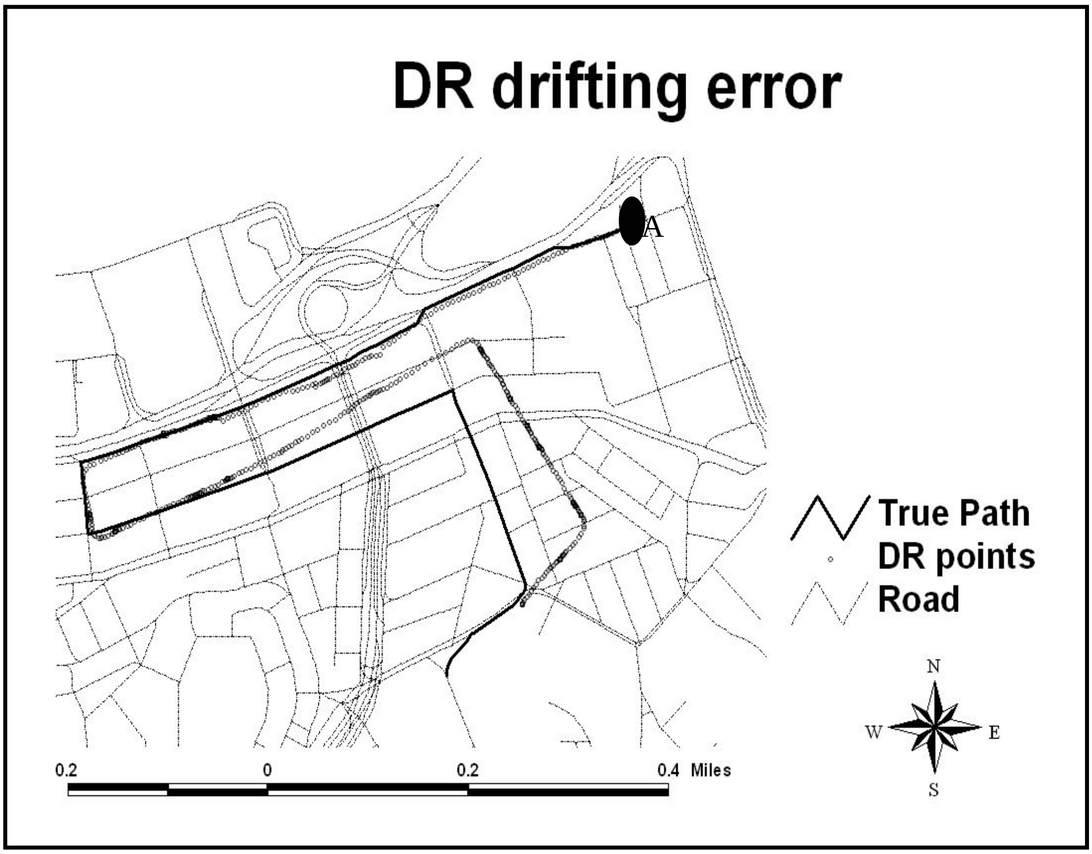


Figure 4-3 DR accumulated drifting error

4.3 Global Positioning System

The GPS is a widely used satellite-based navigation system. It provides a practical and affordable means of determining position, velocity and time. In general, GPS positioning accuracy is within 10 meters (RMS) without the Selective Availability (SA) [Satirapod, et al., 2001]. However, GPS may produce large positional errors for a number of reasons, such as satellite and receiver problems, severe multipath effects and other interferences, and large refraction errors caused by the earth’s atmosphere. The positioning error with multipath alone can reach a maximum of 100 m with the C/A code [Nee, 1992; Braasch, 1996]. Moreover, GPS suffers from signal blockage caused by the surrounding tall buildings which makes it less effective in urban canyons.

Macau and Hong Kong are very dense cities with narrow streets surrounded by high-rise buildings. They are not favourable environments for GPS positioning due to signal blockage and multi-path effects.

In order to analyze the GPS visibility, the number of GPS satellites that could be seen in Macau during the experimental period with different elevation cut-off angles is plotted. Figure 4-4 shows the number of available satellites and PDOP values in Macau on September 26, 2001, with an elevation cut-off angle of 7.5 degrees. It can be seen that at least 7 satellites be observed with PDOP values less than 4. However, if the elevation cut-off angle is increased (simulating narrow streets and tall buildings), the GPS visibility is reduced dramatically. Figure 4-5 gives the satellite visibility with a 30-degree elevation cut-off angle. The number of satellites is reduced to 5 most of the time in one day. The PDOP values also increases significantly.

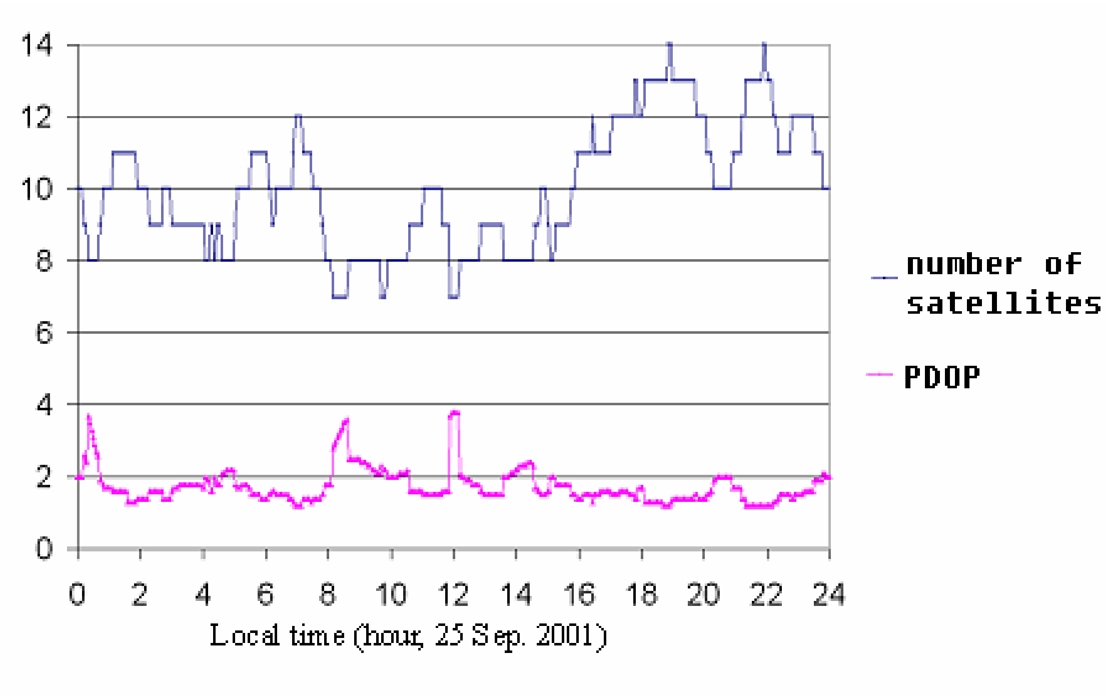


Figure 4-4 GPS satellites visibility in Macau (Elevation angle: 7.5 degrees）

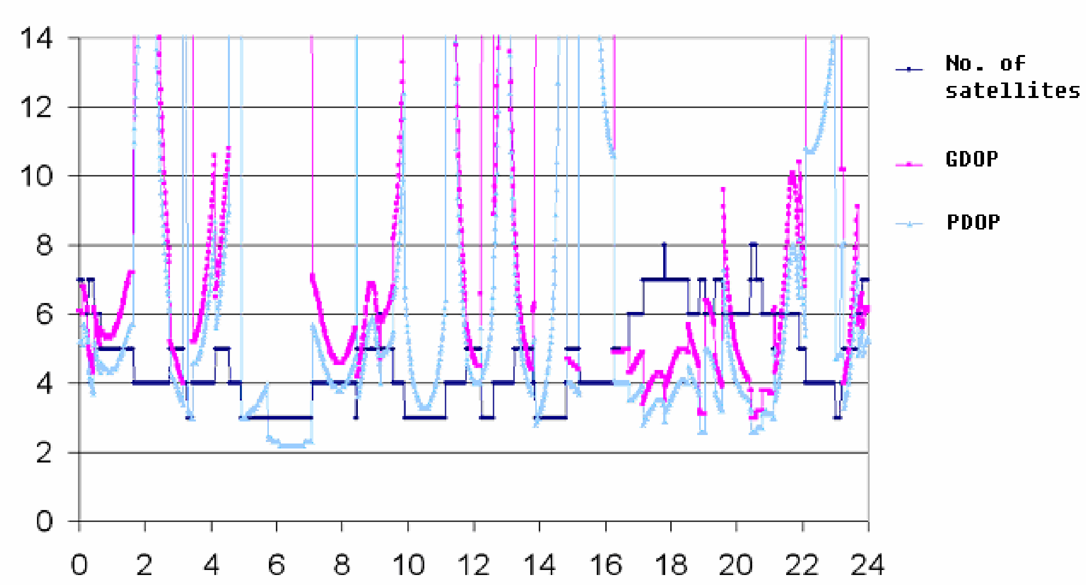


Figure 4-5 GPS satellites visibility in Macau (Elevation angle:30 degrees）

In order to analyze the real performance of GPS in Macau, we checked the number of satellites observed by the receivers in the vehicle that was driven along the road network. Statistical analyses were conducted according to the number of observed satellites separately for primary and secondary roads. For each road category, we counted the number of positioning points for different numbers of observed satellites, and then the ratio of each number of positioning points to the total number of positioning points was calculated to obtain the percentage of each number of observed satellites. As shown in Figure 4-6, 84% of primary roads received signals from at least 3 satellites and 72% of primary roads received signals from at least 4 satellites, while the percentages are only 64% and 52% for secondary roads respectively. Thus stand-alone GPS is not sufficient for vehicle positioning in Macau.

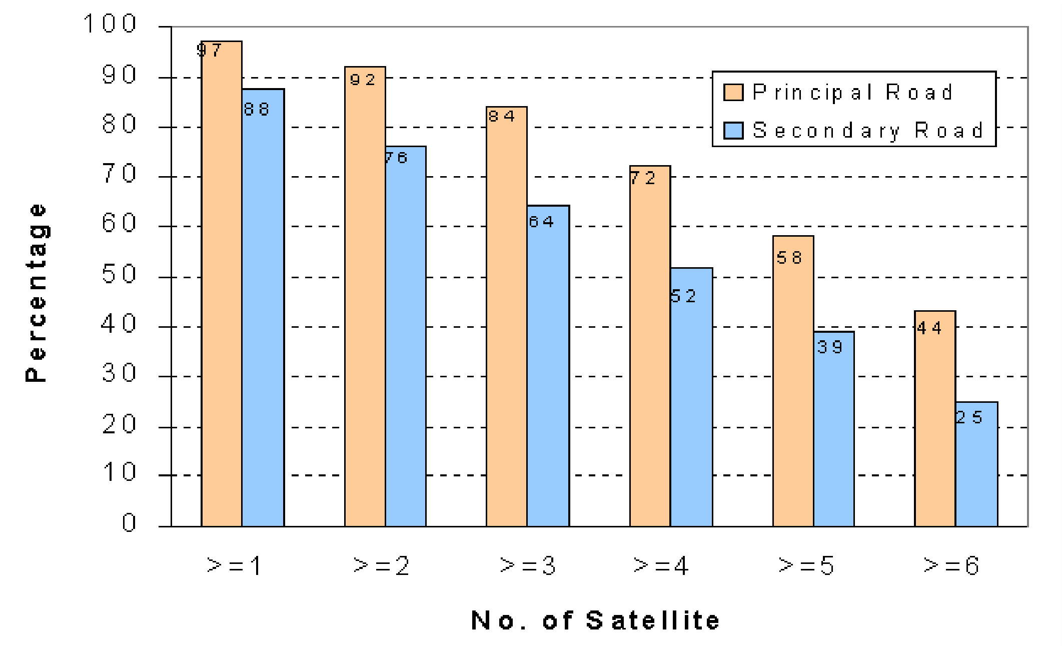


Figure 4-6 Satellite visibility

In Hong Kong, extensive tests have been carried out on GPS visibility. A test vehicle equipped with GPS receivers was driven on a specially designed route covering all different regions. Figure 4-7 shows the test result, which reveals that only about 30% of the test areas are able to receive 4 or more satellites and it can be as little as 7% in some densely built districts. Among the six districts tested, only Sha Tin and Junk Bay, the new towns with relatively low population density, have better satellite visibility. The rest of the tested areas all experience poor satellite signal reception especially in Wan Chai and Mong Kok, where most of the famous skyscrapers and the old ‘downtown’ were located respectively.

The GPS visibility analysis shows that GPS positions are not always available. Even if they are available, some of them may shift away from the true trajectory. Figure 4-8 shows an example of typical GPS errors in Hong Kong. The yellow dots are GPS points. The error can reach up to 150 meters due to the multipath effects. In urban areas, 4-5 minute GPS blockage occurs frequently and sometimes the period of GPS blockage can be up to 20 minutes.

In GPS navigation, the dilution of position (DOP) is commonly used as a quality indicator to represent the satellite geometric condition. The DOP value is a geometric factor that is the ratio of the positioning precision to the measurement error [Drane & Rizos, 1998, Kaplan, 1996]. A high DOP value, e.g. larger than 10, indicates an unreliable position solution. However, DOP values alone are not sufficient. A low

DOP value guarantees only that there is good geometry from the satellite spatial distribution. It cannot guarantee the overall position quality.

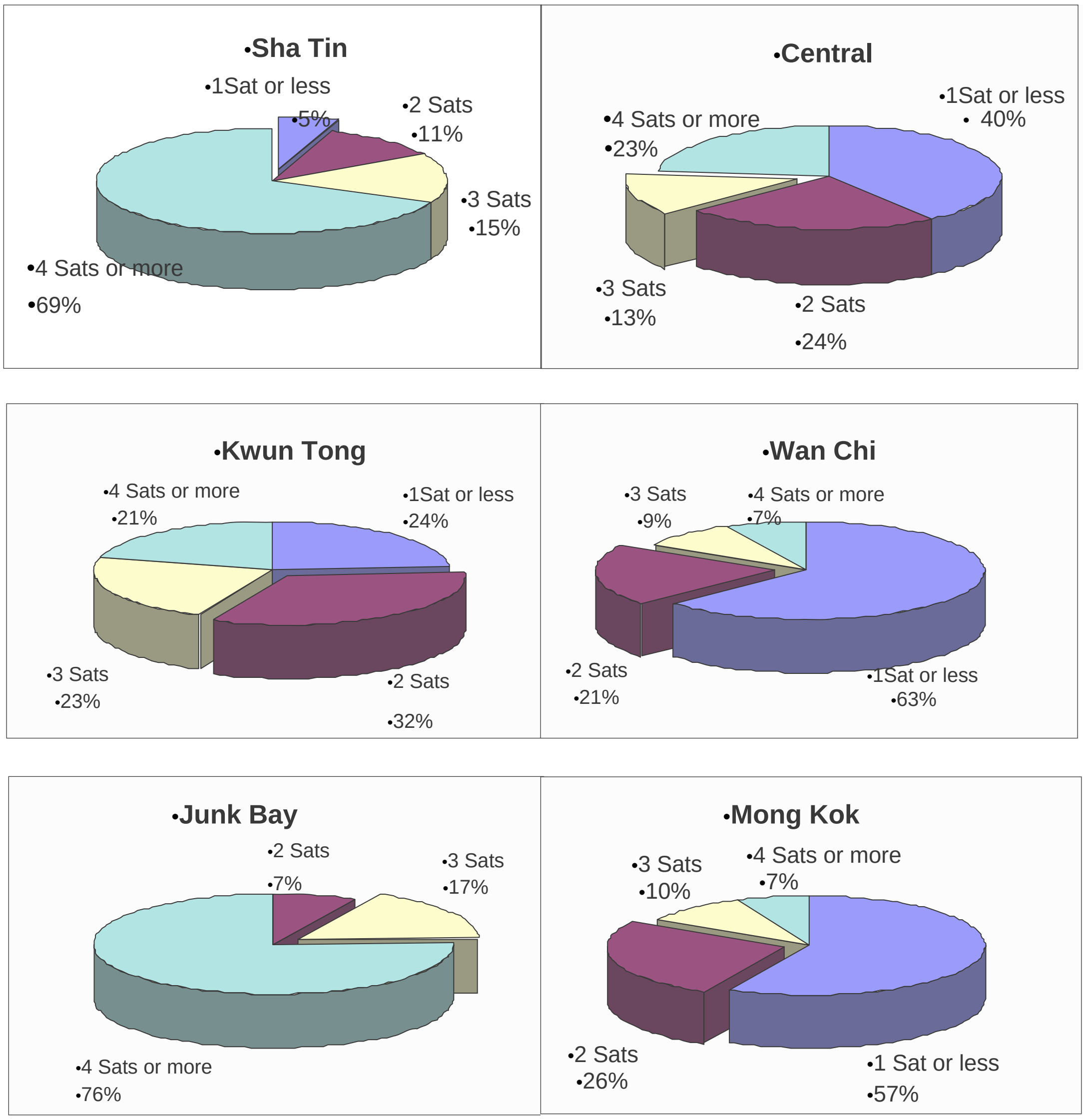


Figure 4-7 Satellite visibility in different districts of HK

Receiver Autonomous Integrity Monitoring (RAIM) methods have been introduced to detect and isolate measurement errors [Corrigan et al., 1999; Hewitson, 2003; Viðarsson, 2001]. However, RAIM methods have not been widely implemented in low end GPS receivers for vehicle navigation purposes. For low-end GPS OEM receivers widely used for vehicle navigation, a number of criteria can be used to indicate the quality of the GPS position output. These include:

- DOP value

Given a DOP threshold, if the observed DOP value is larger than the given value, the GPS observation is regarded as unreliable.

- Number of satellites used

If the GPS observation is obtained from a small number of satellites (i.e. less than 4 or 5 satellites), the results are considered unreliable.

- Comparing with previous GPS observations

As a vehicle always has a speed limit, the successive GPS observations must be within a certain distance. If the velocity derived from GPS observations is larger than the speed limit, the positions derived from GPS can be considered unreliable.

- Signal to noise ratio

Some GPS receivers provide the signal to noise ratios for pseudorange measurements. In general, a small signal to noise ratio may be caused by multipath, interferences, and weak GPS signals. When the ratio is less than a certain threshold, the measurement should not be used for positioning computation.

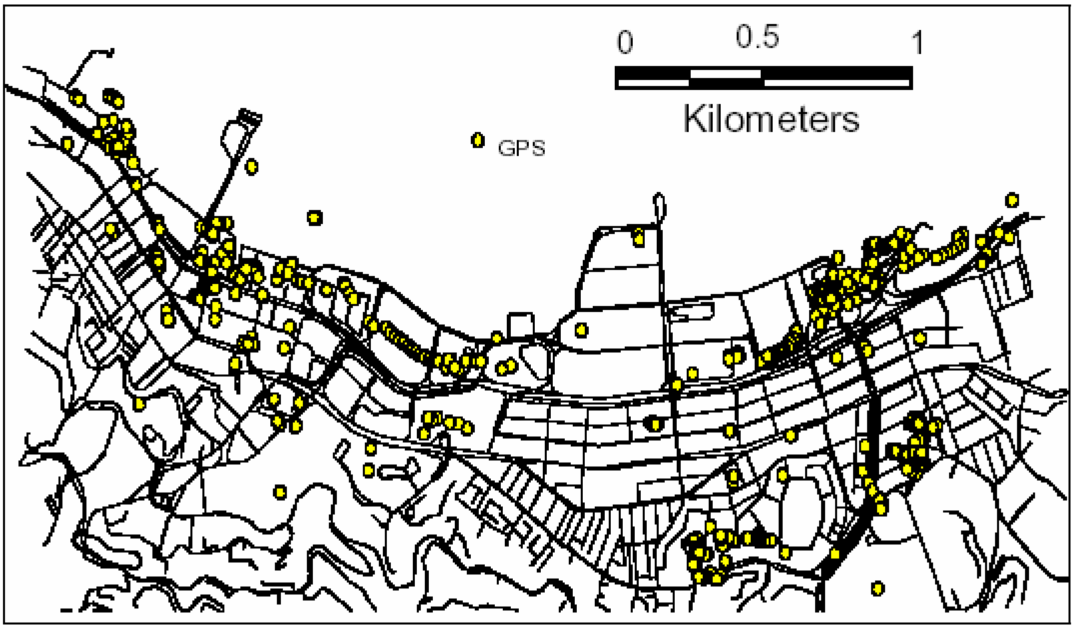


Figure 4-8 Example of GPS positioning blockage and errors

4.4 GPS/DR Integrated System

When using the navigational GPS receiver, GPS positioning availability is only 62% of Macau road network and 30% of Hong Kong testing areas. Therefore, DR, a self-contained navigation system needs to be used as a supplementary system to provide continuous vehicle positioning while GPS positioning is unavailable. GPS and DR errors are different and complementary in nature hence a proper integration of GPS and the DR can improve the system performance.

In the context of urban canyons, the integration should be performed carefully because the position output from GPS may not be reliable. Also, GPS positioning can be unavailable for a long period of time, e.g. 20mins or longer in downtown areas of a metropolis. After losing the GPS signal for a long period of time, the DR position error will accumulate to an unacceptable level. Consequently, map-matching methods are difficult to apply in these cases.

In our experimental system, a number of criteria were used to check the quality of GPS and DR outputs, such as DOP value, SNR, number of satellite, and GPS vs. DR output. However, a number of cases with large GPS errors, sometimes reaching as high as a hundred meters, were still left undetected. Most of these cases happened on narrow streets, roads along mountains or tall buildings with glass walls. Among undetected GPS errors, the average offset of GPS was 27 meters, and the largest offset of GPS was 102 meters.

With the integration of DR, the successful positioning of a vehicle with 10 meters accuracy (RMS) increases to 71% of Macau road network and 60% of Hong Kong testing areas. However, it is still not sufficient for land vehicle navigation and guidance in urban areas.

After applying map-matching to further process the GPS/DR output, the vehicle positioning can be further improved. Figure 4-9 presents an example of map-matching results. The green arrow in the figure indicates the vehicle travelling direction. The red line represents the vehicle trajectory given by GPS/DR, and the blue line represents the map-matched vehicle travelling path. We can see from the figure that the GPS/DR derived trajectory drifts from the true path. After map-matching, the drift errors are corrected and the trajectory is drawn back to the correct streets. The integration of GPS/DR and map matching process improves the successful positioning rate (positioning coverage) to 88% in Macau and 90% in Hong Kong which still cannot satisfy the requirements outlined in chapter 1.

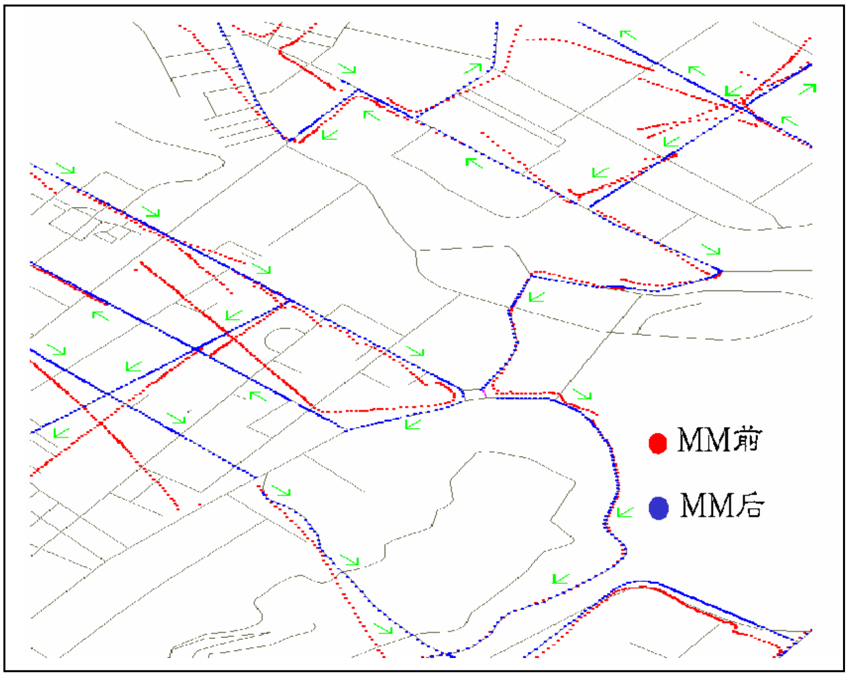


Figure 4-9 A sample of map-matching results

4.5 Digital Road Map Database

It has been widely accepted that a digital road map is essential to vehicle navigation. Generally, it can be used for several purposes in vehicle navigation including address matching, route planning, map-aided positioning (map-matching), and route guidance. For many ITS applications, vehicle positions determined by GPS or other sensors need to be matched to the corresponding positions on a map. A digital map used in a map-matching process should be correct, accurate, complete, up-to-date and rich in traffic information, such as one-way driving, speed restriction, and turn restrictions.

However, a digital road map may contain uncertainties and/or errors which can be categorized into geometric errors, thematic error and road network model uncertainty. The base digital road map used in our studies was released by the 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 maps, GDF 3.0 (European Standard CEN, 1995). It provides the road shape and position in a form of a multi-centreline road network that consists of nodes, arcs, and the basic topological information with high accuracy. In order to design more robust map-matching methods, an analysis of the uncertainties and errors associated with a digital road network is conducted in this section.

4.5.1 Geometric Errors of Digital Road Map

Geometric errors mainly include position error of road segments, missing road segments, distortion of road shapes, and corresponding topological errors.

One of the typical geometric errors is that the position of the road on the map is offset from the true position. Figure 4-10 illustrates an example of road offsets. The dashed line represents roads with position errors and the solid line represents correct roads. Such type of errors may be caused by a careless digitization process. A careless digitization process can also result in missing road segments. However, the latter is sometimes caused by time-lag in map update or intentional feature omission due to map generalization. Figure 4-11 shows an example of a road missing due to the use of an outdated map. From A to B, there should be a road as indicated by GPS points collected from a moving car. However, the road is missing from this map.

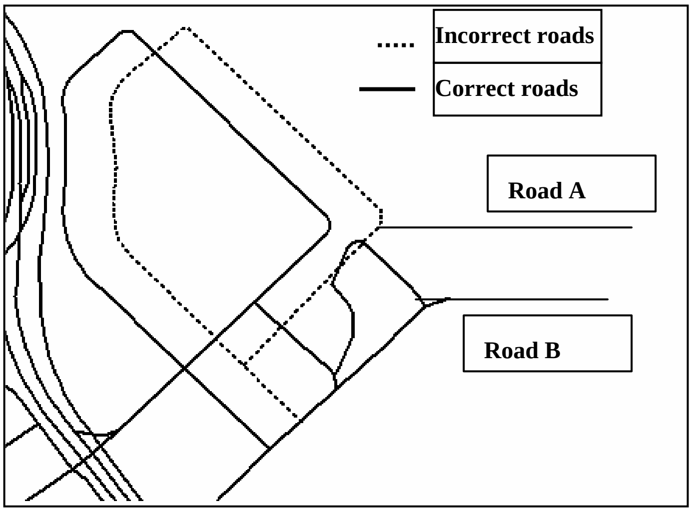


Figure 4-10 Road offset from the true position

Distortion of a road shape is another common error found in digital road maps, which may be caused by an incorrect geographical position or the generalization effect of cartographic processing. As shown in Figure 4-12, the original complex road shape is simplified due to the generalization effect of cartographic processing. Such processing distorts features on the ground and results in a geometric accuracy loss.

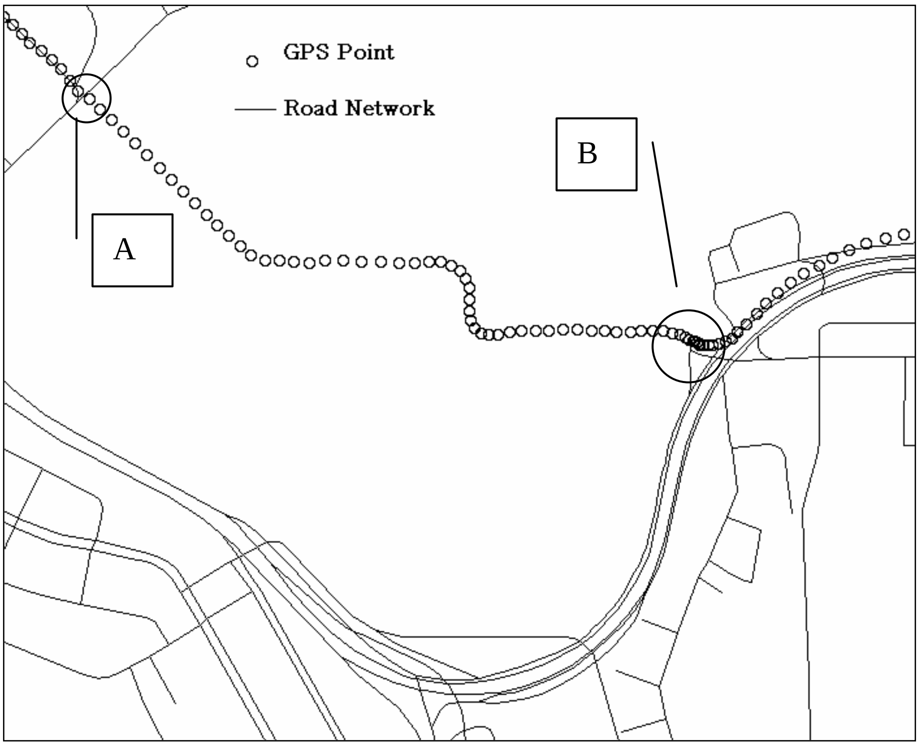
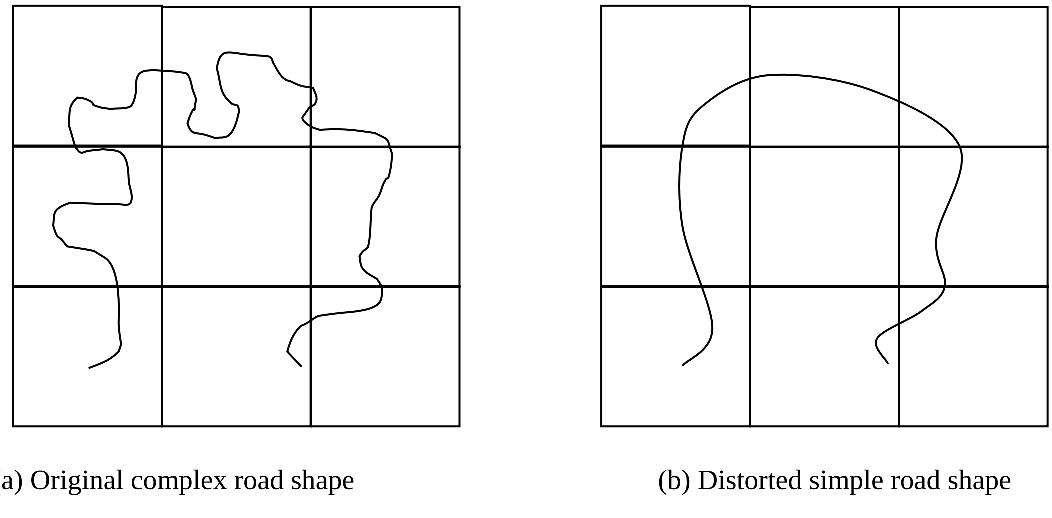


Figure 4-11 Road missing due to time-lag map update



(a) Original complex road shape

(b) Distorted simple road shape

Figure 4-12 An example of distorted road shape

These geometric errors may also result in topological errors, e.g. a wrong spatial connection as shown in Figure 4-8. The wrong connection between roads A and B is caused by the positional offset of road A. These geometric errors may cause incorrect vehicle positioning and ineffective vehicle navigation.

Accuracy is a very important factor in evaluating the geometric quality of a map. The overall accuracy of a map is an accumulated result of the source data and cartographic processing including cartographic generalization. It is specified by national mapping agencies that each map should meet a certain level of requirement in accuracy. Some agencies make use of standard deviation or root mean square error (RMSE) while others use a specified percentage of features within an error range. For example, the accuracy specifications for large-scale Chinese maps are as follows:

built-up area:	0.4 - 0.6 mm (RMS)
other areas:	0.6 - 0.8 mm (RMS)

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 the 'ground truth' [Zhao 1997, Bullock and Krakiwsky 1994]. However, if a digital road map is to be used for the DR calibration, a higher accuracy is desirable. Robert (2002) suggests that maps for ITS applications may be at scales of about 1:5,000 to 1:10,000 in cities and at smaller scales along the major roads outside metropolitan areas. Therefore, in our study, we choose 1:5000 base digital maps released by Hong Kong government, which claims that almost all noticeable natural and artificial features on the ground, e.g. roads, footpaths, buildings, temporary structures, etc. are captured and input to an accuracy of 1 meter (RMS).

4.5.2 Thematic Errors of Digital Road Map

Thematic errors are errors on the attributes of road features. For example, if a highway road is mapped as a pedestrian one, the thematic meaning is changed and such an error is called thematic error. These mistakes can be caused by the digitization process, or sometimes by the delayed update. For example, a road may be expanded from 2 lanes to 6 lanes. In this case, there will be no factual error but the thematic meaning of the features will be altered.

Some thematic errors are caused by real-time traffic conditions and/or temporary traffic regulations. For example, a road may be blocked immediately after a traffic accident, but the road conditions will be restored after a short period. Such a temporary change will never be mapped on a map, though such information is also important for vehicle navigation.

4.5.3 Road Network Model Uncertainty

Road networks are generally modelled by centrelines consisting of arcs and nodes, while in real life they are three-dimensional surfaces. The projection from the curved surface of the earth on a planar map can introduce uncertainties into a road network map database. For example, if a road has a slope, the distance measured from the map will be different from the actual distance.

A road network can be presented as a single centreline or multiple centrelines. The shape of road centrelines is not identical to the vehicle trajectory. When using a single centreline representation, the vehicle tends to deviate from the road when it is wide and has several lanes. In Figure 4-13, the dashed line represents single centreline road and the circle dots are GPS points. The GPS points are not on the dashed line but on the left lane of the road. To deal with this problem, it is better to use multi-centreline representation. Each centreline of lanes will be treated as an individual road segment. The number of lanes to be used for road representation should be carefully chosen, because if the separations between centrelines of lanes are smaller than the positioning accuracy, it would be difficult to identify the correct road segment. Particularly, since lanes of a road are normally parallel to each other, it is almost impossible to determine on which lane the vehicle is travelling.

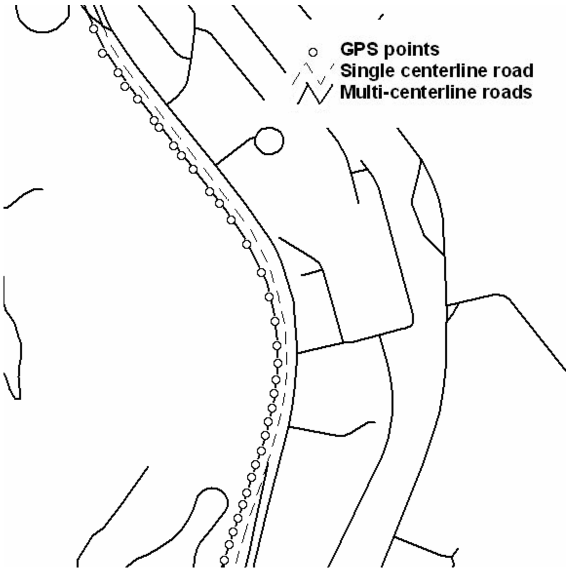


Figure 4-13 GPS points deviate from single centerline roads

Road networks often contain many connected roads with small angles between them, and these roads are called fork-shape roads (Figure 4-14). Some of them are caused by multi-centreline representation. When the accumulated bearing error becomes larger than the angle between some road sections, the road on which the car is travelling is difficult to determine, which may cause a mismatch when performing a map-matching process. Normally, the angles between folk-shape roads range from 10 to 40 degrees. So if the error of bearing measurement is larger than 5 degrees, it is difficult to determine which road section the car turns to.

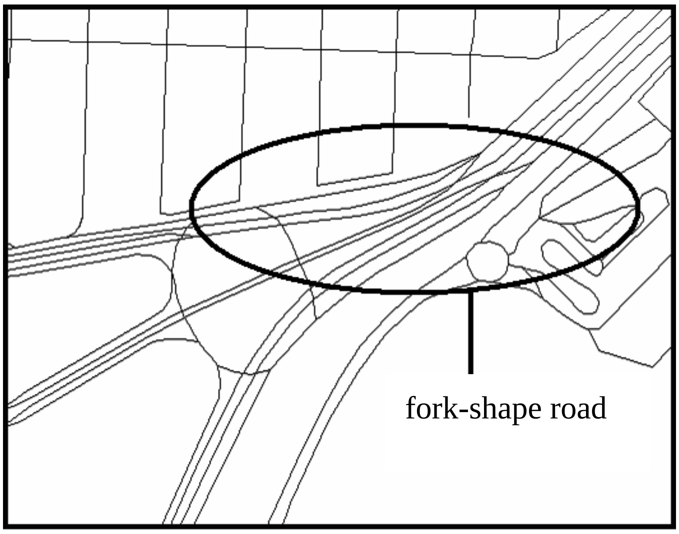


Figure 4-14 Illustration of fork-shape road

Also, a network topology represented by a planar map can introduce uncertainty to the real connectivity of roads. Figure 4-15 shows an example of such a case. A flyover and a road under the flyover which are not connected would be presented as connected in the planar map. This error can be resolved by introducing a non-planar network concept where a flyover that does not have an intersection with the road underneath is modelled as two unconnected line segments, as shown in the right side of Figure 4-13.

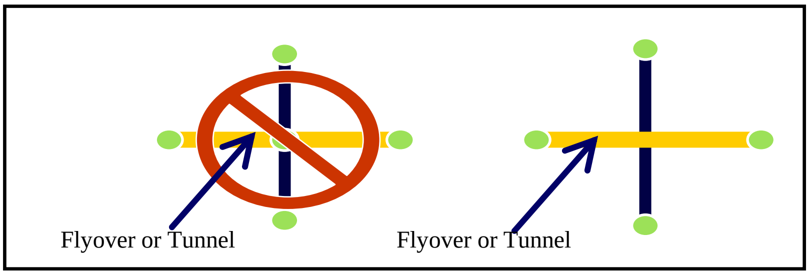


Figure 4-15 An example of confusing road connectivity

4.6 Proposed Integration Framework of Digital Road Map Database and GPS/DR

The objective of this study is to integrate data from positioning sensors with a digital road map database to improve vehicle positioning performance in metropolises. As analyzed above, none of the single positioning sensor/technique can fulfil our requirements and each type of positioning data contains its own shortcoming. Therefore, in this study, GPS, DR and a digital road map/database are integral components of a positioning system. The Bluetooth beacon is an optional positioning sensor in this study because road-side transmitters are generally unavailable because of cost issues.

The traditional way of integrating digital map with GPS/DR (map matching process) is treating the map matching process as an isolated process which mainly focuses on identifying the road the vehicle is travelling on and then determining the vehicle location on the identified road. The map matching process only takes measurements from the GPS/DR output to match the vehicle position to the corresponding location on the map without the ability to control the error of the GPS/DR positioning. Because the data input to the map matching process will greatly affect the performance of map matching process, a new integration framework need to be developed with the ability to control sensors errors and map errors.

Through optimal integration, each data set can be used to validate the other two in order to control the input data error. Figure 4-16 illustrates the data processing flow of the integration. A GPS receiver and DR sensor(s) are two physical positioning sub-systems. A digital road map can be considered as a pseudo-positioning sensor. Roles of each component are:

- DR as the primary positioning sensor
- GPS as a secondary positioning sensor, for (re)initializing and calibrating DR+MM
- The road centreline geometry and road rules as an augment for positioning

The Map-matching (MM) integrates position measurements and a map database for better positioning accuracy and relating vehicle positions to roads. The aims of map-matching are:

- To identify whether a vehicle is travelling on- or off-road.
- To identify which road the vehicle is taking
- If the vehicle is travelling on-road, then to improve positioning accuracy after the road is identified; and
- To correct or eliminate sensor errors using road features.

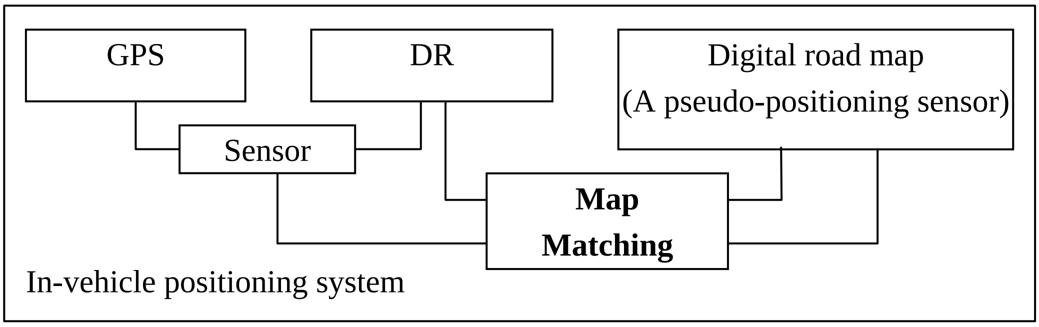


Figure 4-16 The data processing flow

The system should work constantly. This involves three different situations:

1) When GPS is available continuously;
2) When GPS is not available for a moderate period and when GPS is occasionally available; and
3) When GPS is not available for a significant period of time.

GPS signal availability is essential for system initialization when the system starts to work as the DR system needs a reference point. Obviously, the system works well under situation 1. However, situations 2 and 3, especially situation 3, bring challenges for vehicle positioning. When a vehicle is travelling in a dense urban area such as Hong Kong, the system needs to be able to work under situation 3 as GPS positions may not be available for long periods, i.e. more than 15 minutes. The working mode of the system will be pure DR+MM. Then DR is the primary positioning sensor, and the digital road map is used to improve the positioning accuracy. In such a situation, the DR distance scale, bearing bias and drift can only be compensated for by the MM process.

The new proposed integration framework is described in detail in the next chapter.

Chapter 5 A Task-oriented Map-matching Framework

5.1 Basic Structure

A map-matching process can be divided into a number of individual tasks. Based on the analysis of different map-matching algorithms in chapter 3, the map-matching process has been divided into four basic tasks

1). feature extraction,
2). road segment identification,
3). road following, and
4). system reliability and integrity maintenance

When a map-matching process starts, the first task is to identify the road segment taken by the vehicle. This task is called road identification and the selected road is called identified road. Then next task is to determine the location of the vehicle on the identified road segment. This is called road following. Map-matching algorithms require frequent extraction of features (such as turns and intersections) of the road network and vehicle trajectories. For example, the road identification can be done through a feature comparison between a road network and a vehicle trajectory derived from sensor measurements where features from both parties need to be extracted before the comparison. This task is referred to as feature extraction in this paper. Any map-matching process may cause mismatch (when a vehicle is matched to a wrong location in the road network) which may result from poor quality of input vehicle positions and/or map-matching algorithms. Thus, a map-matching method should have the ability to detect blunders in input data and faults in the map-matching process to ensure the performance of the GPS/DR/Map integrated positioning system. Checks of the system integrity and reliability should be built into the whole process of map-matching. The new proposed map-matching framework is divided into four tasks and different functions are applied to each to make it easy to implement and modify. Under this framework, the map matching process is not just an isolated road identification process, but a complete solution for locating vehicles on the digital map.

To start the map matching process, it is assumed that the vehicle is travelling on the road presented in the digital map, the digital road map is accurate and provides all required information (road shape, coordinates, connectivity, turn restrictions, etc.), and GPS positioning is available for the very first initialization of the GPS/DR unit. As mentioned in chapter 2, the GPS/DR unit is designed to record the latest position and bearing of the vehicle in memory when the vehicle stops. Therefore, after the very first initialization, the GPS positioning is not a mandatory requirement for vehicle positioning.

To accomplish the road identification task, not only the similarity or correlation between the vehicle trajectory and the road network and the error estimates of the sensors and the digital road map are considered, but also traffic rules, driving behaviour and other information. A series of simple threshold checks based on these criteria has been developed to evaluate the similarity between each candidate road and the vehicle trajectory. The simplicity of the process is important due to the limited processing power of mounted processing chips and the requirement for real time navigation. The thresholds are determined empirically from analysis of field testing data.

The basic flowchart of the proposed algorithm is illustrated in Figure 5-1. Block A is the pre-map-matching process to check the quality of the digital road map data and sensor data before the map-matching process starts. If the data quality cannot pass the check, the map-matching process will be suspended until reliable sensor data is acquired. Normally, the suspension is not longer than 5 seconds. Block B is to search possible road segments (candidate roads) based on error characteristics of sensor data and then to extract useful positioning information from the possible road segments and the vehicle trajectory. The extracted positioning information is then used to form a series of simple threshold checks to find the most possible road segment in Block C. The vehicle position on the identified road segment is determined in the following

Block D. The correctness of map-matched vehicle positions is checked by using a simple conditional test and curve matching in Block E. Functions in Block A and Block E together ensure the system integrity and reliability.

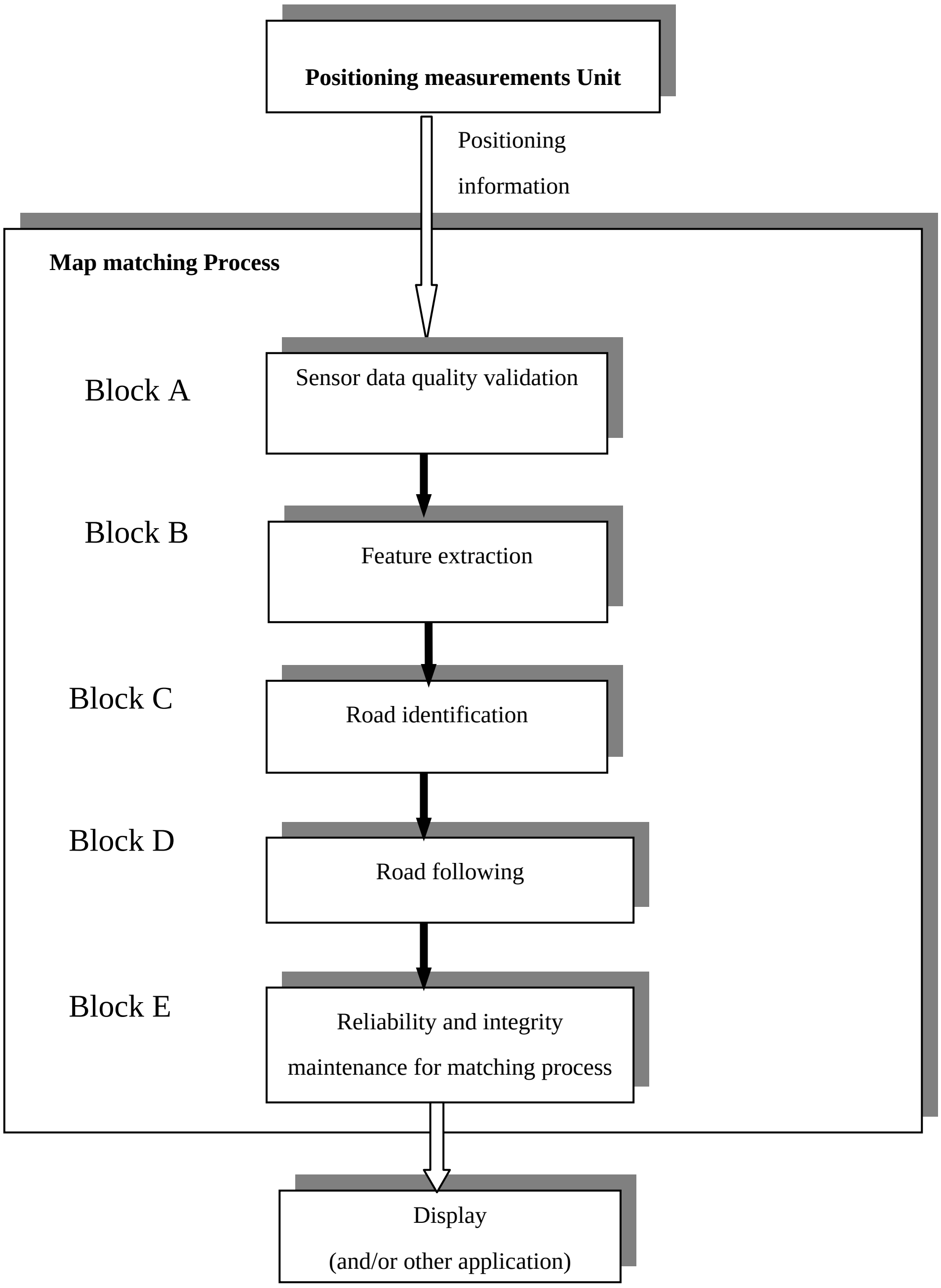


Figure 5-1. The process flowchart of proposed map-matching algorithm

The following sections will give details of the four components of the proposed map-matching method.

5.2 Road Feature Extraction

In the map-matching process, two types of information have commonly been used:

(a) Direct information: position of objects, e.g. roads, intersections, landmarks along roads, and attributes of object, e.g. road width and road class; and

(b) Mined information: neighbourhood and spatial relations

Feature extraction is a procedure for extracting information from the road network and vehicle trajectory.

However, it is neither effective nor necessary to search the whole network to find a match. The search space needs to be narrowed down to a possible region which is a vicinity of the GPS/DR measured position. Such a process is called candidate roads searching in this research. A searching range for selecting possible road segments is set up. If reliable GPS position is available, the searching range of R_S (i.e. 30 meters) is adopted because the accuracy of GPS receiver is 15 meters (RMS). If GPS is not available, the searching radius is set to a multiple of R_S depending on DR drifting rate. Roads fully or partially falling into the possible region are selected as candidate roads for further tests. Figure 5-2 shows that four road segments fall in a possible region of vehicle position measurement P, so these four roads are selected as candidate roads.

If no road falls into the possible region, it means the vehicle is travelling off the known road network. Map-matching can only be applied when a vehicle is travelling on a road network presented in a digital road map. In this case, the position output from the GPS/DR unit will be directly displayed on the map.

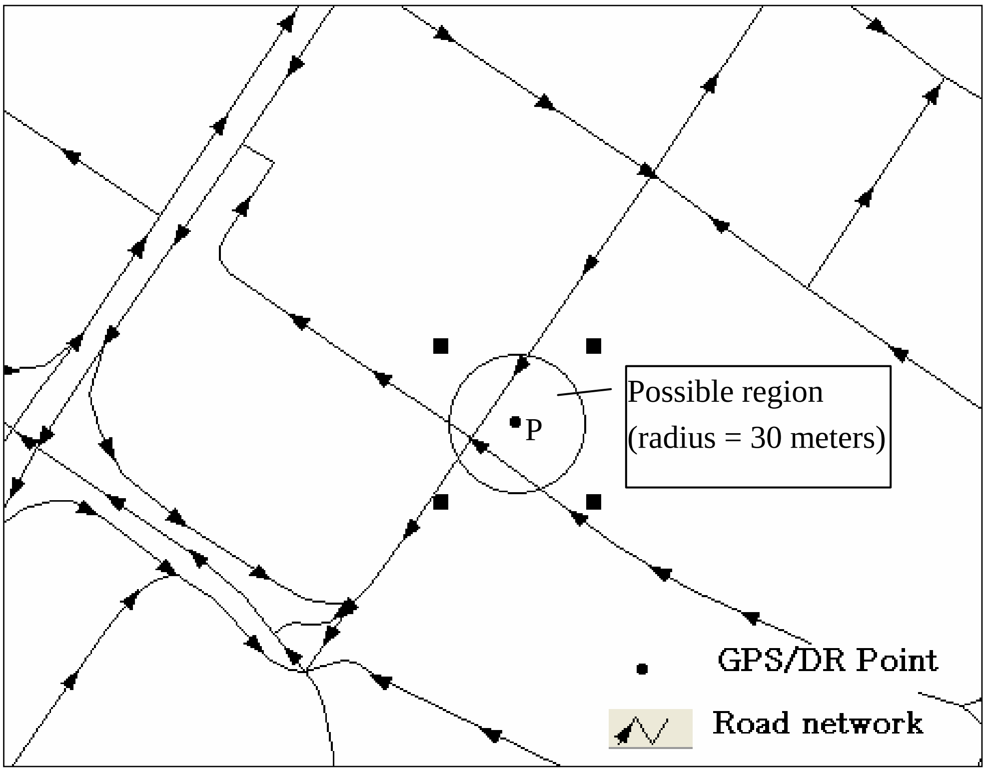
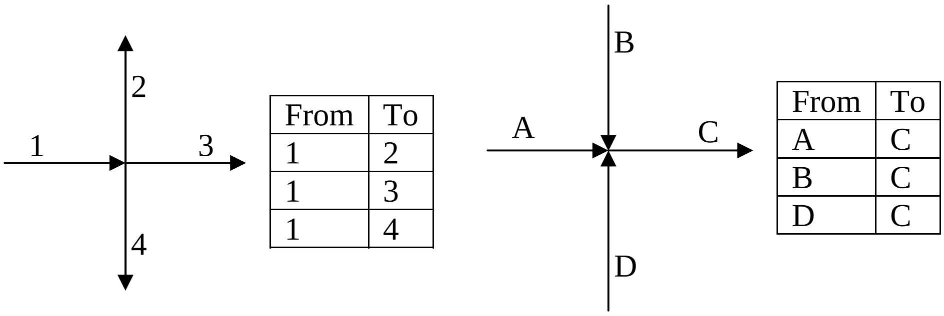


Figure 5-2   Candidate roads selected in possible region

The selected possible road segments and their attributes compose a smaller digital road network. Each segment is a curve composed of arcs, vertexes and nodes (junctions). A special attribute of digital road networks is the turn restrictions at road junctions (see Figure 5-3). The two tables in this figure present the legal turns with road segments. The figure shows that a vehicle is allowed to turn to roads 2, 3, and 4 from road 1 and to road C from roads A, B, and D. Other turns are not allowed in these two cases, i.e. from road A to roads B and D. The benefit of using turn restrictions is to eliminate road segments that are connected at a junction but not accessible from the previous road segment.



From	To
1	2
1	3
1	4

From	To
A	C
B	C
D	C

Figure 5-3 An example of turn restriction

The vehicle trajectory can also be treated as a curve which is approximated by position measurements frequently updated from mounted sensors. Mounted sensors give not only the position measurements of a vehicle but also some other measurements about the vehicle movement including bearing, velocity, and bearing change.

Therefore, in our map-matching method, the following features are used:

1). road connectivity,

2). legal road turns,

3). legal road driving directions,

4). distance between road segments and the vehicle trajectory,

5). curve patterns, e.g. length, corner points, curve direction.

These features are used as multiple criteria to form threshold tests for road identification and integrity and reliability checks., Other information is also useful for map-matching such as road width, road slope, speed limits, and knowledge of driving behaviour. To improve the effectiveness of map-matching, the map database provides a non-planar network which is described in chapter 4. The benefit of this model is to eliminate the cases in which the lines representing roads indicate an intersection of roads while the actual roads do not intersect, i.e. one road flies over another road(s).

5.3 Road Identification

Road identification is the process of finding a road segment that a vehicle is currently travelling on. This is the most important task in the proposed map-matching process which matches the vehicle trajectory to the road network. A match is found if the criteria of maximum similarity are met. In matching, a measure for similarity is required. Such a measure is called matching criterion. The basic idea of the proposed road identification process is to set up threshold-passing tests based on different criteria and then apply the tests to every candidate road. The criteria are formed from the extracted features of candidate roads and the vehicle trajectory, which include the difference between the vehicle bearing and the candidate road direction, distance from the estimated position to candidate roads, the road connectivity, the legal road turn, difference of the change of vehicle bearing and the change of candidate road direction. The thresholds are pre-defined based on the error characteristics of sensors used in this research. *S* parameter is designed based on the matching criteria to determine the identified road. Candidate road segments that cannot pass the tests are eliminated. Among the remained road segments, the one that has the smallest *S* value is considered as the identified road.

There are two cases for road identification. One is the initial step, and the other is at junctions where the vehicle is going to leave a previously determined road segment and enter the next road segment. For these two cases, different criteria are used.

5.3.1 Initial Road Identification

For the initial road identification, no prior road information is available, so the connectivity and turn information is not useful for this step. The helpful information is road direction, legal road driving direction, vehicle bearing and position measurements, and distance between vehicle positions to road. In order to make a reliable identification of road segments, the first road identification will take several consecutive measurements (e.g. data from 5 time epochs) for processing. The following criteria are used for the initial road identification.

- Criterion-1: Difference between vehicle bearing and road direction

The difference between vehicle bearing and road direction, denoted as $\Delta\beta$ and illustrated in Figure 5-4, is a very important criterion for road identification. ‘P_1’ and ‘P_2’ in Figure 5-4 are GPS/DR positions. Roads ‘A’, ‘B’, ‘C’, ‘D’ are candidate roads which fall in the possible region of GPS/DR point ‘P_2’. GPS points, {P1, P2}, are actually on road ‘A’. β is the vehicle bearing measurement at ‘P_2’. It should be noted that the legal driving direction of road is useful for bearing difference calculation. Figure 5-4 shows that road ‘B’ and road ‘C’ are one-way driving roads, and the other two roads are two-way driving roads. Then the direction of road ‘A’ could be 90 or 270 degrees depending on which is closer to the vehicle bearing, but the direction of road ‘B’ could only be 270 degree starting from the y axis. $\Delta\beta$ is the difference between the vehicle bearing at ‘P_2’ and the direction of road ‘A’, and its values range from 0 to 180 degrees.

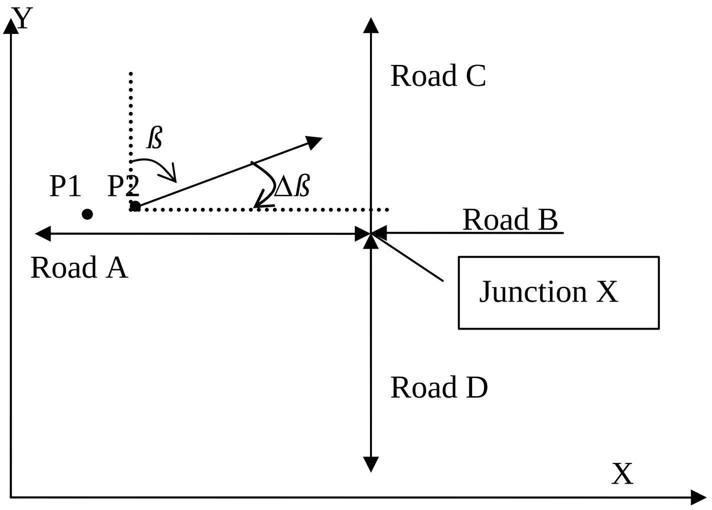


Figure 5-4 $\Delta\beta$ - Difference between vehicle bearing and road direction

For each candidate road, the direction difference test can be set as

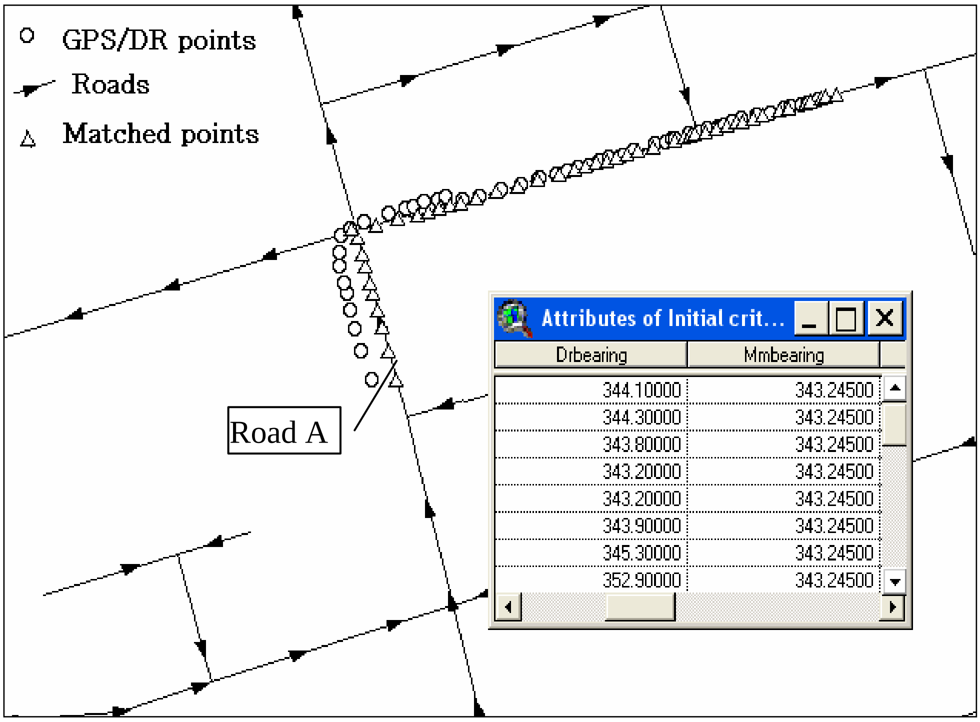
$$H = 0, \text{ if } \Delta\beta \geq Threshold\_H ; \qquad \text{(Eq. 5-1)}$$

$$H = \frac{\Delta\beta}{Threshold\_H}, \text{ if } \Delta\beta < Threshold\_H ; \qquad \text{(Eq. 5-2)}$$

where, $\Delta\beta = \frac{\sum_{i=1}^{n} \Delta\beta_i}{n}$, and $(0 \leqslant \Delta\beta_{i,j} < 180)$; i denotes the time epoch ranging from1 to n. In our experiment, n = 5 is adopted. The *Threshold-H* is set to 30 degree which is the largest error of vehicle bearing measurement of the GPS/DR units used in this research.

If $\Delta\beta$ is larger than or equal to a predefined threshold (Threshold-H), then this road will be eliminated from the candidate roads list. Otherwise, the possibility of the vehicle position measurement (H) on each candidate roads is calculated. As shown in

Figure 5-5, the GPS/DR points are matched to road A. The left column of the table shows the bearing measurements of vehicle and the right column of the table presents the road direction. $\Delta\beta$ between the direction of road A and vehicle bearings in the first five time epochs is about 0.5 degrees which is small enough to pass the threshold test.



Drbearing	Mmbearing
344.10000	343.24500
344.30000	343.24500
343.80000	343.24500
343.20000	343.24500
343.20000	343.24500
343.90000	343.24500
345.30000	343.24500
352.90000	343.24500

Figure 5-5 Example of initial road identification with Criterion-1

- Criterion-2: Distance to road segment

The perpendicular distance (Dp) from the measured vehicle position and a candidate road is very useful information for road identification. Generally, the smaller the distance, the larger the chance that the road segment is the right one. Therefore, for each remaining candidate road after the bearing difference test, the parameter of distance from vehicle positioning measurements to each candidate road (D) is calculated as presented in Equation 5-3.

$$D = \left. \sum_{i=1}^{n} Dp_i / n \middle/ R \right. \qquad \text{(Eq. 5-3)}$$

where, R is the radius of the possible region; i denotes the time epoch ranging from1 to n. In our experiment, n = 5 is adopted.

Then the initial road identification can be performed by using the following method. For each possible candidate road, we calculate a score as

$$S = a * D + b * H \qquad \text{(Eq. 5-4)}$$

where a and b are predefined coefficients. The road segment with distinct smallest S values will be considered as the correct road segment. The coefficients (a and b) can select different values depending on whether GPS is available or not. If GPS is available, then a>>b is used, otherwise, b>>a. When GPS is available, the position measurement is more accurate than the bearing measurement, so the candidate road which has the smallest distance to the position measurement is the identified road. When GPS is not available, the candidate road which has the smallest difference of the direction compared with the vehicle bearing is the identified road.

Figure 5-6 is an example of initial road identification when GPS positioning is available. It is clear that roads “A”, “B”, “C”, and “D” are very close together and have a similar direction within the first five starting time epochs. Road “A” is identified because GPS/DR points are closest to Road “A”.

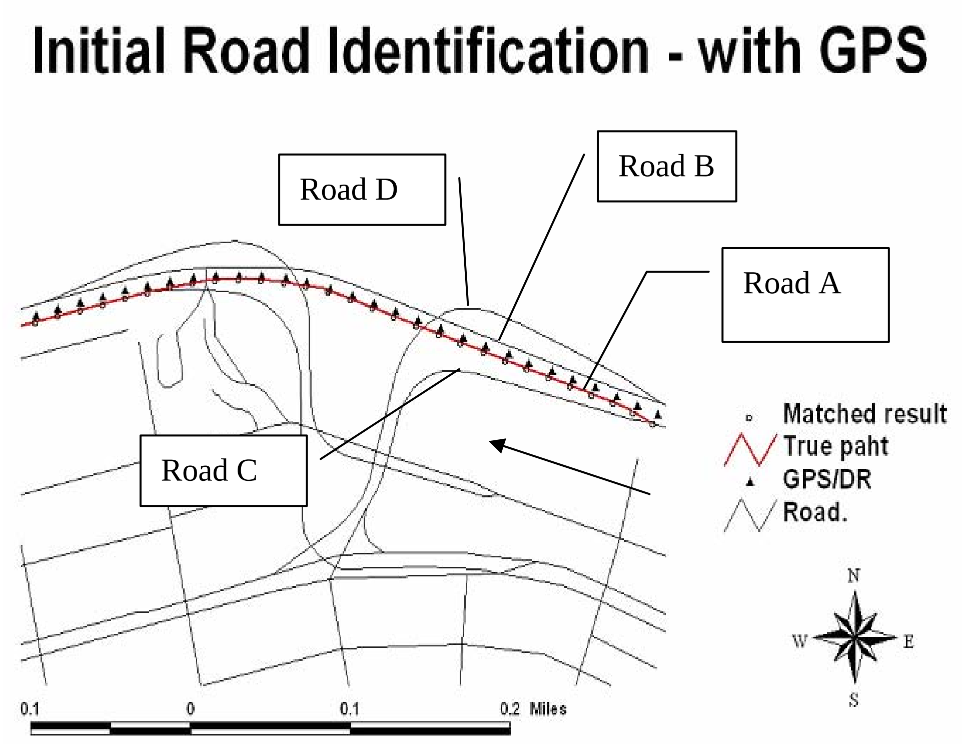


Figure 5-6 Initial road identification – with GPS

Figure 5-7 is an example of initial road identification when GPS positioning is not available. GPS/DR points are in the middle of roads “A” and “B”. As shown in Table 5-1, it is obvious that the bearing measurements have smaller differences to road “A” than to road “B”. Therefore, road “A” is identified.

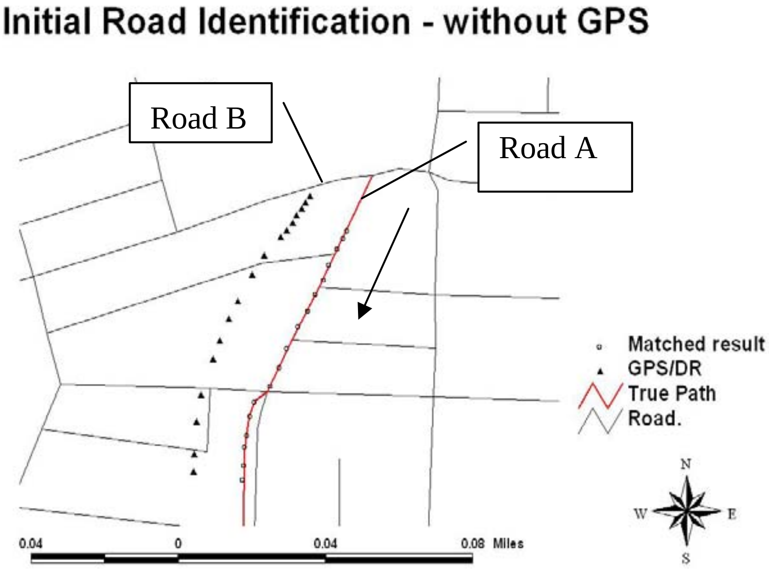


Figure 5-7 Initial road identification – without GPS

The GPS/DR bearing measurements compare with direction of candidate roads.				
Time Epoch	Bearing measurement	GPS availability	Direction of Road A	Direction of Road B
1	208.2	No	208	256
2	207.9	No	208	256
3	209	No	208	256
4	209.5	No	208	256
5	209.6	No	208	256
6	209.4	No	208	256

Table 5-1 Example of initial road identification – without GPS

5.3.2 Road Identification at Junctions

When the vehicle is approaching a junction, it is about to change to another road which is connected to the current one through the approaching junction. When identifying a road segment at the junction, other useful information in addition to the geometric information used in the initial road identification is necessary. In such a case, road connectivity, legal turn at junction, road legal driving direction, distance between candidate roads and vehicle trajectory, bearing, and bearing changes are all useful for road identification. Also, the road is identified with a number of consecutive position measurements (e.g. data from 5 time epochs) for processing to ensure the robustness.

- Criterion-3: Connectivity

The road connectivity test is firstly applied to candidate roads which are selected from the possible region. Roads which share the same junction towards which the vehicle is heading will be kept for further processing and the others will be eliminated from the candidate roads list (see Figure 5-8). When a vehicle is approaching junction A, six road segments fall into the possible region which is centred at the red GPS/DR point with the search range of 30 meters. Out of the six road segments, only roads A, B and C are connected at junction A. Therefore, the other three roads are eliminated from the candidate roads.

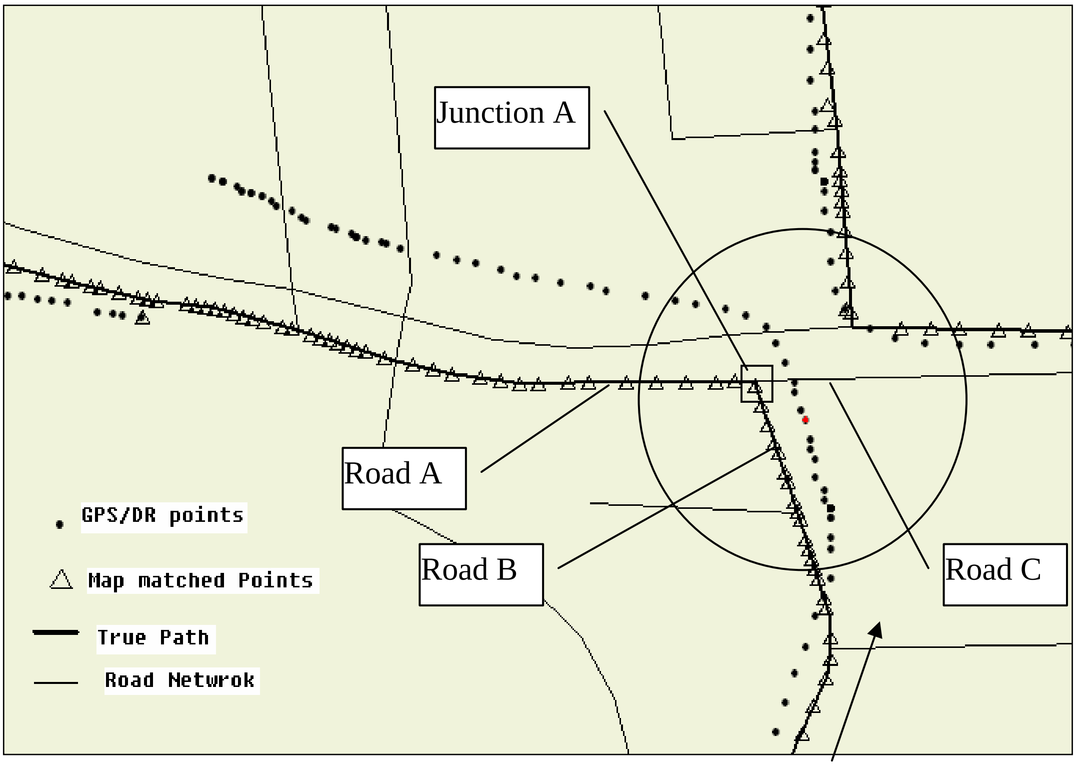


Figure 5-8 Example of road connectivity test

With the accuracy of GPS/DR positions, if there are more than one junction, road segments connected to all road junctions will be considered as the possible candidates. For example, as shown in Figure 5-9, when a vehicle is approaching junction A, fourteen road segments fall into the possible region which is centred at the red GPS/DR point with the search range of 30 meters. However, there are three other junctions (B, C and D) which are only 10 meters away from junction A. In this case, all road segments which are connected to these four junctions will be considered as candidate roads for the next stage in processing.

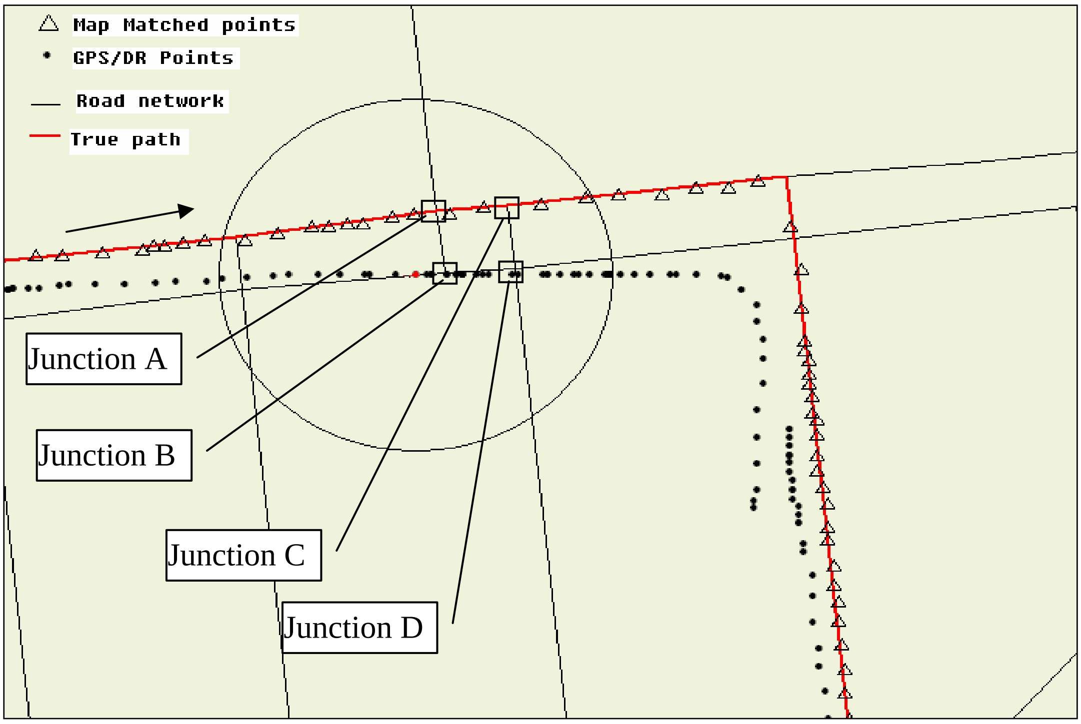


Figure 5-9 Example of road identification at dense junctions

- Criterion-4: Legal possible turn

The vehicle has to follow certain driving rules on the road, such as the legal possible turn shown in Figure 5-3. For each of the candidate roads, if the turn from the current road segment to the candidate is not allowed, then this candidate will be eliminated from the list of candidate roads.

- Criterion-5: Difference of vehicle bearing change and road direction change

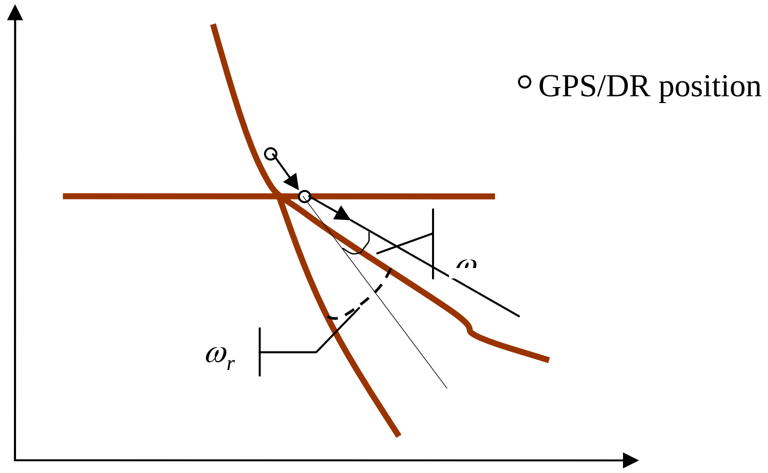


Figure 5-10 $\Delta\omega$ - the difference between vehicle bearing change and road direction change

In Figure 5-10, ω_r is the direction change of the road segments, and ω_c is the bearing change of the vehicle trajectory which is obtained from the gyro. For each candidate road, the bearing change difference test can be designed as

$$W = 0 \text{, if } \Delta\omega \geq Threshold\_W \text{;} \qquad \text{(Eq. 5-5)}$$

$$W = \Delta\omega / Threshold\_W \text{, if } \Delta\omega < Threshold\_W \text{;} \quad \text{(Eq. 5-6)}$$

$$\Delta\omega = \left| \omega_r - \sum_{i=1}^{n} \omega_c \right|$$

where, $\Delta\omega$ is the bearing change difference; i denotes the time epoch from 1 to n. The road direction change obtained from a digital map is sharper than the vehicle bearing change due to the generalization of the road network. Therefore, the road direction change should be compared with the sum of several vehicle bearing changes. The *Threshold-W* is set to 10 degrees which is the largest error of the change of bearing.

In the process of identifying a new road segment at junctions, Criterion-3 and Criterion -4 are applied first to eliminate candidate roads which are not accessible from the current road segment. For the remaining candidate roads, Criterion-1 is applied. The candidate road whose direction has large difference to vehicle bearing will be eliminated. If more than one candidate road remains, then more tests need to be applied to select one road which is most probably taken by the vehicle.

The road identification at a junction can then be performed by using the following method. For each possible candidate road, we calculate a score as

$$S = a * D + c * W \qquad \text{(Eq. 5-7)}$$

where a and c are predefined coefficients. The road segment with distinct smallest S value will be considered as the correct road segment. The coefficients (a and c) can select different values depending on the GPS availability. When GPS is available, a>>c is used because GPS position is reliable and accurate when combined with DR. Otherwise, c>>a is adopted because the gyro is reliable in measuring the change in bearing.

Figure 5-11 illustrates an example of road identification at a junction. When a vehicle is approaching junction P, as junction Q is very close to junction P, road segments connected to both junctions are considered as candidate roads. After applying Criterion-4, only roads A and B are kept as candidate roads. By applying criterion-1, road B is identified. Figure 5-12 illustrates that after applying Criterion-1, two candidate roads, roads A and road B still remain. Therefore, Equation 5-7 is applied, and road A is identified.

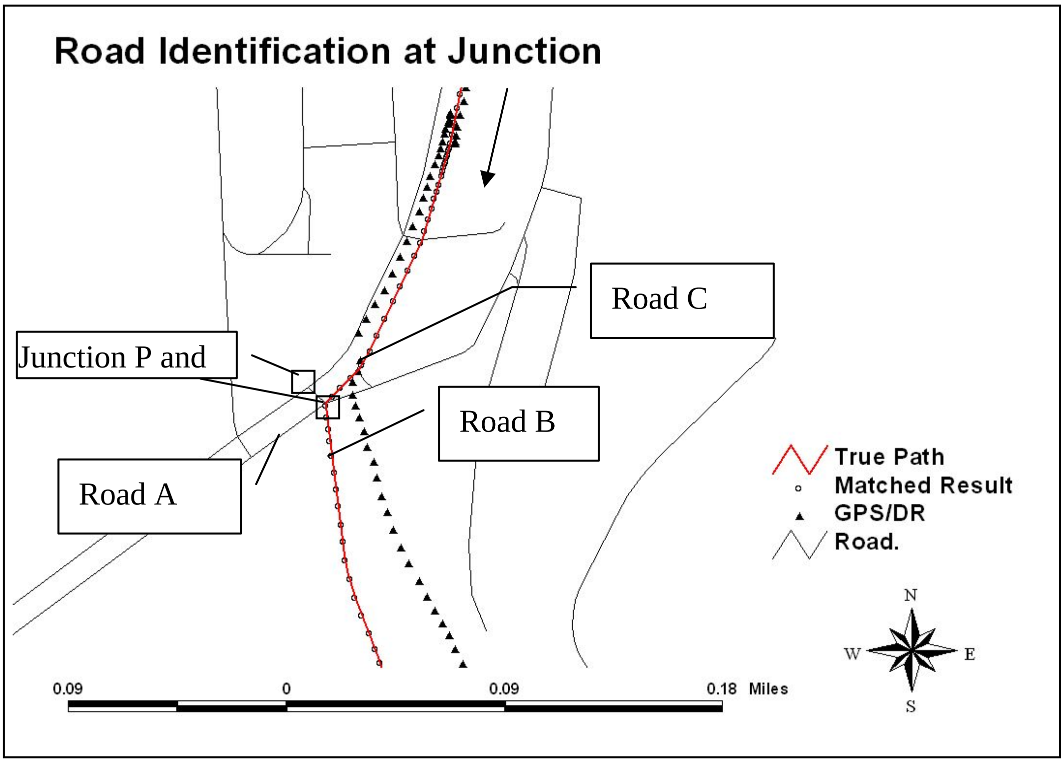


Figure5-11 Example of road identification at junction

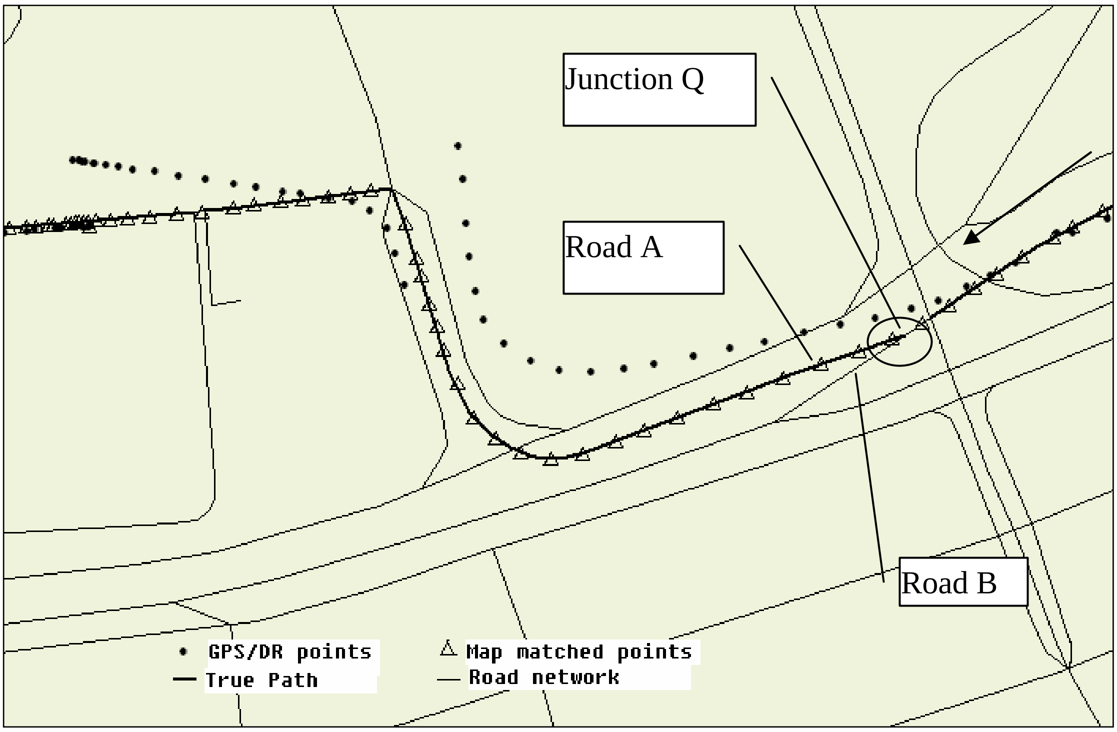


Figure 5-12 Example of road identification using distinct smallest *S*

5.4 Road Following

Road following is the process of determining the location of the vehicle on an identified road segment. After a candidate road is determined, a new position can be obtained from two sources. One is the predicted position based on the vehicle velocity and the road direction and the other is from the measured position projected on the identified road. The final position is obtained by the weighted average of the two solutions, as shown in the following equations:

$$P_r = \begin{pmatrix} X_i \\ Y_i \end{pmatrix} + \begin{pmatrix} V\sin\beta \\ V\cos\beta \end{pmatrix} \qquad \text{(Eq. 5-8)}$$

$$P_p = \begin{pmatrix} X_p \\ Y_p \end{pmatrix} \qquad \text{(Eq. 5-9)}$$

$$\hat{P} = C_1^{-1}(C_1 + C_2)^{-1} P_r + C_2^{-1}(C_1 + C_2)^{-1} P_p \qquad \text{(Eq. 5-10)}$$

where P_p is the projected position measurement and P_r is the predicted position. C_1 and C_2 are the corresponding covariance matrices. (X_i , Y_i) is the last relocated position. V is the vehicle travelling distance from accumulated odometer readings. β is the road direction. If the last relocated position doesn't exist, then $\hat{P} = P_p$.

5.5 System Reliability and Integrity Maintenance

One of the reliability and integrity issues is the integrity of positioning data. If the original positioning data is incorrect, then obtaining a correct vehicle location after data integration is unlikely. Therefore, establishing the integrity of the positioning data is the first step in the map-matching process. Another reliability and integrity issue is in the map-matching process. It would be a serious problem if a vehicle were matched to a wrong road without notice. As a consequence of this mismatch, the positioning function may be totally lost unless reliable GPS is available.

For the first reliability and integrity issue, the measurement quality needs to be verified. The preliminary step is checking the integrity of the sensor measurement. If the vehicle position given by the GPS/DR unit is P(X, Y) and the DR speed measurement is S, then Equation 5-9 should be satisfied:

$$\sqrt{(x_i - x_{i-1})^2 + (y_i - y_{i-1})^2} \approx s \qquad \text{(Eq. 5-11)}$$

where i represents the time epoch, i = 1, 2, … n. The interval between the time epochs is 1 second.

The second step checks the agreement between the sensor output and road network. It means that with the identified road, if the vehicle bearing measurement suddenly develops a large deviation (i.e. >45 degrees) compared with the road direction, then the measurement is considered unreliable and cannot be used in road identification if the vehicle is approaching a junction. As shown in figure 5-13, large GPS positioning errors are detected in places “A” and “B”. Consequently, the data are not used in the road identification, and, negative effects on the final matching result are avoided.

For the second reliability and integrity issue, the reliability check is the procedure which ensures that the vehicle location is correctly matched to the road network map, while the integrity check attempts to identify any mismatch. As the integrity requirements for land vehicle navigation are 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 long periods, and vehicle positions are provided by the DR unit. Even when GPS is available (>4 satellites in view), the positioning error may still be too large due to bad geometry and multipath. If a vehicle location is matched wrongly on the road network, the ensuing process will be completely wrong as DR uses this location to derive the next position unless reliable GPS is obtained again.

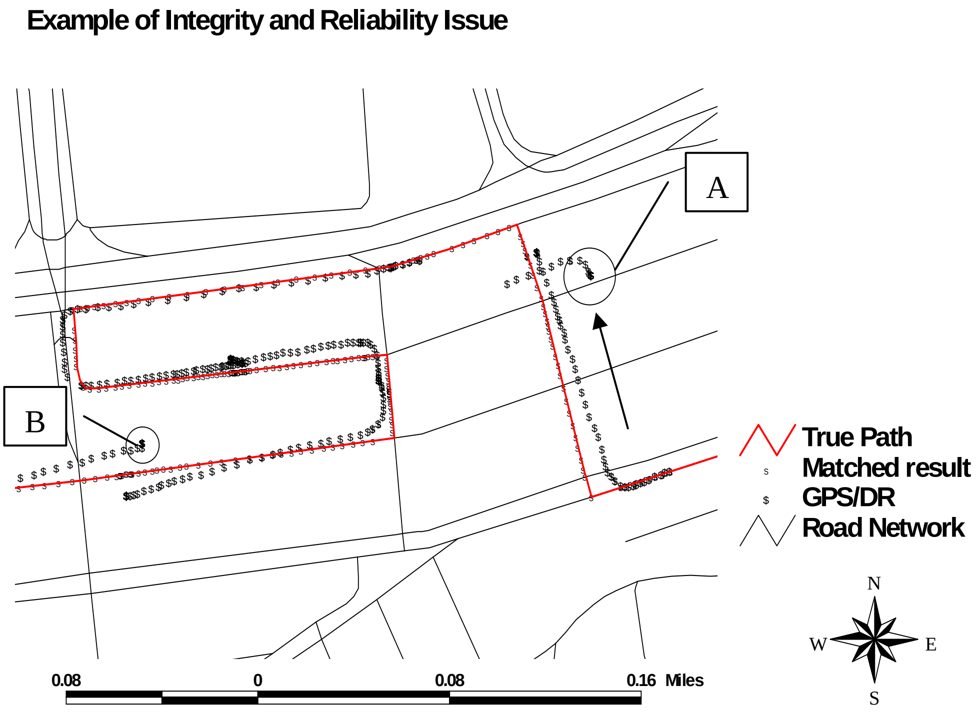


Figure 5-13 Example of Integrity and Reliability of positioning data

In practice, mismatch occurs mostly at junctions and in those situations when more than one road segment can pass the multiple criteria based threshold-passing tests. During the road identification processing, a number of consecutive position measurements (e.g. data from 5 time epochs) are used to find the correct road segments. However, there is still a chance of mismatch occurring.

A simple method referred to as a confidence region test is used here to find out the mismatch. The basic assumption of this method is that the vehicle position should fall into the elliptical error region of sensor measurement. The proposed simple method is to generate an elliptical error region by the calculated error covariance of the position derived from sensors and test if the corresponding map-matched position is inside the region. When a mismatch is detected, a re-initialization process will start to identify the road segment where the vehicle is on. Figure 5-14 illustrates the concept of confidence region test. The elliptical error region is created for each GPS/DR point. At point A, the matched point is outside the corresponding elliptical error region, thus a mismatch is detected.

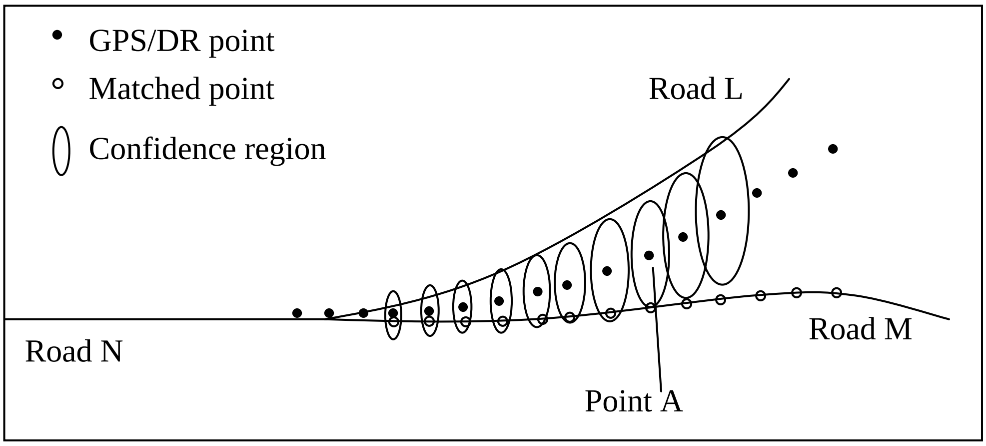


Figure 5-14 Illustration of confidence region test

An example of detecting a mismatch is shown in Figure 5-15. The thick black lines are true path of the travelling vehicle. The solid black dots are GPS/DR points. The cross symbols and hollow circles are map-matching results. The matching goes wrong starting from junction "A" because of two similar roads connected to junction "A". Based on the test derived from Equation 5-5, road A is identified. After applying the confidence region test, mismatch is detected at point Q. Then the ongoing map-matching thread is stopped and a new map-matching thread starts to implement the initial road identification at point "Q" to recover the matching process from mismatch.

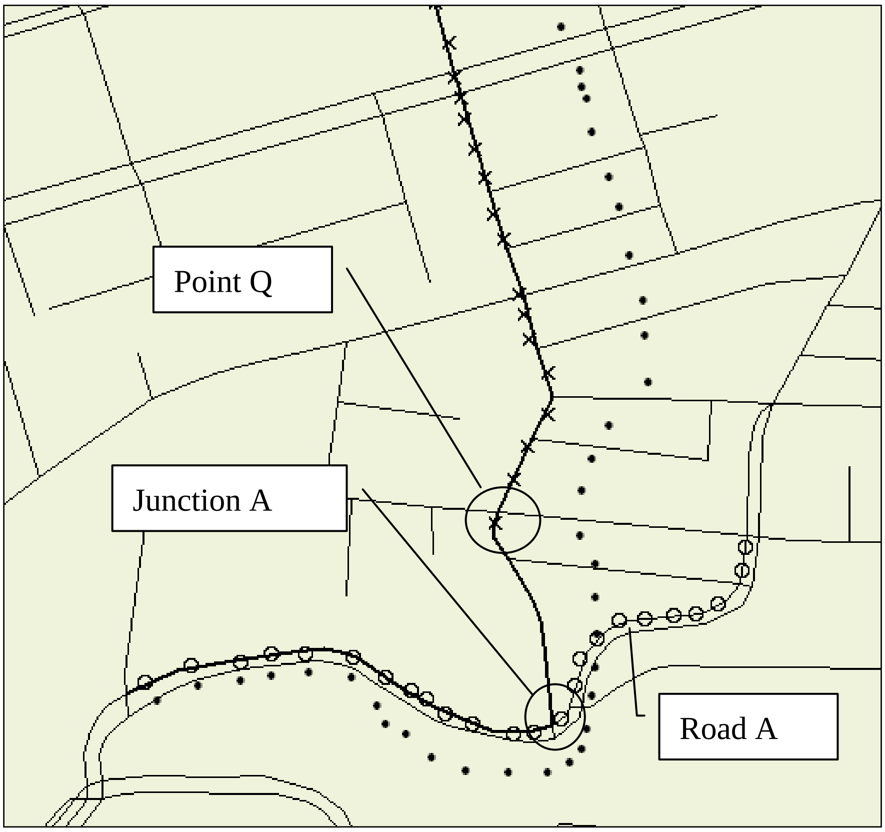


Figure 5-15 Example of integrity and reliability of map-matching process

5.6 Summary

A new map-matching method is introduced in this chapter. It is comprised of 4 main tasks: system feature extraction, road identification, road following and reliability and integrity maintenance. Different algorithms can be used for each task. Road identification is conducted through an easy-to-implement method called threshold-passing tests based on different criteria formed from road and vehicle trajectory features which are geometry information (distance, bearing and bearing change), road connectivity, and traffic rules. Different threshold-passing tests can be applied under different situations. The road and vehicle trajectory features are handled in feature extraction after finding candidate roads in possible region of vehicle location. The vehicle is located on the identified road in the road following process. The system integrity and reliability is ensured by checking quality of sensor data and map-matching results. The thresholds used in the map matching process are based on error behaviours of sensors used in this research. When applying the map matching process with GPS/DR units in places other than Hong Kong, if the GPS/DR sensors are the same type as used in this research, the thresholds do not need to be changed.

This newly developed map-matching method is simple, highly efficient and easy to implement which is important to real time navigation in urban areas with the limited processing power of mounted processing chips.

Chapter 6 Experimental Evaluation of the Task-oriented Map Matching Method

Map-matching, as an efficient method, has been widely applied in car navigation systems to display the location of vehicles on maps [Zhao, 1997]. Various map-matching algorithms have been proposed. Inevitably, the correctness of map-matching is closely related to the accuracy of positioning sensors, such as GPS, Dead Reckoning (DR), and the complexity of road networks and maps, especially in urban areas where GPS signals may constantly be blocked by buildings. Mismatch is an inevitable problem for every map-matching algorithm. In order to improve the quality of map-matching, it is important to better understand the effects of sensor errors and map errors on mismatches. This chapter investigates the performance of the task-oriented map matching technique (see chapter 5) integrated with the GPS/DR units (see chapter 2) in Hong Kong. The analysis is based on the data collected from extensive field tests (over 3100 km of test roads in urban Hong Kong).

6.1 Configuration of Experimental System

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

The map-matching processing is implemented based on the framework proposed in chapter 5. It is a task oriented map matching method. The road identification algorithm is a multiple criteria decision-making process which is described in detail in chapter 5. The candidate roads are searched in the vicinity of position measurement. The search area is defined according to the GPS/DR error. The topological and traffic rule information is used cooperatively with the geometric similarity comparison to select the road segment on which the car is travelling. After the identification of the road, a new position can be obtained from two sources: (1) the predicted position based on the vehicle velocity and the road azimuth and (2) the measured position projected on the identified road. The final position is obtained from the weighted average of the two solutions.

The digital road map used here has been described in chapter 4. A sample map is shown in Figure 6-1. The digital road map 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.

In order to obtain comprehensive understandings of the performance of the map matching processing, the testing areas cover different road conditions including tunnel, high way, narrow street, main transportation road, road to the hill, etc. The total travelling distances of the test are over 3,100 km. Because the GPS blockage and blunder errors are the main problems for vehicle positioning in urban area, the test mainly focuses on the densest and the busiest transport areas in Hong Kong. There are no specific pre-defined testing routes. The vehicle drives randomly like a taxi, sop some roads were repeated many times. In the tests, the map-matching module processes the map data and GPS/DR data in real-time.

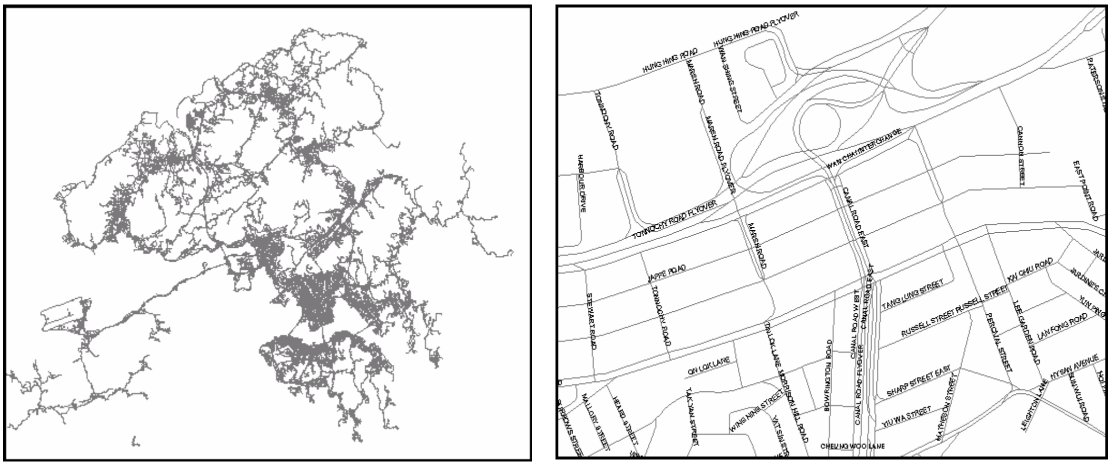


Figure 6-1 Sample of digital road map of Hong Kong used in experiment

6.2 Effects of Sensor Errors and Map Errors on Map Matching Performance

Roads on which vehicle travelled during the experiment are manually recorded in sequence. The centrelines of the recorded roads are taken as the true trajectory of the test vehicle. Vehicle positions which are located to incorrect road segments are considered as mismatches. A mismatch case means a set of consecutive vehicle positions which are located to incorrect road segments.

Through the analysis of the experimental data, a total number of 267 mismatch cases were identified. Then every case of mismatch is examined to identify its exact causes. This analysis revealed the following main reasons for mismatch:

- Map errors, which include missing road features, wrong road attributes, and inappropriate representations of road networks;
- GPS position errors;
- Travelling distance measurement errors, which come from the odometer and planar map;
- Travel bearing measurement errors, which come from the GPS course measurement and the gyroscope;
- Others, the limitation of the road identification procedure and the road following procedure of map matching process.

The percentages of mismatch for different factors are shown in Figure 6-2. It can be seen that 76% of mismatch cases result from positioning sensor errors, while map errors contribute 20% of mismatch cases.

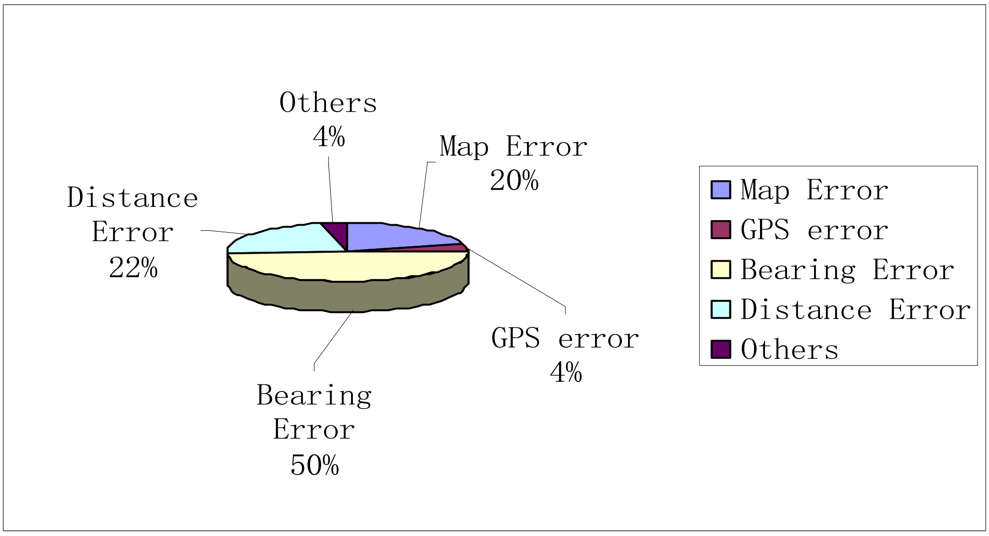


Figure 6-2 The percentage of each mismatch cause

6.2.1 Map Errors

Map errors include missing road features, wrong road attributes, and inappropriate representation of road network.

Missing road features are the result of map databases for example not including newly-built roads. Consequently, the map-matching module could not find the road to match the GPS/DR positions on the map. Figure 6-3 shows the mismatch resulting from the absence of a newly-built road.

In our map-matching algorithm, we used information on legal turns, one way streets, and restricted access as constraint factors. Errors of such information can also cause mismatch. In the tests, most of the mismatch cases were due to incorrect information regarding legal turns. For example, a car turned into a new road segment, and the turn was classified as illegal according to the database information. As a result, the map-matching process could not find the correct road segment to match GPS/DR position on the map (as shown in Figure 6-4).

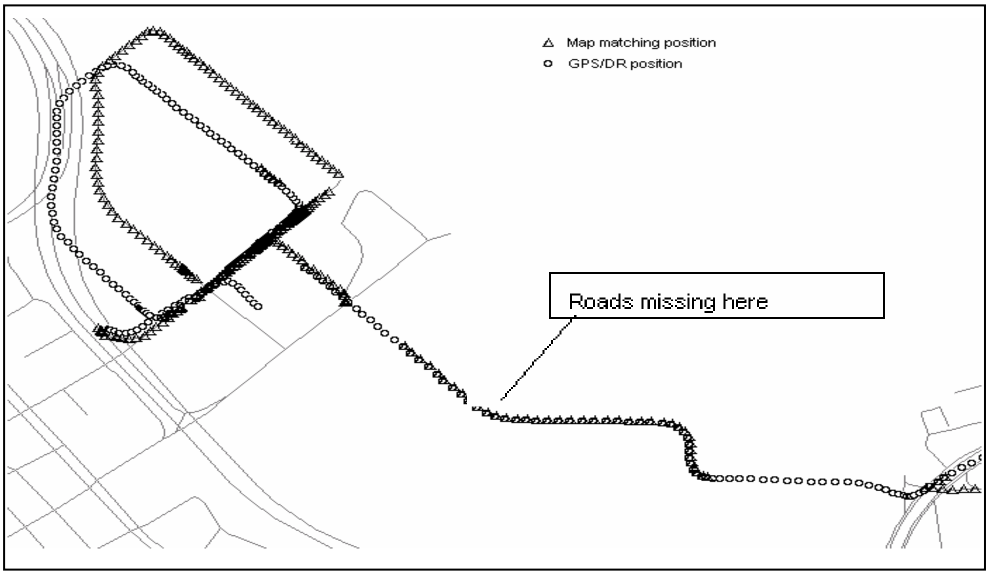


Figure 6-3 Example of missing road feature

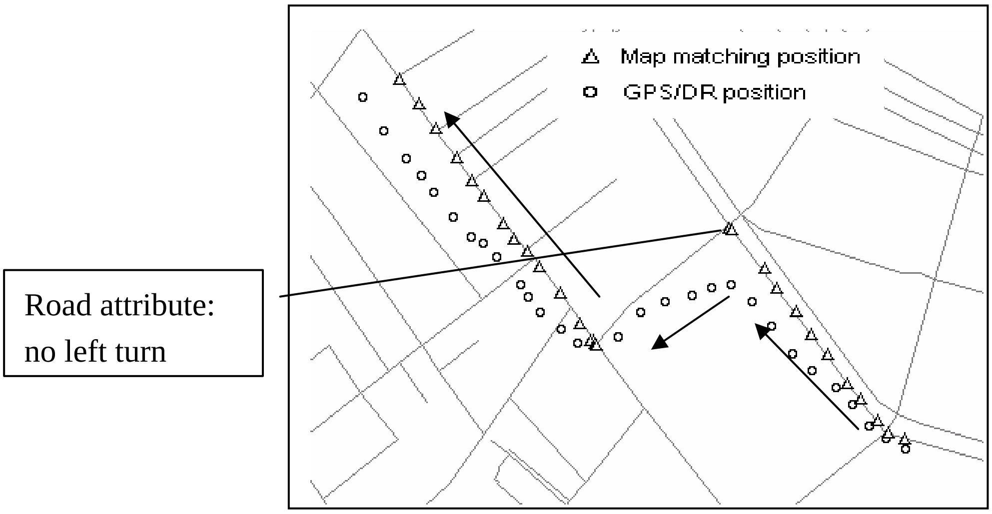


Figure 6-4 Example of wrong road attributes

In the digital map of Hong Kong used in this research, the representation of road networks is multi-centreline based. The complicated road network is represented in the form of multiple centrelines. Each lane is represented by a centreline and is considered as an isolated road. In Hong Kong, most of the roads are narrow, and the distances between the centrelines of lanes are mostly less than 20 meters and the accuracy of the GPS/DR system is not high enough to distinguish between lanes. In these situations, the map-matching process cannot identify which road segment the car is taking until the car takes a turn to another road, because lanes are parallel, similar and too close to each other. When the car turns to another road segment, only one lane is connected to it. Therefore if the car is located on other lanes, the new road segment is not connected and the car is forbidden to turn. One such cases given in Figure 6-5.

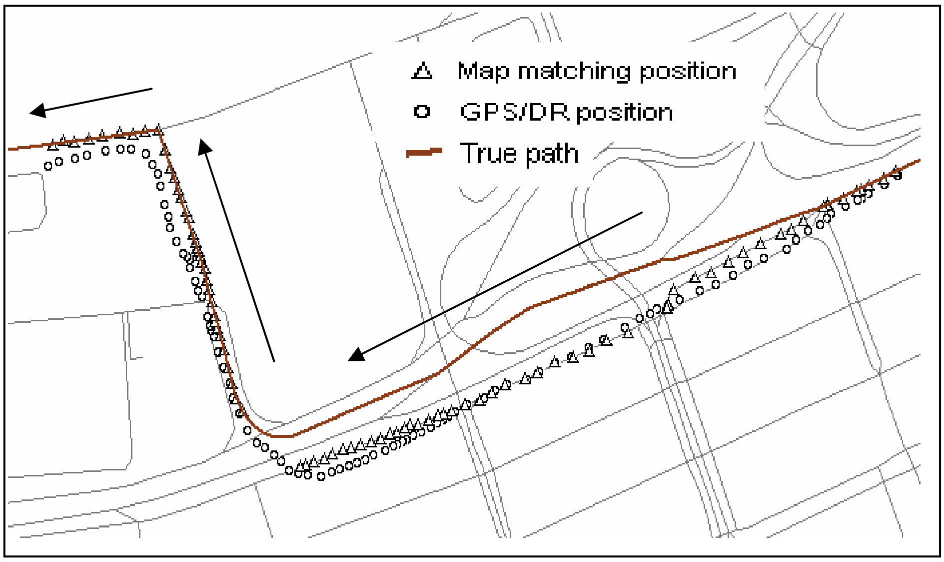


Figure 6-5 Mismatch caused by multi-centreline representation

6.2.2 GPS Position Error

Over the last two decades, GPS has been widely used in navigation due to its high accuracy, global coverage and low price. Satirapod et al. (2001) report that GPS positioning accuracy is normally within 10 meters (RMS) without the Selective Availability (SA). However, the GPS satellite visibility is severely reduced in urban areas because the high-rise buildings block the GPS signal. For example, in Central Hong Kong, a business and banking area where full of skyscrapers, only 20% of this area can receive signals from 3 or more satellites [Chao et al., 2001]. Moreover, the strong multipath effects and weak satellite geometry in cities make GPS very difficult to use. In our tests, large GPS errors happened in narrow streets, roads along mountains or the tall buildings with glass walls. The average GPS error in such environment is 27 meters, and the largest ones can reach over 100 m.

In the testing navigation system, a GPS receiver is integrated with a DR unit to overcome the GPS coverage problem. 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 bad GPS positions, we set up stringent criteria to check the quality of GPS positions, such as checking PDOP, SNR, numbers of satellites, and agreement of GPS and DR on relative positions. With this method, most bad GPS positions can be eliminated.

However, if GPS errors appear to be a near constant bias, it is difficult to remove them, especially at times when GPS signals are just recaptured by the receiver after a loss of lock for a significant time period. The remaining GPS position errors contribute 4% of mismatch cases in this evaluation experiment. Figure 6-6 shows one such case. In this case, there were no GPS positions up to point M and then a GPS position was then obtained at point M, but biased with about 110 meters to point N. The bias is caused by multipath effects as roads shown in the figure are surrounded by tall buildings with grass walls. As GPS is considered as a reliable position to calibrate DR errors, the position estimate from the integrated system jumps to point N. After that, GPS signals were lost again and DR system was used to provide positions, with point N as the reference. That, inevitably, caused a mismatch, until a new GPS position was available at point L.

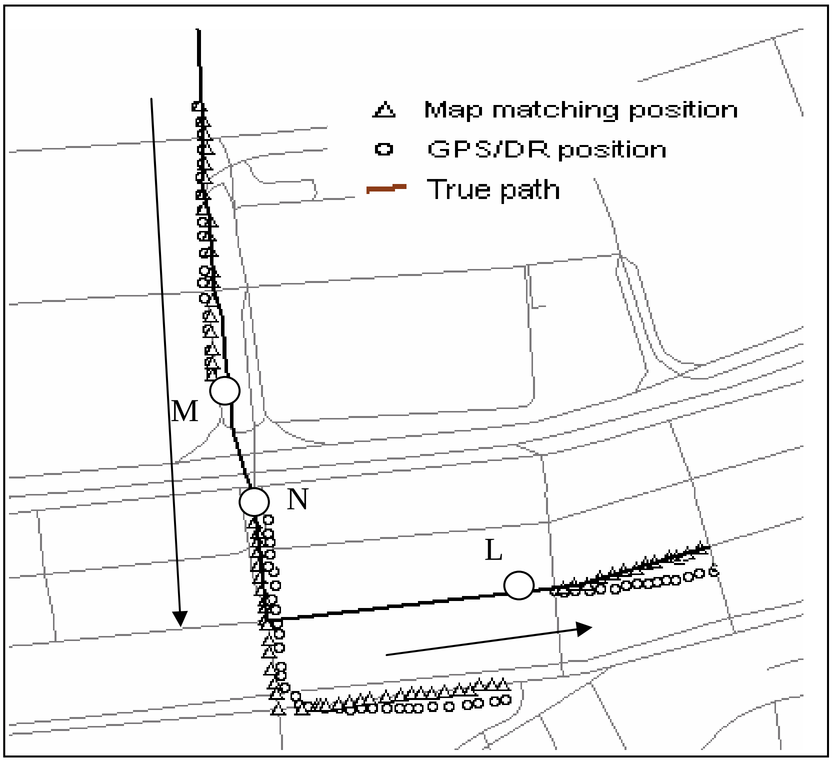


Figure 6-6 Mismatch caused by GPS multipath errors

6.2.3 Travelling 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 mismatch cases are caused by distance errors. Distance errors mainly come from two sources: the speed sensor and the map.

An odometer sensor counts the number of revolutions of the vehicle’s wheels, which can be converted to a travel distance through 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 slipping and skidding, tire pressure variation, tire wear, and vehicle speed. If left uncompensated, the scale-factor error will accumulate rapidly, causing a significant positional error. Though we can use GPS positions or corresponding corners between the car trajectory and the 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 is accumulated over 20 m, it is difficult to distinguish two or more turns that are close (i.e. <40 meters) to each other. Figures 6-7 and 6-8 show one case of the mismatch caused by inaccurate distance measurements. Figure 6-7 illustrates the true vehicle 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 the streets close to each other. Consequently the car locations are matched to the wrong roads (Figure 6-8).

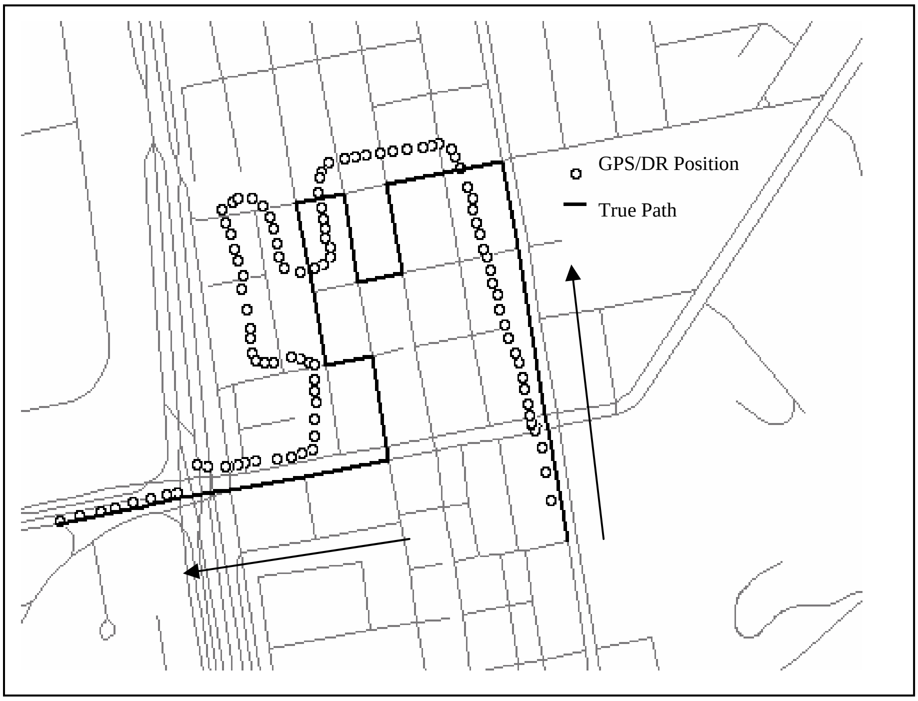


Figure 6-7 Mismatch caused by error of distance measurements

(vehicle trajectory and its true travelling path)

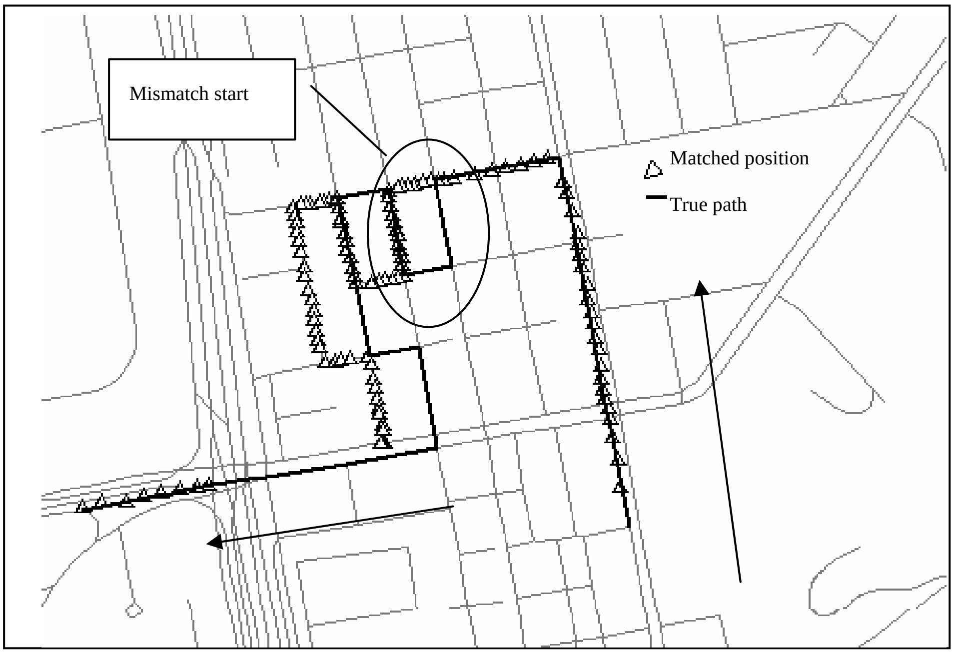


Figure 6-8 Mismatch caused by error of distance measurements

(incorrect match results)

There are two more problems related to distance/road length which may cause a mismatch. One is the difference between the actual road length and the road length from a digital map. The digital map is a planar map, so the actual lengths of roads are longer than the lengths derived from the map, especially for those roads which have slopes. This means the distance measurement is longer than the road segment on the map. The other problem arises as a result of the zigzag movement of the car. Cars do not always move straight along the road centreline. In many map-matching algorithms, in order to reduce the bearing error effects, the car movement is constrained to the road centreline as a one-dimensional movement to eliminate the cross-track noise. However, it is difficult to recognize whether the erratic car trajectory results from an actual zigzag movement or from a bearing measurement noise. Thus, determining the car location on a given road will be a problem, which can affect the matching processing at road intersections.

6.2.4 Travel bearing measurement errors

The bearing of the vehicle is provided by a gyro and GPS. The GPS course is used to estimate the initial direction of travel. Then a gyro is used to measure the relative direction changes. If the GPS course is wrong, the DR bearing will definitely go wrong which may cause a mismatch. In order to obtain reliable information about the initial bearing, our experiments show we need to drive the car on a straight road in an open area for at least 50 meters. This may not be possible in urban environments. Similar to the odometer sensors, gyroscopes suffer from error accumulation due to the gyro bias and scale-factor instability. Due to cost restriction, low quality gyros are normally used for car navigation systems. For Murata ENV 05 gyro, the linearity of output is reasonably good. However, the variation of the gyro bias is large, and temperature-sensitive.

We examined the bearing errors of our experimental system by comparing the gyro output with the turning angles on the map. The analysis shows that the average accumulated bearing error is 3.56 degrees, with a standard deviation of 27.34 degrees. The largest accumulated bearing error can reach up to 50 degrees. The bearing errors can cause a mismatch when there are multiple exits at road intersections, such as fork-shape roads. As there are many intersections in cities, bearing errors cause most mismatches (50% of all cases in our experiments). Figure 6-9 shows a typical mismatch case at a fork-shape junction. At the junction, the angle between roads A and B is about 20 degrees; the gyro cannot distinguish these two roads and the route is matched to the wrong one. This mismatch error can only be corrected when a new GPS position comes or a significant route feature difference appears between roads A and B.

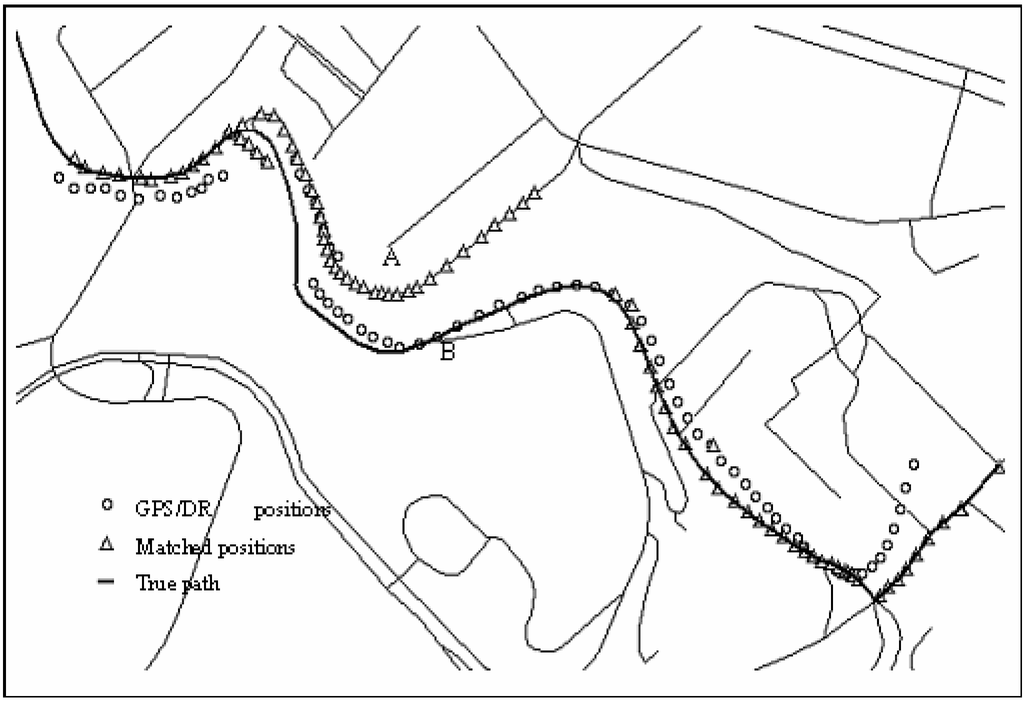


Figure 6-9 Mismatch occurred in fork-shape roads

6.3 Discussion on Improvement of Map-matching Method

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

When it comes to the map database, the main problems are wrong information about traffic rules, missing road segments and multiple centreline representations of multiple lanes of the same road segment. The multiple centreline representations are important for vehicle guidance as in cities the vehicle needs to be in the right lane in advance in order to turn into the next road segment. However, as the positioning system is not able to distinguish lanes, for map-matching purpose, the road network needs to be simplified and each road segment should be 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 temporally changed and to update such information is difficult. Actually, land vehicle navigation systems can not only locate the vehicle and provide guidance to driver, but also be used to update the digital map database.

In urban environments, GPS coverage is low and GPS positioning errors can be very large due to multipath and weak satellite geometry. However, the accuracy of the current car navigation grade DR system is not sufficient, if used without GPS calibration. If a bad GPS position is used to provide the reference point for DR, the estimated car position will be inaccurate and this will cause mismatches. In this study, we have applied different criteria to check the quality of GPS positions, but we find in a number of cases bad GPS data were still left undetected because GPS errors appear to be a near constant bias.

The DR system with GPS calibration is the main positioning sensor in our system. However, DR position errors drift very quickly if there is no GPS. The odometer errors are a few percentage of the travelling distance. If, for example, an odometer error of 5%, results in a 20 meter error over a distance of 400 meters, this may cause a mismatch in the city environment. The distance error is contributed to not only by the odometer, but also by the map and car trajectories. Including road slope information in the map database can reduce some of the errors. Most mismatches are caused by the bearing errors, especially the gyro bias. As the gyro bias is affected by temperature, adding temperature compensation can reduce part of the errors. Another way to monitor the change in the gyro bias is to examine the gyro output when a vehicle is stationary, as the angle velocity of the car is zero in this case. Also, as the accuracy of a map is much higher than DR positions, the map coordinates and directions of road segments can be used to calibrate DR errors.

Test results also reveal that most of the mismatch cases occurred at junctions where a vehicle leaves the current road for the next. Therefore, extra attention should be paid to junctions, especially roads with similar patterns connected together. Methods for automatic mismatch detection need to be developed to improve the system integrity and reliability, which will be presented in the next chapter.

Chapter 7 Improvement of System performance on Integrity

This chapter focuses on the process of improving the performance of our system in terms of its integrity, a significant requirement of any positioning system. Due to sensor and map errors, it is impossible to locate a vehicle on a map with 100% accuracy. Therefore, it is important for a positioning system to have the ability to detect and recover from mismatches. Such ability is called system integrity. To enhance the integrity of a system, first of all, it is necessary to develop a new method to detect automatically and recover from a mismatch by comparing matching results and sensor-derived data in addition to conducting the simple confidence region test described in chapter 5 because the simple confidence region test sometimes fails to detect the mismatch when the positioning error is large. Secondly, it is important to reduce the risk of mismatches, which can be done by increasing the accuracy of positioning sensors based on the analysis of the effects of sensor and map errors on map-matching.

7.1 Curve Pattern Matching for Map Matching Results Validation

Based on the analysis presented in the last chapter, mismatches occur most frequently at junctions as a vehicle changes to another road through junctions. Therefore, the process of map matching results validation is to validate the map-matching results and to determine from which junction the mismatch starts.

Due to the error nature of GPS and DR, the curve of the vehicle trajectory generated by the integrated GPS/DR unit is normally similar to the curve of the driving route derived from a digital road map even if GPS is unavailable. Figure 7-1 demonstrates the error of GPS/DR positioning compared with the true driving route. It reveals that the GPS/DR trajectory is drifting from the road but the curve of GPS/DR trajectory is similar to the curve of the true driving route. If the map-matched positions are correct, the curve formed from map-matched positions should be similar to the curve of the true driving route. Thus the curve formed from map-matched positions can be fitted to the corresponding curve of GPS/DR trajectory by applying a similarity transformation. Consequently, the validation problem of the map-matching process can be transferred into a problem of planar curve matching and dealing with junctions (points).

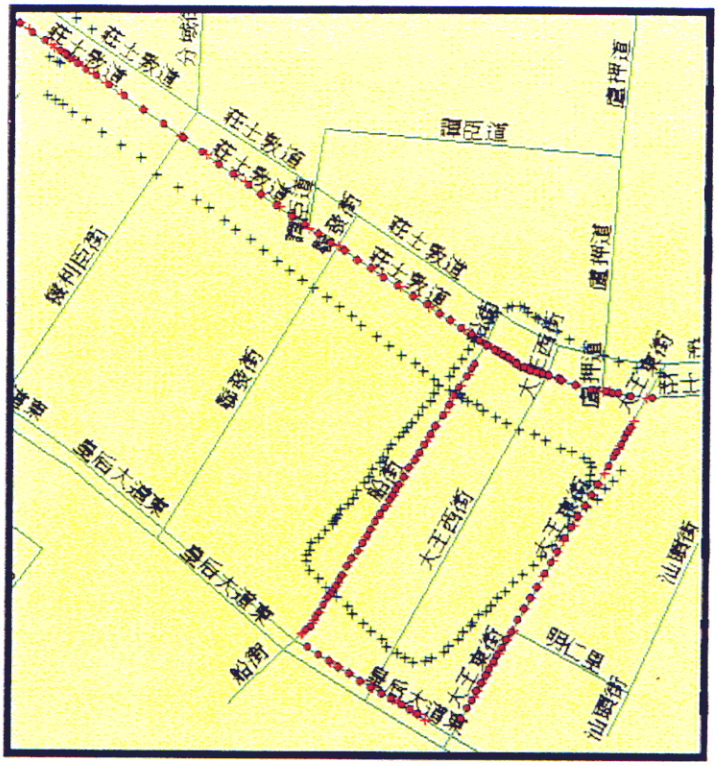


Figure 7-1 Errors of GPS/DR positioning compared with the true driving route

7.1.1 Planar Curve Matching

Planar curve matching means to establish corresponding relations between curves. Many commonly used curve matching algorithms are based on invariant-features *[Pickaz and Dinstein, 1995]*. Invariant features are points on the curve, e.g. inflection points, which are invariant to the relevant transformations. Feature-based approaches need sufficient feature points and a reliable extraction of features. If the extracted feature points hold sufficient information, then the problem of curve matching is reduced to a problem of point matching.

As our problem is defined as planar curve matching and deals with junctions (points), a feature-based approach is chosen in this study. Critical points of a curve are important features which include its maxima, minima, discontinuities in curvature, end points, points of inflection, and points of tangency. Different critical point detection algorithms have been developed which are reviewed in Rattarangsi and Chin, (1992) and Li, (1995). To maintain the fidelity of the original curve with less computing time, which is the requirement of the limited processing power of on-board processors, a local maxima and minima method is adopted *[Li, 1988]* in this study.

7.1.2 Local Maxima and Minima Method of Critical Point Detection

The principle of this method is to identify the points with local maxima and minima. Figure 7-2 presents a curve with several critical points. According to the method, points “a” and “c” that have maximum and minimum values, respectively, are first located within the local coordinate system XY, where line “12” is the X axis and the Y axis is perpendicular to the X axis. Then the original curve is decomposed into three sub-curves “1a”, “ac” and “c2”. For each sub-curve, a new local coordinate system is set up. For example, for sub-curve “c2”, line “c2” is the X axis and the Y axis is perpendicular to the X axis. Then for each curve, new local maxima and minima can be selected.

The procedure can be repeated until a predefined criterion is met. The criterion used in this study is the Y coordinate of the point with local maxima and minima in its local coordinate system. If the Y coordinate of the point detected is smaller than a threshold, the procedure stops.

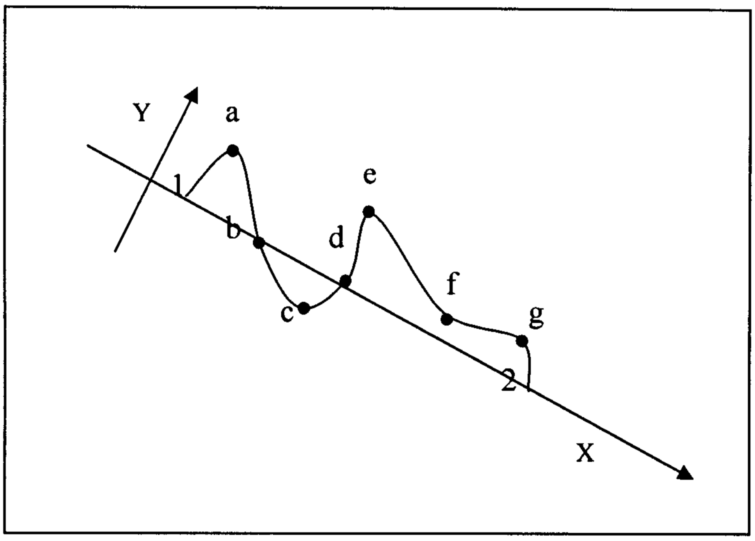


Figure 7-2 Local maxima and minima method of critical point detection

7.1.3 Mismatch Detection through Pattern Matching

After applying the map-matching algorithm (see chapter 5) for real time determination of the vehicle position on map, sensor measurements and the map-matched positions are recorded for further processing. The whole procedure can be divided into four steps:

1) Curve segmentation
2) Critical point detection

3) Invariant value calculation

4) Validation

Curve segmentation is the procedure for determining the size of a curve for processing, because a small size will cause a curve without an obvious pattern while a large size will prolong the computation time. In this research, a path curve with four turns is sufficient for curve matching in the majority of cases. For simplicity, the turn can be determined by the angles between recorded roads and a turn is considered for further processing if the angle is smaller than 135 degrees. Figure 7-3 is an example of a pair of similar curves. For curve MN, the first processing sub-curve ML is from turn 1 to turn 4, and the next successive sub-curve 1K will be from turn 2 to turn 5.

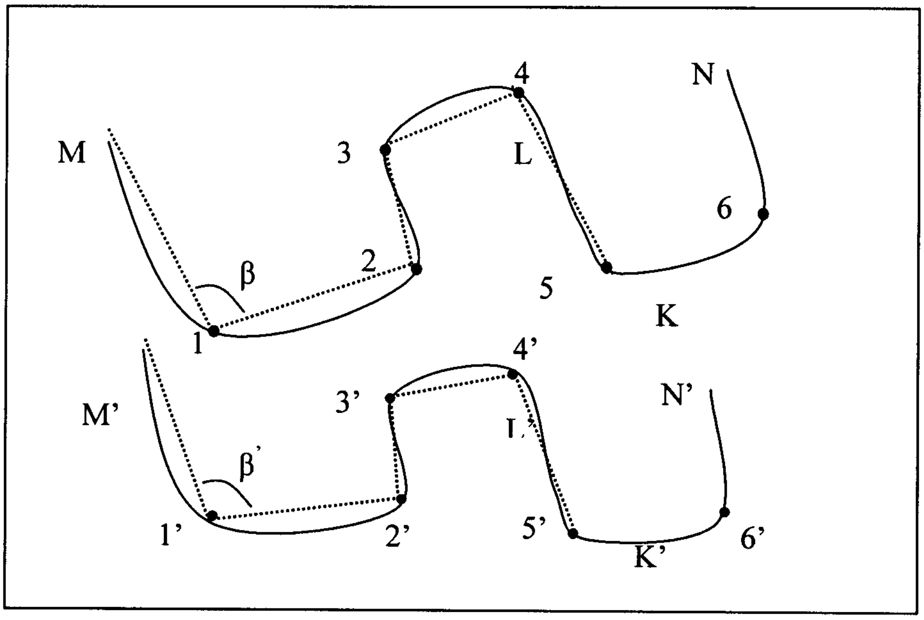


Figure 7-3 Invariant feature of curve

Then the mentioned critical point detection method is applied to identify all critical points for curves derived from both the GPS/DR data and the map-matched positions. For example, the critical points of curve ML are points 1, 2, 3 and 4, and accordingly curve ML is divided into 5 arcs (M1, 12, 23, 34, 4L) by these four critical points. The invariant features with similarity transformation are the angle of arcs (β) and the ratio of arc-length ($R_{arc} = {D_i}/{D_{i+1}}$), where D is arc length of an arc, e.g. arc M1 and i is the sequence number of the arc in a curve. For two similar curves, their corresponding values of R_{arc} and β should be similar.

After calculating each pair of ratios of arc-length and angles of arcs, their values are compared individually. If there is an obvious difference between a pair of corresponding values, it is considered a mismatch and the last road junction is taken as the starting point of the mismatch because mismatches normally occur at junctions. The road identification task of the proposed map-matching processing is then applied again at this junction.

7.1.4 Mismatch Recovery through Pattern Matching

After detecting a mismatch and identifying its location, in order to recover the map-matching from the mismatch, the road identification task of our map-matching algorithm is re-applied from the identified mismatch junction. According to the previous analysis, when a mismatch occurs, there are normally two or more similar roads, which have similar scores and connect to the junction. Therefore, to recover from the mismatch, during road identification processing, all other similar roads should be considered. As more data are available now, to identify a candidate road can be identified more reliably. After road re-identification, road following is applied to determine the vehicle position along the identified road.

Field testing shows that with the map-matching described in chapter 5, vehicles can be located on the right road most of the time, even with long period GPS signal blockage. However, mismatches are inevitable as described in chapter 6. Without a post-validation, the positioning system may not be aware of the mismatch by applying the confidence region test because the GPS/DR positions with errors could appear closer to incorrect road segments. Furthermore, even if the mismatch is found, the mismatch location cannot be identified. For example, in Figure 7-4, the triangle symbols represent recovered map-matching results, the cross symbols are map-matching results before validation, and the circle dots are GPS/DR points. The thick line represents the true trajectory of the test vehicle. Three small rectangles represent Turn 4 on three curves, the true trajectory, the matched path without validation, and the GPS/DR trajectory. At Turn 4, the mismatched points (represented as cross symbol) are still within the confidence region generated by corresponding GPS/DR points. Therefore, the mismatch cannot be detected by the simple confidence region test. By applying the curve pattern matching method, a mismatch is detected after Turn 4 and junction A was also determined as the place where the mismatch started. Applying the road identification task at junction A, the correct road segment was identified to recover the map-matching process from the error.

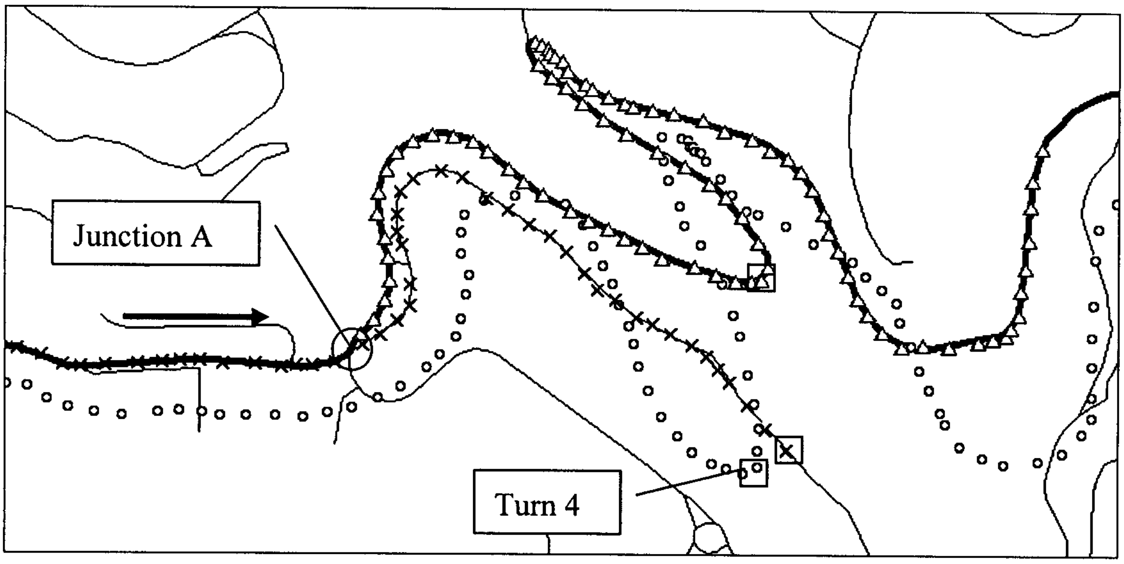


Figure 7-4 Example 1 of mismatch detection and recovery

Figure 7-5 is another example from field testing data. The test vehicle was located to the wrong road which had the smallest designed *S* value in road identification. The green circle dots are map-matching results before the validating process. The position was firstly matched on the wrong road after junction A. With curve matching to validate the map-matching result, the mismatch was found even without the GPS positioning signal. The start of the mismatch was detected in junction A. Then the road identification task was re-applied from junction A and all connected roads excluding the current selected one were evaluated to find the correct road.

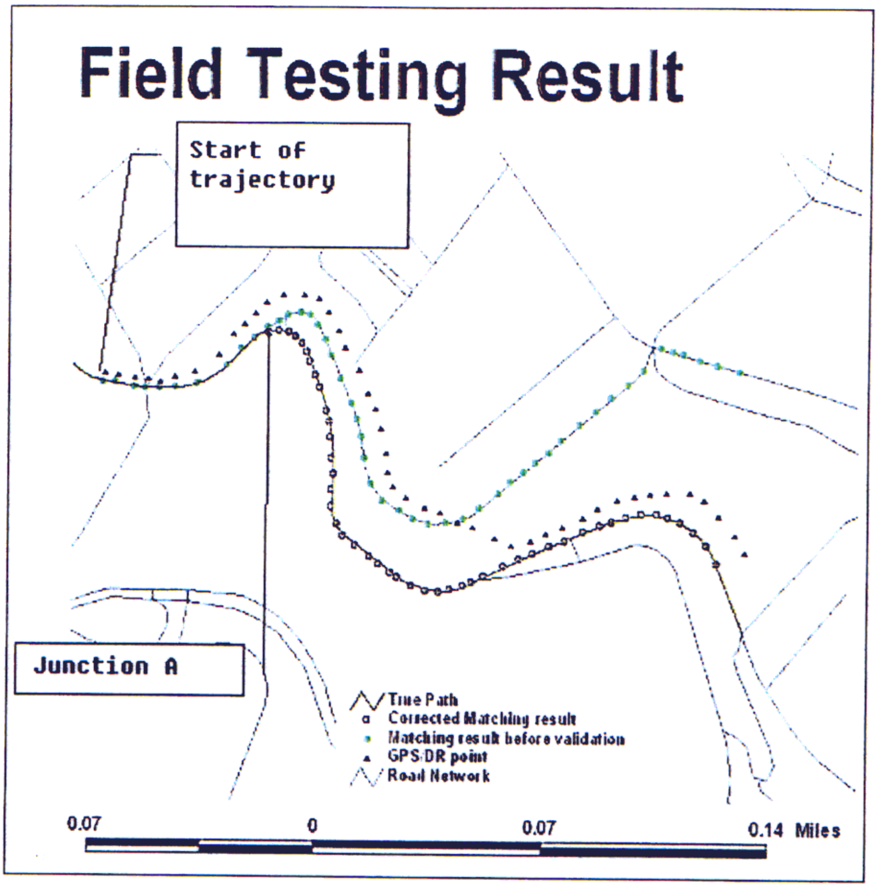


Figure 7-5 Example 2 of mismatch detection and recovery

This method is very useful when a vehicle is travelling along mountains or in city centres in which roads are complex curves. In addition to the simple confidence region test described in chapter 5, applying the post-validation based on curve pattern can further enhance the ability of error alert of the vehicle positioning system, hence to improve the system integrity. However, it is still difficult to identify mismatches in real time.

7.2 Correction Feedback for DR Calibration

7.2.1 Feedback Filter for DR Calibration

The testing data reveal that the accuracy of DR sensors plays a dominant role in successful vehicle positioning and affects map-matching results more than other factors. How to improve the quality of the DR system without using frequent GPS updates is a crucial issue for urban navigation. Digital maps have higher accuracy than DR sensors; therefore, map-matching results, if they are correct, can be used to calibrate DR drifting error. There are different ways to correct DR error. One way is to input map-matching results to a Kalman filter to estimate DR sensor errors based on DR sensor error models. The other way is to simply correct DR errors by giving new initial positions and directions. By frequently updating new initial positions from map-matching results, DR position errors can be constrained to a reasonably small level.

When using map-matching results for DR calibration, one key issue is that the matching results must be correct and reliable. If incorrect matching results are used to calibrate the DR, a fatal positioning error will occur. Another problem that should be noted is that it is not suitable to correct the bearing error by giving a new starting direction when the vehicle is making a turn, because the current vehicle bearing is obviously different to the previous vehicle bearing, and it cannot be approximated by using the previous bearing. For example, the vehicle bearing is 30 degrees at time t-1 (P_{t-1}), and becomes 50 degrees at time t (P_t), so it is not appropriate to give 30 degrees as a new starting angle to the DR at time t.

The correctness of map-matching results can be first examined by the curve matching process described in this chapter. If the previous matching results are wrong, then it is clear that the current matching result is wrong as well. After the previous matching results are proved correct, the current matching result will be evaluated. The criteria for current matching result evaluation are:

1) There should not be uncertainty for the road identification. That means only one road can pass threshold tests based on multiple criteria with a significant low *S* value. It can be expressed as

   $C_1 = 1/N$; where N is the number of roads passing criteria-testing

2) The angle of the road should agree with the vehicle bearing to a certain extent. It can be described as:

   $C_2 = 1$, if $\Delta\theta <$ Bearing-threshold, otherwise, $C_2 = 0$;

$$\Delta\theta = \frac{1}{n}\sum_{i=1}^{n}\left|\theta_i - v_i\right|$$

where $\Delta\theta$ is the average difference between road angle θ and vehicle bearing v; i is the time epoch; n is the number of sampling times.

For a moving vehicle, we need to make certain that the vehicle is not turning so that we can use the reliable map-matching result to correct the DR sensors. Based on the analysis of the test data, the following criteria are considered:

3) The selected road segment should be a straight road segment where the vehicle is unlikely to make a turn on the road. It can be expressed as:

C_3= 1, if ω>angle-threshold2, otherwise, C_3= 0;

$$\omega = \sum_{i=1}^{n} \beta_i$$

where β is the angle change between two consecutive parts of the road segment; n is the number of parts.

4) The selected road segment is long enough and the vehicle is travelling in the middle of the road, so that the vehicle is unlikely to make any turn in a short time. It can be expressed as:

C_4= 1, if $L >$ road-length-threshold and $D < L/2$, otherwise, C_4= 0;

where L is the length of the road and D is the distance from the current vehicle position to the start of the road.

5) Even if the above criteria are all met, however the vehicle might still make a turn due to the change of lanes or other phenomena. It is necessary to check the vehicle movement before performing the calibration because when the vehicle turns for any unpredicted reason, it normally accelerates and makes a quick small turn. This criterion can be expressed as:

$$C_5 = 1, \text{ if } f \times g = 1, \text{ otherwise, } C_5 = 0;$$

$$f = 1, \text{ if } \frac{1}{n-1}\left|\sum_{i=1}^{n}(\theta_{i+1} - \theta_i)\right| < heading\_change\_threshold; \text{ else, } f = 0$$

$$g = 1, \text{ if } \frac{1}{n-1}\left|\sum_{i=1}^{n}(V_{i+1} - V_i)\right| < Velocity\_threshold; \text{ else, } g = 0$$

where i is the time epoch, θ is the vehicle bearing and V is the vehicle velocity.

All these criteria can be used to set up a filter for the correction feedback to DR. This filter can then be defined as:

$$F = C_1 \times C_2 \times C_3 \times C_4 \times C_5$$

If F = 1, then the matching result is reliable and will be fed back to the GPS/DR unit to calibrate it. The thresholds used in the feedback filter are empirical values based on field data analysis.

7.2.2 Improvement of System Performance with Correction Feedback

After the validation, the map-matching results that pass the feedback filter can be used to correct DR sensors. Field tests have shown that with correction feedback from map-matching, DR can be frequently calibrated in addition to correction from GPS. The drifting error of DR is well controlled through re-initialization. Accordingly, the higher accuracy of DR position can also improve the map-matching process and the performance of the entire navigation system.

For example, in Figure 7-6, GPS positions are not available within the data set. However, at points L, M and N, the DR errors are corrected by using map-matching results, especially at point M where the DR position drifts from the true position for about 120 meters.

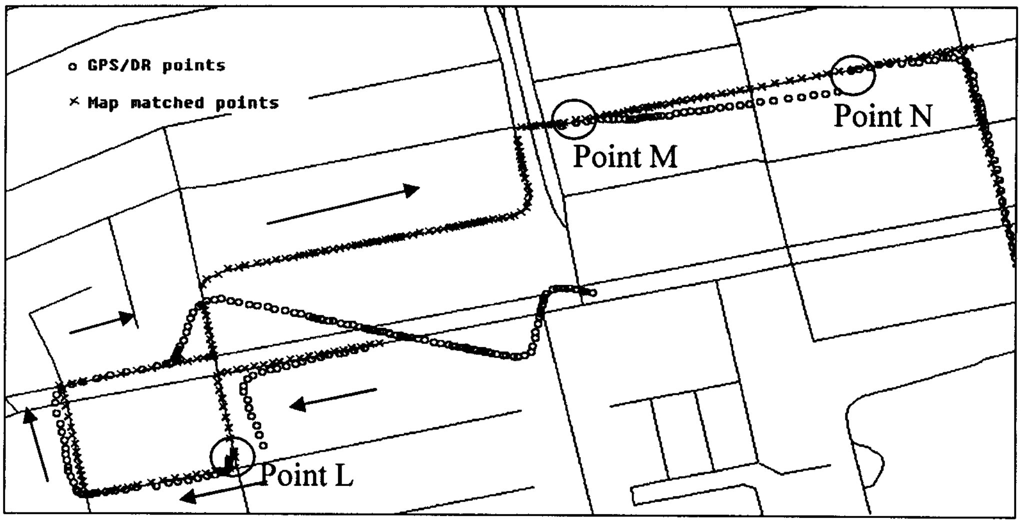


Figure 7-6 DR calibration by using map-matching results

The improved DR accuracy also reduces the chance of a mismatch. A test example is given in Figure 7-7 and Figure 7-8. Figure 7-7 shows the map-matched vehicle position in an urban area without any correction control, while Figure 7-8 shows the vehicle position derived from the newly developed GPS/DR/Digital Map integration through a feedback filter. From this example, we can see how the correction feedback method improves the positioning.

In Figure 7-7, the yellow line represents the true path that the vehicle travelled. The green dots represent the map-matched vehicle positions, and the blue dots represent the GPS/DR unit given vehicle positions. We can see that without any feedback, the DR error increased when GPS was not available. As the DR given vehicle track is closer to Johnston Road and the vehicle bearing is also similar to the direction of Johnston road, the map-matching process matched the vehicle location to Johnston road while the vehicle was travelling on Hennessy Road from the junction of Hennessy road and Johnston road.

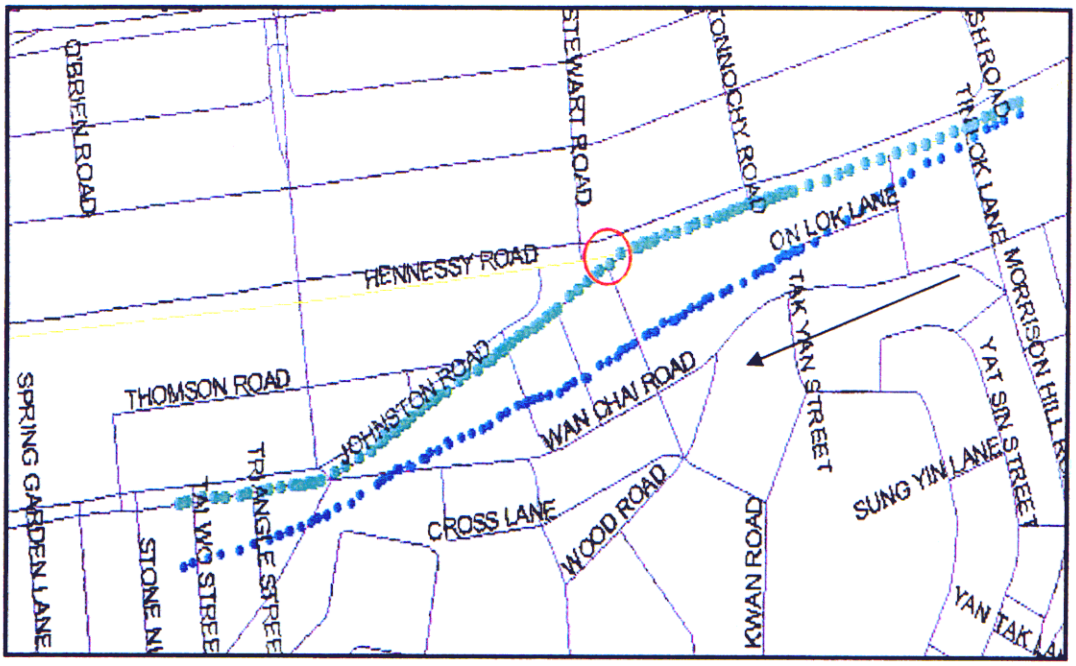


Figure 7-7 Map-matching result without correction feedback

In Figure 7-8, the yellow line represents the true path that the vehicle travelled. The blue dots represent the map-matched vehicle positions, and the green dots represent the GPS/DR unit given vehicle positions. Now, we can see that with feedback, the map-matched vehicle positions are exactly on the true path. In place of red circles, the map-matching process gives reliable and correct vehicle position and bearing, and they all pass the filter to be used to calibrate the DR. After calibration, mismatch in the junction of Hennessy road and Johnston road is avoided because the vehicle track given by DR has been drawn back near the true path.

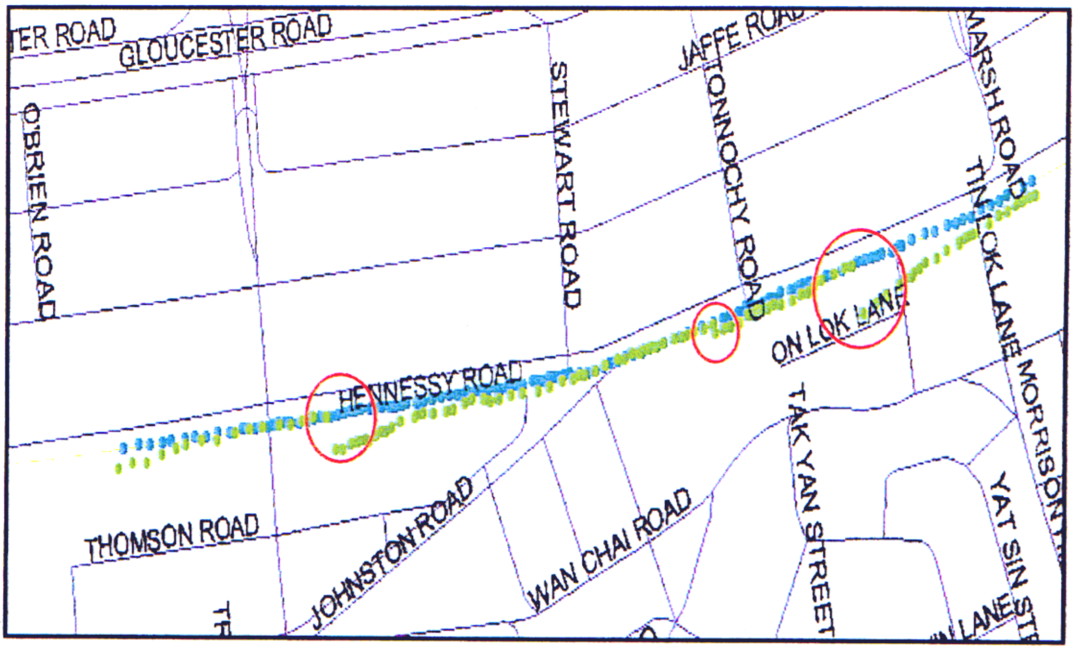


Figure 7-8 Map-matching result with correction feedback

The correction feedback can improve the performance of the vehicle navigation unit. In particular, the improved DR accuracy increases the map-matching performance on the road junctions.

Chapter 8 Performance Analysis of Integrated Vehicle Navigation System

A vehicle navigation system has been developed which integrates GPS/DR and digital maps under a new integration framework proposed in chapter 5. By implementing the map-matching algorithm described in chapters 5 and 7, the integrated vehicle navigation system overcomes the problem in urban areas where GPS is frequently blocked for substantial periods of time. The new prototype system has been extensively tested in Hong Kong. The testing area covers most of the road network in Hong Kong and focuses on the central area of Hong Kong.

8.1 Experimental Navigation Prototype System

The prototype system consists of a DR, a GPS receiver, a Bluetooth beacon, a digital road network map, and a map-matching processing unit. The configuration of the system used in the experiment is illustrated in Figure 8-1. Unlike other GPS/DR navigation systems, this experimental navigation system is tightly integrated with a digital road map by feeding map-matching results back to the positioning unit to calibrate DR errors.

The author has developed the integration framework and the map matching algorithm, and also implemented the map matching process software, while her colleagues built the hardware and sensor fusion part.

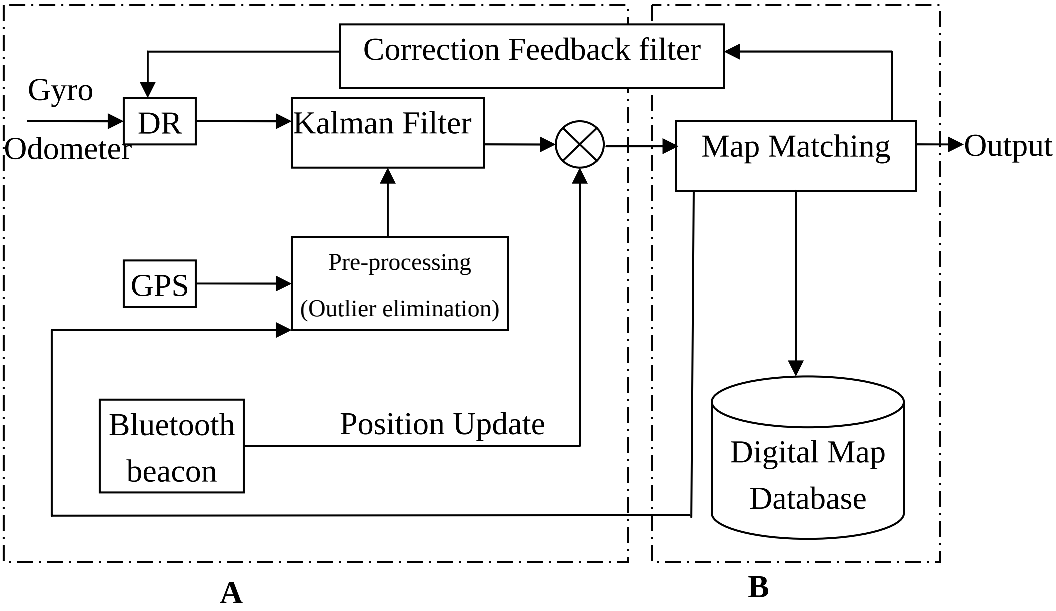


Figure 8-1 The new integrated navigation system prototype

There are a few conditions to be met so that the experimental system can work properly. Firstly, it requires reliable and accurate GPS position for the very first initialization of the system. Secondly, it requires driving the test vehicle for a known distance to calculate the odometer scale factor of the test vehicle. The accuracy of the digital map should be higher than the sensor accuracy and with information that is used in the map matching process. Although a Bluetooth beacon sensor is used in the experimental prototype system it has not been tested because the roadside Bluetooth beacons were generally not available in Hong Kong at that moment.

8.2 Data Processing Flowchart

The real-time map-matching algorithm implemented in the system is the task-oriented multiple criteria decision making map-matching (enhanced system integrity and mismatch reduction) described in chapters 5 and 7. The basic processing flowchart is illustrated in Figure 8-2.

Firstly, the quality of sensor data (from both GPS and DR) will be examined. Then, all the possible candidate roads are selected based on the quality of sensor data, and road features from all candidates are extracted. Road identification and road following processes are then carried out based on the multiple criteria tests. Even if all the tests are passed, the system still validates the results through a reliability and integrity check. Then the position matched on the map will be output. Meanwhile, the feedback filter checks if this position/bearing should be used for DR calibration.

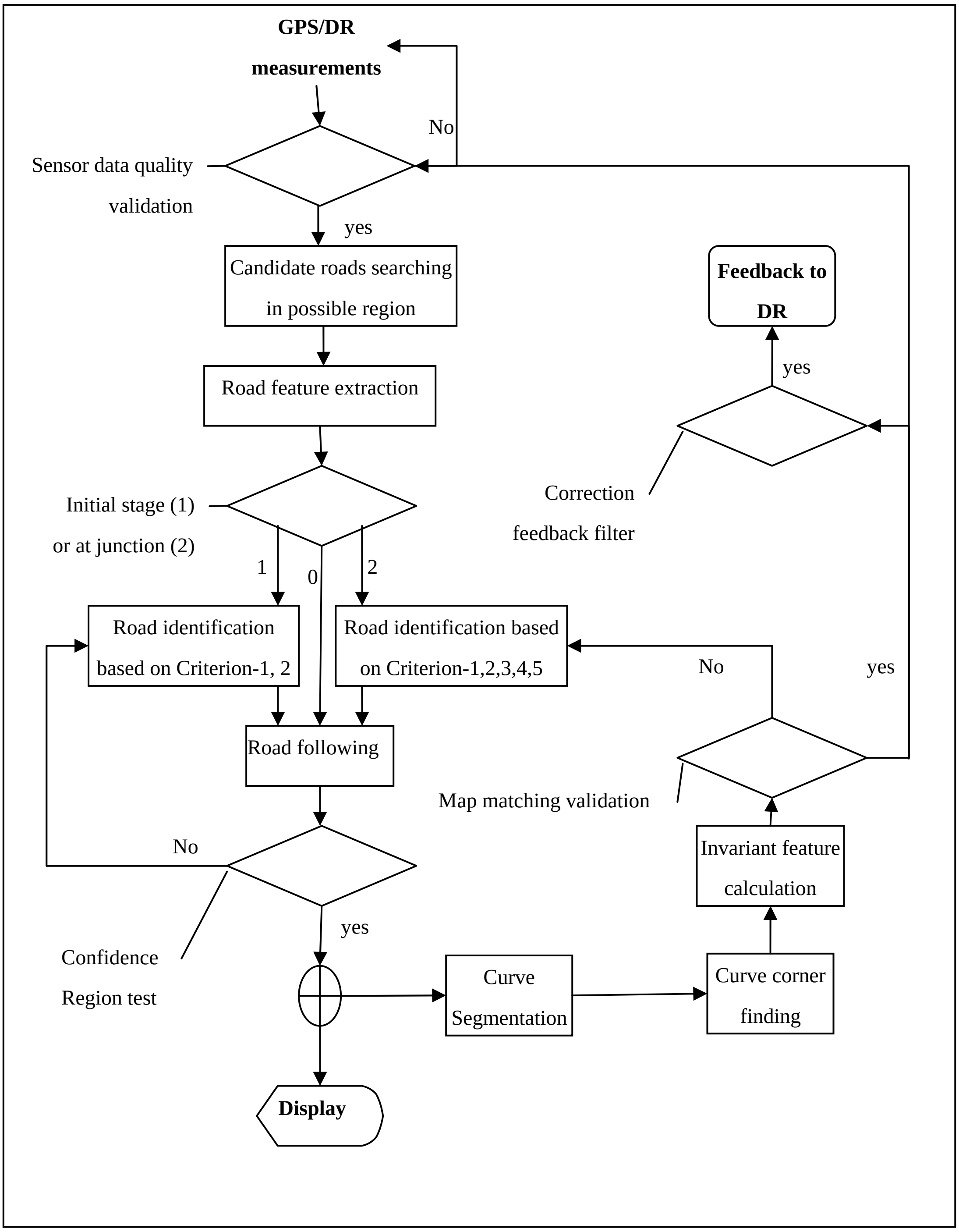


Figure 8-2 Data processing flowchart

8.3 Field Experiments

To evaluate the performance of the newly developed full-functional positioning system, extensive tests have been carried out covering the busiest areas of Hong Kong. The sensor configuration and the digital road map are almost the same as described in chapter 6, with some minor corrections and editions in the digital road map such as additional new roads, change of turn information and rectification on map distortions. The positioning data was collected and processed in real time.

To achieve a comprehensive understanding of the system performance, testing areas cover large area and combined with different type of roads. Specifically, test areas mainly concentrate on urban areas because the developed new prototype system aims to overcome the problem of vehicle positioning in urban areas where GPS signal blockage is severe. Urban areas are shown as red lines in Figure 8-3. The total length of test routes is around 3,000 kilometres and some roads in high density areas were tested repeatedly. The system was evaluated in the terms of coverage, accuracy and integrity to achieve a clear image of system performance.

To evaluate the coverage, accuracy and integrity of the new system, it is compared with other GPS-based systems, such as a stand-alone GPS and a GPS/DR system which are actually the subsystems of the new prototype system. The new prototype system is designed to output all the position measurement (GPS, DR, GPS/DR and

GPS/DR/MM). Therefore, with one integrated system installed in the test vehicle driving randomly in the testing areas, different data sets (GPS position measurements, GPS/DR positioning measurements, and GPS/DR/MM position measurements) can be obtained at the same time.

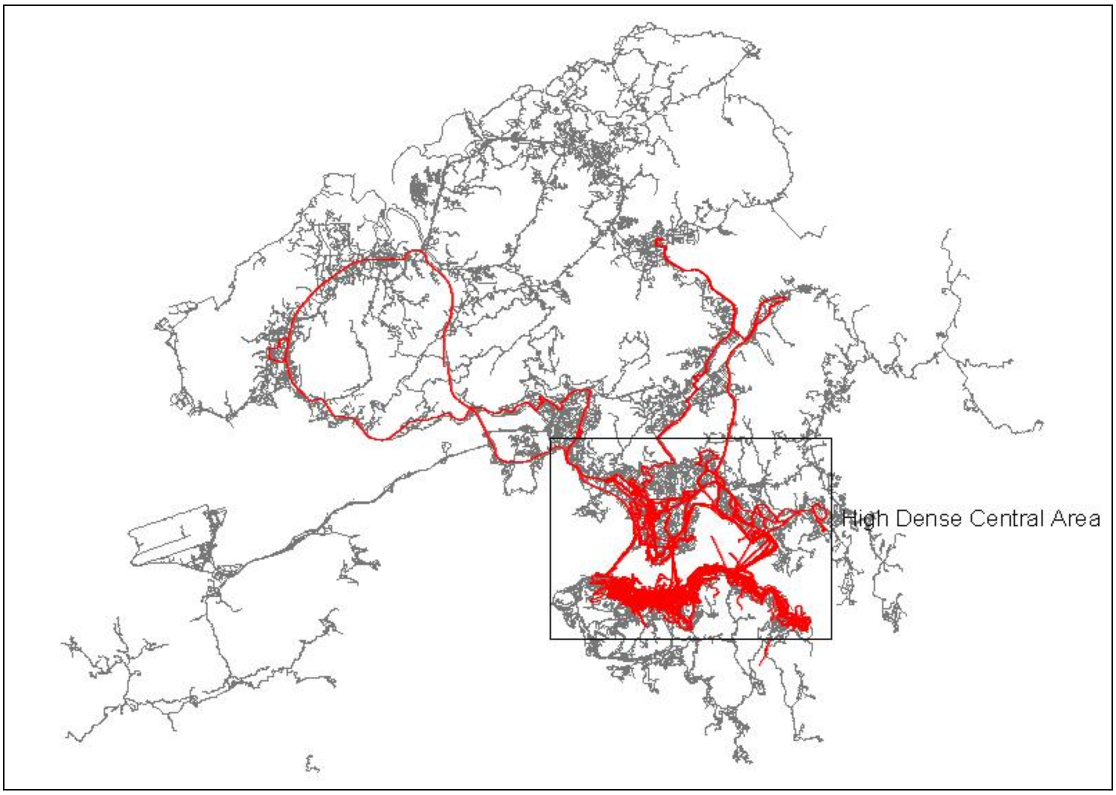


Figure 8-3 Testing area in Hong Kong

Ideally, the accuracy of the positioning system should be evaluated by comparing the position coordinates from the positioning system with the position coordinates of higher accuracy from another independent system. However, it is difficult to determine the true coordinates of the testing vehicle, as the testing vehicle moved on roads at high speed, and GPS positioning signals are blocked on most of the testing areas. The centrelines of road segments from the digital map are considered as the true trajectories of the test vehicle since the digital map has higher accuracy than the positioning sensors.

8.4 System Performance Evaluation

8.4.1 Coverage

The positioning coverage can be described by the successful positioning rate which is the ratio of the number of successful positions which are points located on correct road segments with certain accuracy (i.e. 10 meters RMS) to the total number of points.

Position measurements which are within 10 m distance from the road centreline of the travelling route are considered as successful positions according to navigation requirements because the centrelines from the digital map are considered as true trajectories. In Figure 8-4, red dots are the GPS points and blue dots are the GPS/DR points. If any vehicle position derived from the testing systems falls into the 10 m orange buffer zone of the route, it is considered as a successful position.

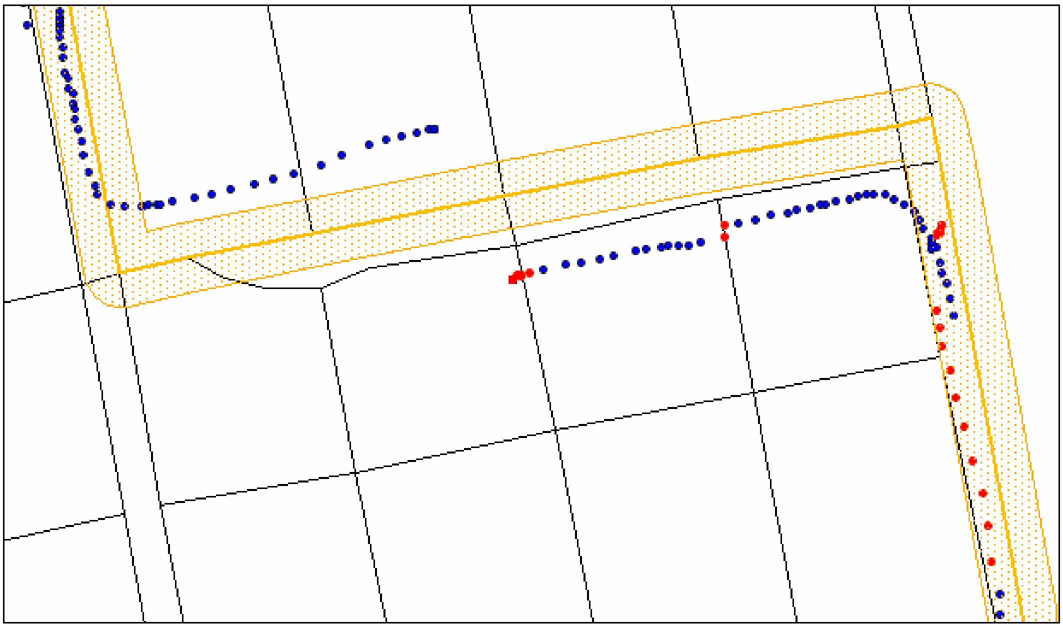


Figure 8-4 Illustration of successful positions

Table 8-1 illustrates the positioning coverage of testing systems. The total number of vehicle position measurements is 500,583 (around 140 hour test data). As the travelling routes of testing vehicle are mostly in the central business districts of Hong Kong, only 150230 positions were obtained with GPS available, and among the GPS positions there were 134103 GPS positions within 10 meters buffer zone of road centrelines. Therefore, the positioning coverage of the stand-alone GPS system is 30%. With GPS/DR positions, 300,109 points were successful, resulting in a positioning coverage of 60%. With the GPS/DR/MM system based on the algorithm described in chapter 5, the coverage is 90%. With our new system, by using reliable map-matching results to reinitialize DR sensors, the coverage is improved from 90%

to 96.5%. The remainder of 3.4% of the new prototype systems, are mismatches which are not able to be recovered.

Table 8-1 Positioning coverage of different systems

GPS	GPS/DR	GPS/DR/MM	GPS/DR/MM/feedback (the newly developed)
30%	60%	90%	96.5%

8.4.2 Accuracy

To evaluate the accuracy, the corner points extracted from road centrelines are used as the ‘true’ positions of control points. The corresponding corner points from vehicle trajectory obtained from our test system were compared with the corner coordinates derived from the map to assess the accuracy of the system (as shown in Figure 8-5). The triangular points represent GPS/DR system outputs. Coordinates of point Q in the road network were considered as the ‘true’ position of the point P in the vehicle trajectory. Point M is the map matched result of point P and its corresponding ‘true’ position is also point Q.

482 dispersedly distributed corner points in the vehicle travelling routes (see Figure 8-6) were selected to evaluate the system accuracy. Within this 482 corner points, 151 corresponding sensor derived positions were determined with GPS available, thus our dataset was divided into two groups: GPS available and GPS unavailable.

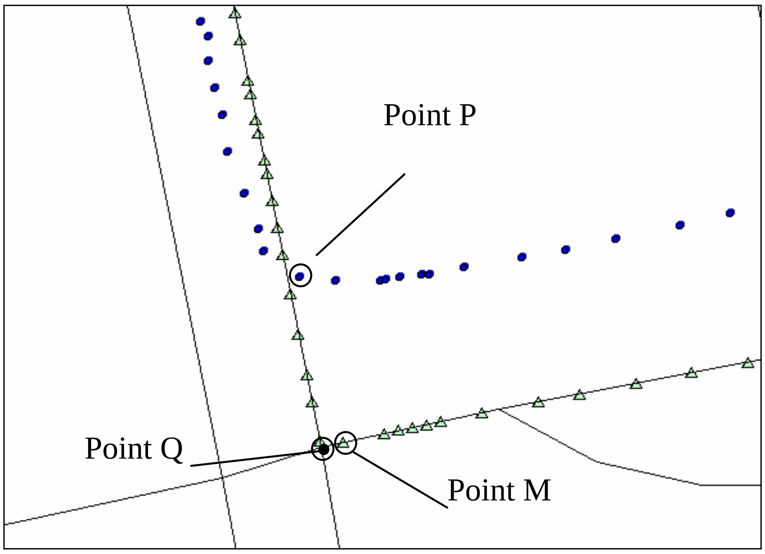


Figure 8-5 Selection of control point for accuracy evaluation

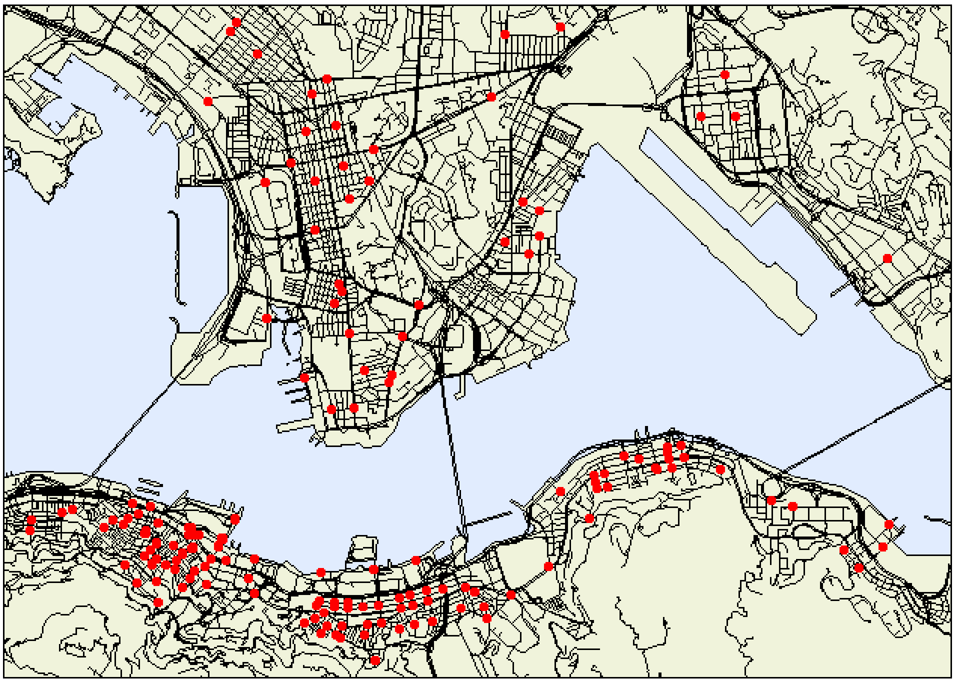


Figure 8-6 Control points for accuracy evaluation

Table 8-2 presents the RMS error of our new system. When GPS is available, the RMS error is 5 m, with the maximum error of 10 m. When GPS is not available, the RMS error is 8 m, with the maximum error of 19 m. The results of error analysis demonstrate that the system developed in this study is able to maintain the accuracy in all the circumstances, with and without GPS. Compared with other GPS-based positioning systems (see Table 8-3 and Table 8-4), the accuracy of the new system is increased. It should be noted that the positioning accuracy is not applicable for stand-alone GPS system when GPS positioning is not available.

Table 8-2 Positioning error of the new system

	New System (GPS available)		New System (GPS unavailable)	
	RMS(m)	Max(m)	RMS(m)	Max(m)
Accuracy	5	10	8	19

Table 8-3 Positioning error of the stand-alone GPS system

	GPS only (GPS available)		GPS only (GPS unavailable)	
	RMS(m)	Max(m)	RMS(m)	Max(m)
Accuracy	10	150	______	______

Table 8-4 Positioning error of the GPS/DR positioning systems

	GPS/DR (GPS available)		GPS/DR (GPS unavailable)	
	RMS(m)	Max(m)	RMS(m)	Max(m)
Accuracy	8	80	60	250

It is known that vehicles do not always travel on centrelines. Using centrelines as the true trajectory can introduce errors which may affect the accuracy of the system evaluation. However, by comparing the accuracy of different systems using the same method, the new prototype system is certainly more accurate.

8.4.3 Integrity

In the new prototype system, an integrity check algorithm (see chapter 7) based on curve pattern comparison is implemented. In the test, there are a total of 4.4% mismatches in real-time processing. However, there is still 96.5% positioning coverage, because among the 4.4% mismatches, 20% of them can be detected and recovered to the correct routes (and thus can be considered as successful positioning) which adds a positioning coverage up to 96.5%. 48% of mismatches can be detected but cannot be recovered from mismatch, and 32% of mismatches are undetected (see Figure 8-8). Of the detected mismatches, most can be identified within 10 seconds, and the longest time for identifying a mismatch is 50 seconds.

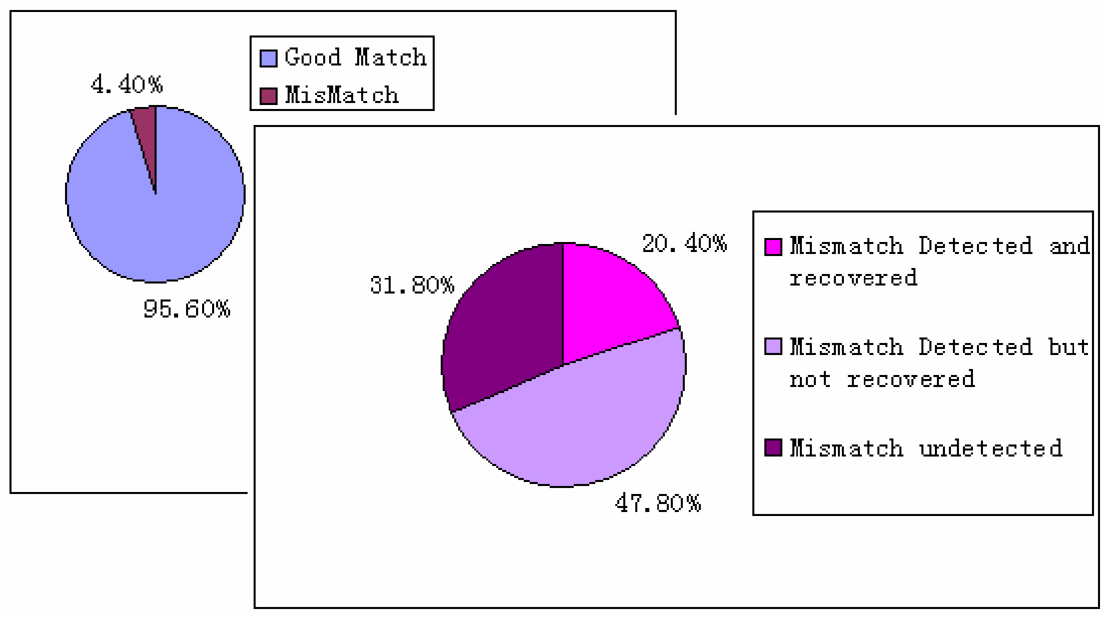


Figure 8-7 Integrity of the new system

The undetected mismatches occur mostly on roads with multiple parallel lanes or in the form of small similar square blocks. These roads have similar patterns, so it is difficult to find the mismatch and then recover from it with our algorithms. They are illustrated in Figures 8-8, 8-9 and 8-10. In Figure 8-8, a number of road sections are close to each other and parallel. If the road identification at the junction were wrong, it is difficult to detect and recover. In Figure 8-9 and 8-10, the purple points represent vehicle trajectory, and the thick black line is the true route on which the vehicle travelled. As the road pattern is similar, the vehicle trajectory is matched to the wrong route (blue line in Figure 8-10) and such a mismatch is not able to detect in our system.

Figure 8-8 Undetected mismatches in parallel lanes

Extensive tests in Hong Kong, it demonstrate that the system developed in this research can satisfy the navigation requirements (10 m accuracy, with 95% coverage) for most ITS applications in Hong Kong. By applying the feedback of map-matching results, the system performance is significantly improved on both accuracy and coverage. Although there are still some mismatches (4.4% of total test data), the system is able to detect them most of the time. Thus the integrity of the system is also significantly improved over conventional vehicle navigation systems.

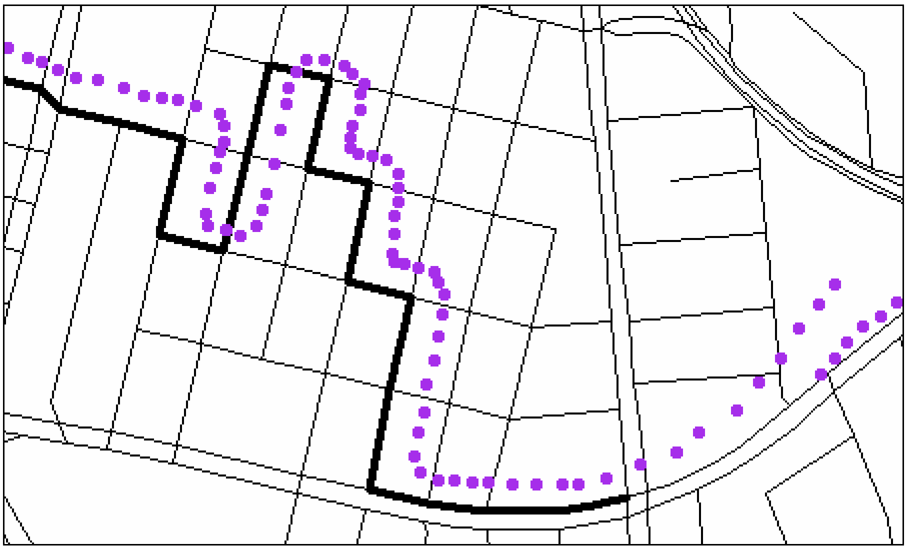


Figure 8-9 Undetected mismatch in similar blocks – correct route

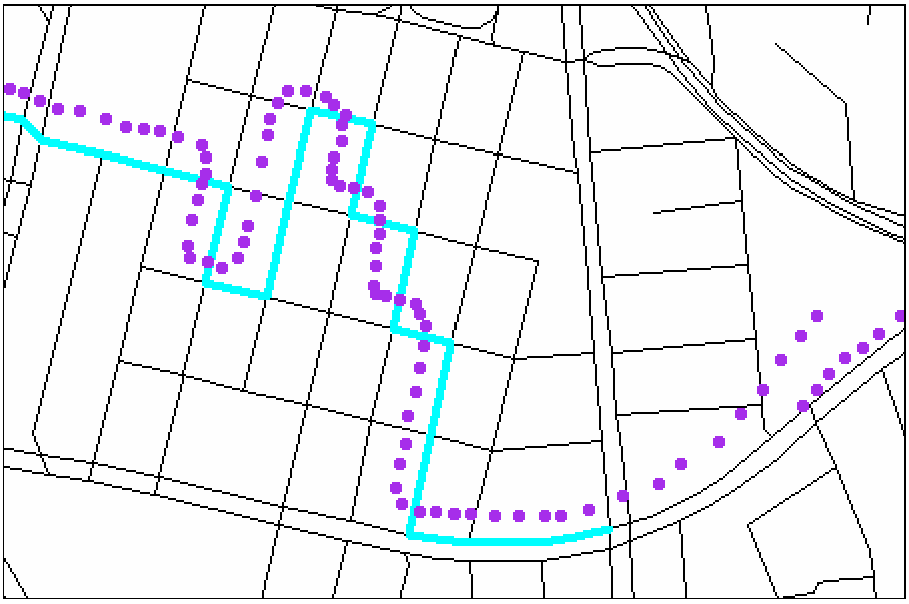


Figure 8-10 Undetected mismatch in similar blocks – incorrect matching

Chapter 9 Conclusions and Recommendations

9.1 Summary

In recent years, along with the development of satellite navigation technology, vehicle positioning systems have been widely applied to different transportation applications. However, due to signal blockage, there are limitations for the use of satellite navigation systems in urban areas. The DR system is a convenient way to bridge short-term gaps of satellite positioning, but it cannot solve the problem when the satellite signals are blocked for substantial periods of time (i.e. 10 to 20 minutes). The aim of this thesis was to improve the performance of land vehicle positioning systems so that they could be used in high density urban areas. To achieve this goal, an integrated approach was developed to optimally integrate positioning sensors, digital maps, and other accessory information. Because of the complexity of city road networks, a new map-matching strategy - divided into 4 tasks was proposed in this study. These tasks are namely road identification, feature extraction, road following, system integrity and reliability maintenance. A multiple criteria decision process was used to for road identification. Extensive tests were carried out in Hong Kong and Macau to study the error characteristics of different positioning sensors and digital maps and their effects on map-matching. Based on the analysis of test data, two new techniques were developed to improve the accuracy, integrity, and reliability of vehicle positioning systems. One was to use the curve pattern comparison algorithms to examine the integrity of map-matching results and the other was to use reliable map-matching results to control the growth of DR errors. As a result, a new land vehicle navigation system was specifically developed to overcome the challenges of navigation in urban areas with complex road networks, and extensively tested in Hong Kong. The results have demonstrated that the new integration strategy can significantly improve the performance of vehicle navigation systems, with an accuracy of over 10 m and a coverage of over 96% on Hong Kong roads.

A case study was also carried out in Macau to evaluate the performance of GPS-based navigation, which provides valuable information for the development of the ITS applications in Macau.

9.2 Conclusions

1) Through extensive tests in Hong Kong and Macau, the performance of GPS-based vehicle navigation systems was systematically analyzed. Using GPS alone, the coverage was around 50-60% for the whole road network. However, in downtown areas, the coverage was around 30% in the less built up areas such as North Point, and only 7% in densely built areas such as Central and Wan Chai. The GPS test data accuracy was 9 m which is in line with the general performance of stand-alone GPS. However, the quality of GPS position cannot be guaranteed because of the satellite geometry and multipath. Positioning errors of up to 150 m have been found in the

experiment data. Integrating GPS and DR improved the coverage to 60-70%, with a slightly improvement on accuracy over stand-alone GPS systems when GPS signal was available. However, during periods when GPS signal was not available, the DR positioning errors increased rapidly. The error of a low-cost gyroscope can reach up to 10 degrees after a 90-degree turning. The angle error from the gyroscope combined with the odometer error can result in a large vehicle positioning error which can reach up to 150 m after the vehicle has traveled 2.2 kilometers (about 15 minutes).

2) A novel map-matching algorithm called Task-oriented Map-matching Method Using Multiple Criteria Decision was developed in this research. The algorithms are different from conventional map-matching algorithms which mainly focus on determining the road taken by a vehicle and then projecting the vehicle position on the determined road. The new map-matching algorithm is an implementation framework of map matching process which provides a complete solution for map matching processing. It divides the map-matching process into four tasks: road identification, feature extraction, road following, system integrity and reliability maintenance. Different algorithms can be applied to different tasks. For example, the conventional map-matching algorithms can be used in road identification tasks. In this algorithm, the decision-making processes in different tasks are accomplished by applying a series of simple threshold-pass tests based on multiple criteria. Such a threshold-pass

method is simple to implement in low processing power chips and is easy to modify according to sensor configuration. Such a task-oriented method makes the map-matching process concise and easy to implement, and also provides an integrating framework to combine various information sources (e.g. sensor measurements of vehicle motion and data from digital road map) to locate a land vehicle.

3) The major factors that affect the performance of map-matching, including: map errors, GPS position errors, travelling distance measurement errors and travel bearing measurement errors, have been identified in this research.

For map database, the main problems are wrong information about traffic rules, missing road segments and multiple centreline representation on multiple lanes of the same road segment. The multiple centreline representation is important for vehicle guidance as in the city the driver needs to be in the right lane in advance, in order to turn into the next road segment. However, as the positioning system is not able to distinguish lanes, then for the purpose of map-matching, the road network needs to be simplified and each road segment should be represented by a single centreline. To reduce the map errors, the database needs to be updated frequently and the quality of data needs to be checked carefully. Moreover, in cities, the traffic signs may be temporarily changed and to update such information is difficult.

In urban environments, GPS coverage is low and GPS positioning errors can be very large due to multipath and weak satellite geometry. The accuracy of the current car navigation grade DR system is not adequate without calibration from GPS. If a bad GPS position is used to provide the reference point for DR, the estimated car position will be shifted away and that will cause mismatch. Currently we have applied different criteria to check the quality of GPS position, but it was found there were still a number of cases where bad GPS data were not detected.

The DR system with GPS calibration was the main positioning sensor in our system. However, DR position errors drift very quickly without GPS positioning signal. The odometer error was a few percent of travelling distance (e.g. 5%). About 2 km travelling distance resulted in a 100 m distance error. This could cause mismatch in a city environment. The distance error was contributed to by the odometers, the map and car trajectories; therefore, including road slope information in the map database can reduce some of the errors. Most mismatches were caused by the bearing errors, especially gyro bias. As the gyro bias is affected by temperature, adding temperature compensation can reduce part of the errors. Another way to monitor the gyro bias change is to examine the gyro output when the vehicle is stationary, as the angle velocity of car is zero in this case. These have been implemented in our prototype system.

4) It was found that DR error accumulated quickly without error control and significantly contributed to the mismatches. Therefore, an alternate method to correct DR errors is necessary when GPS positioning is not available. In most modern cities, the quality of digital maps is very high, for example, the digital map of Hong Kong at 1 m. Therefore it is possible to use coordinates of map-matched positions and the direction of roads in the road network to calibrate DR errors. By calibrating DR with frequently updating map-matching results, DR position errors can be constrained to a reasonably small level, even when GPS is not available. Also, an increase in accuracy of DR positioning makes the map-matching results more reliable. Using map-matching results for DR calibration, one key issue is that the matching results must be correct and reliable. Otherwise wrong results would offset the DR initial positions to wrong locations. A feedback filter was developed to evaluate the quality of the map-matching results and to decide the time to calibrate the DR. Only those map-matching results which pass the filter will be fed back to the DR system.

5) It is important for a system to have integrity, i.e. ability of automatic fault detection and correction. In the proposed system, integrity monitoring are implemented in two ways. Firstly, the sensor data quality is checked by the agreement between data from different sensors. Thus sensor blunders, which may affect map-matching processing, can be eliminated. Secondly, the map-matching results are validated by applying a

confidence region test and a curve pattern matching. The confidence region test method generates an elliptical error region based on the calculated error covariance of position derived from sensors to determine if the corresponding map-matched position is inside the region. The curve pattern matching method compares the corresponding curve pattern e.g. corner points, ratio-of-arc-length, and angle between arcs from both curve derived from sensors and curve formed from map-matched positions. If any obvious difference is found, a mismatch is determined and the last road junction is taken as the starting point of mismatch. The road identification task of our map-matching algorithm is applied again at this junction to recover from mismatch. Consequently, integrity of the system is maintained.

Field tests using these methods showed that 68% of mismatch could be detected, and 20% of them could be recovered. There were still some cases where the mismatches could not be detected or they are detected but could not recovered. The main reason for these cases was the high incidence of similar road patterns in the areas that could not be distinguished by the algorithm developed in this study.

6) Based on this research, a new integrated vehicle positioning system was developed to improve the performance of vehicle positioning in urban areas. The system optimally integrated GPS, DR, road beacon, digital map and other accessory information (i.e. traffic rules). The positioning sensors were firstly integrated through

an adaptive Kalman filter. Then map-matching algorithms developed in this study were implemented in the system for real-time processing. Extensive tests in Hong Kong have demonstrated that the system can significantly improve the performance of vehicle positioning in urban areas to an accuracy of 8 m and a coverage of 96% on Hong Kong roads.

9.3 Recommendations

In this research, a new integrated system has been developed which integrates GPS, DR, radio beacon, and a digital road map through a new map-matching algorithm, to significantly improve the performance of land vehicle navigation systems. In recent years, new technologies, such as mobile phone network positioning and image-based navigation techniques, have been developed. With these new technologies, the function of vehicle positioning systems can be extended further. For example, the mobile phone positioning technology provides both positioning and communication functions that will have very wide applications. However, the positioning accuracy of existing mobile phone positioning technology does not satisfy the accuracy requirements of this study. The image-based navigation system can be used for positioning and for collusion avoidance. Further study in the uses of these emerging technologies and their integration for vehicle positioning in urban areas is needed.

This research concentrated on developing a general purpose vehicle positioning system that can be used in urban areas. For some applications such as lane recognition, better accuracy is required. It would be better to increase the positioning accuracy to 1 meter which is much better for vehicle navigation and route guidance. This can be achieved by using local differential GPS network, when GPS is available. However, if GPS is not available for substantial periods, then it becomes difficult to maintain accuracy with conventional DR system. New technologies with affordable cost need to be developed in the future. Also, the GPS/DR integration was not carried out entirely in the measurement domain in this research, because the low-cost GPS OEM receivers generally provide the final position result in NEMA format instead of the raw measurements. Such integration should be carried in the further research.

The accessory information used in this study included traffic flow (one-way road) and turn restriction in addition to geometric and topological information. Other types of information, e.g. digital terrain model, height information, speed limits and other temporary traffic rules, are also useful for vehicle navigation. Therefore, in order to improve vehicle navigation, it is necessary to develop a digital road map database which is enriched with these types of information and has the ability to handle real-time information.

Due to the limitation of the algorithm developed and used in this research, some mismatches were remaining either not detected or were detected but not recovered. Therefore, further research on developing new methods to for mismatch detection and recovery is need to solve these problems.

Data used for the performance analysis have their own limitation because the new prototype system developed has been tested only in Hong Kong and Macau. As Hong Kong is one of most crowded cities in the world and the system was tested extensively, it is believed that the system developed in this study should be able to have a better performance in other places. It would be more convincing if the system can be tested in other major cities in the world.

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