

# The Experimental Study on GPS/INS/DVL Integration for AUV

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**Abstract**—To Navigate the Autonomous Underwater Vehicle (AUV) accurately is one of the most important aspects in AUV's study. The paper presents the basic composition and integration method of the AUV's navigation system using Extended Kalman Filtering (EKF) technique. In the specified application, GPS receiver, Strapdown INS and Doppler Velocity Log (DVL) are mounted aboard on the test vessel. The 3-day experiment was carried out in Songhua Lake, nearby Harbin City. The test results show that the system is able to achieve high precision, which is one meter approximately, with GPS and DVL working properly. Without GPS augmentation, which is the usual configuration for AUV application, accurate positioning and navigating results are still available, provided that the DVL satisfies its working requirements. Under this situation, a 3-meter precision could be reached. Besides the theoretical and experimental analysis of the integrated navigation system, the alignment technique in swing base is also discussed in detail.

## I. INTRODUCTION

Autonomous Underwater Vehicle (AUV) has extensive applications in the martial fields and the non-martial fields. Navigation technology is becoming more and more important as a branch of AUV research. Based on the long-distance and independent characteristics of AUV, GPS/SINS/DVL integrated navigation system is in common use for its navigation.

At present, few techniques exist for reliable three-dimensional navigation of underwater vehicles. The precision and reliability of navigation devices are severely limiting the performance of fine maneuvering [1]. Strapdown Inertial Navigation System (INS) is a good choice for autonomous navigation of AUV, but its position error accumulates with time, especially in the case of low-speed, low-acceleration and long-time working regime typical for oceanographic robotic vehicles. GPS provides superior three-dimensional navigation capability for both surface and air vehicles, but its signal cannot be directly received by deeply submerged ocean vehicles. Recently, Doppler Sonar has been using in the field of measuring marine vehicles' speed. The 1200kHz bottom-lock, rated to 6000 meter depth, is an RD Instruments "Workhorse Navigator" unit equipped with four acoustic beams, an internal flux-gate compass, roll/pitch sensors, and

temperature sensor[2].

The paper reports the design, implementation, and field-evaluation of the integration of GPS/INS/DVL navigation system and gives the lake test and land test results.

## II. GPS/INS/DVL INTEGRATIO MODEL

### Strapdown INS Model:

The position error, velocity error, misalignment angle and gyro drift are chosen as the elements of state variable aiming at constructing the Kalman filter. The gyro drift's error model is treated as a first-order Markov process. The accelerometer has high precision and steady performance, so the random time-varying drift caused by accelerometer is taken into account in the accelerometer error model. The corresponding linear error equation of SINS is as follows [3][4]:

$$\begin{aligned} \delta\dot{\varphi} &= \frac{1}{R_m} \delta V_y \\ \delta\dot{\lambda} &= \frac{V_x \tan \varphi}{R_n \cos \varphi} \delta\varphi + \frac{1}{R_n \cos \varphi} \delta V_x \\ \delta\dot{V}_x &= (2\Omega_e V_y + \frac{V_x V_y}{R_n \cos^2 \varphi}) \delta\varphi + \frac{V_x \tan \varphi}{R_n} \delta V_x + (2\Omega_e + \frac{V_x \tan \varphi}{R_n}) \delta V_y - f'_x \phi_x + f'_y \phi_y + a_x \\ \delta\dot{V}_y &= -(2\Omega_e V_x + \frac{V_x^2}{R_n \cos^2 \varphi}) \delta\varphi - (2\Omega_e + \frac{2V_x \tan \varphi}{R_n}) \delta V_x + f'_x \phi_x - f'_y \phi_y + a_y \\ \dot{\phi}_x &= -\frac{1}{R_m} \delta V_y + (\Omega_e + \frac{V_x \tan \varphi}{R_n}) \phi_x - (\Omega_e + \frac{V_y}{R_n}) \phi_y + C_{11} \varepsilon_x + C_{12} \varepsilon_y + C_{13} \varepsilon_z \\ \dot{\phi}_y &= -\Omega_e \delta\varphi + \frac{1}{R_n} \delta V_x - (\Omega_e + \frac{V_x \tan \varphi}{R_n}) \phi_x - \frac{V_y}{R_n} \phi_y + C_{21} \varepsilon_x + C_{22} \varepsilon_y + C_{23} \varepsilon_z \\ \dot{\phi}_z &= (\Omega_e + \frac{V_x}{R_n \cos^2 \varphi}) \delta\varphi + \frac{\tan \varphi}{R_n} \delta V_x + (\Omega_e + \frac{V_x}{R_n}) \phi_x + \frac{V_y}{R_n} \phi_y + C_{31} \varepsilon_x + C_{32} \varepsilon_y + C_{33} \varepsilon_z \\ \dot{\varepsilon}_x &= -\beta_x \varepsilon_x + w_x \\ \dot{\varepsilon}_y &= -\beta_y \varepsilon_y + w_y \\ \dot{\varepsilon}_z &= -\beta_z \varepsilon_z + w_z \end{aligned}$$

Where

$\delta\varphi, \delta\lambda$  ---latitude and longitude error, respectively;  
 $\delta V_x, \delta V_y$  ---east and north velocity error, respectively;  
 $V_x, V_y$  ---east and north velocity, respectively;  
 $\phi_x, \phi_y$  ---north and east horizontal misalignment angle;  
 $\phi_z$  ---azimuth misalignment angle;  
 $R_m, R_n$  ---the radii of curvature of the reference ellipsoid in Prime Meridian and Vertical Meridian, respectively;  
 $f'_x, f'_y, f'_z$  ---the projection on the local-level frame of the

accelerator's measurement;  
 $C'_b(C_{ij}, i, j = 1,2,3)$  ---attitude matrix;  
 $\omega_{ie}$  ---earth's rate;  
 $\Omega_y = \omega_{ie} \cos \varphi, \Omega_z = \omega_{ie} \sin \varphi$ ;  
 $a_x, a_y$  --- the accelerometer random drift;  
 $\varepsilon_x, \varepsilon_y, \varepsilon_z$  ---gyro drift;  
 $\beta_x^{-1}, \beta_y^{-1}, \beta_z^{-1}$  ---correlative time of gyro drift; and  
 $w_x, w_y, w_z$  --- stimulating white noise.

### DVL error model

According to the principle of DVL, it measures the velocity and log angle relative to the seabed. The measuring error consists of velocity offset's error  $\delta V_d$ , log misalignment angle error  $\delta \Delta$ , expressed by first-order Markov process, and scale coefficient error, which is random constant drift. The error equation is

$$\left. \begin{aligned} \delta \dot{V}_d &= -\beta_d \delta V_d + w_d \\ \delta \dot{\Delta} &= -\beta_\Delta \delta \Delta + w_\Delta \\ \delta \dot{C} &= 0 \end{aligned} \right\}$$

Where

$\beta_d^{-1}, \beta_\Delta^{-1}$  ---correlative time of velocity offset's error and log misalignment angle error;  
 $w_x, w_y, w_z$  ---stimulating white noise.

As for the model of GPS receiver, it is so common that it can be found in many literatures [5].

## III. TEST RESULTS

The lake test was carried out during Oct. 15-17, 2003 in Songhua Lake, Jinlin Province, near Harbin Engineering University. The lake is 30m to 90m deep and suitable for acoustic study.

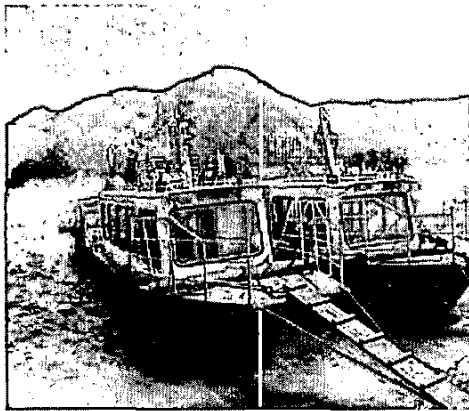


Fig. 1. Fixing of Test Devices

### The Fixing of Devices

The Fiber-Optic Gyro INS model PHINS imported from France, GPS receiver model GG24 from Ashtech Company

and DVL model Workhorse300 from RDI Company were fixed in the two boats, shown in Fig. 1. The two boats were attached by slot wares and brackets with 40cm gap, though which the DVL was put beneath 1.5m underwater. And the antenna of GPS receiver was put on the roof of one of the boats.

### Experiments Phases

The experiment was carried out by three phases, i.e. preparation phase, performance test phase, and long-distance test phase.

#### PHASE I: preparation phase

In this phase, the GPS positioning data was regarded as the benchmark. The integrated navigation system of INS/DVL behaved very well, shown in Fig. 2, which position error was no more than 3 meters.

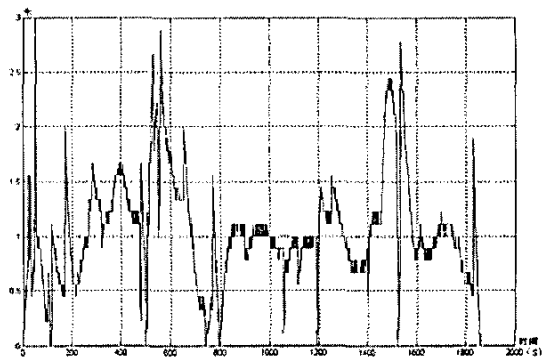


Fig.2. Error curve of integrated navigation system compared to GPS position

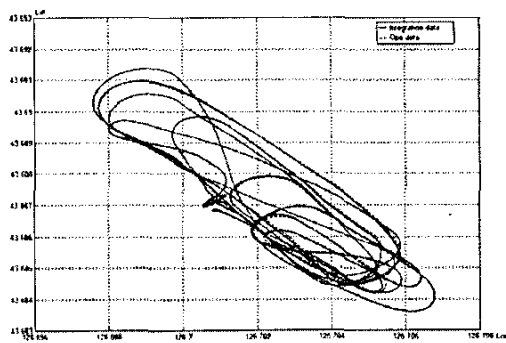


Fig.3. Trajectory of Test Vessel

#### PHASE II: performance test

During Phase II, in the valid area of DVL, the integrated navigation system was tested in the following trajectory, shown in Fig. 3. Using the DGPS data as the reference, the

position error and velocity error were shown in Fig.4 and Fig. 5, respectively. It can be seen that the positioning error of integrated navigation system didn't accumulate during the test period and the maximum error was 14 meters. And its average position error was only 3.825 meters.

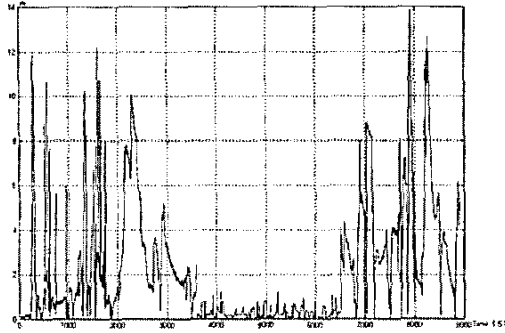


Fig. 4. Position Error of Integrated System

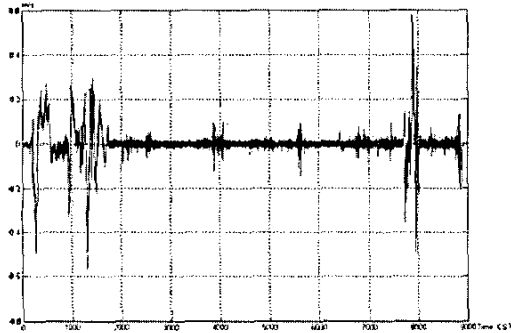


Fig. 5. Velocity Error of Integrated System

### PHASE III: long-distance test

This phase was a long distance voyage, shown in Fig. 6. At the very beginning, INS/DVL/GPS integrated navigation system was used to align the INS. After a while, INS/DVL was adopted to test the different integration modes, during which stand-by GPS data of 4 minutes were used to correct the system. Using DGPS as the reference, three typical parts were chosen to illustrate the integration effect.

Due to invalidity of DVL, the first part was chosen to illustrate the accumulation of position error compared to GPS, shown in Fig. 7. The second part was chosen just after the integrated navigation system was corrected by stand-by GPS data, shown in Fig. 8. And the last part was chosen to test the pure INS performance when the DVL data is not available, shown in Fig. 9.

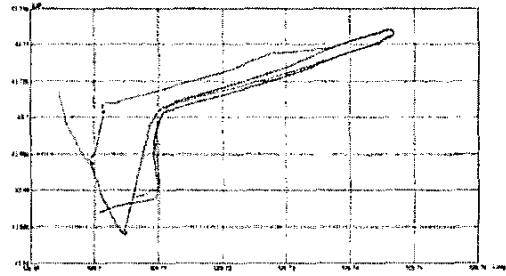


Fig. 6. Trajectory of Integrated Navigation System

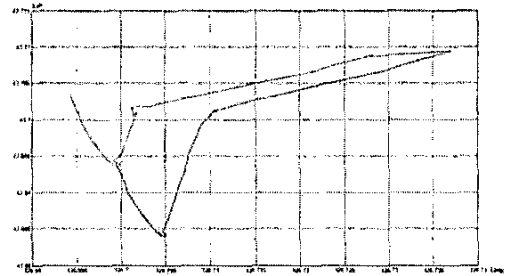


Fig. 7. Accumulation of position error due to invalidity of DVL

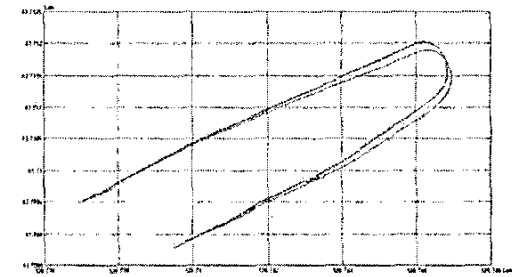


Fig. 8. Corrected by GPS data

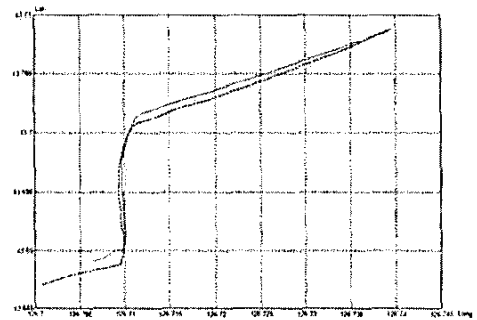


Fig. 9. Pure INS Performance

From above test results, it can be seen that the average position error reached 870.6m because of the long-time invalidity of DVL. After the INS/DVL was corrected by GPS,

the position error was rapidly reduced to 6.3m average. Meanwhile, it can be found that the position error of pure INS didn't increase very fast (about 132.3m after 40 minutes) without DVL data. It should be mentioned that DGPS data was used as reference during the whole experiment.

A land test was also carried out around Harbin Engineering University campus, which is shown in Fig. 10. In the test, only GPS/INS integration was observed. The result showed that the integration is much better than INS/DVL with average error of 12.2 meters.



Fig. 10. A Land Test of GPS/INS integration

#### IV. CONCLUSION

Aiming at the self-characteristic of AUV, the paper proposes a Kalman filter method working in the GPS/SINS/DVL integrated mode which combines output of SINS, DVL and GPS (when available). The lake tests and land test results show that the integrated navigation system is effective on limiting the position errors and velocity errors of SINS and DVL equipped onboard the vehicles. The results also show that the system can satisfy the AUV's requirements for long-time working characteristic and high navigational precision.

#### ACKNOWLEDGMENTS

We gratefully acknowledge the invaluable collaboration and support of Acoustic Engineering College at Harbin Engineering University. The land test figure is courtesy of Dr. Yuxin Zhao, Automation College of Harbin Engineering University.

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