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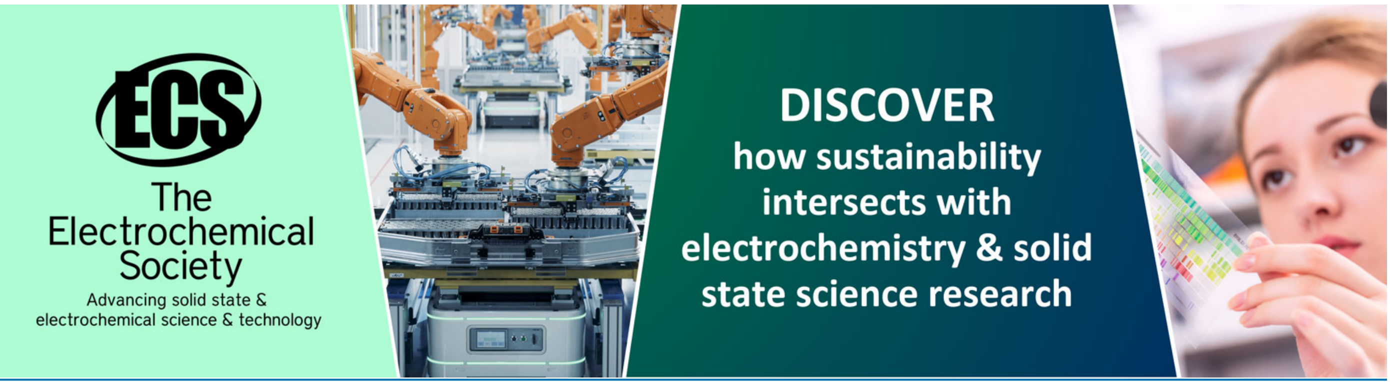

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Research of Motion Resolving and Filtering Algorithm of a Ship's Three-Freedom Motion Simulation Platform Based on LabVIEW

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Abstract. A method to measure, resolve and filter the attitude of the three-freedom simulation platform is presented in this paper. The strapdown measurement system is composed of three single-axis angular speed gyros and three acceleration transducers. Kalman filtering algorithm and self-adaptive Kalman filtering algorithm are adopted to filter the signal. The strapdown measurement system's signal measurement, resolving and filtering are realized through LabVIEW, and the result shows that the measurement, resolving and filtering of the attitude are correctly done using this method , providing correct platform motion attitude signal.

1. Introduction

Motion simulation platform is widely used in the fields of ship and aircraft simulation [1]. Under laboratory conditions, the motion course of the real ship or ship model in different oceanic conditions can be simulated on the simulation platform, providing data evidence for the ship motion analysis and control. Measurement, motion resolving and filtering of the platform's motion attitude are important segments to acquire the platform's motion attitude data.

In recent years, strapdown measurement system is widely applied in ship motion attitude measurement, the starting point of the system is to build a math platform. Different strapdown measurement system proposals are determined by the different ways to build the math platform. For example: seven acceleration transducers [2,3], three single-axis acceleration gyros and three acceleration transducers [5] or four acceleration transducers and one two-axis gyros [4] can all makeup a strapdown measurement system. Since Kalman filtering algorithm was put forward in 1960, it has become one of the most important and basic tools in the fields of control and signal processing. Lots of exploratory work has been done to suppress filtering divergence and raise the filtering accuracy [7]. LabVIEW is a kind of development environment based on graphic program language, widely used in the fields of instrument control, data acquisition, data analysis and etc [8,9].

Pitch, roll and heave are three most important parameters aims at which the three-freedom motion simulation platform. On the basis of LabVIEW platform and data acquisition card, strapdown measurement method and Kalman filtering algorithm is adopted to measure, resolve and filter the platform's motion attitude.

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2. Strapdown measurement method

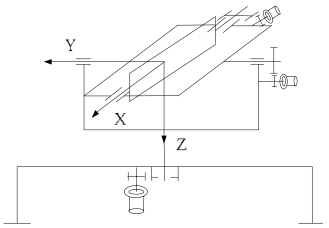

Figure 1. Structure of three-freedom simulation platform.

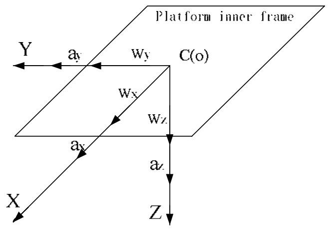

Figure 2. Distribution of angular rate gyros and acceleration transducers.

The three-freedom simulation platform is composed of inner frame, middle frame and outer frame as shown figure 1. Strapdown measurement system which is composed of three angular rate gyros and three acceleration transducers as shown figure 2 is fixed at the centroid of inner frame. The centroid is taken as measured point c. Three acceleration transducers are laid at point c, the initial point *o* of fixed coordinate is just the measured point c. The revolution axises of the three angular rate gyros are *ox, oy,* and *oz* which are also the sensing axises of three acceleration transducers.

2.1. Definition of the coordinate

Translation coordinate $o_0-x_0y_0z_0$ (or inertia coordinate) moves straightly at the ship's average speed, positive direction of o_0x_0 axis is the same as the ship's heading direction, positive direction of o_0z_0 axis is vertical downward , positive direction of o_0y_0 axis points at starboard. $\vec{i}_0, \vec{j}_0, \vec{k}_0$ is taken as the unit vector of the coordinate axis; and the body coordinate *o-xyz* is fixed to the ship body, positive direction of *ox* axis points at bow, positive direction of *oz* axis is vertical downward, positive direction of *oy* axis points at starboard , $\vec{i}, \vec{j}, \vec{k}$ is the unit vector of the coordinate axis. Here, the centroid of inner frame is taken as body coordinate zero *o*.

Accelerations $\vec{a}_o$, $\vec{a}$ in the translation coordinate and the body coordinate have the following relations:

$$\vec{a}_0 = [A](\vec{a} - \begin{bmatrix} 0 & 0 & g \end{bmatrix}^{\mathrm{T}}) \tag{1}$$

Here in, $[A] = \begin{bmatrix} \cos\theta\cos\psi & \sin\phi\sin\theta\cos\psi - \cos\phi\sin\psi & \cos\phi\sin\theta\cos\psi + \sin\phi\sin\psi \\ \cos\theta\sin\psi & \sin\phi\sin\theta\sin\psi + \cos\phi\cos\psi & \cos\phi\sin\theta\sin\psi - \sin\phi\cos\psi \\ -\sin\theta & \sin\phi\cos\theta & \cos\phi\cos\theta \end{bmatrix}$ is the coordinate transformation matrix.

2.2. Strapdown measurement formulas

According to the ω_x, ω_y,ω_z measured by the three angular rate gyros, solve the following equations:

$$\begin{aligned} \dot{\phi} &= \omega_x + tg\theta(\omega_y \sin\phi + \omega_z \cos\phi) \\ \dot{\theta} &= \omega_y \cos\phi - \omega_z \sin\phi \\ \dot{\psi} &= \frac{\omega_y \sin\phi + \omega_z \cos\phi}{\cos\theta} \end{aligned} \tag{2}$$

Roll Γ ϕ, Pitch, θ and yaw ψ can be worked out.

The acceleration vector $\vec{a}_c = [a_{cx}, a_{cy}, a_{cz}]$ at point c can be measured by three acceleration transducers, and vector $\vec{a}_c$ in the translational coordinate is

$$\vec{a}_{c0} = [A](\vec{a}_c - [0 \quad 0 \quad g]^{\mathrm{T}}) \tag{3}$$

Through double integral transformations to $\vec{a}_{c0}$, the linear displacement in the translation coordinate at three directions: sway, surge, and heave are worked out.

Figure 3 describes resolving error comparison of the three-freedom motion at 0.5Hz. The comparison curve shows that, the resolving and measurement accuracy of angular displacement (roll and pitch) is high, while the accuracy of the heave is lower, yet satisfying the requirements of engineering accuracy.

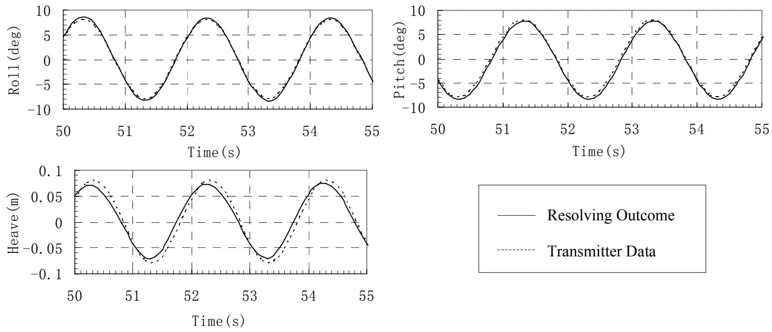

Figure 3. Resolving error comparison.

3. Filtering algorithm

There must exist random noise disturb in the acceleration and angular speed signal measured by the three angular rate gyros and three acceleration transducers. Traditional Kalman filtering algorithm and Sage-Husa self-adaptive Kalman filtering algorithm are used to filter the measured signal, getting rid of the system noise disturb and measurement noise disturb to provide correct ship motion attitude for following work.

3.1. Kalman filtering algorithm

Traditional Kalman filter is built on the assumption that accurate model and noise signal statistical characters are known. Assume equations of linear discrete random system are as follows:

$$\left.\begin{aligned} X_{k+1} &= \Phi_{k+1,k} X_k + \Gamma_{k+1,k} W_k \\ Z_{k+1} &= H_{k+1} X_{k+1} + V_{k+1} \end{aligned}\right\} \tag{4}$$

Kalman filter:

$$\begin{aligned} \hat{X}_{k+1,k} &= \Phi_{k+1,k} \hat{X}_k \\ \hat{X}_{k+1} &= \hat{X}_{k+1,k} + K_{k+1}\left[Z_{k+1} - H_{k+1} \hat{X}_{k+1,k} \right] \\ K_{k+1} &= P_{k+1,k} H_{k+1}^T \left[H_{k+1} P_{k+1,k} H_{k+1}^T + R_{k+1} \right]^{-1} \\ P_{k+1,k} &= \Phi_{k+1,k} P_k \Phi_{k+1,k}^T + \Gamma_{k+1,k} Q_k \Gamma_{k+1,k}^T \\ P_{k+1} &= \left[I - K_{k+1} H_{k+1} \right] P_{k+1,k} \end{aligned} \tag{5}$$

3.2. Sage-Husa self-adaptive Kalman filtering algorithm

Actually, models are mostly not definite and the statistical characters are also not completely known, both of which would deprive the optimality of Kalman algorithm, even leading to filtering divergence. Sage-Husa self-adaptive filtering algorithm uses the observation data to proceed recursive filtering, at the meantime, the statistical character of the system noise and observation noise is evaluated and amended at real-time through time-varying noise statistical estimator, so that the model error is reduced, filtering divergence suppressed and the filtering accuracy raised.

Considering system with time-varying noise statistic, its statistical character satisfies:

$$EW_k = q_k,\quad EV_k = r_k,\quad EW_kW_l^T = Q_k\delta_{kl},\quad EV_kV_l^T = R_k\delta_{kl} \tag{6}$$

Time-varying noise statistic recursive estimator:

$$\begin{aligned}
\hat{r}_{k+1} &= (1-d_k)\hat{r}_k + d_k(Z_{k+1} - H_{k+1}\hat{X}_{k+1,k}) \\
\hat{R}_{k+1} &= (1-d_k)\hat{R}_k + d_k(\varepsilon_{k+1}\varepsilon_{k+1}^T - H_{k+1}P_{k+1,k}H_{k+1}^T) \\
\hat{q}_{k+1} &= (1-d_k)\hat{q}_k + d_k(\hat{X}_{k+1} - \Phi_{k+1,k}\hat{X}_k) \\
\hat{Q}_{k+1} &= (1-d_k)\hat{Q}_k + d_k(K_{k+1}\varepsilon_{k+1}\varepsilon_{k+1}^T K_{k+1}^T + P_{k+1} - \Phi_{k+1,k}P_{k+1}\Phi_{k+1,k}^T)
\end{aligned} \tag{7}$$

Here in, $d_k = (1-b)/(1-b^k)$ ($0 \prec b \prec 1$) is amnestic factor.

Self-adaptive Kalman filter:

$$\begin{aligned}
\hat{X}_{k+1} &= \hat{X}_{k+1,k} + K_{k+1}\varepsilon_{k+1} \\
\hat{X}_{k+1,k} &= \Phi_{k+1,k}\hat{X}_k + \hat{q}_k \\
\varepsilon_{k+1} &= Z_{k+1} - H_{k+1}\hat{X}_{k+1,k} - \hat{r}_k \\
K_k &= P_{k+1,k}H_{k+1}^T\left[H_kP_{k+1,k}H_{k+1}^T + \hat{R}_k\right]^{-1} \\
P_{k+1,k} &= \Phi_{k+1,k}P_k\Phi_{k+1,k}^T + \hat{Q}_k \\
P_{k+1} &= \left[I - K_{k+1}H_{k+1}\right]P_{k+1,k}
\end{aligned} \tag{8}$$

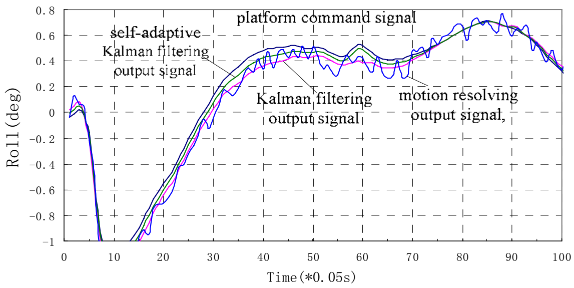

Figure 4. Filtering effect of Kalman filter and self-adaptive Kalman filter.

The four curves showed in figure 4 are the platform motion command signal, motion resolving output signal, Kalman filtering output signal and Sage-Husa self-adaptive Kalman filtering output signal. Analysis of the curves shows that Kalman filtering algorithm, especially Sage-Husa self-adaptive Kalman filtering algorithm, can get rid of the random disturb in the sensor signal.

4. Development of the data software based on LabVIEW

Using LabVIEW and high-performance data acquisition card, the sensor's output signal can be acquired correctly and quickly, then the data acquired is processed by MATLAB called through LabVIEW, completing the resolving and filtering.

4.1. Data acquisition
M-series data acquisition card PCI-6251, produced by American NI Company is adopted to acquire the sensor's output signal. NI-DAQmx provides a series of VI through which the acquisition device configuration, signal acquisition and output can be done.

4.2. LabVIEW calling MATLAB
LabVIEW has great advantages in design of customer graphic interface and data acquisition; MATLAB is powerful in signal processing and also flexible, yet it's weak in programming human-machine interaction interface. Combining the two softwares, MATLAB is called through LabVIEW to complete large-scale and complicated algorithm, realizing the resolving and filtering of the signal measured, as shown in Figure 5.

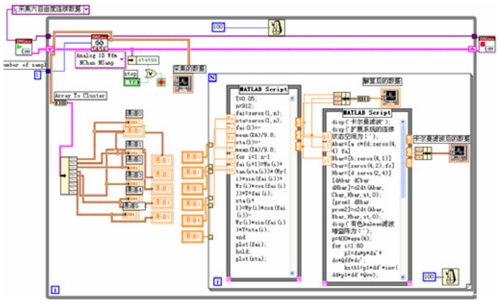

Figure 5. Block diagram of data acquisition motion resolving and filter.

5. Conclusion
LabVIEW is used to realize the application of strapdown measurement method to the attitude measurement of the three freedoms platform. Kalman filter and Sage-Husa self-adaptive Kalman filter are used to filter the measurement signal, verifying the advantages of the strapdown measurement method and the two filtering algorithms, providing correct ship attitude signal for the following work.

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