

Line-of-Sight of Reflectors Reconstruction and Stabilization Technique based on Fastest Differential Tracker

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Abstract. In order to overcome the shortcomings of half-angle reflectors mechanism stabilization configuration, we study the Line-of-Sight (LOS) of reflectors reconstruction and stabilization technique. A LOS reconstruction and stabilization configuration of reflectors is designed and modeled. Firstly, we design the Fastest Differential Tracker (FDT) to estimate relative angular rates, then propose a two-coordinate modeling method that is easy to analyse disturbance isolation performance, thirdly we study the control system isolation degree to the measurement noise and carrier disturbance. The simulations indicate that FDT has superior performance in tracking speed, noise suppression and steady state vibration suppression, and that the stabilization accuracy, in consideration of both noise and carrier disturbance, is about $70\mu\text{rad}(1\sigma)$. The experimental results show that reflector platform stabilization accuracy based on LOS reconstruction configuration is about $80\mu\text{rad}(1\sigma)$.

1. Introduction

The LOS stabilization configuration using reflectors has the characteristics of small exposed volume and easy to stealth, and is widely used in airborne photoelectric systems. The main scheme of traditional reflector stabilization configuration eliminates the half-angle transmission relationship between reflector rotation and LOS rotation with half-angle assembly, and realizes the measurement of the LOS inertial angular rates directly [1-3].

However, the half-angle transmission relationships need to be realized by steel belt and cam. The mechanism is prone to elastic deformation; consequently the mechanical resonance frequency is below the ideal value. As a result, control system bandwidth is limited and disturbance isolation ability is insufficient. The LOS reconstruction technology makes gyroscope installation position flexible and easy to miniaturize the scanning mechanism. The researches of LOS reconstruction technology have been widely carried out in the United States and European military powers, even has been used in engineering, such as AIM-9X air-to-air missile, Iris-T air-to-air missile, and General infrared countermeasure system of Northrop Grumman Company.

In recent years, Chinese research on LOS reconstruction technology has gradually begun. Zhou Ruiqing[4] fused the gyro information and the angular differential information, proposed a design method of dual channel coupled target tracking filter, and improved the decoupling accuracy of the system to the missile disturbance, He verified the feasibility of the application of the LOS reconstruction on the antenna stabilization platform. Liu Wei [5] used the differential tracker to make up for the deficiency of the classical differential algorithm, and the differential tracker have superior disturbance suppression performance.



In present paper, the engineering application of LOS reconstruction technology is studied on the background of stabilization configuration of two-axis gimbal. A LOS reconstruction scheme based on FTD is designed, the control system is modelled and analysed. A two-coordinate system modelling method that is easy to achieve disturbance isolation analysis is proposed for the first time in modelling. On this basis, the isolation degree to the noise and carrier disturbance of the control system is analysed. In order to verify the FDT performance, the simulations in noise elimination and steady-state high-frequency vibration suppression are carried out. Furthermore, the influence of noise and carrier disturbance on the system stability accuracy is simulated and analysed by using the modelling method in this paper. Finally, the simulation results are verified by experiments.

2. LOS Reconstruction Scheme

2.1. LOS Reconstruction

As shown in Figure 1, the stabilization configuration with two-axis gimbal can stabilize the LOS in two axes [6]. In the paper, the configuration of the gyroscope mounted on the reflector is designed in detail. The inertial angular rates of the reflector are fused with gyroscope measured angular rates, to obtain the inertial angular rates of the LOS in the Y-axis.

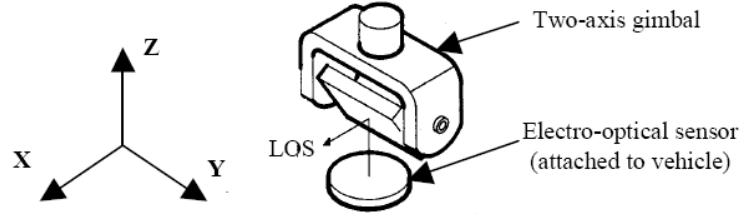


Figure 1. two-axis reflector stabilization configuration

This scheme involves two coordinate system transformations; the first one is Z-axis coordinate system to Y-axis (Reflector pitch) coordinate system, setting the rotation angle of pitch frame relative to azimuth frame is θ_{ry} , the second one is from Reflector coordinate system to LOS coordinate system, the rotation angle is θ_{ry} too. The corresponding Euler transformation is given as follows (1):

$$\begin{cases} \omega_M = R_y(\theta_{ry})\omega_Z + P_y(\theta_{ry}) \\ \omega_L = R_{Ly}(\theta_{ry})\omega_{Mx} + P_{Ly}(\theta_{ry}) \end{cases} \quad (1)$$

The rotational translation matrix is defined as formula (2) and formula (3):

$$\begin{cases} R_y(\theta_{ry}) = \begin{bmatrix} C\theta_{ry} & 0 & -S\theta_{ry} \\ 0 & 1 & 0 \\ S\theta_{ry} & 0 & C\theta_{ry} \end{bmatrix} \\ R_{Ly}(\theta_{ry}) = R_y(\theta_{ry}) \end{cases} \quad (2)$$

$$\begin{cases} P_y(\theta_{ry}) = \begin{bmatrix} 0 \\ \dot{\theta}_{ry} \\ 0 \end{bmatrix} \\ P_{Ly}(\theta_{ry}) = P_y(\theta_{ry}) \end{cases} \quad (3)$$

From formulas (1), (2), (3), the reconstructed LOS inertial angular is obtained as follows (4):

$$\begin{cases} \omega_{Ly} = \omega_{My} + \dot{\theta}_{ry} \\ \omega_{Lz} = \omega_{Mz} \cdot \cos \theta_{ry} + \omega_{Mx} \cdot \sin \theta_{ry} \end{cases} \quad (4)$$

Formula (4) shows that the relative angular rates $\dot{\theta}_r$ of the mechanism need to be accurately estimated from the angular information to reconstruct the LOS Y-axis inertial angular rates. Estimation of velocity signal from position signal usually results in amplification of noise signal, and the synchronization between estimation algorithm and gyro data is not easy to guarantee, which also affects the accuracy of LOS synthesis. Therefore, reconstruction of Y-axis LOS is challenging. To solve this problem, the reconstruction technology of Y-axis LOS is studied in the paper.

2.2. Angular rates estimation algorithm by FDT

The traditional differential angular rates measurement methods amplify noise signal seriously. When the relative angular rates of frame rotation are slow, the algorithm will significantly reduce the rate estimation accuracy. Differential tracker theory [7] provides a real-time velocity estimation method based on position measurement. It is not based on the object model, uses integral method to approach the tracking position signal. It avoids the noise amplification problem caused by conventional differential algorithm, and can quickly estimate the differential signal from the noise-contaminated signal. In order to avoid steady-state high-frequency vibration, this paper designs FDT to estimate the angular rates, as shown in equation (5):

$$\begin{cases} x_1(k+1) = x_1(k) + Tx_2 \\ x_2(k+1) = x_2(k) + Tfh \\ fh = fhan(x_1(k) - v(k), x_2(k), r, h) \end{cases} \quad (5)$$

Where, T is the sampling time, r is the velocity factor, h is the filtering factor, Filtering factor mainly affect the filtering effect. fh is the fastest control synthetically function of the system. The synthetically function is shown as follows (6):

$$\begin{cases} d = rh \\ d_0 = hd \\ y = x_1 - v + hx_2 \\ a_0 = \sqrt{d^2 + 8r|y|} \\ a = \begin{cases} x_2 + \frac{a_0 - d}{2} \text{sign}(y), |y| > d_0 \\ x_2 + \frac{y}{h}, |y| \leq d_0 \end{cases} \\ fhan = - \begin{cases} r \text{sign}(a), |a| > d \\ r \frac{a}{d}, |a| \leq d \end{cases} \end{cases} \quad (6)$$

3. Modelling and analysis

By traditional modelling method, the default output of stabilization control loop is angular rates in inertial reference frame [8], while the actual load output variables drove by actuator is the relative angular rates or angle value in the body reference frame. The traditional modelling of LOS reconstruction control for photoelectric stabilization platform is shown in Figure 2, Where ω_m is the attitude disturbance angular rates, ω_p is the inertial angular rates of the platform, and the difference between them is the relative angular rates in body reference frame [5]. Traditional modelling method of the LOS reconstruction based on reflector has the following drawbacks easily:

- The inertial angular rates of the reflector are actually resultant that the synthesis of carrier inertial angular rates and relative angular rates in body reference frame. The traditional modelling method neglects it.

- The actual load output drove by actuator is in body reference frame, but the traditional modelling method neglects it. Once the disturbance of the carrier exists, the control system will superimpose the disturbance on output. However, the angular rates disturbance has no direct input point in the traditional control model, and can only be converted into one of the torque disturbance elements, where T_d in Figure 2. The influence of carrier disturbance on the control system accuracy is not intuitive, and it is not easy to design the isolation degree of stabilization loop.

- There are many disturbance moments in airborne photoelectric system, such as friction moment, mass unbalance moment and wind resistance moment. It makes disturbance analysis more complex when multiple disturbance moments are superimposed at the same input point.

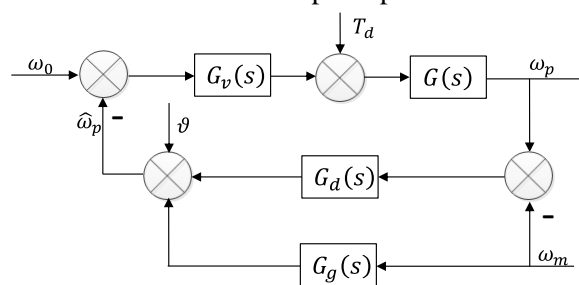


Figure 2. Conventional modelling of stabilization loop

When modelling, the coordinate of variables in the model is considered, and the variables coordinate relationship between the body system and the inertial system is clarified. The model is established as shown in Figure 3. Where the motor driving output angular rates ω_{rela} and angle θ_{rela} is in the body frame, the other angular rates are in the inertial frame. ω_{I_in} is the LOS inertial angular rates instruction input, $\omega_{I_L_out}$ is the LOS inertial angular rates output, ω_{I_M} is the reflector inertial angular rates measured by the gyroscope, T_d is disturbance torque, ζ is synthesis noise of speed measurement and gyro, $G_v(s)$ is speed loop controller transfer function, $G_d(s)$ is velocities estimation loop transfer function, $G_g(s)$ is gyro transfer function.

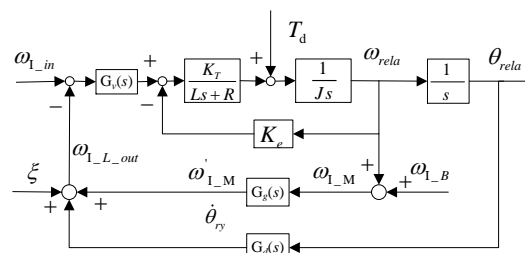


Figure 3. Two-coordinate modelling of stabilization loop

The modelling method has the following advantages:

- It truly reflects the output reference frame of the actuator and avoids the equivalent conversion of the disturbance to the moment disturbance in the traditional modelling method.
- The main disturbance (carrier disturbance) of the reflector stabilization configuration has disturbance input points, which is convenient for the stability accuracy design of the stabilization loop.

Without considering other disturbance moments, the model in Figure 3 can be reduced as Figure 4:

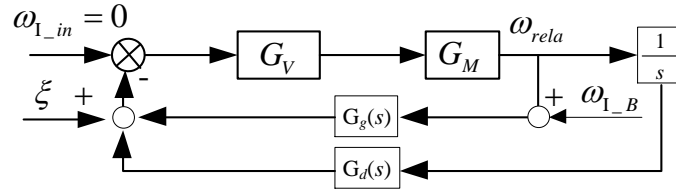


Figure 4. Reduced modelling of stabilization loop

Where G_M is the transfer function of the object. The expression of the LOS inertial angular rates is obtained as follows:

$$\omega_{I_L_out} = \frac{G_g(s)}{1 + G_M G_V (G_g(s) + G_d/s)} \omega_{I_B} + \frac{1}{1 + G_M G_V (G_g(s) + G_d/s)} \xi \quad (7)$$

Considering the control system bandwidth of the reflector stabilization configuration is lower than 30 Hz the paper studied, the following conclusions are drawn [9]:

$$G_M G_V (G_g(s) + G_d/s) \gg 1,$$

Then,

$$\omega_{I_L_out} = \frac{1}{G_M G_V (G_g(s) + G_d/s)} (G_g(s) \omega_{I_B} + \xi) \quad (8)$$

After the isolation of the large inertia aircraft, the disturbance frequency is concentrated in the low frequency range, which usually does not exceed 10 Hz. The gyro gain G_g and velocity measurement gain G_d/s both approximate to 1 in the range of less than or equal to 10 Hz. Correspondingly, the carrier disturbance isolation, the gyro and differential velocity measurement noise isolation are expressed as equation (9), and the LOS output expression affected by disturbance and noise is expressed as equation (10):

$$\frac{\omega_{I_L_out}}{\omega_{I_J}} \doteq \frac{\omega_{I_L_out}}{\xi} = \frac{1}{2G_M G_V} \quad (9)$$

$$\omega_{I_L_out} = \frac{1}{2G_M G_V} (\omega_{I_J} + \xi) \quad (10)$$

The expression of disturbance isolation degree is obtained as formula (11).

$$I = 20 \log \left(\frac{\omega_{I_L_out}}{\omega_{I_J}} \right) = 20 \log \left| \frac{1}{2G_M G_V} \right| \quad (11)$$

After defining the typical disturbance form, the desired stability precision can be achieved by reasonable design of the isolation degree in formula (11). By adjusting the controller gain G_v , the isolation degree of the control system to carrier disturbance and the suppression degree of velocity measurement noise can be changed. Under the classical control configuration, isolation is positively correlated with control system bandwidth. Due to the limitation of mechanical resonance frequency and gyro noise, the design bandwidth of the actual system based on reflector configuration is difficult to reach more than 40Hz [10]. Therefore, the isolation should not be too high in the actual system design; otherwise the stability of the system will deteriorate under the vibration condition.

4. Simulation

4.1. Simulation of FDT Performance

The simulation environment is MATLAB R2012a Simulink, with fixed simulation step size of 0.001s. The encoder noise is set to white noise, peak value of 20 angular seconds, and the gyro noise is also set to white noise, standard deviation of 0.07 °/s.

Compared with the linear differential tracker (LDT), the FDT can reduce the velocity estimation delay [7]. However, attention should be paid to balancing the estimation delay, estimating noise and steady state high-frequency tremor when design the FDT. In this section, the tracking speed and velocity estimation errors of LDT and the FDT under different filtering factors are simulated, as shown in Figure 5 and Figure 6. The simulation speed factor is set to 250 of LDT, and the FDT speed factor is set to 40000.

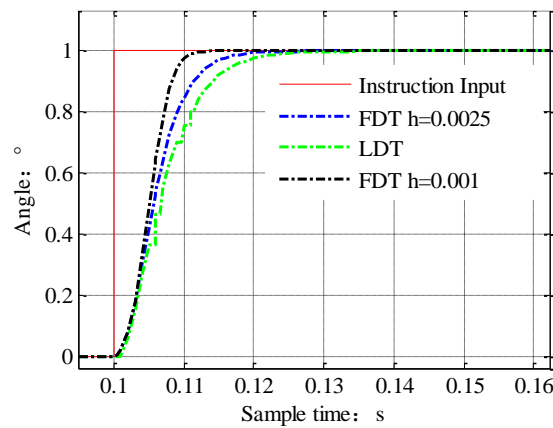


Figure 5. Track speed comparison to 1° step signal.

Figure 5 shows that the FDT's rise time with filter factor H of 0.0025 is about 6 ms shorter than the LDT's in tracking the angle step signal with amplitude of 1 degree. This delay will cause a phase lag of about 21.6 degrees at 10 Hz of the control system. The FDT can improve the tracking speed. Figure 5 and Figure 6 simulation results show that the noise suppression ability is proportional to the value of filter factor H . The larger the filter factor, the better the filtering performance, but it also will increase time delay of speed estimation signal. In Figure 6, when h increases from 0.001 to 0.0025, the amplitude of speed estimation noise decreases to about one third.

In engineering application, the FDT design also needs to consider the problem of steady state high-frequency Vibration. The performances simulation of suppression to steady state Vibration of different filtering factors is carried out in MATLAB. The simulation results are shown in Figure 7.

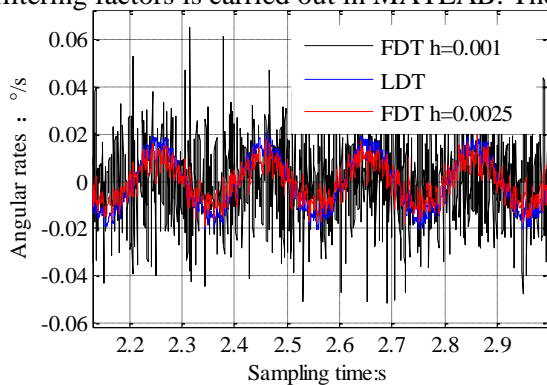


Figure 6. Error comparison of speed estimation.

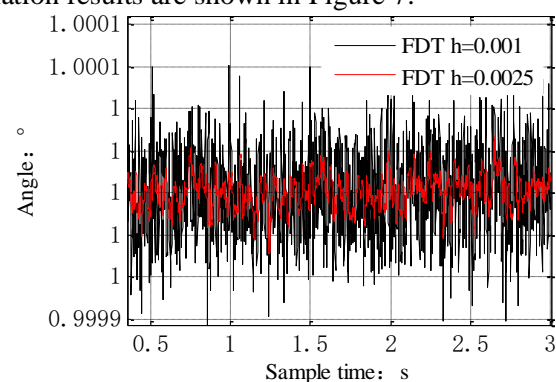


Figure 7. Suppression effect to steady state vibration

As shown in Figure 7, unreasonable filter factor H value will lead to excessive amplitude of steady state high-frequency vibration; the actual static mechanism is estimated a larger velocity value. Through repeated simulation, it is found that setting a slightly larger H value than the control period can greatly reduce the steady state high-frequency vibration problem. In Figure 7, the high-frequency vibration amplitude at 0.0025 is about 0.00003° , which is about one third of the value of h at 0.001.

4.2. Simulation of stability accuracy

Adopting the control modelling method in Section 3, the stability accuracy of the stabilization loop is simulated under the condition of considering the noise of encoder and the gyroscope and the carrier disturbance. The velocity estimation algorithm is the FDT with the speed factor of 40000 and filtering factor of 0.0025. The other parameters are as follows: load inertia: $8442 \text{ kg}\cdot\text{mm}^2$, motor inductance: 5.5mH , resistance: 7.8Ω , moment sensitivity coefficient: $0.29 \text{ N}\cdot\text{m/A}$ motor back EMF coefficient: $0.29 \text{ V}/(\text{rad/s})$, gyro bandwidth: 260 Hz, controller: Lead-lag Correction Controller, stability loop bandwidth: 40 Hz, Isolation: 39 dB The stabilization simulation effect is shown in Figure 8, and the stability accuracy is about $70\mu\text{rad}(1\sigma, 10\text{s})$.

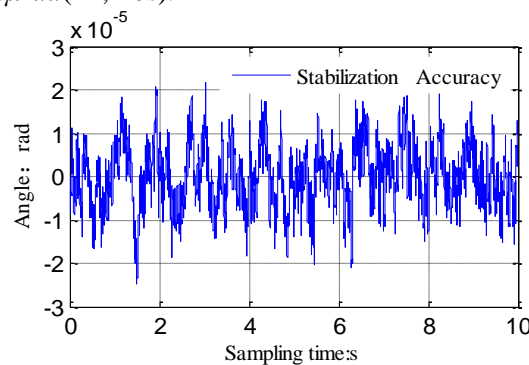


Figure 8. Stabilization accuracy in consideration of both noise and carrier disturbance

5. Stabilization experiment

In the experiment, Angular swing test turntable is used to simulate the typical disturbance signal of the aircraft, and the autocollimator is used to measure the LOS stability accuracy in the inertial space. The test scheme is shown in Figure 9. The experimental result of stabilization accuracy is shown in Figure 10.

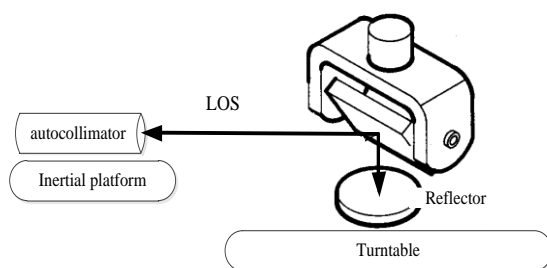


Figure 9. Schematic diagram of Stabilization accuracy test

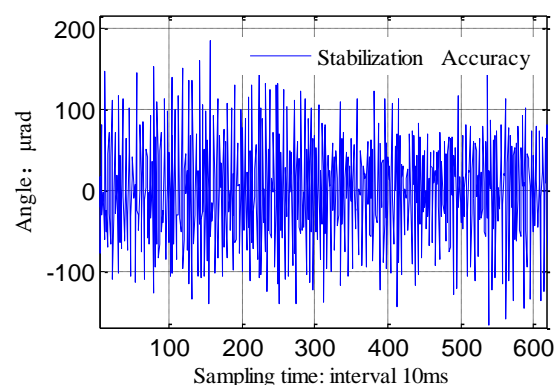


Figure 10. Experimental data of Stabilization accuracy without gyroscope drift

The stability accuracy of the LOS reconstruction configuration designed in the paper is about $80\mu\text{rad}(1\sigma, 6\text{s})$, which is slightly worse than the simulation result (subsection 4.2). This is because the disturbance moment such as friction moment is not taken into account in the simulation, and the disturbance moment of the actual mechanism is also an important factor affecting the stability accuracy.

6. Conclusions

The present paper designs a LOS reconstruction scheme that is suitable for the stabilization configuration with reflectors. We design the FDT to estimate relative angular rates in body frame; then model and analyse the LOS stabilization control configuration. Finally, test and verify the design on the prototype. The proposed two-coordinate control modelling method considered that the output angular rates of the motor can only be in the body frame, which truly reflects the output reference standard of the actuator. Avoiding the problem of traditional disturbance transforming complexly, the proposed two-coordinate control modelling method facilitates the isolation degree analysis of the carrier disturbance. Without considering the influence of disturbance moment, the isolation degree expression to carrier disturbance and noise (gyroscope noise and differential velocity measurement noise) is deduced. The desired stability accuracy can be achieved by reasonably designing the isolation degree. The modelling and analysis method in the paper simplified the relationship between stability accuracy and noise or carrier disturbance, which is convenient for system accuracy allocation and design.

Simulation results showed that the FDT has superior performance in estimating velocity, noise elimination and steady state high-frequency vibration by setting reasonable parameters. The comprehensive influence of system stability accuracy under the condition of considering noise and typical aircraft disturbance is about $70\mu\text{rad}(1\sigma)$. Experiments showed that the LOS reconstruction stabilization accuracy of the reflector platform is about $80\mu\text{rad}(1\sigma)$. The results of simulation and experiment proved the feasibility of engineering application of the LOS reconstruction and stabilization the present paper designed.

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