

Research Article

Modified Sage-Husa Adaptive Kalman Filter-Based SINS/DVL Integrated Navigation System for AUV

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This paper presents a modified Sage-Husa adaptive Kalman filter-based SINS/DVL integrated navigation system for the autonomous underwater vehicle (AUV), where DVL is employed to correct the navigation errors of SINS that accumulate over time. When negative definite items are large enough, different from the positive definiteness of noise matrices which cannot be guaranteed for the conventional Sage-Husa adaptive Kalman filter, the proposed modified Sage-Husa adaptive Kalman filter deletes the negative definite items of adaptive update laws of the noise matrix to ensure the convergence of the Sage-Husa adaptive Kalman filter. In other words, this method sacrifices some filtering precision to ensure the stability of the filter. The simulation tests are implemented to verify that expected navigation accuracy for AUV can be obtained using the proposed modified Sage-Husa adaptive Kalman filter.

1. Introduction

Autonomous underwater vehicle (AUV) has been widely used in ocean exploration, where accurate navigation and positioning ability are essential to ensure the long voyage operation of AUV. Considering the underwater environment, various navigation methods cannot be applied to the AUV, such as optical navigation, radio navigation, and satellite navigation. In response to this problem, a lot of novel navigation methods are studied in [1–3].

Since the strapdown inertial navigation (SINS) is with the advantages of strong autonomy, high precision, and full navigation parameters, it is widely used in the navigation system of AUV. However, the navigation error of SINS is accumulated over time, which results in low navigation accuracy. In view of this problem, the Doppler velocimeter (DVL) is combined with SINS in [4–7] to construct the SINS/DVL integrated navigation system, where the navigation error of SINS is corrected by the DVL. To provide the accurate initial attitude angles to the SINS/DVL integrated navigation sys-

tem, the initial attitude alignment algorithms for SINS/DVL are studied. In [8, 9], the robust alignment methods are proposed to improve the alignment accuracy in complex working environment. In [10], a new Kalman filter-based alignment method is presented to modify the initial attitude alignment algorithm. But the state equations of above studies ignore the error of DVL, such as the calibration coefficient error, the velocity deviation error, and the drift angle error. That results in limited navigation accuracy.

For the SINS/DVL integrated navigation system, how to integrate the output information of SINS and DVL to obtain high-precision navigation information is the core issue. Since the Kalman filter is able to estimate the system states in the presence of noises, it is widely applied in the SINS/DVL integrated navigation system. However, the inaccurate measurement model under the time-varying measurement noise results in substantial estimation errors or even filter divergence. To solve this problem, the interacting multiple model algorithm which uses more than one model is proposed in [11], where a variable model set based on the model

probability weighted average of the model parameter is generated to pursue the real model. Considering the nonlinearity of the model of SINS/DVL, the square root unscented information filter is designed in [12], the randomly weighted cubature Kalman filter is discussed in [13], and the unscented Kalman filter (UKF) is employed in [14–16]. Furthermore, considering the influence of unknown environment and the inexact error model caused by model simplification, various adaptive Kalman filters are proposed in [17–20], where statistical characteristics of noises are online estimated in [17–19] and the recursive filtering gain is adaptively adjusted in [20]. However, the adaptive filter might be divergent when the positive definiteness of noise matrix cannot be guaranteed.

In this paper, a modified Sage-Husa adaptive Kalman filter-based SINS/DVL integrated navigation system is proposed to provide the AUV with accurate navigation parameters, where the adaptive update laws of the noise matrix are modified by deleting the negative definite items. Therefore, the filtering convergence can be guaranteed, while the expected filtering accuracy can be obtained.

The rest of this paper is organized as follows. The error equations of SINS and DVL are given in Section 2. The Kalman filter equation and a modified Sage-Husa adaptive Kalman filter for the SINS/DVL integrated navigation system are presented in Section 3. Numerical simulations are conducted to verify the superiority of the proposed approach in Section 4. Conclusions are drawn in Section 5.

2. Error Equations of SINS And DVL

2.1. Error Equations of Strapdown Inertial Navigation. When the AUV moves on the water surface, considering the drift of the gyroscopes and accelerometer, the error equations of SINS are presented.

Define the longitude and latitude as L and λ , the longitude error and latitude error as δL and $\delta \lambda$, the east and north velocity as v_x and v_y , the east and north velocity error as δv_x and δv_y , the earth radius as R , the angular velocity of the earth as ω_{ie} , the output of accelerometer in the navigation coordinate system as f_x , f_y , and f_z , the horizontal drift of the accelerometer in the navigation coordinate system as ∇_x and ∇_y , and the drift of the gyroscope in the navigation coordinate system as ε_x , ε_y , and ε_z . Then, the attitude error equation is calculated as

$$\begin{aligned}\dot{\varphi}_x &= -\frac{\delta v_y}{R} + \left(\omega_{ie} \sin L + \frac{v_x}{R} \tan L\right) \varphi_y - \left(\omega_{ie} \cos L + \frac{v_x}{R}\right) \varphi_z + \varepsilon_x, \\ \dot{\varphi}_y &= -\omega_{ie} \sin L \delta L + \frac{\delta v_x}{R} - \left(\omega_{ie} \sin L + \frac{v_x}{R}\right) \varphi_x - \frac{v_y}{R} \varphi_z + \varepsilon_y, \\ \dot{\varphi}_z &= \left(\omega_{ie} \cos L + \frac{v_x}{R} \sec^2 L\right) \delta L + \frac{\tan L}{R} \delta v_x + \left(\omega_{ie} \cos L + \frac{v_x}{R}\right) \varphi_x + \frac{v_y}{R} \varphi_y + \varepsilon_z.\end{aligned}\quad (1)$$

The horizontal position error equation of SINS is calculated as

$$\begin{aligned}\delta \dot{L} &= \frac{\delta v_y}{R}, \\ \delta \dot{\lambda} &= \frac{\delta v_x}{R} \sec L + \frac{v_x}{R} \delta L \tan L \sec L.\end{aligned}\quad (2)$$

The horizontal velocity error equation of SINS is calculated as

$$\begin{aligned}\delta \dot{v}_x &= \left(2\omega_{ie} v_y \cos L + \frac{v_x v_y}{R} \sec^2 L\right) \delta L + \frac{v_y}{R} \tan L \delta v_x \\ &\quad + \left(2\omega_{ie} \sin L + \frac{v_y}{R} \tan L\right) \delta v_y - f_z \varphi_y + f_y \varphi_z + \nabla_x, \\ \delta \dot{v}_y &= -\left(2\omega_{ie} v_x \cos L + \frac{v_x^2}{R} \sec^2 L\right) \delta L \\ &\quad - 2\left(\omega_{ie} \sin L + \frac{v_x}{R} \tan L\right) \delta v_x + f_z \varphi_x - f_x \varphi_z + \nabla_y.\end{aligned}\quad (3)$$

The drift of the gyroscope in the navigation coordinate system can be described as

$$\varepsilon^n = C_b^n \varepsilon^b, \quad (4)$$

where C_b^n is the attitude matrix, and the drift of the gyroscope in the body coordinate system can be described as

$$\begin{aligned}\dot{\varepsilon}_x^b &= -\beta_g \varepsilon_x^b + \omega_x, \\ \dot{\varepsilon}_y^b &= -\beta_g \varepsilon_y^b + \omega_y, \\ \dot{\varepsilon}_z^b &= -\beta_g \varepsilon_z^b + \omega_z,\end{aligned}\quad (5)$$

with the correlation time β_g , the drift of the gyroscope in the body coordinate system ε_x^b , ε_y^b , and ε_z^b , and the white noise ω_x , ω_y , and ω_z .

2.2. Error Equations of the Doppler Velocimeter. For the four-beam Doppler velocimeter, the calibration coefficient error is defined as δC , the velocity deviation error is defined as δv_d , and the drift angle error is defined as $\delta \Delta$. Then, the output of the Doppler velocimeter can be presented as

$$\begin{aligned}v'_{dx} &= (1 + \delta C)(v_d + \delta v_d) \sin(K_v + \varphi_z + \delta \Delta), \\ v'_{dy} &= (1 + \delta C)(v_d + \delta v_d) \cos(K_v + \varphi_z + \delta \Delta),\end{aligned}\quad (6)$$

where φ_z is the azimuth angle, K_v is the track angle, and v_d is the true velocity.

Since δC , δv_d , $\delta \Delta$, and φ_z are small, ignoring the small quantities of the second order, equation (6) can be simplified as

$$\begin{aligned}v'_{dx} &= v_x + v_y(\varphi_z + \delta \Delta) + \delta C \cdot v_x + \delta v_d \sin K_v, \\ v'_{dy} &= v_y - v_x(\varphi_z + \delta \Delta) + \delta C \cdot v_y + \delta v_d \cos K_v,\end{aligned}\quad (7)$$

where

$$\begin{aligned}
v_x &= v_d \sin K_v, \\
v_y &= v_d \cos K_v, \\
\delta v_{dx} &= \delta v_d \sin K_v, \\
\delta v_{dy} &= \delta v_d \cos K_v, \\
\delta \dot{v}_d &= -\beta_d \delta v_d + \omega_d, \\
\delta \dot{\Delta} &= -\beta_\Delta \delta \Delta + \omega_\Delta, \\
\delta \dot{C} &= 0,
\end{aligned} \tag{8}$$

with the correlation time β_d and β_Δ and the white noise ω_d and ω_Δ .

3. SINS/DVL Integrated Navigation System

3.1. State Equation and Measurement Equation. Since the navigation error of SINS is accumulated over time, the four-beam Doppler velocimeter is used to correct the navigation information of SINS. Define the state vector as $X = [\delta L, \delta \lambda, \delta v_x, \delta v_y, \varphi_x, \varphi_y, \varphi_z, \varepsilon_x, \varepsilon_y, \varepsilon_z, \delta V_d, \delta \Delta, \delta C]^T$.

The state equation is presented as

$$\dot{X} = AX + BW, \tag{9}$$

where $W = [0, 0, a_x, a_y, 0, 0, 0, \omega_x, \omega_y, \omega_z, \omega_d, \omega_\Delta, 0]^T$ is the noise matrix, A is the state-transition matrix, B is the noise distribution matrix, and

$$A = \begin{bmatrix} A_{\text{SINS}4 \times 7} & 0_{4 \times 3} & 0_{4 \times 3} \\ A_{\text{SINS}3 \times 7} & C_{b3 \times 3}^n & 0_{3 \times 3} \\ 0_{3 \times 7} & A_{\text{Gyro}3 \times 3} & 0_{3 \times 3} \\ 0_{3 \times 7} & 0_{3 \times 3} & A_{\text{DVL}3 \times 3} \end{bmatrix}, \tag{10}$$

$$B = I_{13 \times 13},$$

with

$$A_{\text{Gyro}3 \times 3} = \begin{bmatrix} -\beta_g & 0 & 0 \\ 0 & -\beta_g & 0 \\ 0 & 0 & -\beta_g \end{bmatrix}, \tag{11}$$

$$A_{\text{DVL}3 \times 3} = \begin{bmatrix} -\beta_d & 0 & 0 \\ 0 & -\beta_\Delta & 0 \\ 0 & 0 & 0 \end{bmatrix}.$$

Since the velocity is selected as the measurement, the measurement equation is presented as

$$Z = \begin{bmatrix} Z_x \\ Z_y \end{bmatrix} = \begin{bmatrix} v_{sx} - v'_{dx} \\ v_{sy} - v'_{dy} \end{bmatrix}, \tag{12}$$

where

$$\begin{aligned}
v_{sx} &= v_x + \delta v_x, \\
v_{sy} &= v_y + \delta v_y.
\end{aligned} \tag{13}$$

From equations (7) and (12), it is calculated that

$$\begin{aligned}
Z_x &= \delta v_x - v_y(\varphi_z + \delta \Delta) - \delta V_d \sin K_v - \delta C v_x + \eta_x, \\
Z_y &= \delta v_y + v_x(\varphi_z + \delta \Delta) - \delta V_d \cos K_v - \delta C v_y + \eta_y,
\end{aligned} \tag{14}$$

where η_x and η_y are the system measured noises.

Thus, equation (12) can be rewritten as

$$Z = HX + V, \tag{15}$$

where

$$H = \begin{bmatrix} 0 & 0 & 1 & 0 & 0 & 0 & -v_y & 0 & 0 & 0 & -\sin K_v & -v_y & -v_x \\ 0 & 0 & 0 & 1 & 0 & 0 & v_x & 0 & 0 & 0 & -\cos K_v & v_x & -v_y \end{bmatrix} V = [\eta_x, \eta_y]^T. \tag{16}$$

By discretizing the state (equation (9)) and measurement (equation (15)), the Kalman filter equation of the SINS/DVL integrated navigation system is obtained as

$$\begin{aligned}
X_k &= \phi_{k/k-1} X_{k-1} + \Gamma_{k-1} W_{k-1}, \\
Z_k &= H_k X_k + V_k,
\end{aligned} \tag{17}$$

where X_k is the state vector at time k , Z_k is the measurement vector at time k , H_k is the measurement matrix at time k , V_k is the system measurement noise matrix at time k , X_{k-1} is the state vector at time $k-1$, W_{k-1} is the noise matrix at time $k-1$, Γ_{k-1} is the noise distribution matrix at time $k-1$, $\phi_{k/k-1}$ is the state one-step transition matrix, and W_k and V_k are white Gaussian noises with $W_k \sim WN(q_k, Q_k)$, $V_k \sim WN(r_k, R_k)$, and

$$\begin{aligned}
\phi_{k/k-1} &= I_{13 \times 13} + AT, \\
\Gamma_{k-1} &= BT, \\
H_k &= H,
\end{aligned} \tag{18}$$

with the sampling period T .

3.2. Modified Sage-Husa Adaptive Kalman Filter. Due to the fact that the measurement noises of the Kalman filter equation are usually time-varying and difficult to be accurately predicted in the practical environment, the filter accuracy of the conventional Kalman filter is easy to be decreased and even be divergent. In response to this problem, the Sage-Husa adaptive Kalman filter is proposed to improve the filter performance by estimating the unknown noises,

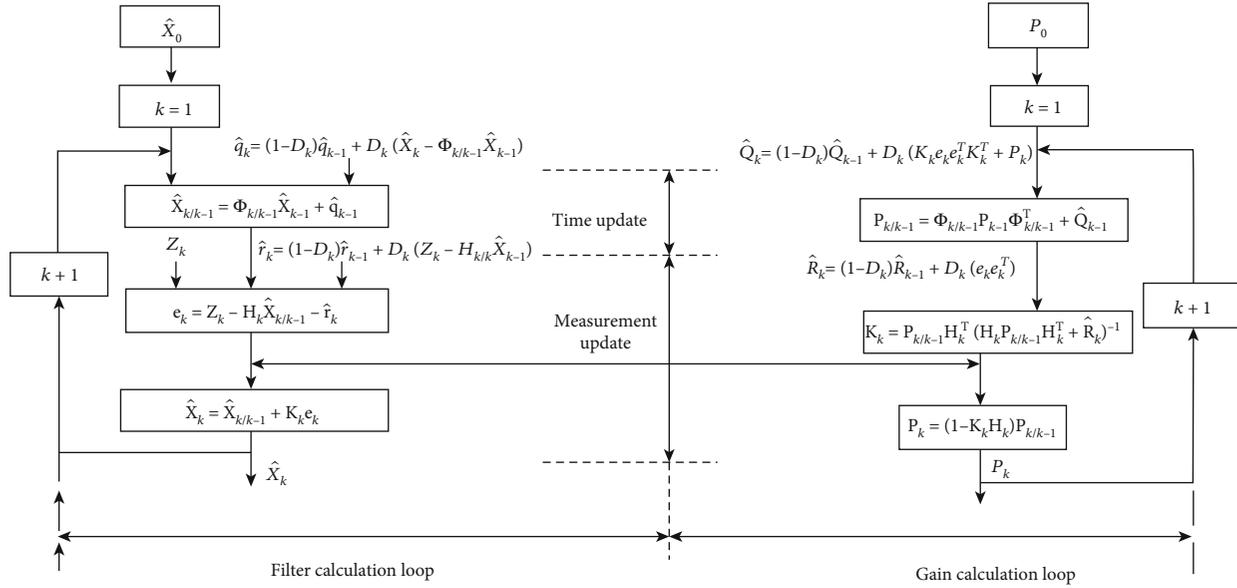


FIGURE 1: Calculation loop of the modified Sage-Husa adaptive Kalman filter.

whose calculation loop is presented in Figure 1. The Sage-Husa adaptive Kalman filter is designed as

$$\begin{aligned}
 \hat{X}_{k/k-1} &= \Phi_{k/k-1}\hat{X}_{k-1} + \hat{q}_{k-1}, \\
 P_{k/k-1} &= \Phi_{k/k-1}P_{k-1}\Phi_{k/k-1}^T + \hat{Q}_{k-1}, \\
 e_k &= Z_k - H_k\hat{X}_{k/k-1} - \hat{r}_k, \\
 K_k &= P_{k/k-1}H_k^T(H_k P_{k/k-1}H_k^T + R_k)^{-1}, \\
 \hat{X}_k &= \hat{X}_{k/k-1} + K_k e_k, \\
 P_k &= (1 - K_k H_k)P_{k/k-1},
 \end{aligned} \tag{19}$$

where

$$\begin{aligned}
 \hat{r}_k &= (1 - D_k)\hat{r}_{k-1} + D_k(Z_k - H_k\hat{X}_{k/k-1}), \\
 \hat{R}_k &= (1 - D_k)\hat{R}_{k-1} + D_k(e_k e_k^T - H_k P_{k/k-1} H_k^T), \\
 \hat{q}_k &= (1 - D_k)\hat{q}_{k-1} + D_k(\hat{X}_k - \Phi_{k/k-1}\hat{X}_{k-1}), \\
 \hat{Q}_k &= (1 - D_k)\hat{Q}_{k-1} + D_k(K_k e_k e_k^T K_k^T \\
 &\quad + P_k - \Phi_{k/k-1}P_{k-1}\Phi_{k/k-1}^T), \\
 D_k &= \frac{D_{k-1}}{D_{k-1} + b}, \quad D_0 = 1,
 \end{aligned} \tag{20}$$

with the forgetting factor b and $b \in (0.95 \sim 0.999)$.

To suppress filter divergence, \hat{Q}_k must be nonnegative definite and \hat{R}_k must be positive definite. However, considering the existence of $-\Phi_{k/k-1}P_{k-1}\Phi_{k/k-1}^T$ and $-H_k P_{k/k-1} H_k^T$ in the above equation, the positive definiteness of \hat{Q}_k and \hat{R}_k cannot be guaranteed. Since $-\Phi_{k/k-1}P_{k-1}\Phi_{k/k-1}^T$ and $-H_k P_{k/k-1} H_k^T$ have little influence on filter accuracy, they can be

deleted to ensure the convergence of the Sage-Husa adaptive Kalman filter. In other words, this method sacrifices some filtering precision to ensure the stability of the filter.

Thus, \hat{Q}_k and \hat{R}_k are modified as

$$\begin{aligned}
 \hat{R}_k &= (1 - D_k)\hat{R}_{k-1} + D_k(e_k e_k^T), \\
 \hat{Q}_k &= (1 - D_k)\hat{Q}_{k-1} + D_k(K_k e_k e_k^T K_k^T + P_k).
 \end{aligned} \tag{21}$$

From equation (21), it is obtained that both \hat{Q}_k and \hat{R}_k are affected by the innovation vector e_k . That means that the filter accuracy cannot be guaranteed when \hat{Q}_k and \hat{R}_k are changing abnormally with e_k . In response to this problem, \hat{Q}_k is assumed to be known such that \hat{R}_k can be accurately estimated.

4. Simulation

In this section, numerical simulations are investigated to verify that expected navigation accuracy can be obtained under the proposed modified Sage-Husa adaptive Kalman filter-based SINS/DVL integrated navigation system for AUV.

The forgetting factor of the modified Sage-Husa adaptive Kalman filter is set as $b = 0.99$. For the gyroscopes of SINS, the constant drift is $0.01^\circ/\text{h}$ and the random drift is $0.001^\circ/\sqrt{\text{h}}$. For the accelerometers of SINS, the constant drift is $10 \mu\text{g}$ and the random drift is $3 \mu\text{g}/\sqrt{\text{s}}$. The velocity measurement error of DVL is 0.5%. The initial covariance matrix is set as $P_0 = \text{diag} \{ [1.5679 \times 10^{-5} \text{rad}, 1.5679 \times 10^{-5} \text{rad}, 5 \text{ m/s}, 5 \text{ m/s}, 10^\circ, 10^\circ, 10^\circ, 0.1^\circ/\text{h}, 0.1^\circ/\text{h}, 0.1^\circ/\text{h}, 0.005 \text{ m/s}, 1', 0.0001]^2 \}$, the initial variance matrix of state noise is set as $Q_0 = \text{diag} \{ [0, 0, 5 \times 10^{-4} \text{g}, 2 \times 10^{-4} \text{g}, 0.1^\circ/\text{h}, 0.1^\circ/\text{h}, 0.1^\circ/\text{h}, 0, 0, 0, 0.005 \times (1 - e^{-2\beta_d T}) \text{ m/s}, 1 \times (1 - e^{-2\beta_d T})', 0.0001]^2 \}$ with $\beta_d^{-1} = 5 \text{ min}$, and the variance matrix of measurement noise is set as $R_0 = \text{diag} \{ [0.01 \text{ m/s}, 0.01 \text{ m/s}]^2 \}$.

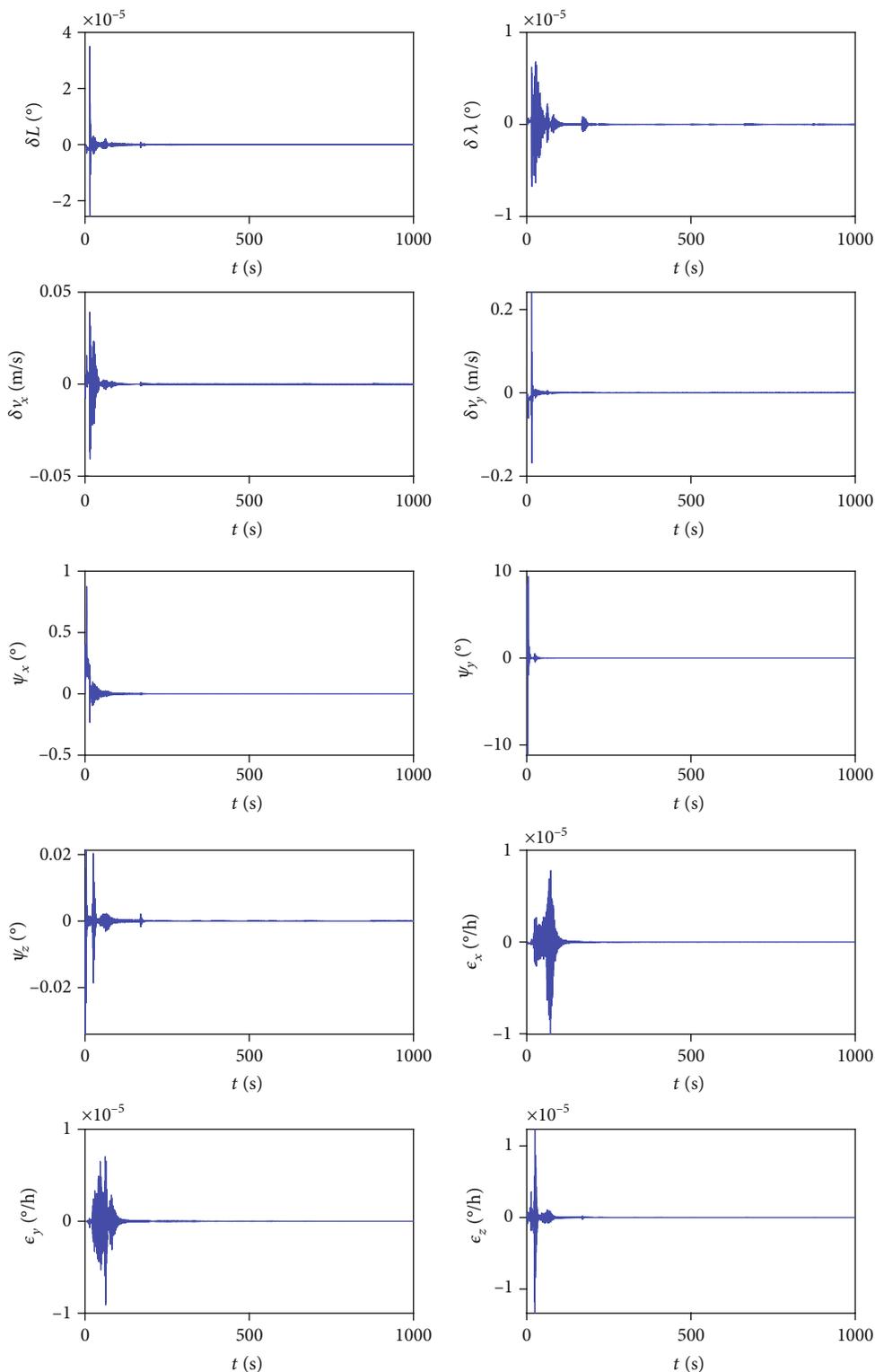


FIGURE 2: System states of the Kalman filter for the SINS/DVL integrated navigation system.

The simulations are presented in Figures 2–6. From the system states of the Kalman filter for the SINS/DVL integrated navigation system presented in Figure 2, it is observed that all the system states can converge to the constants. Then, velocities and positions of AUV under the SINS and SINS/DVL integrated navigation system are presented in

Figures 3–6. From Figures 3 and 4, velocity measurements under two navigation systems are with local differences. Furthermore, the velocity errors shown in Figure 4 depicted that under the SINS/DVL integrated navigation system, the velocity errors converge to zero, where velocity errors of SINS are diverging. Positions of AUV under the SINS and SINS/DVL

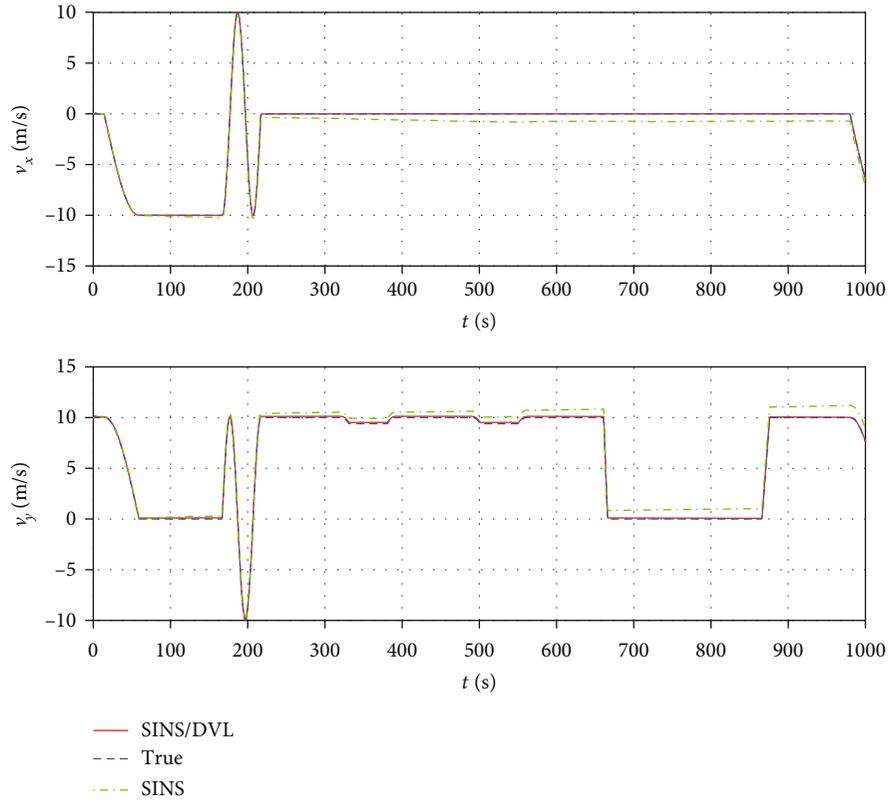


FIGURE 3: Velocities of the SINS and SINS/DVL integrated navigation system.

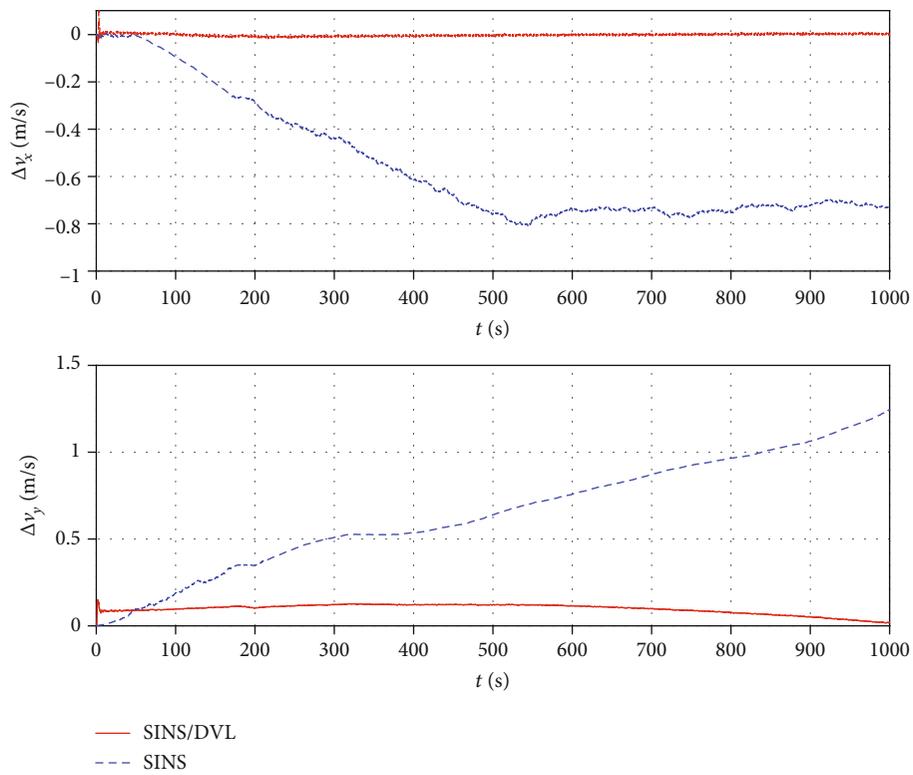


FIGURE 4: Velocity errors of the SINS and SINS/DVL integrated navigation system.

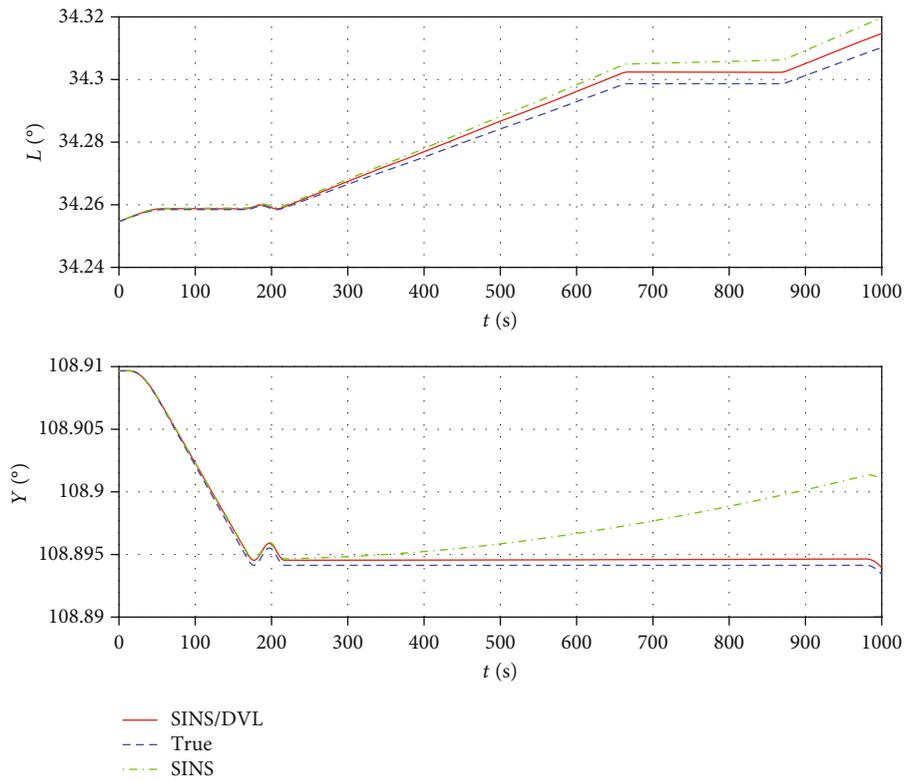


FIGURE 5: Positions of the SINS and SINS/DVL integrated navigation system.

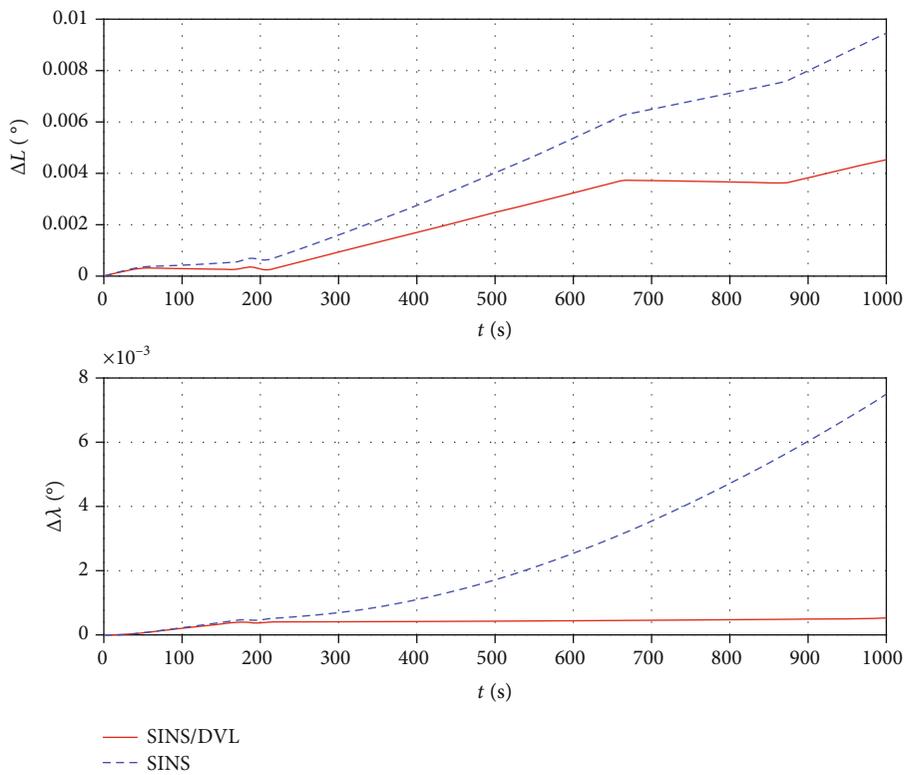


FIGURE 6: Position errors of the SINS and SINS/DVL integrated navigation system.

integrated navigation system are presented in Figure 5, and then, the position errors shown in Figure 6 depict that under the SINS/DVL integrated navigation system, the position errors of SINS/DVL are much smaller than those of SINS. In a word, the expected navigation accuracy is obtained using the proposed modified Sage-Husa adaptive Kalman filter-based SINS/DVL integrated navigation system.

5. Conclusion

For AUV, a modified Sage-Husa adaptive Kalman filter-based SINS/DVL integrated navigation system is designed in this paper to obtain expected navigation accuracy. The negative definite items of adaptive update laws of the noise matrix are deleted to guarantee the positive definiteness of noise matrices, such that the filter stability can be ensured. Simulations are presented to verify that expected navigation accuracy for AUV can be obtained using the proposed filter method.

Data Availability

The data supporting the findings of this study are available within the article.

Conflicts of Interest

The authors declare that they have no conflicts of interest.

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