The Development and Validation of a Navigation Grade EGI System for Land Vehicular Navigation Applications

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ABSTRACT:

In recent years, most people use commercial integrated navigation systems to develop navigation algorithms. However, due to the different levels of sensors on the market, it is difficult to customize commercial systems and leads to limited development of navigation algorithms. Therefore, the purpose of this research is to develop a real-time integrated navigation system EGI-1000 (Embedded GNSS and INS) including software and hardware, and effectively reduce the cost with the commercial price. The real-time integrated navigation system EGI-1000 contains a navigation-grade IMU, IMU1000 and NovAtel OEM 7720 GNSS receiver module. In this research, the integration process can be divided into three parts. The first part is the integration of hardware, and the architecture diagram of the real-time integrated navigation system will be displayed. The second part is the pre-processing of data. In the multi-sensor time synchronization problem, this research will propose a method about cross-correlation to validate whether the timestamp of IMU data is delay. The last part is algorithm about fusing data from multiple sensors and motion constraints. Extended Kaman Filter (EKF) will be the core and motion constraints including Zero Velocity Update (ZUPT) and Non-Holonomic Constraints (NHC) are integrated in the Loosely Coupled (LC) scheme. The calibration of Inertial navigation Measurement Unit (IMU) will also be conducted to determine the parameter in algorithm. The results of the experiments will be shown in this paper. Both of hardware and navigation algorithm in the integrated navigation system of this research are used to conduct multiple experiment including open sky environments, GNSS challenging environments, and GNSS denied environment. In comparison with the reference data, the navigation accuracy of the developed integrated navigation system can achieve centimeter-level accuracy (“Active Control” level and “Where in lane” level) in open sky and GNSS challenging environments. According to the propagation error theory, the result in GNSS denied environment also meet the expected value. The navigation algorithm is also feasible for the commercial integrated navigation system.

1. INTRODUCTION

Land vehicular navigation (LVN) is the procedure of determination of position, velocity, and attitudes of a land vehicle. This technology which is based on multi-sensor is used for various navigation purposes especially in autonomous vehicle. According to the classification method proposed by the International Society of Automotive Engineers (SAE), autonomous driving system can be divided into 6 levels (Level 0 ~ Level 5) (SAE International 2018). To reach Level 4 or above, there are three major challenges need to be solved. The first challenge is how to accurately knows its position and navigation information. The second challenge is how to solve sensor’s signal is masked and too far to sense. The third challenge is how to communicate with another vehicle. Among the above, the functional safety is the most important, namely precise position and navigation information. The classification of navigation accuracy is illustrated in **Figure 1**. These four classes describe the level of accuracy which is needed for different Intelligent Transportation System (ITS) applications (Stephenson et al. 2011). Furthermore, vehicles need positioning in uncertain driving conditions and in harsh environmental conditions to avoid potential danger. Therefore, self-driving vehicles need a robust positioning system with centimeter-level accuracy (T. G. et al. 2019) which is at the “where in lane” level or “active control” level. In recent years, most people use Global Navigation Satellite System (GNSS) to conduct navigation. Nevertheless, the navigation system based on GNSS will be interrupted in challenging environment (Chiang et al. 2013). Furthermore, in the GNSS denied environment like the tunnel, the GNSS receiver cannot obtain any signal. Hence, Inertial Navigation System (INS) has been widely integrated with GNSS due to their complementary features (Angrisano, 2010). With a navigation-grade INS/GNSS based system, it can satisfy a robust positioning system with centimeter-level accuracy. For the system that applies to LVN, this may divide into three main components (Liu et al. 2020). The first component is the core algorithm. The second component is the client system including hardware platform. The third component is the cloud platform including how to store the data. In addition to these three points, the system needs to be validated to ensure that accidents occur due to system failures in actual use.

Among the previously mentioned factors, this research aims at developing a self-designed navigation-grade embedded EGI system (EGI-1000) including a core algorithm, hardware integration, and data storage that can meet the three main points of LVN system. Meanwhile, the system is aimed to achieve centimeter-level accuracy (“Where in lane” and “Active Control” level) and accepts actual driving tests to confirm the integrity of the embedded EGI system. In this research, we will present the navigation-grade embedded EGI system (EGI-1000) specifications and the details of hardware integration architecture and core fusion algorithm. A method of confirm whether the hardware integration is available will be presented. The accuracy of the navigation-grade embedded EGI system (EGI-1000) as evaluated based on the results of a road test will also present in this research.

The contributions of this research are as follows:

1. The hardware integrated architecture which is suitable for embedded GNSS/INS system in land vehicular navigation is proposed.
2. The navigation integrated algorithm that aims at navigation-grade IMU and GNSS receiver in embedded GNSS/INS system used in land vehicular navigation is proposed.
3. A method and a set of procedures of validating whether the hardware integration and navigation integrated algorithm are available is proposed.

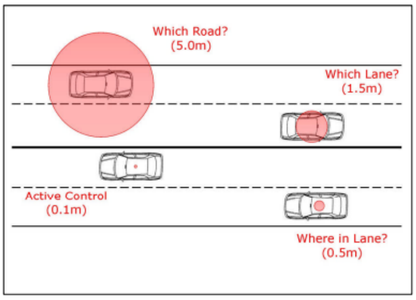

Figure 1. Navigation accuracy classification

The structure of this paper, the introduction is mentioned in Section 1. Section 2 will put the emphasis on the methodologies which are used to accomplish the integration navigation system. Section 3 will show the setting of the experiments in this research. Next, the result of the real-time integrated navigation system EGI-1000 is presented in Section 4. In the end, conclusion is presented in Section 5.

2. NAVIGATION-GRADE EGI SYSTEM FRAMEWORK

In this section, we will introduce the Navigation-grade EGI system framework. This framework including hardware and software development and validation. The development of EGI system can be divided into the following steps:

1. Hardware integration
2. Time Synchronization detection method.
3. Calibration of EGI system.
4. Integrated Algorithm.

2.1 Hardware integration

In hardware integration, a navigation-grade real-time integrated navigation system includes a navigation-grade IMU, a GNSS receiver module, a Real Time Clock (RTC), a microcontroller and an IPC were developed in this research. These are shown in **Figure 2**. IMU1000 whose sampling rate is set to 200 Hz and bias instability of gyro is about 0.005 degree per hour is selected to be the inertial sensor in EGI-1000 for this research. NovAtel OEM 7720 which the sampling rate was set in 1Hz is chosen to be the GNSS receiver module. With the reliable stability and high frequency, EPSON RX8900SA, a RTC chip is adopted to complete the time synchronization process. Focus on the time synchronization process, when GNSS signal is obtained, GNSS receiver module will provide Pulse Per Second (PPS) signal and GNSS solution. PPS signal will first set RTC to the current GPST and start to calculate the time accurately. In the meanwhile, the microcontroller (MCU) will put the GPST timestamp which provide by the RTC chip on the IMU data. Finally, MCU will be used to determine whether the time synchronization is done and send both GNSS and IMU data with GPST to Industrial Personal Computer (IPC). As the core of the entire hardware integration architecture, the IPC must be able to allow the entire system to operate completely independently without additional connections to the computer (Standalone) and it should operate successfully in harsh environments with high temperature and high humidity. A NXP i.MX8 module which is the ARM Cortex architecture processor currently used by most car manufacturers is chosen as the IPC to achieve the above issues. In IPC, with an Embedded Multimedia Card (eMMC) which is an embedded flash memory, Linux system and real-time navigation algorithm are all installed in this chip. IPC also designed Ethernet and Universal Asynchronous Receiver/Transmitter (UART) two transmission methods to connect with Real-time kinematic (RTK) service and communicate with external computers respectively. With the complete hardware integration in this research, the IMU data including GPST timestamp and GNSS PVT solution signal can be obtained continuously. The whole architecture of hardware integration is shown in **Figure 3**.

Figure 2. Main components in EGI-1000

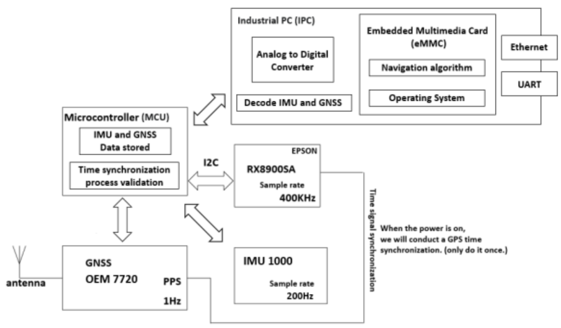

Figure 3. Hardware integration architecture.

2.2 Time Synchronization Detection Method

The issue of time synchronization is extremely important during the initial hardware integration steps. If the wrong time information is given in the hardware, the error will increase greatly due to error propagation when entering the navigation algorithm. Therefore, this research proposes a time synchronization detection method. The purpose of this method is to confirm whether the timestamp of the IMU data is delayed. In this method, an IMU (iMAR-iNAV-RQH-10018) of the same class is used as the reference system. Its timestamp will be compared as the true value. Since the sampling rate of the reference system is different from that of the IMU1000, interpolation will be used. With the characteristic of the IMU measurement signal, the value of cross correlation at different time can be computed. Therefore, the information about delay time can be used to adjust the hardware integration architecture. In **Figure 4**, this case represents zero-time delay, that is, the time synchronization is correct. Because the value calculated by cross correlation has its maximum value at 0. If it is wrong, its

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maximum value will appear in other fields. The equation of the proposed method is expressed as follows:

$$Value^{(Ref,\ IMU1000)}{}_{Cross-correlation}(n) = \frac{1}{n} * \sum_{i=0}^{n-1} IMU\ Measurement^{(Ref)}(i) IMU\ Measurement^{(IMU1000)}(i+n) \quad (1)$$

where i = timestamp of IMU measurement
n = quantity of data after interpolation

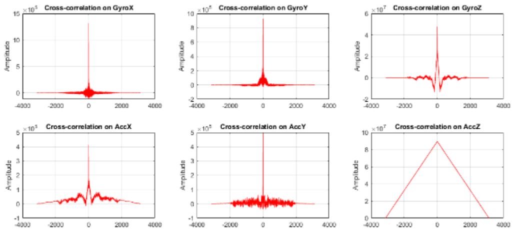

Figure 4. The illustrations of cross-correlation test results

2.3 Calibration of EGI System

To estimate the systematic error from the EGI-1000, the bias and scale factor value is estimated on the accelerometers side by static calibration. As for the gyroscopes, a high accuracy rotation table EVO-20M whose specification is shown in **Table 1** is used to conduct the calibration process as shown in **Figure 5**. With static and dynamic calibration, the bias and scale factor can be put into the navigation algorithm to compensate the systematic error of IMU and help to build the error model.

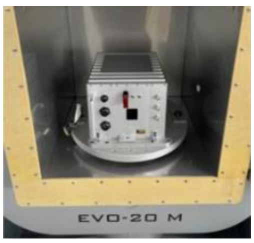

Figure 5. Dynamic calibration of EGI-1000

Table 1. Specification of EVO-20M

Position accuracy	≤ ±1 arc sec
Maximum wobble	≤ 1 arc sec
Orthogonality	≤ 2 arc sec
Maximum rate	3000 °/s
Peak acceleration	2000 °/s²
Bandwidth	100 Hz

Furthermore, noise including random noise and systematic noise are the major factor that cause the error in navigation system. The error model based on these factors should be accurately build before using IMU measurements. The parameters of the error model can usually be found on the official website and in the user manual. However, when an IMU is processed or shipped from the original factory, its specification will be inconsistent with the official parameters. Therefore, the Allan variance test is adopted to estimate the error model parameters including Angular Random Walk (ARW), Velocity Random Walk (VRW), and bias instability of accelerometers and gyroscopes. The comparison of the parameters between in the user manual and from the Allan variance test shows in **Table 2**.

Table 2. Parameters of error model from the official document and Allan variance test

Error model	Specifications (IMU1000)	Allan variance (EGI-1000)
Gyroscope		
Bias Instability	0.005 (deg/hour)	0.0015 (deg/hour)
Angular random walk	0.0007 (deg/√hour)	0.0005 (deg/√hour)
Accelerometers		
Bias Instability	1000 (μg)	1.211 (μg)
Velocity random walk	0.009 ((m/sec)/√hour)	0.003 ((m/sec)/√hour)

2.4 Integrated Algorithm

In the research, the EKF is adopted to fuse the measurements from IMU and GNSS receiver module. The EKF is a general technique about integration with INS and GNSS. In the EKF, the Taylor series expansion under assumption of Gaussian error distribution are applied. Moreover, the prediction and measurements update are conducted successively in EKF (El-Sheimy et al. 2007). Due to the simplicity of LC scheme, it has been widely used to integrate multiple sensors for navigation. Hence, in this research, loosely coupled is selected to be the fusion architecture which is shown in **Figure 6**.

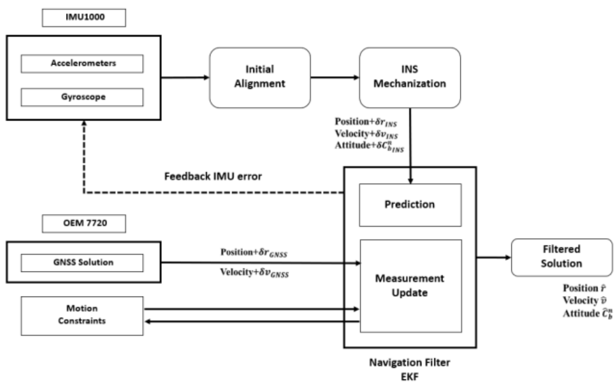

Figure 6. Loosely coupled integration architecture

2.4.1 Initial Alignment

The core of inertial navigation system is the measurements of IMU. To integrate the IMU and GNSS data, the measurements of IMU should be transformed from body frame to navigation frame before navigation. This process is initial alignment. Since the earth rotation can be sensed by the tactical grade IMU, the initial alignment can be conducted with the earth rotation measurements after obtaining the initial position from the GNSS solution. The process of initial alignment method consists of coarse alignment and fine alignment. The flow chart of initial alignment is shown in **Figure 7**.

In coarse alignment, the mean value of a series of IMU measurements are calculated at first. Moreover, the ideal measurements in navigation frame in static state can be set. With both measurements in body and navigation frame, the initial rotation angles can be obtained. The equation of coarse alignment is expressed as follows:

$$\begin{bmatrix} f^b \\ \omega_{ib}^b \\ v^b \end{bmatrix} = C_n^b \times \begin{bmatrix} f^n \\ \omega_{ib}^n \\ v^n \end{bmatrix} \quad (2)$$

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$$C_b^n = \begin{bmatrix} (f^n)^T \\ (\omega_{ib}^n)^T \\ (v^n)^T \end{bmatrix}^{-1} \times \begin{bmatrix} (f^b)^T \\ (\omega_{ib}^b)^T \\ (v^b)^T \end{bmatrix} \quad (3)$$

$$\begin{bmatrix} (f^n)^T \\ (\omega_{ib}^n)^T \\ (v^n)^T \end{bmatrix}^{-1} = \begin{bmatrix} 0 & 0 & -\gamma \\ \omega_e & 0 & -\omega_e sin\varphi \\ 0 & -\gamma\omega_e cos\varphi & 0 \end{bmatrix} \quad (4)$$

where $f^b,\ f^n$ = specific force in b-frame and n-frame
$\omega_{ib}^b,\ \omega_{in}^n$ = angular rate in b-frame and n-frame
$v^b,\ v^n$ = cross product of specific force and angular rate in b-frame and n-frame
C_n^b = rotation matrix from n-frame to b-frame
C_b^n = rotation matrix from b-frame to n-frame
ω_e = earth rotation rate
γ = normal gravity
φ = latitude

For fine alignment, the Extended Kaman Filter (EKF) is utilized to obtain more accurate initial rotation matrix from body frame to navigation frame. There are two measurements are used for updating. One is the zero velocity, and another is east channel earth rotation vector. The equation of Zero Velocity Update (ZUPT) and East Channel Earth Rotation Update (ECERU) are expressed as follows:

$$Z_{ZUPT} = [v_{ins}^n - 0_{3\times1}]_{3\times1} \quad (5)$$

$$H_{ZUPT} = [0_{3\times3} \quad I_{3\times3} \quad 0_{3\times15}]_{3\times21} \quad (6)$$

$$Z_{ECERU} = \left[C_b^n(2,1) \times \omega_x + C_b^n(2,2) \times \omega_y + C_b^n(2,3) \times \omega_y\right]_{1\times1} \times \frac{1}{Sampling\ rate} \times 180/pi \quad (7)$$

$$H_{ECERU} = \begin{bmatrix} 0_{1\times6} \\ \omega_{ie}^n(3,1) \\ 0 \\ -\omega_{ie}^n(1,1) \\ C_b^n(2,1) \\ C_b^n(2,2) \\ C_b^n(2,3) \\ 0_{1\times9} \end{bmatrix}_{1\times21} \quad (8)$$

where v_{ins}^n = estimated velocity in n-frame
Z_{ZUPT} = observation matrix
H_{ZUPT} = design matrix
ω = angular rate of the IMU
ω_{ie}^n = rotation rate from i-frame to e-frame under the n- frame

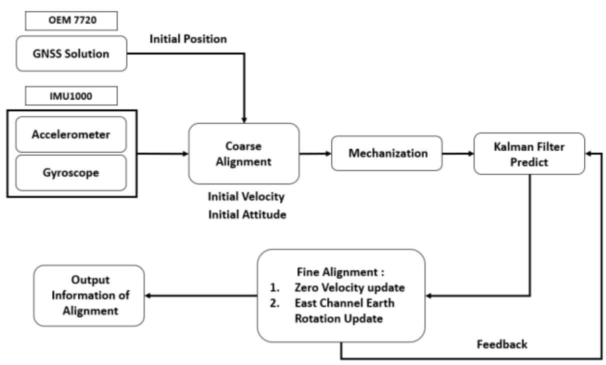

Figure 7. Flow chart of initial alignment

2.4.2 GNSS Update

While the GNSS receiver can obtain signal from 4 satellites at least, the coordinate of the GNSS receiver will be computed. Therefore, Coordinate Update (CUPT) can be conducted with the GNSS solution. The equation of GNSS CUPT is expressed as follows:

$$Z_{CUPT} = \begin{bmatrix} r_{INS_N}^n - r_{GNSS_N}^n \\ r_{INS_E}^n - r_{GNSS_E}^n \\ r_{INS_D}^n - r_{GNSS_D}^n \end{bmatrix}_{3\times1} \quad (9)$$

$$H_{CUPT} = [I_{3\times3} \quad 0_{3\times3} \quad A_{CUPT} \quad 0_{3\times12}]_{3\times21} \quad (10)$$

$$R_{CUPT} = \begin{bmatrix} \sigma_N^2 & 0 & 0 \\ 0 & \sigma_E^2 & 0 \\ 0 & 0 & \sigma_D^2 \end{bmatrix} \quad (11)$$

where N, E, D = North, East, and Down in l-frame
r_{INS}^n = estimated position
r_{GNSS}^n = position from GNSS solution
σ = standard deviation in the GNSS data

2.4.3 Motion Constraints

With motion constraints including Non-Holonomic Constraints (NHC), Zero Velocity Update (ZUPT), and Zero Integrated Heading Rate (ZIHR), the navigation error can be constrained in specific situation. For NHC, unless the vehicle slides on a slope or jumps off the ground, the velocity in the plane perpendicular to the forward direction is almost zero. Hence, the measurements can be assumed to conduct update in EKF. The assumption is expressed as follows:

$$v_y^b \approx 0, and\ v_z^b \approx 0 \quad (12)$$

where $v_y^b,\ v_z^b$ = velocity in the plane perpendicular to the forward direction in b-frame

The equation about ZUPT is displayed in Section 2.4.1. Hence, the theory about ZUPT will not be mentioned in this section. For ZIHR, since the vehicle becomes static, the rotation rate of the heading angle will be zero. Therefore, the value of heading angle before becoming static can be adopted to conduct measurement update in EKF to improve navigation accuracy.

$$Z_{ZIHR} = [\hat{\psi} - \psi]_{1\times1} \quad (13)$$

$$H_{ZIHR} = \left[0_{1\times10} \quad \frac{\sin\phi}{\cos\theta}\Delta t \quad \frac{\cos\phi}{\cos\theta}\Delta t \quad 0_{1\times9}\right]_{1\times21} \quad (14)$$

where $\hat{\psi}$ = heading angle value
$\psi,\ \phi,\ \theta$ = stored heading angle value, roll angle value, pitch angle value while the vehicle starts to become static
Δt = time interval to check whether the ZIHR can be conducted

3. EXPERIMENT

In this research, a ground vehicle is used as a test platform to verify the real-time inertial navigation system EGI-1000. To ensure that the hardware architecture and navigation algorithm proposed in this research are feasible, the experiment will be carried out in three different scenarios including open sky, GNSS challenging environments, and GNSS denied which are shown in

Figure 8. As for the reference system, Novatel PwrPak 7D-E2 is used to collect GNSS data and navigation-grade IMU, iMAR-iNAV-RQH-10018 is used to collect IMU data. Inertial Explorer (IE) software which is a well-known commercial INS/GNSS software is used to calculate reference trajectory. In the antenna part, this research uses 72GNSSA-XT-1 antcom GNSS antenna. The experiment equipment and the specification of the IMU in reference system are shown in **Figure 9** and **Table 3** respectively.

Figure 8. Street view of the scenario in the car experiment

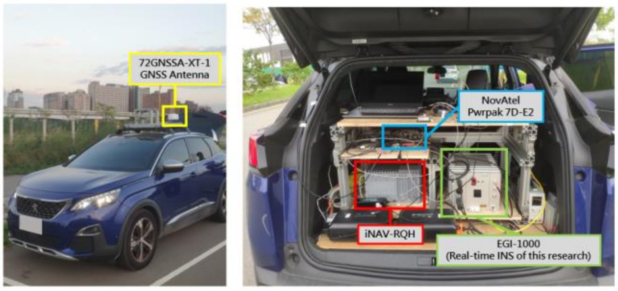

Figure 9. Device in the car experiment

Table 3. Specification of iMAR-iNAV-RQH-10018

Gyroscope	
Bias Instability	0.002 (deg/hour)
Angular random walk	0.0015 (deg/√hour)
Accelerometers	
Bias Instability	10 (μg)
Velocity random walk	8 (μg/√Hz)

4. RESULT AND DISCUSSION

4.1 Open Sky Experiment

The route of the open sky experiment is an open area of the national highway. The total length of this experiment is about 54 km, and the vehicle speed is maintained at 90~110 km per hour speed. In this experiment, the GNSS solution was set to Real-Time Kinematic (RTK) mode. With the solution of RTK mode and the assistance of IMU with navigation level, we can expect the navigation accuracy of real-time inertial navigation system EGI-1000 that under the proposed integration scheme to be below 10 cm in this environment. In **Figure 10**, the red trajectory represents the solution from reference system, and the purple trajectory is the solution from EGI-1000 system in this research. In the numerical analysis, with the proposed integration of hardware and navigation algorithm, the root mean square error of horizontal and 3D can reach 2.5 cm and 2.7 cm respectively. This satisfies the goal of "Active control" level set by this research. Moreover, while maintaining high dynamics, the root mean square error in velocity is less than 2 (cm/s) in all directions. This means that the navigation solutions are available in continuity and high dynamic situation. Basically, the proposed integration scheme can efficiently estimate the current attitude and get the attitude angle similar to the reference system. This indicates that there is no unreasonable error in the installation angle inside the hardware and at the moving platform. The root mean square errors of the three rotation axes are all less than 0.1°. The accuracy analysis is shown in **Table 4**. For experiments in this environment, the integration of hardware and navigation algorithm are both feasible.

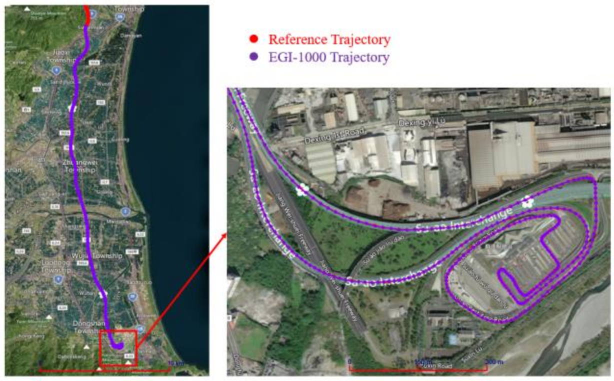

Figure 10. Trajectory of the open sky experiment

Table 4. Accuracy analysis of proposed system in open sky experiment

Position (m)			
Position Error	2D		3D
Mean Error	0.023		0.025
Max Error	0.090		0.091
Error Std	0.011		0.011
RMSE	0.025		0.027
Velocity (m/s)			
Velocity Error	2D		3D
Mean Error	0.011		0.012
Max Error	0.050		0.050
Error Std	0.007		0.007
RMSE	0.013		0.013
Attitude (degree)			
Attitude Error	Roll	Pitch	Heading
Mean Error	0.005	-0.008	0.016
Max Error	0.041	-0.046	0.076
Error Std	0.012	0.015	0.020
RMSE	0.013	0.016	0.023

4.2 GNSS Challenging Environments Experiment

Multi-building urban areas are the route of this GNSS challenging environments experiment. The total length of this experiment is about 25 km, and the vehicle speed is maintained at 30~50 km per hour speed. In this experiment, the GNSS solution is also set to Real-Time Kinematic (RTK) mode. In **Figure 11**, the red trajectory represents the solution from reference system, and the purple trajectory is the solution from EGI-1000 system in this research. With the solution of RTK mode and the assistance of IMU with navigation level, we expect the navigation accuracy of real-time inertial navigation system EGI-1000 to be "Active Control" level in this environment. However, under the influence of multipath effect, the reliability of GNSS solutions will also be affected. The STD of GNSS solutions is always bigger than the one derived in open sky environment. Therefore, the factors in the weighted matrix of GNSS measurements will become bigger. This leads to errors in the judgment of the algorithm. In the numerical analysis, the maximum horizontal error came to 1.25 meters. The horizontal accuracy and 3D accuracy only reach 38 cm and 40 cm respectively. On the other hands, due to the multipath effect, the velocity update is also influence. This also indirectly leads to an error in the estimation of the attitude angle. In terms of position, velocity, and attitude, it is worse than the results in the open sky area. The accuracy analysis is shown in **Table 5**. In terms of accuracy, although it doesn't reach "Active control" level, but remain in the centimeter level which is "Where in Lane" level, this meets our expectations. As mentioned before, multipath effect affects the calculation of the navigation algorithm. The problem of multipath effect must be resolved with the help of navigation algorithms. Therefore, how to distinguish the quality of the GNSS solution will be the subject of further improvement in the navigation algorithm of this research.

Figure 11. Trajectory of the GNSS challenging environments experiment

Table 5. Accuracy analysis of proposed system in GNSS challenging environments experiment

Position (m)			
Position Error	2D		3D
Mean Error	0.333		0.362
Max Error	1.249		1.260
Error Std	0.277		0.290
RMSE	0.384		0.404
Velocity (m/s)			
Velocity Error	2D		3D
Mean Error	0.123		0.130
Max Error	0.934		0.934
Error Std	0.126		0.127
RMSE	0.177		0.182
Attitude (degree)			
Attitude Error	Roll	Pitch	Heading
Mean Error	0.051	0.018	0.052
Max Error	0.112	0.078	1.399
Error Std	0.011	0.020	0.065
RMSE	0.032	0.027	0.073

4.3 GNSS Denied Environments Experiment

The mountain tunnel is the route of this GNSS denied experiment. The GNSS outage is about 215 seconds. In **Figure 12**, the red trajectory represents the solution from reference system, and the purple trajectory is the solution from EGI-1000 system in this research. In this experiment, since the GNSS is blocked by the tunnel, the navigation solution will only rely on the IMU for inertial navigation. Because the use of the navigation-grade IMU in this research, which is the same grade as the IMU of the reference system. We will use the degree to which bias instability drifts over time for comparison. The bias instability of the reference system is 0.002 (deg/hour), and the bias instability of the IMU of EGI-1000 in this study is 0.005 (deg/hour). According to the error propagation theory, the error is proportional to the bias instability. Therefore, the trajectory error of EGI-1000 will be 2~3 times of that of the reference system. In **Figure 13**, the driving lane in tunnel is the actual driving lane of the car. The error of purple (EGI-1000) is about 1~2 times of the error of red (reference system). This is exactly what the theory expects.

Figure 12. Trajectory of the GNSS denied environments experiment

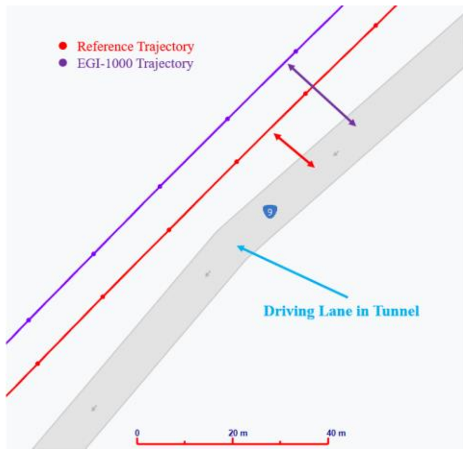

Figure 13. Bias drift error of EGI-1000 and reference between driving lanes

Moreover, once there is no auxiliary information to aid INS in the process of navigation, the bias instability of gyroscopes is the major error source which drifts over time (Chuanbin et al. 2004). The equation of the drifting error is regarded as the standard for validation of developed EGI-1000 system and described as follows. With the results in **Table 6**, both horizontal and 3D positional errors are smaller than the theoretical value. This represents that EGI-1000 has ability to supply feasible solution. For experiments in this environment, the integration of hardware and navigation algorithm are both feasible. But the gap between the two systems may also be due to incorrect estimation of the IMU error model. Therefore, the error model estimation of EGI-1000 needs further optimization.

$$Error_{b_g} = \frac{1}{6} \times g \times b_g \times t^3 \tag{15}$$

Table 6. Drifting error with 215-seconds in GNSS denied experiment.

Error (m)	Theoretical maximum errors (m)	Horizontal maximum errors (m)	3D maximum errors (m)
EGI-1000	9.254	4.318	4.430
Error drift over the time travelled (TT): 0.131 (cm/s)			

4.4 Summary

With the hardware integration scheme and navigation algorithm scheme proposed in this research, EGI-1000 can achieve centimeter-level ("Active Control" level and "Where in lane" level) accuracy in open sky and GNSS challenging environments experiments. In the GNSS denied experiment, according to the verification of the error theory, the EGI-1000 can also meet the theoretical standard in the GNSS-denied environment. This shows that our proposed hardware integration architecture and algorithm are stable and feasible in navigation performance. Under such an architecture, an embedded EGI system can be realized and applied in the field of land vehicular navigation with high accuracy requirements.

5. CONCLUSION

This research proposes and developed a navigation-grade real-time integrated navigation system EGI-1000 including hardware architecture and navigation algorithm. In the hardware architecture, a proposed architecture combines a navigation-grade IMU and GNSS module. This architecture is paired with a precise real time clock (RTC) chip to ensure exact time synchronization. The time synchronization verification method will use cross-correlation to compare the IMU data of the reference system with the IMU data of the test system, which is proposed in this research. After finishing the hardware integration part, the IMU will be calibrated. The calibrated IMU will get the value of systematic error, including bias and scale factor. The parameters for establishing the IMU error model will also be obtained, including angular random walk, velocity random walk, and bias instability. With the proposed coarse alignment and fine alignment method, the most suitable time for threshold automatically can be determined with the standard deviation of heading angle value stored in one second period. The integrated algorithm based on loosely coupled scheme uses extended Kaman filter to perform IMU and GNSS data fusion. With the proposed initial alignment method and motion constraints for auxiliary update observations, the navigation solutions from the integration of IMU and GNSS receiver module can be gained.

There are three experimental results in this research. A ground vehicle was chosen as the platform for three test environments including open sky, GNSS challenging environments, and GNSS denied. In the first open sky test environment, the root mean square errors in 2D and 3D are all less than 0.1 meters. According to this result, EGI-1000 can reach the level of "active control" in this environment. In the second GNSS challenging environments environment, the root mean square errors in 2D and 3D are all less than 0.5 meters. According to this result, EGI-1000 can reach the level of "where in lane" that also meets the expectation of centimeter-level accuracy this environment. However, according to the instrument specifications of EGI-1000, we believe that the "active control" level should also be achieved in the GNSS challenging environments environment. Therefore, how to correctly judge the quality of the GNSS solution in the algorithm will be an important issue in this research in the future. In the third GNSS denied experiment, according to the error propagation theory of gyro drift rate, the error of EGI-1000 meets the standard of theoretical error. But the actual numerical statistics are at the "which lane" level. Hence, how to overcome the positioning error in GNSS denied environment is the critical issue in the future of this research.

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