Miniaturized Electron Optic Tracking System On Aerostat

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Abstract. In this paper, a miniaturized electron optic tracking system (EOTS) is proposed to improve the disturbance suppression performance when attached to near space aerostat. The electron optic tracking system, widely used in moving platforms can isolate the movement of the carrier and has high stability accuracy. However, the payload weight is limited for near space aerostats. The miniaturization of EOTS can effectively improve load distribution. To satisfy the demand of lightweight, micro-electro-mechanical system (MEMS) accelerometer is used in EOTS instead of fiber-optic gyroscopes (FOG). This paper employs position and acceleration double close-loop control method with MEMS linear accelerometer to improve the system performance especially in medium frequency. Meanwhile the disturbance observer (DOB) is introduced to suppress the measurably external disturbance. Furthermore, the disturbance performance of the EOTS is verified by MATLAB/Simulink. The results show that the improved miniaturized system can increase the payload of the aerostat effectively when the total load is limited.

1. Introduction

The near space aerostat can effectively fill the blank in space-base synthetic information networks, realizing the space, near space, air and ground integration network, and offers strong support for information society development. Compared to traditional aviation platforms, aerostat, in figure 1, can work in higher space, cover a wider field, and hover over the target area for long time with lower energy consumption. The aerostat plays an important role in communication, remote sensing, navigation, to name but a few [1-3].

Figure 1. Near space aerostat

The EOTS can isolate the vast majority of external disturbances, and is widely used in astronomical observation, quantum communication, adaptive optics and environmental monitoring [4]. The aerostat carried a EOTS could be easier to detect the small target at a low speed. Owing to its large field observation ability, the detection range radius of the aerostat is longer than unmanned aircrafts. The aerostat works quietly and smoothly, however, it is easy to be affected by wind disturbances. Although the high frequency disturbance can decrease significantly using a mechanical damper, the low frequency noise still exists. Therefore, it is necessary to carry the EOTS on the aerostat to diminish interference.
Considering the loading capacity of aerostat is limited, lightened motion platforms becomes a trend in future aviation system design. Traditional high-accuracy gyro is too heavy and expensive for lightened motion platforms; the lighter and smaller MEMS accelerometer and gyroscope with lower price satisfies the demand of lightweight for aerostat. The speed loop requires several hundred Hz bandwidth. However, the MEMS gyroscopes tend to have narrow bandwidth under 100 Hz, which is too low for the speed loop. The system’s anti-disturbance capability will be restricted by MEMS gyroscope. We choose MEMS accelerometer with high bandwidth to form an acceleration loop to achieve the high-precision robust control [5].

However, the remarkable drift of MEMS accelerometer in the low frequency band and the high noise will weaken the performance of acceleration loop. In traditional double-loop feedback control, the performance in low-frequency is critical. The whole system needs a mechanical damping structure to improve the characteristic of vibration by restraining the high frequency vibration. But using MEMS linear accelerometer in double-loop feedback control will degrade the anti-noise and disturbance suppression ability. The article mainly focuses on the characteristics of MEMS linear accelerometer [6] and using the disturbance observer (DOB) to observe external disturbances. These modalities improve system’s anti-disturbance ability. Meanwhile, the DOB does not affect the closed-loop characteristic of control system.

This article proposes a comprehensive optimization of the sensor selection and a control system using the EOTS on aerostats. The real-time demand and stability of the system are verified.

2. Related work

2.1. Dynamic Models

In EOTS, the stabilization precision of the inertial stability platform determines the imaging quality. The inertial stability platform includes inertial devices, the controlling part, driving part, platform and load.

The structure diagram of two-axe inertial stability platform, including azimuth and pitch axis, is in Figure 2:

![Gimbal structure and servo system](image)

**Figure 2.** Gimbal structure and servo system

The damping mechanism is equipped between the carrier and stabilized platform to improve the passive inhibitory ability. To a certain extent, the damping mechanism isolates the movement influence of the carrier on inertial stabilization platform. The amount of vibration transferred to the inertial platform through the damping mechanism is regarded as the final amount of disturbance. The damping mechanism mainly inhibits the high-frequency disturbance, reflecting the passive inhibition ability of the motion platform. The performance of the mechanical structure in the low-frequency disturbance inhibition mainly depends on the active inhibition ability of the inertial stabilized platform. Thus, the problem can be simplified to mainly reduce the middle and low frequency disturbance of the system. The design in this paper improves the capability of system’s stability and tracking accuracy.

The structure and servo system can be described as follows:
Where $J_m, J_l$ are the moment of inertia of the motor and load in the system respectively. $\theta, \omega$ are the load angular position and angular velocity. $T_m$ is motor’s input torque. $i$ is the current of the servo motor. $f$ represents all the disturbance uncertainties of the system. $k_d$ is the damping coefficient. $k_t$ is the torque coefficient. $a$ is the acceleration value of the system.

According to the relations above, the transfer function from motor input torque to acceleration of the system is as follows:

$$G(s) = \frac{a}{u} = \frac{s}{Js + B}$$

The inertial stability platform is mainly affected by:

- disturbance of the system.
- sensor’s accuracy and systematic control algorithm.

### 2.2 Conventional dual-loop feedback control

Inertial stabilization platform usually adopts the speed and position double close-loop control strategy; position loop guarantees the target can be tracked in a large stroke. Because the position loop bandwidth is limited, it is difficult to obtain higher tracking accuracy. The speed loop is the critical factor for systematic high accuracy. The control block diagram is in Figure 3:

![Figure 3. Dual-loop structure scheme](image)

Where $C_p, C_v$ are position and velocity controllers, and $G_v$ is velocity open-loop transfer function, $\theta_i$ is target position, $\theta_d$ is the outer disturbance, and $\theta_o$ is the output.

The ratio between deflective angle of the output and the disturbance quantity of the system is:
After simplification, the ratio is:

\[
\frac{\theta_{d_2}}{\theta_{d_1}} = \frac{1}{1 + C_p G_v} \cdot \frac{1}{1 + C_p} \cdot \frac{C_v G_v}{1 + C_v G_v} \cdot \frac{1}{s}
\]  

(3)

Conventional dual-loop feedback control strategy can guarantee the system’s tracking performance, which mainly depends on the position loop controller and the speed loop controller, especially the speed loop controller. Even if the speed loop can enhance the system’s ability to suppress the disturbance, it is difficult to eliminate the external disturbance of the system effectively, which degrades the system’s tracking accuracy. Compared with the fixed base using large high-precision gyros, the lightweight design using MEMS gyros performs better. The low bandwidth of MEMS gyro cannot satisfy the speed loop bandwidth requirement. To realize a stable system, a new closed loop can be formed by adopting MEMS linear accelerometer with high bandwidth and good medium-frequency features.

2.3. The acceleration loop with DOB

MEMS linear accelerometer with lower high-frequency noise is of high detection bandwidth, which can reach 1000Hz. So the MEMS linear accelerometer is suitable for the inertial stability platform to measure the linear velocity of rotating axis relative to the inertial space. Then the angular acceleration can be resolved.

EOTS carried on the aerostat requires a simple structure and light weight. To reach a lightweight design, we use the MEMS linear accelerometer to form an inner acceleration loop instead of the speed closed-loop with optical fiber gyro. Reported in many domestic and abroad research, the acceleration feedback control performs well in the field of mechanical arms. So it is gradually introduced to EOTS to improve the stability of the system, Figure 4 is acceleration dual-loop control. As an inertial sensor, acceleration sensors can also improve the tracking ability of the system to a certain extent [7].

![Figure 4. Acceleration dual-loop control](image)

Where \( C_p \), \( C_a \) are position and acceleration controllers, \( G_a \) is acceleration open-loop transfer function, \( \theta_{t_1} \) is target position, \( \theta_{d_2} \) is the outer disturbance, and \( \theta_{o_2} \) is the output.

The ratio between deflective angle of the output and the disturbance quantity of the system is:

\[
\frac{\theta_{o_2}}{\theta_{d_2}} = \frac{1}{s^2}
\]
After simplification, the ratio is:

\[
\frac{\theta_{s_2}}{\theta_{d_2}} = \frac{1}{1 + C_p G_a} \cdot \frac{1}{\frac{C_s G_a}{1 + C_s G_a} s^2}.
\]

(5)

Theoretically, we can get a similar result by replacing the gyroscope with an accelerometer, but in practice, due to the dynamic noise of the accelerometer’s output, using position-acceleration double closed-loop cannot equal to position-speed double closed-loop control. Because of the delay of CCD and the system’s mechanical oscillation, the bandwidth of position loop cannot be increased further. And improving the system’s performance by increasing the system’s bandwidth is not desirable.

Practically, the influence of outer disturbance and attitude variations of aerostat cannot be ignored. Wind disturbance dominates in the outer disturbance. All of the disturbance will deteriorate seriously the tracking and observation performance. It is difficult to compensate the disturbance without an accurate model. Fortunately the wind disturbance is usually considered as low-frequency disturbance. To observe the disturbance of EOTS with DOB can improve the system’s anti-disturbance ability, achieving the goal of improving stability performance [8].

Disturbance feedforward is added into the control system to form a compound control to measure external disturbance and improve the platform’s ability to suppress disturbance. Based on the disturbance, the feedforward control method is designed to eliminate the disturbance itself; it is easy for its implementation. In this way, we can reduce the influence of the disturbance on controlled object in time. The advantage of feedforward control is that it does not affect the stability of the feedback part; its precision is only determined by the measurement precision of the carrier and the feedforward controller. Therefore, the feedforward-feedback method is adopted in this paper to ensure the stability performance of the whole system. By introducing the DOB and the acceleration inner loop, an improved control block diagram is shown in Figure 5:

![Figure 5. Feedforward - feedback control structure with disturbance observer](image)

Where \(C_p, C_a\) are position and acceleration controllers, and \(G_a\) is acceleration open-loop transfer function, \(\tilde{G}_a\) is the approximate model of the controlled plant, which obtains from fitting the measured transfer model, \(C_f\) is the DOB controller, \(\theta_i\) is the target position, \(\theta_{d_i}\) is the outer disturbance, and \(\theta_{o_3}\) is the output.
The ratio between deflective angle of the output and the disturbance quantity of the system is:

\[ \frac{\theta_{d_s}}{\theta_{d_i}} = \frac{1 - G_u C_f}{1 + C_\delta G_u + C_p C_\delta G_u \cdot \frac{1}{s^2} + C_u (G_u - \tilde{G}_u) C_f} \]  

(7)

After simplification, the ratio is:

\[ \frac{\theta_{d_s}}{\theta_{d_i}} \approx \frac{1 - G_u C_f}{1 + C_\delta G_u \cdot \frac{1}{s^2}} \]  

(8)

To ensure the DOB does not affect the closed-loop performance of the system, the \( C_f \) should be satisfied:

\[ C_f = \frac{1}{G_u} \]  

(9)

Where \( \tilde{G}_u \) can be regarded as the idealized model of \( G_u \), when \( G_f = 1/\tilde{G}_u \), \( 1 - G_u C_f \approx 0 \). In theory, system disturbance can be completely eliminated.

### 3. Model analysis

To ensure the tracking ability of position loop, the inertial stability platform model should be an integral element, so it should meet the requirement:

\[ C_u \cdot G_u = \frac{K}{s} \]  

(10)

By scanning the EOTS, we can get the acceleration object model of the racks. The curve fitting method of the acceleration object model is in Figure 6:

\[ G_u = \frac{5.5s}{0.71s + 1} \]  

(11)

![Figure 6. Acceleration object model](image-url)

The idealized acceleration control model is:
\[ C_a = \frac{K(0.7 \, \text{s} + 1)}{s^2} \]  

Because the sampling frequency of the inner loop of the acceleration is 5000Hz, the accelerometer has a delay of 2.5 frames. The actual acceleration controller can be designed as follows, and the acceleration controller is in Figure 7:

\[ C_a = \frac{66 \cdot (1 + 0.7 \, \text{s})}{s^2 \cdot (1 + 0.00 \, \text{s})} \]  

In Figure 7, the phase margin is 61, the amplitude margin is 15.4, and the acceleration bandwidth is close to 100Hz. The position open loop object characteristic with the acceleration close loop is in Figure 8.

The delay of CCD is about 2 frames (100Hz); the closed-loop bandwidth is severely limited to less than 10Hz. The actual position controller can be designed as follows, and the position controller is in Figure 9. Finally, we can get a position closed-loop in Figure 10.

\[ C_p = \frac{17 \, \text{s}}{1 + 0.005 \, \text{s}} \]  

4. Overall structure design

Out of the considerations above, control module simulation is shown in Figure 11.
The total anti-disturbance performance with DOB is presented in Figure 12. It is obvious that there is a significant improvement on the anti-disturbance ability with DOB.

In Figure 12, we can see the DOB performs well in medium and low frequency (high frequency performance is related to mechanical structure design). This approach can cover the shortage of the traditional speed and position double close-loop control.

The experimental results show that the anti-disturbance ability of the EOTS can be improved obviously after using the position-acceleration double closed-loop structure and DOB.

5. Conclusion
According to the lightweight demand of aerostat, the contribution of this paper is the selection of sensors, utilization of the MEMS accelerometers with high bandwidth, the formation of acceleration close-loop with small size and low cost. A miniaturization load EOTS is designed for aerostat. Stability control method is proposed based on DOB and acceleration closed loop of compound control algorithm. The experimental results show that the control method with DOB and acceleration closed-loop can integrate the advantages of both MEMS linear accelerometer and DOB. The MEMS linear accelerometer improves the system bandwidth. Moreover, DOB makes the system stable in low-frequency bandwidth and guarantees the system's anti-disturbance ability. In this paper, the advantages of feedback and disturbance feedforward control model are combined; the bandwidth of the system is improved. The design realizes the miniaturization and stability of EOTS carried on aerostats.

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