

AN INITIAL ALIGNMENT METHOD OF INERTIAL NAVIGATION SYSTEM FOR THE STATIC STATE

Hsing-Yun Liu^{1*}, Syun Tsai², Meng-Lun Tsai³, Kai-Wei Chiang⁴

¹ NCKU, Department of Geomatics, No. 1, Daxue Rd., East Dist., Tainan City 701401, Taiwan – qwerim101117@gmail.com

² NCKU, Department of Geomatics, No. 1, Daxue Rd., East Dist., Tainan City 701401, Taiwan – dino920135@gmail.com

³ NCKU, Department of Geomatics, No. 1, Daxue Rd., East Dist., Tainan City 701401, Taiwan

taurusbryant@geomatics.ncku.edu.tw

⁴ NCKU, Department of Geomatics, No. 1, Daxue Rd., East Dist., Tainan City 701401, Taiwan – kwchiang@geomatics.ncku.edu.tw

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ABSTRACT:

The navigation means the process of determining the position, velocity, and orientation of the moving object such as the land vehicle, aerial vehicle, and even autonomous vehicle. Nowadays, Global Navigation Satellite System (GNSS) is most used for positioning. Nevertheless, the navigation system based on GNSS would be interrupted in the challenging environments. Therefore, the inertial navigation system (INS) has been widely combined with GNSS to overcome this issue. For INS, the core concept is the measurements of Inertial Measurement Unit (IMU). In order to integrate the measurements of IMU with several sensors such as GNSS receivers, odometers, and so on, we should transform the measurements of IMU from body frame to navigation frame. The initial alignment just represents the process of finding the accurate initial rotation matrix between body frame and navigation frame in the beginning of navigation. However, initial misalignment angles would cause large error of INS. Hence, obtaining an accurate initial rotation matrix from body frame to navigation frame is an important issue to get the better navigation performance. In the research, an integrated navigation system is developed to validate the initial alignment algorithm. With the data pre-processing and accurate calibration, the proposed method of initial alignment can get precise initial rotation matrix. The errors of roll pitch, and yaw angle are all smaller than 1 degree after initial alignment. Moreover, the time threshold of initial alignment is set by manual traditionally. A method of finding threshold of coarse alignment is proposed in this research.

1. INTRODUCTION

Inertial navigation system can track the position, velocity, and orientation relative to a known point with the measurements of gyroscopes and accelerometers (Titterton, D., Weston, J. L., & Weston, J et al, 2004). Nevertheless, the initial information including position, velocity, and attitudes should be determined before starting navigation. If the IMU is in the static state during initial alignment, the initial position can be determined from the GNSS solution. The velocity can also be set to zero from the static condition. Unlike the initial position and velocity, the initial attitudes are more difficult to obtain (Li, J., Xu, J., Chang, L., & Zha, F. et al, 2014). Moreover, because of sensor error, the navigation error of INS will accumulate with the integration operation. It causes that the initial motion parameters of the carrier are critical to the inertial navigation system (Zhu, Y., Zhang, T., Li, M., Wang, D., & Wu, S. et al, 2019). Hence, the purpose of the initial alignment is to obtain the accurate transformation matrix from body frame to navigation frame, and drive the misalignment angles to zero (Weixi, G., Lingjuan, M., & Maolin et al, 2011). The process of initial alignment can be divided into two parts. One is coarse alignment, and another is fine alignment. The initial attitudes are roughly determined during coarse alignment (Huang, Y., Zhang, Y., & Chang, L. et al, 2018). Traditionally, the time for coarse alignment is set by manual. Nonetheless, if the time is not enough to let the attitudes become convergent, the initial alignment results will become bad. Then poor alignment accuracy will end up with poor navigation

performance (Jiang, Y. F. et al, 1998). Consequently, how to determine the suitable time for coarse alignment is critical for each IMU. As for fine alignment, the Extended Kaman Filter (EKF) is adopted in the process (Li, Q., Ben, Y., Zhu, Z., & Yang, J. et al, 2013). Thus, the error model of IMU should be built. The systematic characterization of the various random errors contained in the output data of the inertial sensor can be estimated from Allan variance test (El-Sheimy, N., Hou, H., & Niu, X. et al, 2007). With the Allan variance test, the error model can be built accurately. During the entire process of initial alignment, the vibration is a major error source (Wang, W., & Chen, X. et al, 2018). Moreover, the accuracy and time of initial alignment process always suffer from the measurement noise of sensors (Rong, H., Gao, Y., Guan, L., Zhang, Q., Zhang, F., & Li, N. et al, 2019). Therefore, the outlier detection and denoising method play an important role to improve the initial alignment performance. In this research, data pre-processing methods including outlier detection and denoising are proposed. With the Allan variance test and calibration process, the initial alignment results have significant improvement. Furthermore, the time for coarse alignment can be determined automatically. 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 integrated navigation system and initial alignment process. Section 3 will show the setting of the experiments in this research. Next, the result of initial alignment with the proposed methods is presented in Section 4. In the end, conclusion is presented in Section 5.

*Corresponding author

2. METHODOLOGY

2.1 Hardware integration

To validate the initial alignment algorithm of this research, we integrate a GNSS receiver and IMU to a navigation system. For the hardware integration, the integrated navigation system developed in this study is composed of a tactical grade IMU, a GNSS receiver module, a Real Time Clock (RTC), and a microcontroller as shown in Figure 2. IMU500 whose sampling rate is 600 Hz and bias instability of gyro is about 0.3 degree per hour is selected to be the inertial sensor in this research. Septentrio Mosaic-X5 is chosen to be the GNSS receiver module. With accurate and high time resolution, RX8900SA is adopted to conduct time synchronization. For the microcontroller, it will be used to determine whether the time synchronization is done and send both of GNSS and IMU data to Inter-Process Communication (IPC). As the GNSS signal is obtained, GNSS receiver module will provide two types of signals including Pulse Per Second (PPS) and GNSS solution. When PPS signal is gained, the RTC will start to calculate the time accurately. In the meanwhile, the microcontroller will put the GPST timestamp on the IMU data. With the complete hardware integration in this research, the IMU data including GPST timestamp and GNSS PVT solution signal can be obtained continuously.

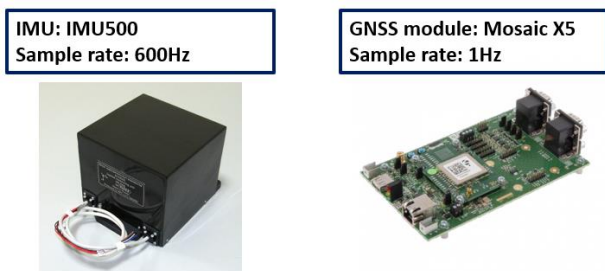


Figure 1. IMU500 and Septentrio Mosaic-X5 in the integrated navigation system

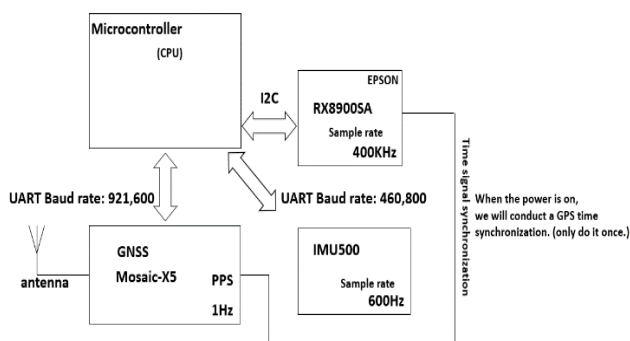


Figure 2. Hardware integration architecture

Gyroscope	
Bias instability	0.3 (deg/hour)
Angular random walk	0.007 (deg/√hour)
Accelerometers	
Bias instability	20 (μg)
Velocity random walk	0.0288 ((m/sec)/√hour)

Table 1. Specification of IMU500

2.2 Calibration Of IMU

To estimate systematic error of the measurements from IMU500, the static calibration is done for the bias and scale factor value of the accelerometers. As for the gyroscopes, a high accuracy

rotation table EVO-20M from iXBlue whose specification is shown in Table 2 is used to conduct the calibration process as shown in Figure 3. With static and dynamic calibration, the bias and scale factor can be put into the initial alignment algorithm to compensate the systematic error of IMU.

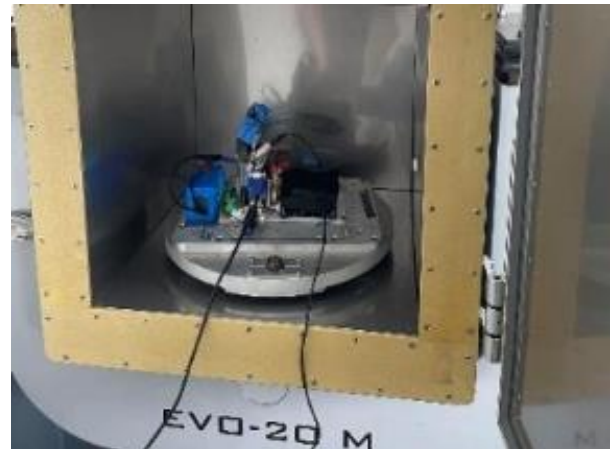


Figure 3. Dynamic calibration of IMU500

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

Table 2. Specification of EVO-20M

Furthermore, since the noise is the major factor which will cause the error in the navigation system, the error model of IMU500 should be built accurately before using the IMU measurements in the initial alignment algorithm. Most of the IMU user manuals contain the parameters of error model. However, the specification of different IMUs will not be the same. 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 3 and Table 4. The Allan variance results of IMU500 is displayed in Figure 4 and Figure 5.

Gyroscope	
Bias instability	0.3 deg/hr
Angular random walk	0.007 deg/√hr
Accelerometers	
Bias instability	20 μg
Velocity random walk	0.0288 (m/sec)/√hr

Table 3. Parameters of error model from the user manual

Gyroscope	
Bias instability	0.01 deg/hr
Angular random walk	0.005 deg/√hr
Accelerometers	
Bias instability	17 μg
Velocity random walk	0.0292 (m/sec)/√hr

Table 4. Parameters of error model from Allan variance test

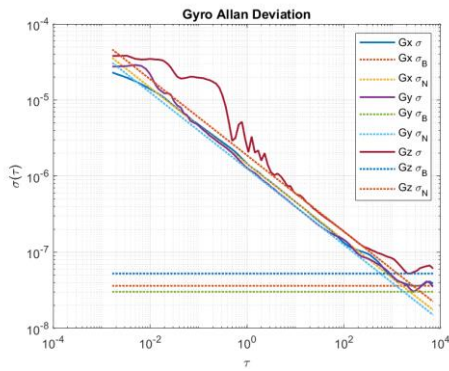


Figure 4. Allan variance result of the gyroscope

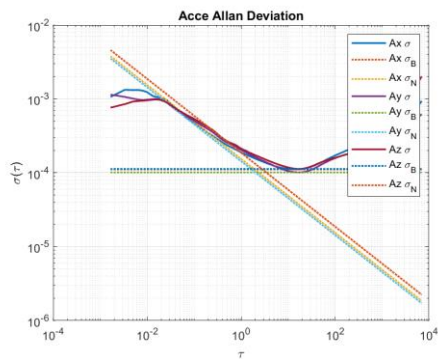


Figure 5. Allan variance result of the accelerometer

2.3 Data Pre-processing

For the pre-processing of IMU data, the approaches including the outlier detection and low-pass filter are adopted to optimize the algorithm. While the initial alignment is being conducted, there are lots of outside interference which affects the performance of initial alignment. Therefore, the standard deviation of the IMU measurements during initial alignment is calculated to build the threshold to eliminate the outliers. In this research, we set the threshold to three times the standard. If the measurements of IMU is bigger or smaller than the threshold, the measurements will not be used in the process of initial alignment. After removing the outliers, there is still some noise. During initial alignment, there is noise from external objects such as the engine of the car, the people in the car, and so on. Hence, the sinc filter is used to denoise. By these measurement processing methods, the wrong information and high frequency noise can be removed well.

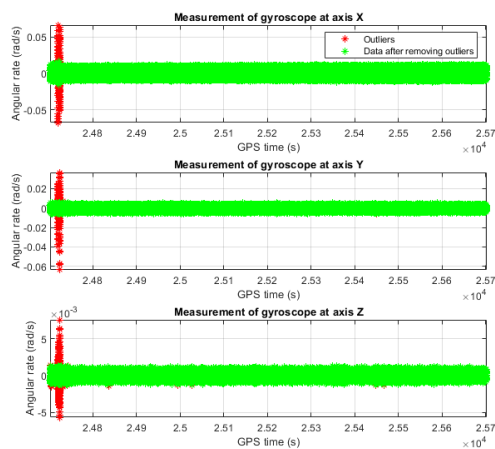


Figure 6. Gyroscope measurements after removing outliers

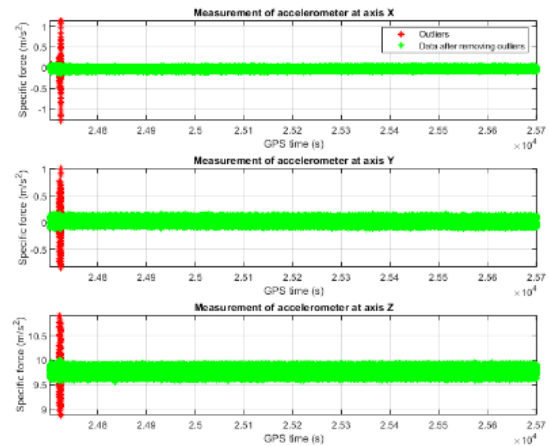


Figure 7. Accelerometer measurements after removing outliers

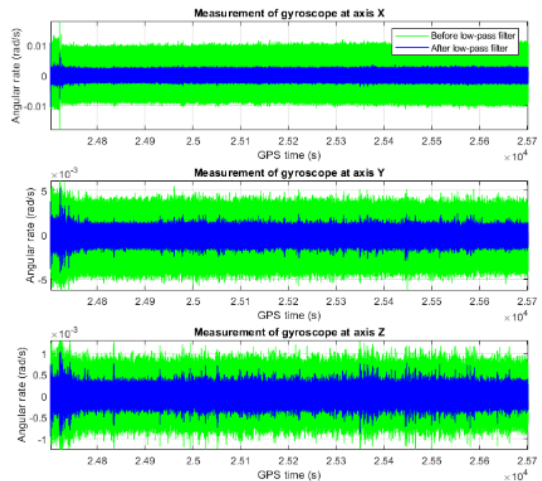


Figure 8. Gyroscope measurements after the low-pass filter

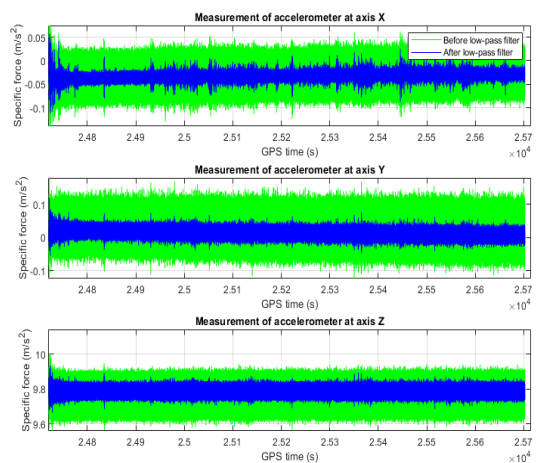


Figure 9. Accelerometer measurements after the low-pass filter

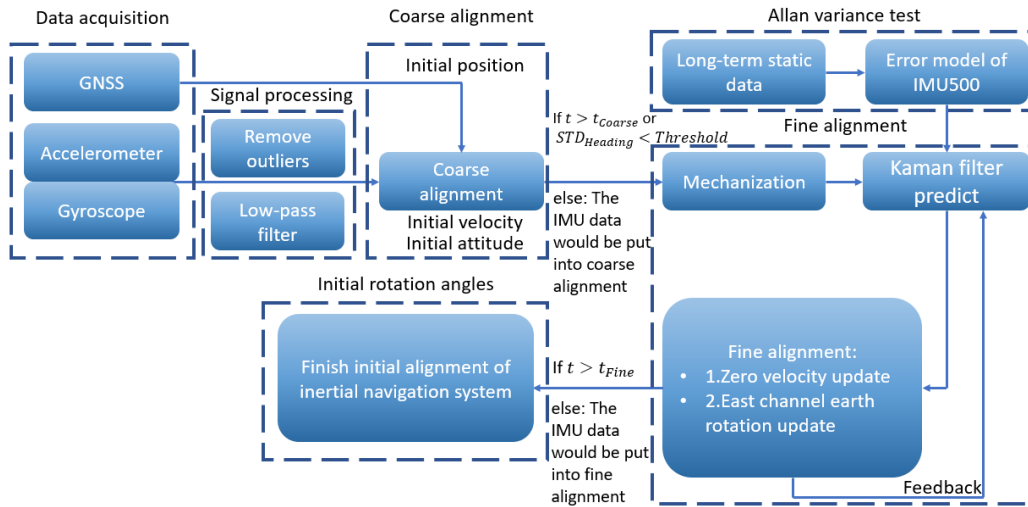


Figure 10. Flow chart of initial alignment

2.4 Initial Alignment Algorithm

As shown in Figure 10, the process of initial alignment method consists of coarse alignment and fine alignment. For the 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 of the measurements in body and navigation frame, the initial rotation angles can be obtained.

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

where f^b = specific force in body frame
 ω_{ib}^b = angular rate in body frame
 v^b = cross product of specific force and angular rate in body frame
 f^n = specific force in navigation frame
 ω_{ib}^n = angular rate in navigation frame
 v^n = cross product of specific force and angular rate in navigation frame
 C_n^b = rotation matrix from navigation frame to body frame

$$C_n^b = \begin{bmatrix} (f^n)^T \\ (\omega_{ib}^n)^T \\ (v^n)^T \end{bmatrix}^{-1} \times \begin{bmatrix} (f^b)^T \\ (\omega_{ib}^b)^T \\ (v^b)^T \end{bmatrix} \quad (2)$$

where C_b^n = rotation matrix from body frame to navigation frame

$$\begin{bmatrix} (f^n)^T \\ (\omega_{ib}^n)^T \\ (v^n)^T \end{bmatrix}^{-1} = \begin{bmatrix} 0 & 0 & -\gamma \\ \omega_e & 0 & -\omega_e \sin\varphi \\ 0 & -\gamma\omega_e \cos\varphi & 0 \end{bmatrix} \quad (3)$$

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

where ω_e = earth rotation rate
 γ = normal gravity
 φ = latitude

During conducting coarse alignment, the standard deviation of yaw angle for 10 seconds would be stored by a sliding window as shown in Figure 11. If the standard deviation of yaw angles in the sliding window is smaller than 0.1 degree, the process of coarse alignment would be terminated. With the variation of yaw angle at different time, the method of finding threshold for coarse alignment automatically is proposed in this research. The most suitable time for coarse alignment of each IMU can be obtained with the method.

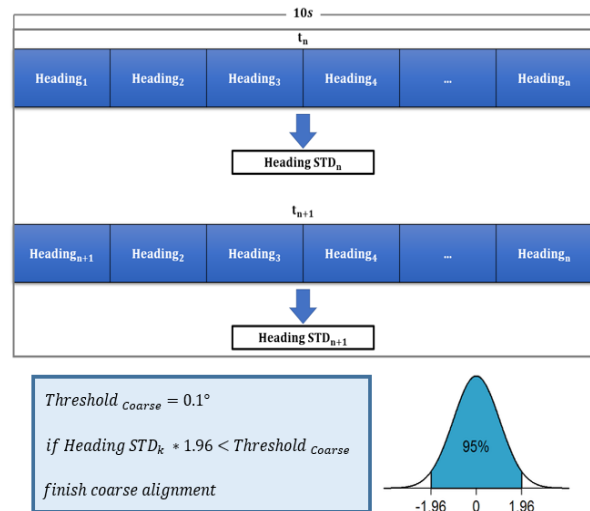


Figure 11. Automatic coarse alignment threshold finding method

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:

$$Z_{ZUPT} = [v_{ins}^n - 0_{3 \times 1}]_{3 \times 1} \quad (5)$$

where Z_{ZUPT} = the observation matrix of ZUPT.
 v_{ins}^n = the estimated velocity in navigation frame

$$H_{ZUPT} = [0_{3 \times 3} \quad I_{3 \times 3} \quad 0_{3 \times 15}]_{3 \times 21} \quad (6)$$

where H_{ZUPT} = the design matrix of ZUPT.

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

where Z_{ECERU} = the observation matrix of ECERU
 C_b^n = the estimated rotation matrix from body frame to navigation frame
 ω = angular rate of the IMU

$$H_{ECERU} = \begin{bmatrix} 0_{1 \times 6} & \omega_{ie}^n(3,1) & 0 & -\omega_{ie}^n(1,1) & \dots \\ C_b^n(2,1) & C_b^n(2,2) & C_b^n(2,3) & 0_{1 \times 9} & \dots \end{bmatrix}_{1 \times 21} \quad (8)$$

where H_{ECERU} = the design matrix of ECERU

3. EXPERIMENT SET UP

In this research, a land vehicle is used to be the platform to validate the integrated navigation system. We conduct an experiment in North Dist., Tainan City, Taiwan to verify the feasibility of the algorithm in this research. As for the reference system, Novatel PwrPak 7D-E2 is used to collect GNSS data and iMAR-iNAV-RQH-10018 is used to collect IMU data. With Novatel Inertial Explorer software, the information of position, velocity and attitude which is the reference data in this research can be acquired.

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)

Table 5. Specification of iMAR-iNAV-RQH-10018



Figure 12. Device above the car

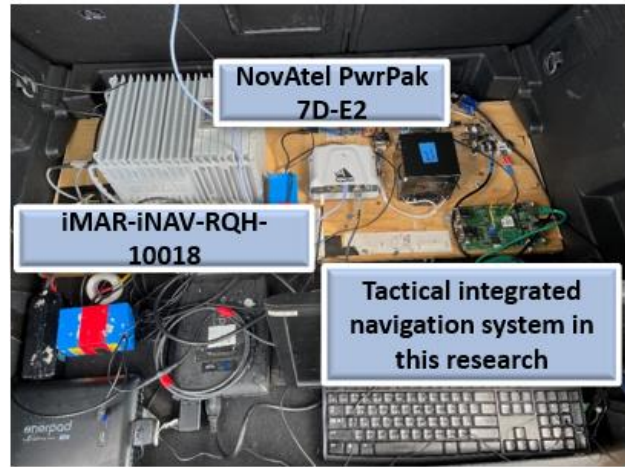


Figure 13. Device in the car

4. RESULTS

After removing the outliers and using the low-pass filter, the initial alignment results are shown in Figure 14, Figure 15, and Figure 16. From these figures, we can recognize that there is no significant improvement of roll and pitch angle. Nevertheless, the error of yaw angle becomes smaller after the data pre-processing.

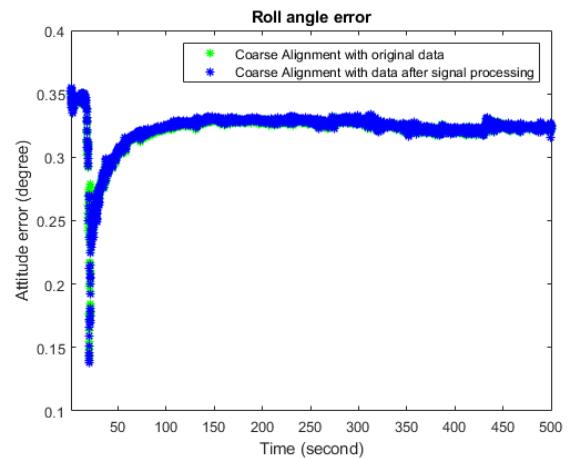


Figure 14. Roll angle error in coarse alignment

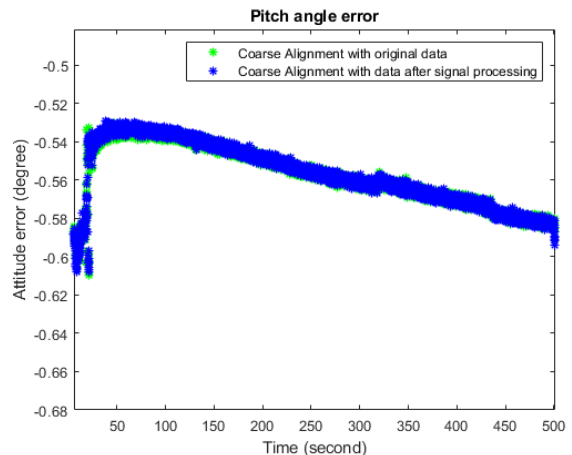


Figure 15. Pitch angle error in coarse alignment

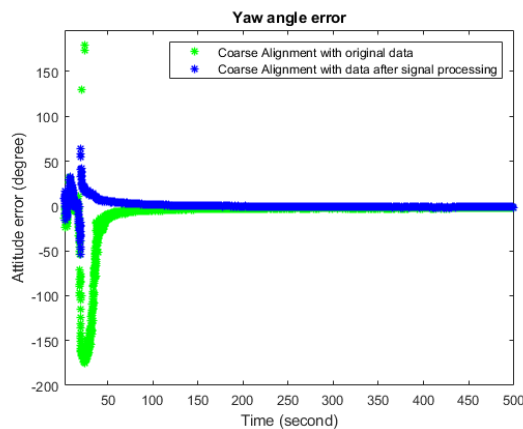


Figure 16. Yaw angle error in coarse alignment

The numerical analysis is applied to display the performance of initial alignment. From the **Table 6** and **Table 7**, the root-mean-square-error of yaw angles reduce about 6 times. We can recognize that after conducting signal processing and using parameters of error model from Allan variance test, the initial alignment performance of yaw angle during experiment becomes better.

Unit: degree	Roll	Pitch	Yaw
Mean error	0.341	-0.582	-4.732
Max error	0.419	-0.685	179.497
Std of errors	0.026	0.034	18.810
RMSE	0.342	0.583	19.396

Table 6. Accuracy of angles during conducting initial alignment with original data and parameters of the IMU error model in user manual

Unit: degree	Roll	Pitch	Yaw
Mean error	0.327	-0.584	-0.099
Max error	0.385	-0.673	63.681
Std of errors	0.013	0.033	3.347
RMSE	0.327	0.585	3.349

Table 7. Accuracy of angles during conducting initial alignment with data after processing and parameters of the IMU error model from Allan variance test

Table 8 shows the errors of three attitudes after finishing initial alignment. With the initial alignment method proposed in this research, the initial attitudes can achieve smaller than 1 degree accuracy.

Units: degree	Roll	Pitch	Yaw
Error of angle	0.322	-0.631	-0.411

Table 8. Error of angle after finishing alignment

5. CONCLUSION

In conclusion, with the method of initial alignment proposed in this research, the initial rotation matrix from body frame to navigation frame can be gained accurately. Also, the most suitable time of each IMU which is used to conduct coarse alignment can be obtained automatically. Moreover, with the measurement signal processing methods and the parameters of error model from Allan variance test, the performance of initial alignment process becomes better.

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