

Mass Imbalance Compensation Control for Stabilized Platform Based on UKF Identification

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Abstract. Due to the mass imbalance about the center of rotation, the stability of stabilized platform system degrades with carrier's disturbances. Various feed-forward control methods are provided by researchers to solve this problem, however these methods are not well applied because the eccentricity of stabilized platform could not be measured directly. The dynamics model of a typical 2-axis stabilized platform is given. The eccentricity vector is identified through Unscented Kalman Filter(UKF) algorithm. Imbalance torque is precisely observed so that the real-time nonlinear compensation for mass imbalance is achieved through a feed-forward loop. The simulation result indicates that the Root Mean Squared Error (RMSE) of parameters estimation is 0.024 after convergence. the LOS stabilization with carrier's 2.5Hz vibration is 0.04 rad/s, which improves 78% compared to conventional feed-back control.

1 Introduction

There are several effects inherent to the stabilized platform that could have a marked influence on overall pointing and tracking performance, such as noise, random error, and disturbance torque. Among these factors, the most complex nonlinear phenomenon is the effective torque due to mass imbalance and gimbal friction[1], [2], [3], [6].

When the center of gravity (CG) of the gimbal frame deviates from the rotation center, the imbalance torque is generated due to the acceleration in the direction perpendicular to the eccentricity. The line-of-sight (LOS) stabilization degrades seriously when the vibration of carrier is reinforced by high speed airflow or other environment factors.

A conventional approach is to increase the stabilizing loop gain or insert proportional-integral cascaded compensator[7]. However, these methods may not work well for dynamic, highly nonlinear disturbances, or even increase loop sensitivity to sensor noise. If the imbalance torque is observed, feed-forward controller could be introduced to compensate the imbalance effects[8], [9].

2 Dynamics model of stabilized platform

Two processes should be considered in the dynamics model of the stabilized platform system, the first is the disturbance transmitting process from the carrier to the

payload, the second is the controlling process. A typical 2-axis stabilized platform is given (see fig.1). $OX_B Y_B Z_B$ is the carrier coordinate system in which X_B is the spin axis, Y_B is the yaw axis and Z_B is the pitch axis. $OX_O Y_O Z_O$ is defined when the carrier coordinate system rotate the angle ψ with Z_B . $OX_I Y_I Z_I$ is defined when $OX_O Y_O Z_O$ rotate the angle θ with Y_O . The origin of these coordinate system coincides with the intersection of the gimbal axis system.

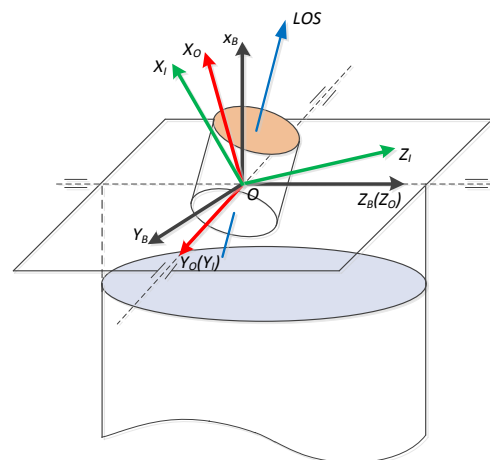


Figure 1. 2-axis stabilized platform.

According to kinematics relationship the inertial LOS rate is given by:

$$\boldsymbol{\omega}_I = \begin{bmatrix} \omega_{Ox} \cos \theta - \omega_{Oz} \sin \theta \\ \omega_{Oy} + \dot{\theta} \\ \omega_{Ox} \sin \theta + \omega_{Oz} \cos \theta \end{bmatrix} \quad (1)$$

The torque of the gimbal axis is:

$$\mathbf{M}_r = \frac{d\mathbf{H}}{dt} + \boldsymbol{\Omega} \times \mathbf{H} + \boldsymbol{\rho} \times m\mathbf{a} \quad (2)$$

In equation (2), $\mathbf{H} = \mathbf{J}\boldsymbol{\omega}$ is the angular momentum of the frame, $\boldsymbol{\rho}$ is the eccentricity vector, m is the frame mass, and \mathbf{a} is the acceleration of the frame. The torque \mathbf{M}_r contains the control torque and other torque disturbances such as coulomb and viscous friction and cable damping effects.

Take the inner frame's situation as example, according to kinematics relationship the coupled acceleration from the carrier is given by:

$$\begin{bmatrix} a_{Ix} \\ a_{Iy} \\ a_{Iz} \end{bmatrix} = \begin{bmatrix} a_{Bx} \cos \psi \cos \theta + a_{By} \sin \psi \cos \theta - a_{Bz} \sin \theta \\ -a_{Bx} \sin \psi + a_{By} \cos \psi \\ a_{Bx} \cos \psi \sin \theta + a_{By} \sin \psi \sin \theta + a_{Bz} \cos \theta \end{bmatrix} \quad (3)$$

The imbalance torque of inner frame is given by:

$$\begin{aligned} M_{imb} = & \rho_{Iz} m_I (a_{Bx} \cos \psi \cos \theta + a_{By} \sin \psi \cos \theta - a_{Bz} \sin \theta) \\ & - \rho_{Ix} m_I (a_{Bx} \cos \psi \sin \theta + a_{By} \sin \psi \sin \theta + a_{Bz} \cos \theta) \end{aligned} \quad (4)$$

3 Feed-forward compensation design

If the imbalance torque is observed, feed-forward compensation could be possible to achieve (see fig.2), and the feed-forward controller is designed as: $G_N = -M_{I_imb} / G_{cl} C_m$. It is hard to precisely measure the eccentricity vector of the platform system, for the reason that the most important part of feed-forward compensation designing is the eccentricity identification.

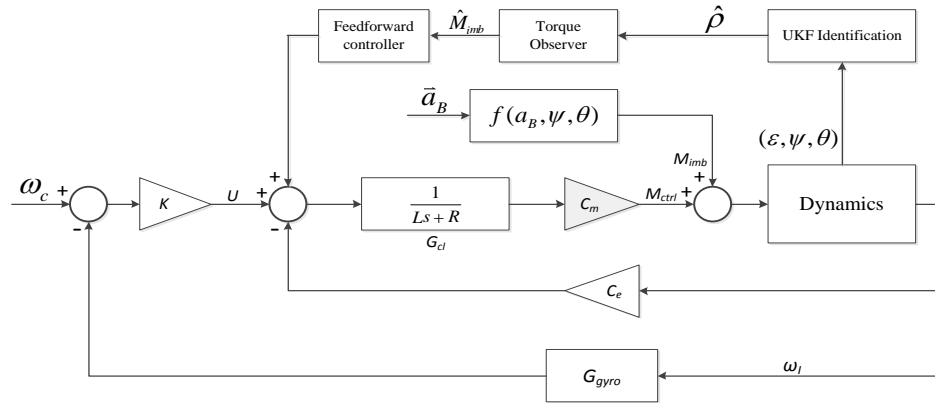


Figure 2. Principle of feed-forward compensation.

Because the relationship between the states and the observations of platform system is nonlinear, it is suitable for using UKF algorithm to estimate the eccentricity [4], [5]. The relationship between the angle acceleration and the eccentricity is:

$$\begin{aligned} \varepsilon_I = & \rho_{Ix} m_I (a_{Bx} \cos \psi \sin \theta + a_{By} \sin \psi \sin \theta + a_{Bz} \cos \theta) / J_I \\ & - \rho_{Iz} m_I (a_{Bx} \cos \psi \cos \theta + a_{By} \sin \psi \cos \theta - a_{Bz} \sin \theta) / J_I \end{aligned} \quad (5)$$

The state vector is given by:

$$\mathbf{X} = [\rho_{Ix} \quad \rho_{Iz} \quad a_{Bx} \quad a_{By} \quad a_{Bz} \quad \psi \quad \theta]^T \quad (6)$$

The measurement vector is given by:

$$\mathbf{Z} = [\varepsilon_I \quad a_{Bx} \quad a_{By} \quad a_{Bz} \quad \psi \quad \theta]^T \quad (7)$$

The initialization of UKF is:

$$\begin{cases} \hat{\mathbf{X}}_0 = \mathbf{E}[\mathbf{X}_0] \\ \mathbf{P}_0 = \mathbf{E}[(\mathbf{X}_0 - \hat{\mathbf{X}}_0)(\mathbf{X}_0 - \hat{\mathbf{X}}_0)^T] \end{cases} \quad (8)$$

And the sigma points are calculated as:

$$\boldsymbol{\chi}_{k-1}^a = \begin{bmatrix} \hat{\mathbf{X}}_{k-1}^a & \hat{\mathbf{X}}_{k-1}^a + \gamma \sqrt{\mathbf{P}_{k-1}^a} & \hat{\mathbf{X}}_{k-1}^a - \gamma \sqrt{\mathbf{P}_{k-1}^a} \end{bmatrix} \quad (9)$$

The time-update equations are:

$$\begin{cases} \boldsymbol{\chi}_{k|k-1}^x = \mathbf{F}(\boldsymbol{\chi}_{k-1}^x, \mathbf{u}_{k-1}, \boldsymbol{\chi}_{k-1}^v) \\ \hat{\mathbf{X}}_k^- = \sum_{i=0}^{2L} W_i^{(m)} \boldsymbol{\chi}_{i,k|k-1}^x \\ \mathbf{P}_k^- = \sum_{i=0}^{2L} W_i^{(c)} (\boldsymbol{\chi}_{i,k|k-1}^x - \hat{\mathbf{X}}_k^-) (\boldsymbol{\chi}_{i,k|k-1}^x - \hat{\mathbf{X}}_k^-)^T \\ \mathbf{Z}_{k|k-1} = \mathbf{H}(\boldsymbol{\chi}_{k|k-1}^x, \boldsymbol{\chi}_{k-1}^n) \\ \hat{\mathbf{Z}}_k^- = \sum_{i=0}^{2L} W_i^{(m)} \mathbf{Z}_{i,k|k-1} \end{cases} \quad (10)$$

And the measurement-update equations are:

$$\begin{cases} P_{\bar{z}_k \bar{z}_k} = \sum_{i=0}^{2L} W_i^{(c)} (Z_{i,k|k-1} - \hat{X}_k^-) (Z_{i,k|k-1} - \hat{Z}_k^-)^T \\ P_{X_i Z_k} = \sum_{i=0}^{2L} W_i^{(c)} (\chi_{i,k|k-1} - \hat{Z}_k^-) (Z_{i,k|k-1} - \hat{Z}_k^-)^T \\ K_k = P_{X_i Z_k} P_{\bar{z}_k \bar{z}_k}^{-1} \\ \hat{X}_k = \hat{X}_k^- + K_k (Z_k - \hat{Z}_k^-) \\ P_k = P_k^- - K_k P_{\bar{z}_k \bar{z}_k} K_k^T \end{cases} \quad (11)$$

where $X^a = [X^T \ v^T \ n^T]^T$, $\chi^a = [(\chi^x)^T \ (\chi^y)^T \ (\chi^z)^T]^T$,
 $\gamma = \sqrt{L + \lambda}$.

The eccentricity is extracted from state estimation vector after every filter step, and is used to calculate the feed-forward control command.

4 Simulation analysis

According to the system dynamics the simulation model is founded. And the control parameters are given: the motor inductance is 2.8mH, the coil resistance is 5.1 Ω , the torque coefficient is 0.21, the feed-back control gain is 34.5, the filter step is 0.01s, and the vibration of the carrier forms a sinusoidal signal with amplitude of 0.5g and frequency of 2.5Hz.

The simulation result indicates that the convergence time of UKF algorithm is <0.4s, and the Root Mean Squared Error (RMSE) of parameters estimation is 0.024 after convergence(see Fig.3-4). the LOS stabilized accuracy with carrier's vibration is 0.04 rad/s, which improves 78% compared to feedback control (see Fig.5-6).

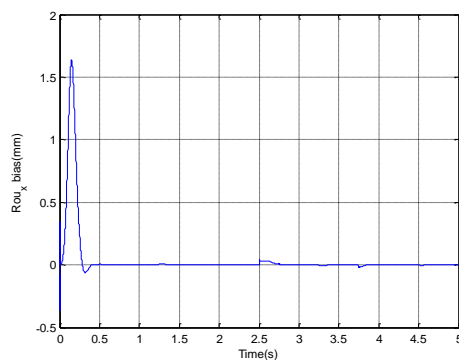


Figure 3. Estimation error of eccentricity in x.

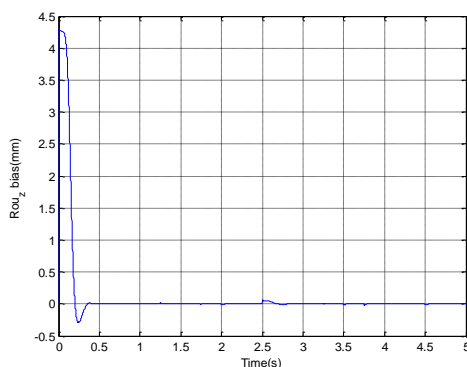


Figure 4. Estimation error of eccentricity in z.

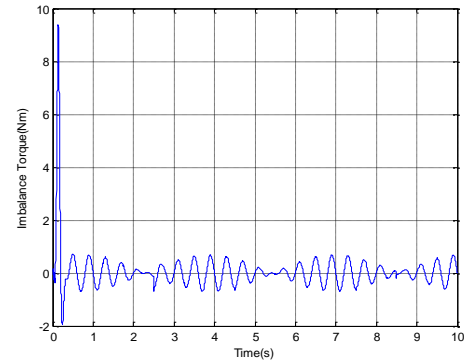


Figure 5. Observed imbalance torque.

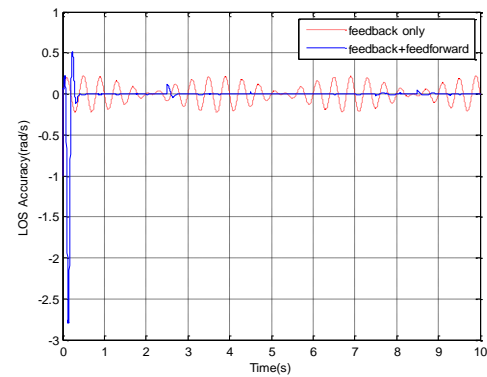


Figure 6. LOS stability comparison.

5 Summary

Because measuring a stabilized platform's eccentricity by conventional instruments is almost impossible, an real-time method of identification is provided. The eccentricity vector is precisely estimated through UKF algorithm, so that the imbalance torque could be completely observed. The convergence time of UKF is very short, and the algorithm consumes few hardware resources. The feed-forward compensation is designed which is effective to suppress the disturbances from the carrier, and better LOS stabilization of platform system is achieved compared to the traditional simple feed-back control method.

6 References

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