行政院國家科學委員會專題研究計畫　成果報告

子計畫五：智慧型車輛導航系統設計

計畫類別：整合型計畫
計畫編號：NSC92-2213-E-009-012-
執行期間：92 年 08 月 01 日至 93 年 07 月 31 日
執行單位：國立交通大學電機與控制工程學系(所)

計畫主持人：陳永平

計畫參與人員：蔡建峰，楊世宏，梁智淵，楊文魁，丁柜展

報告類型：完整報告

處理方式：本計畫可公開查詢

中　華　民　國 93 年 12 月 9 日

Design of GPS/INS/GIS for a Real-Time Vehicle Navigation System (3/3)

Yon-Ping Chen

Department of Electrical and Control Engineering, National Chiao Tung University, Hsinchu, Taiwan, R.O.C

Abstract

In this study, a GPS/INS navigation system integrated by Kalman Filter is proposed. Furthermore, a map-matching algorithm that eliminates the error of GPS/INS and finds the exact road and position on the map is also applied to this real-time vehicle navigation system. Three sensors, GPS, one accelerometer and one gyro are integrated in the system to obtain 2-D displacement, velocity, and heading direction. Two microprocessors are designed to capture the signals of GPS receiver and IMU set respectively, and then transmit data to the main processor. After that, the integration of GPS/INS is processed in the main processor. In addition, a modified map-matching algorithm is adopted to adjust the heading direction of INS. Finally, the optimal navigation information would be shown in a graphical user interface. The experiment results would demonstrate the effectiveness and applicability of the proposed methods as the vehicle runs in the urban area, underground passage, and wooded area.

Introduction

In recent years, many researches are devoted to the real-time car navigation systems. Some of them are concentrated on position estimation; some developed systems gave the shortest route. They are all expected to communicate with traffic management in the future.

The car navigation system in this study mainly provides the position estimation. Dead reckoning and Inertial Navigation System (INS) has been adopted to estimate vehicle’s position by integrating the acceleration and angular rate. However, this would produce large error due to the error of integration for a long time. To remedy this problem, the Global Positioning System (GPS) attractive in car navigation system is employed to provide the absolute position.

In order to combine GPS and INS, most researchers relied on Kalman filter, which is a recursive algorithm and requires external measurements to compute optimal corrections of system state variables. The assumptions in the use of Kalman filter are the system is linear and the noise is white Gaussian. However, the system model in INS is nonlinear and the noises of GPS and INS aren’t Gaussian. Therefore, the position estimation from Kalman filter is not optimal.

The map-matching algorithm is a useful method to eliminate the error of Kalman filter according to the exact position in map, as reliable road maps are available. However, this algorithm would leads to mapping error as the GPS signal is unavailable and the error accumulation from INS is too large.

In this study, a modified map-matching algorithm is proposed to solve this problem. This modified algorithm, heading direction estimation, employs the direction of road to adjust the heading direction of vehicle. Furthermore, as the vehicle makes a turn, the INS would obtain the variation of angular rate and the GIS would detect if there were a node near the vehicle. As there is a node, the modified algorithm would not work until the vehicle leave the node. In some case, some roads that are recently built and don't be updated in the GIS database. The proposed method would detect whether there were a road near the vehicle or not. If not, that means the GIS is fail, the GPS/INS trajectory would replace the matching point from GIS. The practical experiment would show the effectiveness and applicability of the proposed algorithm.

Global Positioning System

NAVSTAR GPS, an acronym standing for Navigation System with Timing and Ranging Global Positioning System, is designed to provide highly accurate, 24-hour and worldwide coverage for position reporting and created by the United States Department of Defense. The NAVSTAR GPS consists of three major segments: (1) the space segment (2) the user segment (3) the control segment.

There are two fundamental observations, pseudo range and carrier phase, which can determine the user location. In general, the pseudo range, the main positioning tool, is utilized with less computation, and the carrier phase is always used in high precision surveying that costs a lot of time to obtain the high precision position.

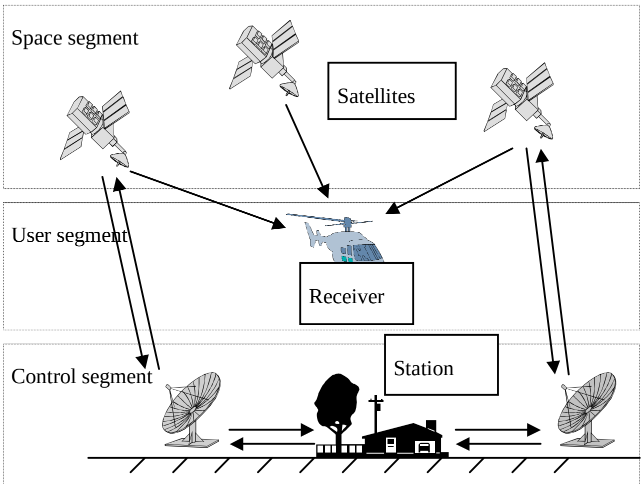


Figure 1 GPS [8]

The space segment of the GPS includes 21 working satellites and 3 spares, and they are arranged in six nearly circular orbit planes, which contain four satellites each plane. The 24 spacecraft are placed in 20,200 km circular orbits inclined at 55 degrees and surround Earth with approximately 12 sidereal hours.

The control segment is made up of a master control station, worldwide monitor stations and ground control stations. These monitor stations track the satellites continuously all day, and they measure signals from the space vehicles (SVs), which are incorporated into orbital models for each satellite. The models compute precise orbital data (ephemeris) and SV clock data to the SVs. Then the SVs send subsets of the orbital ephemeris data to GPS receivers. Thus, the purpose of the control segment is to track the GPS satellites and correct ephemeris constants and clock-bias errors.

The user segment consists of the GPS receivers and the user community. As GPS receivers receive four satellites signals, the four dimensions, *x*, *y*, *z*, and time would be calculated from triangulation. The receiver measures the pseudo range and carrier phase from the satellite. Furthermore, the satellites provide two different accurate signals. Coarse-Acquisition Code (C/A) is used for civilian and Precision Code (P) provides more accurate positional precision.

GPS Satellite Signals

Each satellite transmits a unique coded signal that consists of the identification of the satellite and the ranges to it. The satellite signals based on two L-band frequencies centered on 1575.42 MHz (L1 frequency) and 1227.60 MHz (L2 frequency), which are derived from a fundamental clock frequency of 10.23 MHz. The L1 frequency carries the navigation message and the Standard Positioning Service (SPS) code signals. The L2 frequency is used to measure the ionospheric delay by Precise Positioning Service (PPS) equipped receivers.

The C/A Code, which modulates the L1 carrier phase, is a repeating 1 MHz Pseudo Random Noise (PRN) code. This noise-like code modulates the L1 carrier signal to spreading the spectrum over 1 MHz bandwidth. Each SV has different C/A code PRN, i.e. satellites are identified with their PRN number.

The P-Code, is a 10 MHz PRN code, modulates both the L1 and L2 carrier phases. In the Anti-Spoofing (AS) mode of operation, the P-Code is encrypted into the Y-Code that is used by authorized users with cryptographic keys. Therefore, the C/A Code and P (Y)-Code are the basis of civil SPS and PPS respectively. Figure 2 schemes the structure of GPS satellite signals.

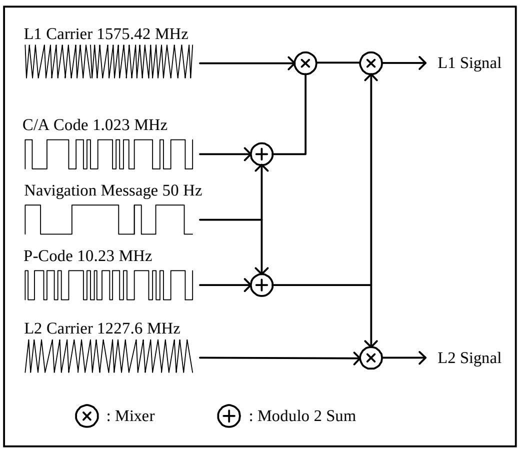


Figure 2 Satellite signals

GPS Navigation Message

GPS navigation message, a 50 Hz signal, consists of data bits that describe the GPS satellite orbits, clock corrections, and other system parameters. A data bit frame, which is transmitted every 30 seconds, consists of 1500 bits divided into five 300-bit subframes. The subframes 1, 2, and 3 contain orbital and clock data where subframe 1 send SV clock corrections and subframes 2 and 3 send precise SV orbital data sets (ephemeris data parameters). Furthermore, subframes 4 and 5 transmit different pages of system data. In addition, each subframe comprises the telemetry word (TLW) and the handover word (HOW). TLW tells the receiver what the subframe data received, and HOW provides the information of TOW (Time Of Week) that helps the locked P code word. Figure 3 shows the scheme of relations between each data format in GPS navigation message.

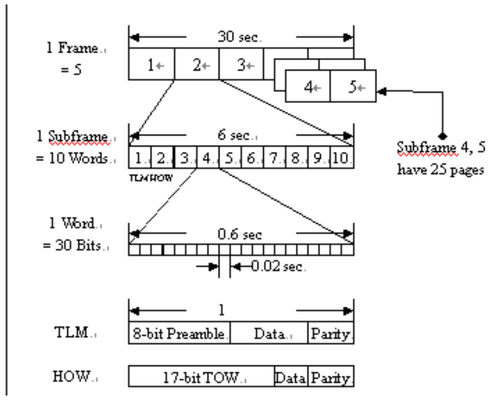


Figure 3 GPS navigation message

Inertial Navigation System

Inertial Navigation System (INS) has been developed for a wide range of vehicles. In general, an INS is mainly built up by a set of inertial measurement units (IMU), which consists of accelerometers and gyros, and the IMU is mounted on a platform. Besides, a processor is required to transform the measured data of acceleration and angular rate into useful navigation information: position, velocity, and attitude. However, INS inevitably has its disadvantage in the errors of position, velocity, and attitude, which are usually caused by alignment, measurement, calculation, and initial states. Furthermore, these errors often accumulate and grow divergently with time in the integral process. Therefore, INS needs external sensor to compensate, and the most popular method is using GPS to correct the divergent error in INS. In strapdown INS (SDINS), the accelerometers and gyros (IMU) are mounted on a platform fixed on the vehicle The IMU can measure the acceleration and angular velocity of vehicle, which are used to calculate the variation of position, velocity, and attitude. In the computing process, numerical errors caused by integrating the accelerations and angular rates would be produced accumulatively and divergently. Besides, the calculation of DCM (Direct cosine matrix) and Euler angle is quite complicated such that a high-performance processor is often needed. Fortunately, the technology of processor has been increasingly improved and good enough to do this work.

It is known that the gimballed INS system, better than the SDINS in accuracy, is commonly adopted for long-term navigation. However, the SDINS is generally employed for short-term navigation due to its small size, low cost, power saving, and easy design. For car-navigation, hence the SDINS is available for car-navigation, which requires short-term data, with external sensors, like GPS, which can compensate the disadvantages in long-term work. Figure 4 shows the strapdown INS (SDINS) that is commonly used.

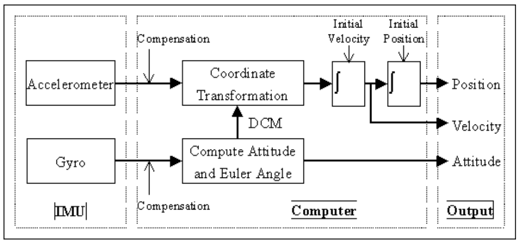


Figure 4 The block diagram of SDINS.

INS Error Model

The inertial navigation system is a rather complex instrument whose components would affect the system errors due to initial random errors and modeling errors. Therefore, in order to understand the influence of the system errors in navigation solution, it is important to develop the dynamic and stochastic models for these system errors.

How the sensor errors affect the position and velocity is described by the dynamic error model which be derived by applying a differential operator δ to the dynamic navigation equations. That is, the variables of the navigation equations are perturbed differentially. There are two approaches generally employed to derive dynamic error model: perturbation approach and psi-angle approach.

Reduced Error Model

In this subsection, the reduced error model for this system will be described and adopted for reducing the computation time in the real-time navigation system.

$$\delta\dot{\boldsymbol{X}} = \boldsymbol{A}\delta\boldsymbol{X} + \boldsymbol{B} \qquad (1)$$

where

$$\delta\boldsymbol{X} = \begin{bmatrix} \delta\boldsymbol{r}_N & \delta\boldsymbol{r}_E & \delta\boldsymbol{V}_N & \delta\boldsymbol{V}_E & \delta\psi & \boldsymbol{w}_g & \boldsymbol{B}_a & \boldsymbol{B}_g & \boldsymbol{SF}_a & \boldsymbol{SF}_g \end{bmatrix}^T$$

$$
\boldsymbol{A} = \begin{bmatrix}
0 & -\dot{\boldsymbol{l}}\sin\boldsymbol{L} & 1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\
\dot{\boldsymbol{l}}\sin\boldsymbol{L} & 0 & 0 & 1 & 0 & 0 & 0 & 0 & 0 & 0 \\
-\boldsymbol{g}/\boldsymbol{R} & 0 & 0 & -\left(2\omega_{ie}^{n} + \dot{\boldsymbol{l}}\right)\sin\boldsymbol{L} & \boldsymbol{f}_E & 0 & \cos\psi & 0 & \boldsymbol{f}_N & 0 \\
0 & -\boldsymbol{g}/\boldsymbol{R} & \left(2\omega_{ie}^{n} + \dot{\boldsymbol{l}}\right)\sin\boldsymbol{L} & 0 & -\boldsymbol{f}_N & 0 & \sin\psi & 0 & \boldsymbol{f}_E & 0 \\
0 & 0 & 0 & 0 & 0 & 1 & 0 & 1 & 0 & \omega \\
0 & 0 & 0 & 0 & 0 & -1/\tau_g & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & 0 & 0 & -1/\tau_a & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0
\end{bmatrix}_{10\times 10}
$$

where $\boldsymbol{B}$ = the input noise vector.

$$\boldsymbol{B} = \begin{bmatrix} 0 & 0 & \Delta_N & \Delta_E & \varepsilon_g & \boldsymbol{w}_{gn} & \boldsymbol{w}_a & 0 & 0 & 0 \end{bmatrix}^T$$

Which has zero mean and with covariance as

$$\boldsymbol{Q} = \boldsymbol{diag}\begin{bmatrix} 0 & 0 & \sigma_{\Delta_N}^2 & \sigma_{\Delta_E}^2 & \sigma_{\varepsilon_g}^2 & \sigma_{w_{gn}}^2 & \sigma_{w_y}^2 & 0 & 0 & 0 \end{bmatrix}$$

This reduced error model will be adopted in the Kalman filter. And the computation time will be reduced in this real-time navigation system.

Geographic Information System

The Federal Interagency Coordinating Committee defined the term *Geographic Information System* in the following manner: " A system including computer hardware, software, and procedure, which is designed to support the capture, management, manipulation, analysis, modeling, and display of spatially referenced data for solving complex planning and management problems" in 1988. Such a system is an electronic spreadsheet coupled with powerful graphic-manipulation and display capabilities. In general, a geographic information system (GIS) combines graphic system and data processing system to manage the graphic data, characters, numeral data, and attribute data. Attribute data is associated with the graphic data and provide more descriptive information about them. Therefore, GIS can give not only the information of the data element itself, but the nearby geographic information.

Taiwan Coordinates

The conventional geodetic datum used in Taiwan was based on the geodetic observations carried out in 1978, and the reference ellipsoid was the Geodetic Reference System 1967 (GRS67). The origin point of this datum locates at the Hu-Tzu-Shan astronomic station. The coordinates, which includes the latitude and longitude based on the GRS67, grid coordinate based on 2°-Zone Transverse Mercator (TM) projection, and the height is above the mean sea level. The set of coordinates adopted in Taiwan was called the Hu-Tzu-Shan coordinate system, and also named the TWD67 (Taiwan Geodetic Datum based on the GRS67). [27]

The recommendations made by the IERS (International Earth Rotation Service) also encourage national agencies to establish their precise national datum based on the ITRF (International Terrestrial Reference Frame). This datum would be linked into regional or continental solutions and employed for many international applications. Thus, a geodetic ellipsoid, GRS80, was adopted with the new national coordinate system called the TWD97 that also employs the Transverse Mercator. Table 4.3 shows the parameters of TWD67TM2 and TWD97TM2 coordinates in Taiwan. The grid coordinate is calculated with a 2-degree zone and 121°E and 119°E. Furthermore, the western offset of the transverse axis is 250,000 m and the scale ratio is 0.9999, where the scale ratio is defined as:

Scale ratio=actual map scale/nominal scale.

Kalman Filter

In this research, the Kalman filter would be adopted to compute the optimal error estimate. Consider the system,

$$x_k = \Phi_{k-1} x_{k-1} + w_{k-1} \quad (2)$$

$$z_k = H_k x_k + v_k \quad (3)$$

where

w_k = plant noise.

v_k = measurement noise.

For prediction:

$$\hat{x}_{k(-)} = \Phi_{k-1} \cdot \hat{x}_{k-1(+)} \quad (4)$$

$$P_{k(-)} = \Phi_{k-1} P_{k-1(+)} \Phi_{k-1}{}^{T} + Q_{k-1} \quad (5)$$

For filtering:

$$K_k = \left[P_{k(-)} \cdot H_k{}^{T}\right] \cdot \left[H_k \cdot P_{k(-)} \cdot H_k{}^{T} + R_k\right]^{-1} \quad (6)$$

$$P_{k(+)} = \left(I - K_k \cdot H_k\right) P_{k(-)} \quad (7)$$

$$\hat{x}_{k(+)} = \hat{x}_{k(-)} + K_k \cdot \left[z_k - H_k \cdot \hat{x}_{k(-)}\right] \quad (8)$$

From Eq.(4)~(8), the optimal estimations can be calculated by the following four steps.

Step 1. Calculate $P_{k(-)}$ from Eq.(5) using $P_{k-1(+)}$, Φ_{k-1}, and Q_{k-1}.

Step 2. Calculate K_k from Eq.(6) using $P_{k(-)}$, H_k, and R_k.

Step 3. Calculate $P_{k(+)}$ from Eq.(7) using K_k, and $P_{k(-)}$.

Step 4. Estimate $\hat{x}_{k(+)}$ from Eq.(8) using K_k, initial value of $\hat{x}_0$, and z_k.

Integrate GPS/INS

In GPS/INS integration, one Kalman Filter is used to combine two different data output rate systems, GPS and INS. Figure 5 shows the scheme of integration where INS gives the estimate $P+\delta P$ with error δP and GPS provides the measurement $P+\delta\mu$. After filtering by Kalman filter, the optimal error estimate would be determined as dP', which would be subtracted from estimate of INS. And then the optimal navigation information would be calculated.

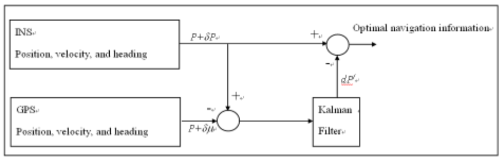


Figure 5 The integration mode of GPS/INS.

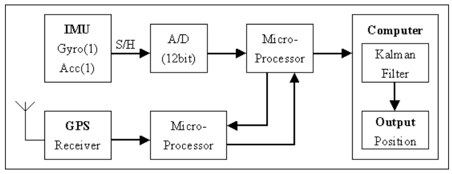


Figure 6 Integrated system hardware block diagram

Figure 6 describes the hardware of GPS/INS where the major sensors in this system are IMUs and GPS receiver. IMUs include one gyro and one accelerometer and their signal outputs are all in analog mode. Therefore, the A/D converters are desired. In order to improve the efficiency, two independent microprocessors are needed. One is to decode and compress the GPS signals, and the other is to handle the signals of IMU and the transmission between the board and the main processor.

Integrated GPS/INS/GIS

The assumptions of Kalman filter are that system is linear and the distribution of noise is white Gaussian. However, the INS model is nonlinear and the GPS noise is not white Gaussian in practice. Therefore, the estimated information from Kalman filter is not optimal. In order to solve this problem, a map-matching algorithm is adopted to eliminate the error of Kalman filter according to the exact position in map, as reliable road map is available.

Map Matching Algorithm

The purpose of the map-matching algorithm is to locate the position of the vehicle on the map. Since the GPS satellite signal has errors and noise due to the tropospheric and ionospheric propagation delays, and GIS database is more accurate. Therefore, a map-matching method using a digital map is a useful approach to correct these errors. Furthermore, the fact that " A vehicle moves always on a road network. " makes the utilization of the map information more effective. With the assumption that land-vehicle almost run on roads, most of vehicle navigation systems translate the GPS position onto a road, and the position errors can be eliminated if the road where the car locates can be found. In other words, the map-matching problem can be defined as the identification problem of the road where the car locates. Furthermore, the map-matching function would integrate measured position and the digital map data to locate the vehicle on proper position relative to digital map. There are several criterion used in the map-matching function and described in the following sections.

Map Matching Issues

There are three issues that would be discussed in the map-matching algorithm and presented as the following description. Projected error is defined as the distance between the measured position obtained from the GPS/INS and its projected position on the road shown as figure 11. Therefore, the first issue of the map-matching algorithm is that the projected error must be small, so that the correct located road would be found. The dot-product implies the similarity between the shape of the road and the trajectory of the vehicle shown as figure 11. Thus, the second issue of map-matching algorithm is that the dot-product value should be big, so that the vehicle would be matched to the correct road due to the fact that the trajectory is similar to the shape of road. The definition of the moving distance is the distance between the present vehicle position and the previous vehicle position shown as figure 11. Accordingly, the third issue is that the difference between the moving distance and the projected moving distance should be small. Consequently, these three issues would be useful to decide which road the vehicle runs. Next section would discuss the map-matching structure and give the flowchart.

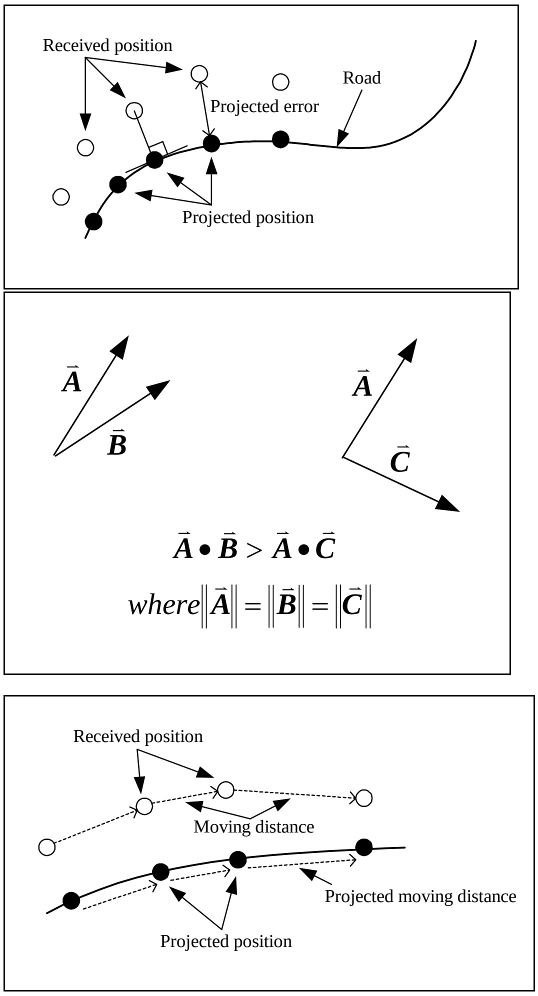


Figure 11 map matching issue

Map Matching Structure

In the map-matching structure, three modes are used and they are initial mode, searching mode, and tracking mode. In the initial mode, only the projected error measurement is used, and the first issue would decide the closest road and the closest point. As the vehicle starts to run, the navigation system would detect how many nodes, which are the junctions of two or more roads, are near the vehicle. If there were nodes nearby, the mode would be changed to the searching mode. As the matched road and matched point are decided, the mode would back to the nodes nearby decision. If there is no node nearby, the mode would be changed to the tracking mode, and that means the vehicle position approaches only one road. Then, the projection method would be employed to decide the projected point of the initial road or the previous matched road. Furthermore, the mode would also back to the nodes nearby decision after the projected point is calculated. The complete map-matching flowchart is shown in figure 8 and the detail procedure of the map-matching structure is presented in the next section.

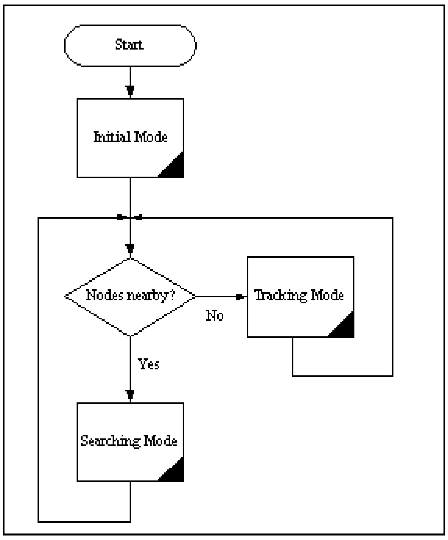


Figure 8 The map-matching flowchart

Modified Map-Matching Algorithm

While the GPS/INS/GIS has been integrated, the matching would, however, still produce error, due to the unavailable GPS for a long time. This phenomenon is described as figure 9 and the GPS signal was unavailable in the duration. Therefore, INS would work alone and the heading direction would accumulate large error. When the vehicle makes a turn, the mapping would make a mistake to map into the wrong road.

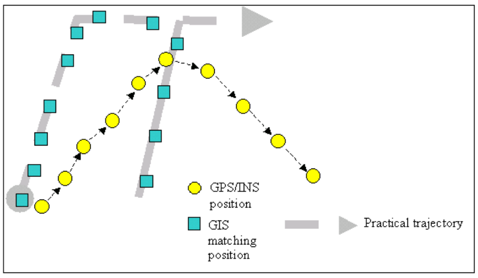


Figure 9 GPS/INS without GIS fix

In order to solve this problem, a modified map-matching algorithm is proposed. Since the heading direction is similar to the direction of the road that vehicle runs. The proposed method is to fix the heading direction from the direction of road. However, the modified algorithm would fail as the vehicle has a turn shown as the left of figure 10. Since the direction of road isn’t the same with the one before the turn. Therefore, an improved method is to detect if there were a node near the vehicle and obtain if the variation of direction from INS were large; if yes, then the GIS heading direction fixing wouldn’t work until the vehicle leaves the node and the variation of direction from INS is small. This description is shown as the right of figure 10.

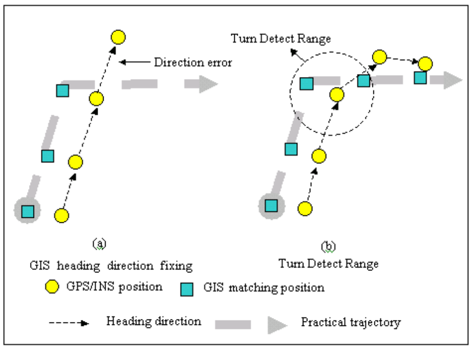


Figure 10 Node and turn detect

Global View in GPS Accuracy

The GPS positioning accuracy is ideally equal to 5 m and may not be stable. Therefore, the heading direction and position measured from two nearby points would not be reliable; this phenomenon is shown as figure 11 (a). As the INS integrated with GPS, the heading direction measured from GPS could not be reliably used to correct the heading direction of INS. In order to solve this problem, a global view method is proposed. This method measures the heading direction from i^{th} and $i+m^{th}$ points where $m>1$ and obtains the continuous stable heading direction. Measuring heading direction from two adjacent points of GPS may not be reliable due to the unstable characteristic in short-term time. The proposed method uses the long-term stability of GPS and measure two points whose time interval is longer shown as figure 11 (b). As there are five GPS points, the 1^{st} and 5^{th} points are chosen to measure the heading direction $\psi 1$, and the same work is done in $\psi 2$. While the $\psi 1$, $\psi 2$, $\psi 3$, and $\psi 4$ are measured, they may not be, however, practical due to the fact that one of them, $\psi 3$, may be the error due to the unstable characteristic of GPS shown as figure 11 (c). Thus, in order to determine the practical heading direction, the proposed method obtains a stable heading direction from several continuous past heading directions shown as figure 11 (d). If these past directions were almost the same, then the last angle $\psi 4$ would be the heading direction, which could fix reliably the direction of INS. If they had large difference as figure 11 (c), the method would keep finding the stable heading direction as heading direction for INS.

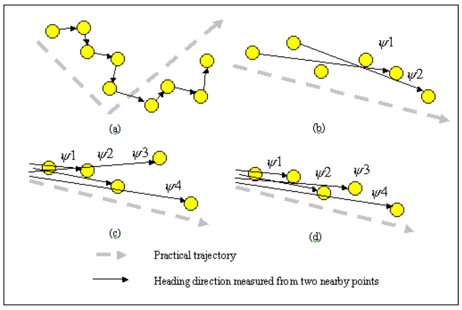
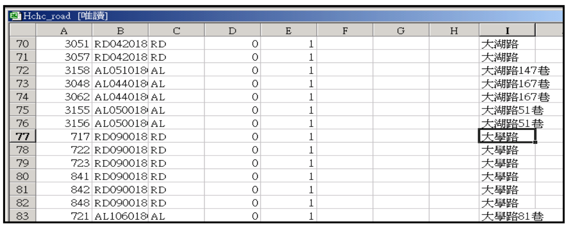


Figure 11 Heading direction estimation

GPS/INS/GIS System Architecture

As the modified map-matching algorithm has been adopted in navigation system, the overall system architecture could be described as figure 13. However, if the vehicle passes through the road that have not been updated in GIS database, the navigation information would depend on the GPS/INS and show the trajectory without the located road information. Furthermore, the output of GPS/INS, such as position, velocity, heading direction, could be also used in car control.



Hchc_road [唯讀]

	A	B	C	D	E	F	G	H	I
70	3051	RD042018	RD	0	1				大湖路
71	3057	RD042018	RD	0	1				大湖路
72	3158	AL051018	AL	0	1				大湖路147巷
73	3048	AL044018	AL	0	1				大湖路167巷
74	3062	AL044018	AL	0	1				大湖路167巷
75	3155	AL050018	AL	0	1				大湖路51巷
76	3156	AL050018	AL	0	1				大湖路51巷
77	717	RD090018	RD	0	1				大學路
78	722	RD090018	RD	0	1				大學路
79	723	RD090018	RD	0	1				大學路
80	841	RD090018	RD	0	1				大學路
81	842	RD090018	RD	0	1				大學路
82	848	RD090018	RD	0	1				大學路
83	721	AL106018	AL	0	1				大學路81巷

Figure 12 raw data format of the map data

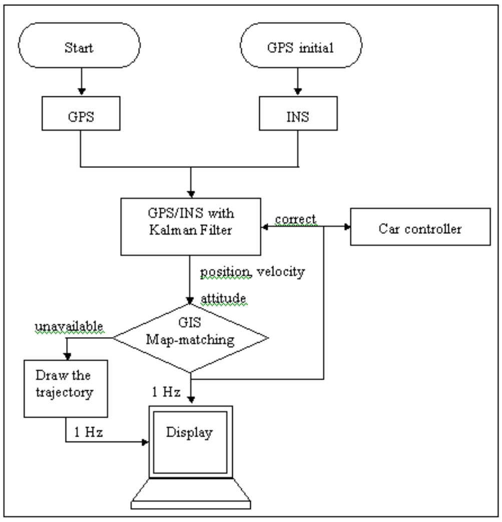


Figure 13 GPS/INS/GIS architecture

Hardware and Software

The navigation system consists of one GPS receiver interface, a two-dimension INS, and two-dimension GIS database. The brief descriptions of the instruments used in this application are given as following sections.

In hardware, a GPS engine board (GM-80-A) is employed to receive GPS signal that decoded and collected by using one microprocessor (8951) via RS232 protocol. The IMU set used in INS consists of one accelerometer (ADXL202) and one gyro (ENV-05A), and transform to digital with 12-bit A/D converter (MAX197). Then the other one microprocessor (8951) would receive the IMU digital signal directly and GPS data from the other microprocessor with 17 Hz, and then send them to main processor (Acer TravelMate 529ATX with Pentium 900 MHz).

In software, all the navigation functions constructed in main processor are developed in Visual Basic that is a useful developed environment and convenient to design real-time navigation system, and the GIS component, MapObjects [25], is also utilized in this environment. Furthermore, all the sensors data and GPS data are received with the Visual Basic interface.

The digital map structure includes seven kinds of map data, regions, railways, rivers, roads, bridges, landmarks and nodes. The developed component, MapObjects, uses the shapefile to show the map data on the graphic user interface. However, the raw data format of the map data is not the form shown as figure 12. Therefore, it is necessary to utilize the GIS software, MapInfo, to transfer the map file to the shapefile shown as figure 14.

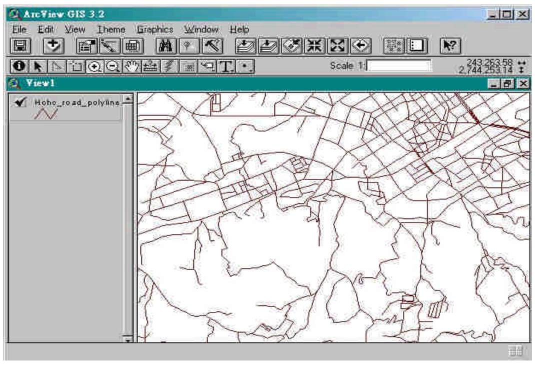


Figure 14 Shapefile

In datum, the GPS receiver uses the WGS84 datum, and the longitude unit is *dddmm.mmmm* where *d* is degree and *m* is minute. However, the GRS80 datum and *x-y* coordinate are applied to the digital electronic map “TWD97TM2”. Therefore, the units are necessary to be transferred to degree. Then, using UTM projection to transfer longitude and latitude coordinates into the *x-y* coordinates. The data in the *x-y* coordinates would be displayed on the map. Although the digital map is constructed based on the GRS80 datum and the GPS receiver uses the WGS84 datum, the difference between the WGS84 datum and the GRS80 datum is very small, so that most researchers often treat them as the same.

In order to replay the trajectory after the driver got home or the goal, an Access file is created to record the GPS/INS data and map-matching position, furthermore, the trajectory would be stored per second.

Experiment Results

In order to test the performance of this navigation system, there are two experiment paths. Path 1 shown as figure 15 would pass through the underground passage, urban area, and wooded area, and these areas would test the GPS/INS/GIS performance while GPS signal is available and examine the INS/GIS performance when GPS signal is unavailable. Path 2 shown as figure 16 would be planed in National Chiao Tung University whose some roads doesn't exist and update in GIS database. Therefore, this path is useful to test GPS/INS performance without GIS correction.

Figure 17 shows the result of GPS/INS without the GIS correction, but the map-matching with GIS. The dash-line circle A and E in figure 17 shows the strange phenomenon of GPS that the longitude is static but the latitude varies, so that the trajectory would keep straight and vertical to parallel. However, the trajectory isn't towards the real path and would cause the error matching shown in dash-line circle A. Therefore, the most convenient and simple solution is to judge if the longitude is static, then the GPS signal would be classified to be unavailable.

Since this phenomenon occurred at short-term time, it is reliable to depend on the INS/GIS in section A and E. In the section B, the vehicle pass through an underground passage, and then the vehicle turn right and enter an urban area.

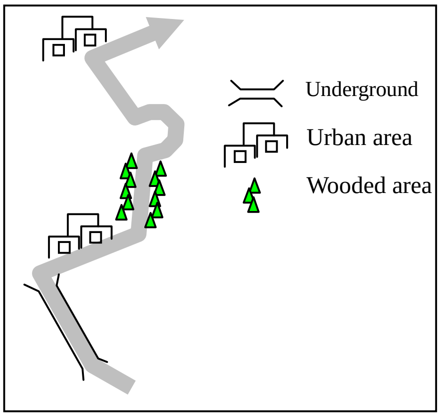


Figure 15 Path 1

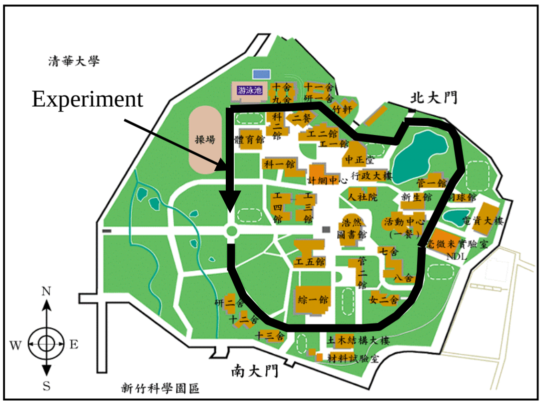


Figure 16 Path 2

From the figure 17, there is no available GPS signal for GPS/INS and the heading direction strayed from the real path, so that the location was matched to the error road until the GPS signal was available in section C. However, the signals seemed to be untidy and the trajectory was rough, since there were more high buildings around the vehicle. In order to solve the phenomenon, the heading direction estimation shown in figure 11 would be adopted to smooth the trajectory for driver. There is a wooded area in Section D; the GPS signal, however, seemed to be available and was sometimes untidy in the middle of section D, so that the error matching would happen. This problem would be solved with the same method, heading direction estimation.

Figure 17 GPS/INS without the GIS correction

The path1 was experimenting with the modified procedure and the result is shown as figure 18. In the section A and E, the problem of strange GPS signal has been solved, so that the trajectory was smoother and there was no error matching. As the vehicle pass through the underground passage, the GIS aided the INS to correction the heading direction until the vehicle turned right. While the INS and GIS detected the node and turn, the INS would work without the heading direction aid from GIS. Therefore, the trajectory was smoother and more correct, and furthermore the matching was more correct.

As the GPS worked alone, the result was shown in figure 19. From the result, the GPS signal would disappear in some special regions. And as the INS worked alone without the correction of GPS, the error would accumulated with time.

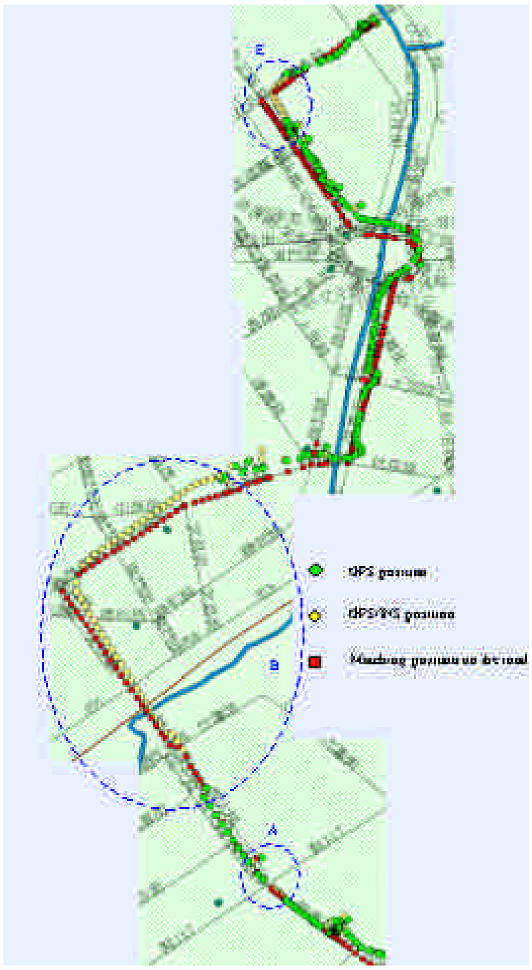


Figure 18 GPS/INS with the GIS correction

The navigation information would not be reliable shown as figure 20. The result of GPS/INS/GIS with modified map-matching algorithm is shown as figure 21. And the result is better than those of GPS, INS, and GPS/INS.

While the GPS/INS/GIS performance and INS/GIS has been tested, the path 2 would be tested the performance of GPS/INS. Some roads in National Chiao Tung University are not updated in GIS database. Therefore, as the vehicle ran in the road shown as figure 22, the GIS would match the position to the other road where vehicle didn't run. While the matching positions were almost on the same location and the vehicle was moving, the GPS/INS position would be substituted for matching position

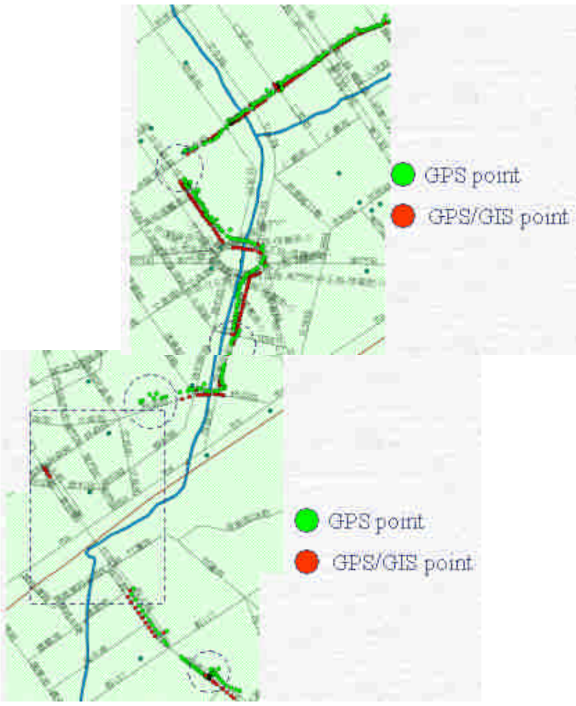


Figure 19 GPS/INS

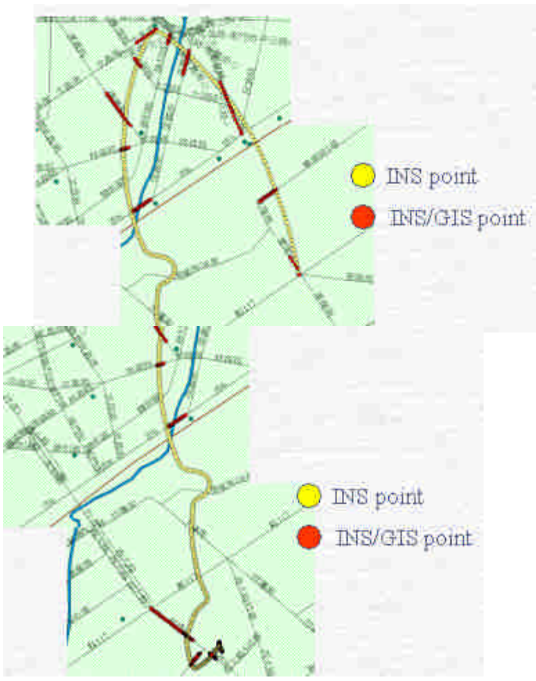


Figure 20 INS/GIS

shown as section B. Section C is a wooded area, so that the GPS signal was unavailable and INS should work alone. Even the INS worked without the aid of GPS or GIS, the trajectory was reliable and smooth due to the integration of

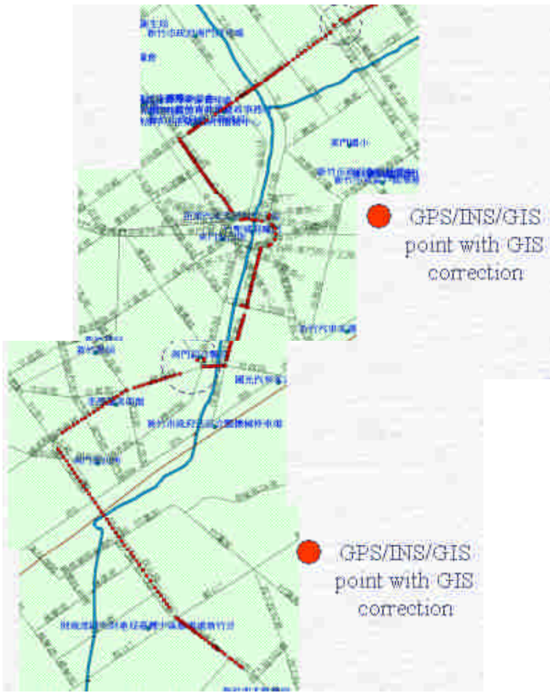


Figure 21 GPS/INS /GIS with modified map-matching algorithm

acceleration and angular rate. The equipment employed in this experiment is shown as figure 23, the IMU set consists of one accelerometer and one gyro.

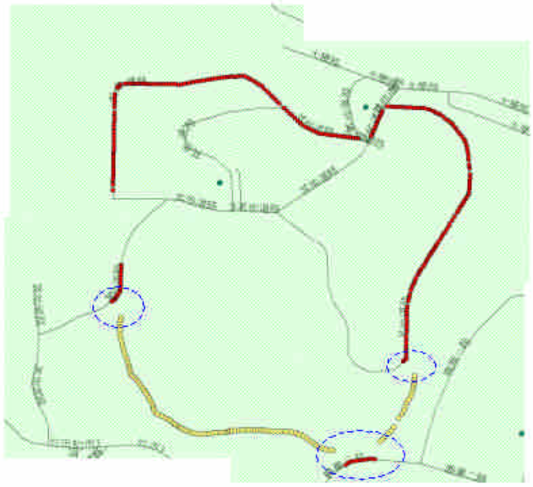


Figure 22 The vehicle ran in the road (yellow points) that doesn't exist in digital map. However, the real-time navigation system could still hold the navigation information.

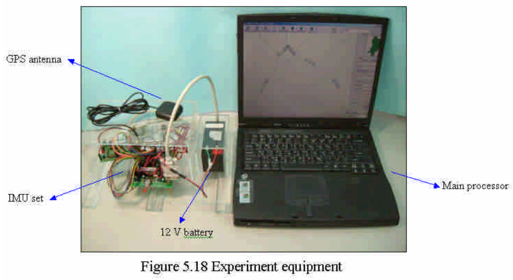


Figure 23 Developed navigation system

Conclusion and Future Works

This research mainly contributes to adopting Kalman filter to integrate GPS with INS and map-matching algorithm to integrate GPS/INS with GIS. The pseudo range would be determined from the positioning equation. With the pseudo range and carrier phase, the absolute position of vehicle would be calculated. However, GPS is not always available for navigation. INS built up by a set of inertial measurement units (IMU) can provide continuous position and would not be affected by external interference. Therefore, in order to get continuous and smooth navigation information, INS is integrated with GPS. The coordinates of GPS and INS are different; thus, the position, velocity, and attitude of them need to integrate. In order to determine the navigation information in INS, the dynamic equation would be adopted to calculate this information. As determining this information from dynamic equation, the error caused from integration would accumulate and affect the performance of INS. Thus, the INS error model is derived to estimate the error. Then the Kalman filter would be employed to integrate GPS/INS and estimate the error based on INS error model and observation model from GPS.

Even the GPS/INS is more accurate and reliable than GPS or INS alone, the absolute position from GPS/INS can't provide sufficient information for driver. GIS would provide more accurate database to match the path. In this research, the position would be matched on the map in Taiwan coordinate. A map-matching algorithm, which includes initial mode, node nearby detection, searching mode, and tracking mode, would be used to match the position of GPS/INS to the correct road and point on map. This algorithm would provide the relative position and the GIS provides the geographic information for driver.

As the system starts to navigate, the hardware constructed based on two microprocessors would receive the data that consists of acceleration and angular rate from INS and signal from GPS. Then these data would be transmitted to the main processor via RS232 interface. In the main processor, these GPS and INS data would be integrated with the conventional Kalman filter that is commonly adopted in navigation system to get optimal solution. As the map-matching algorithm is employed, there are still some matching errors due to the wrong computational heading direction. Therefore, a proposed heading direction correction method would compare and fit the trajectory of GPS/INS to the vehicle's real path. This proposed method would fail as the vehicle makes a turn. Therefore, a method that detects the node from GIS database and measures the variation of direction from angular velocity of vehicle is proposed to adjust the heading direction correction. Furthermore, as the vehicle runs in the road that doesn't exist and isn't updated in GIS database, a proposed strategy would detect whether there is a road near the vehicle or not. If yes, the GPS/INS position would replace the matching position. With the strategy, the navigation system would provide the reliable geographic information for driver. Consequently, with the experiments, the navigation system is flexible in different environments, even the underground passage, wooded area, urban area, and new built road. Furthermore, the results show these methods are feasible, and the trajectory is continuous, smooth, and reliable.

A flexible GPS/INS/GIS real-time navigation system has been proposed in this research. However, there are some drawbacks in this navigation system. One is that the road of GIS database is constructed based on the centerline of road, and the road in the map doesn't have the width. Therefore, the error of GIS database would depend on the width of roads. The other one drawback is that even the experiment tested the performance of system in several different environments. However, there may be some strange environments, such as long tunnels, and the system may be fail in these environments due to the fact that the error in INS would accumulate, as GPS was unavailable for a long time. Another drawback is the small sampling rate due to the ability of main processor. As the navigation system would be adopted in autonomous vehicle control system, the sampling rate is too small to observe the dynamics.

Finally, the measurement error is poor to know and the GPS noise is not white Gaussian in practice. However, Kalman filter is implemented in the linear system and the noises of process and measurement are white Gaussian. Therefore, the estimated information from Kalman filter is not optimal. In order to solve this problem, some researchers adopt the adaptive Kalman filter to improve the poor knowledge of measurement error. [8] The adaptive Kalman filter would update the measurement error and the error estimation would be more accurate. However, the adaptive Kalman filter would take more computation time to estimate and update errors. In this research, the processor isn't able to fulfill the computation in time. Thus, in order to employ the adaptive Kalman filter, it is necessary to modify the entire algorithm used in this research. The future work will be devoted to modify the Kalman filter and map-matching algorithm to reduce the computation time and obtain more accurate navigation information.

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