ULTRA PRECISE ATTITUDE REFERENCE SYSTEM FOR SPACE TRANSPORTATION SYSTEM

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ABSTRACT

To ensure the safety and success of space transportation system's flight mission, the system must perform the high precise attitude control that consists of attitude stabilization and attitude maneuvering. However, the inertial reference system exhibits accumulating drift errors in a long-term flight. To cope with this, a star tracker is usually used to provide a basis for correcting the inertial reference. This results in an celestial-inertial reference system. The star tracker provides necessary offsets for the gyro drift in the inertial system. This integrated system can give attitude information that meets the overall accuracy requirement. In this paper formulas of the ultra precise attitude reference system are developed for the attitude stabilization of a space shuttle with a new type sensor--Charge Inject Device (CID) used in the star tracker that combined with inertial platform system. A scheme of this CID star tracker and its performance are also presented.

INTRODUCTION

Space transportation system is a large system of high complexity, consisting of launch vehicle, astrovehicle and other auxiliary system, which can perform multiple aerospace mission. In this large system, to ensure the safety and success of its flight mission, the space shuttle, space station and space tug must keep a specified attitude that required by the orbital flight mission, it means that the system must perform the high precise attitude control that consists of attitude stabilization and attitude maneuvering.

During flight, especially the space station and space tug's rendezvous and docking, the space shuttle's orbital flight and re-entry, specified attitudes with high precision are required. However, the inertial reference system exhibits accumulating drift errors in a long-term flight. So it is not practical only to adopt Inertial Navigation System to provide high precise attitude reference. Therefore, a star tracker is usually used to provide a basis for correcting the inertial reference. This results in an Celestial-Inertial reference system. By heading and tracking some selected stars, with known position and trajectory, the star tracker provides necessary offsets for the Gyro drift in the inertial system, thereby making the latter be able to give attitude information that meets the overall accuracy requirement.

In this paper formulas of the ultra precise attitude reference system are developed for the attitude stabilization of a space shuttle with a new type sensor --Charge Inject Device (CID) used in the star tracker that combined with inertial platform system. A scheme of this CID star tracker is also presented, expounding its working principles and crucial technique.

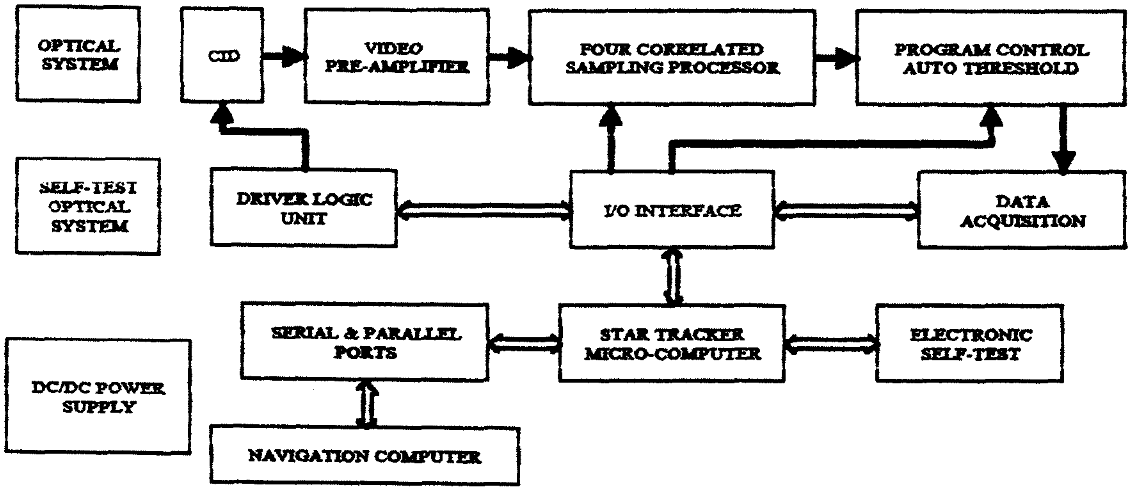

Fig. 1 CID STAR TRACKER SCHEMATIC

CID STAR TRACKER FOR SPACE TRANSPORTATION SYSTEM

Star tracker is main device in Celestial Navigation System, which can search, distinguish and track star from the sky background and measure the angle between star tracker aim line and reference coordinator. In the integrated Celestial-Inertial Navigation System it provides precise space positioning information (flight attitude basis) to conduct measuring or correction of various errors of Inertial reference.

The Integrated Navigation system in American space shuttle "CHALLENGER" adopts photoelectric Dissector as detector in star tracker. This kind of vacuum detector has such disadvantages as high voltage, low precision and low reliability. With the appearance of CCD in 70's, due to its superior performance, CCD had become sensitive device in standardized solid-state star tracker and will be adopted in new Celestial-Inertial integrated system of space shuttle. Now its main performance reaches: dynamic range: 1.5 degree/second, accuracy: 2 to 5 arc-second, magnitude range: 0 to 8 Mv.

CID was developed at the beginning of 80's after the invention of CCD. Not only has CID such advantages as small-size, low voltage, high reliability, wide spectrum respond, high stability of geometric location and efficient quantum, etc. the same as CCD, but also can CID star tracker work properly without refrigeration and with better dynamic performance compared with CCD, as it realize NDRO (non-destroy read operation) method of information acquisition, also with lower hidden electric current noise compared with CCD. We may predict that CID star tracker will be astronomical device for a new generation of Integrated Navigation system for space transportation system.

The typical performance requirement for CID star tracker applied in space shuttle is ,

Precision: $< 1''$ (2σ)

Noise Equivalent angle (NEA): $< 0.1''$ (2σ)

Magnitude : $0 < Mv < 9$

Dynamic range: $> 5\,°/s$

CID star tracker scheme is presented as follows(Figure 1):

1. Optical system

The CAD/CAM of the optical system that is a transmission system (f = 74mm) can correct globe, broom and astigmatic aberration to permissible range so as to enable image quality to meet the performance requirement of the system and meet the environment requirement of space shuttle application.

2. CID layout and its drive logic unit

In deciding the key component of star tracker, following main performance reference should be taken into consideration such as its quantum efficiency, spectrum respond, noise, system gain, dynamic range and linear and hidden hot electrical current.

Driving logic unit design should realize CID integral control, non-destructive quick scanning of whole array random location reading and drive control of fixed slow sampling output.

The scale of CID array matrix is shouldn't less 512 x 512.

3. Four-Correlation processor and analog signal processor

Correlation sampling circuit can effectively eliminate KTC noise in CID video frequency signal and $1/f$, $1/f^2$ noise ,etc. For analog signal processor, properly coordinated filter band should be chosen in order to improve signal to noise rate of the system. (see reference 1)

4. Program controller and automatic threshold

The automatic threshold can be used to automatically search star high sensitivity and reduce searching integral time. And also automatic deviation and program controller can compensate zero drift of CID and other hardware circuit caused by temperature change. It can also compensate star light energy difference.

5. Star tracker computer

Star tracker computer is the high-speed single chip CPU TMS320C30. It can bring about various CID control logic to realize various function control of system. It can carry on interpolation with the collected data, calculation the image center, coordinate angle exchange, static filter, dynamic data smooth and forecast, evaluation data processing in order to obtain the navigation result such as magnitude, coordinate, angle of tracked star.

6. Self-test and electronic system

Self-testing optical system can simulate the star light source to provide simulated navigation star for quantitative self-test of function and performance of the whole system. This part is separated from CID star tracker. After power is switched on, self-testing electronic system carry out the test for each crucial point in other functional units in the system, including test of drive signal logic, relevant processor and data acquisition; Meanwhile it can also simulate and produce electronic star.

7. Data-compressing technique

Adopting the searching method used to data acquisition with window sampling, in order to obtain the coordinate of a star. If we adopt 4 x 4 star picture window, we just need obtain sixteen pixel data of star image. So by avoiding complete data sampling of all field of view (FOV), the time for A/D translate and the data memory can be greatly saved.

8. Dynamic operation pattern

By adopting NDRO method of CID. The CID star tracker can carry out dynamic repeated data reading so as to greatly reduce integral time to realize star searching and tracking in the same integration period. It enable calculation of velocity vector to be more precise and with higher data rate. This is just what CCD star tracker is lacking.

ATTITUDE ERROR FORMULAS OF SPACE SHUTTLE

This paper derives attitude error formula for space shuttle by integrating CID star tracker into platform INS. For other separate system with similar result in space transportation system, formula should change accordingly.

1. Derivation of attitude error

According to the attitude reference provided by INS platform, star tracker located on the platform points towards the navigation star in predetermined sky area and actual star map can be obtained through CID. After star map distinguishing, compare it with the ideal navigation star map of star data in navigation computer. The difference is attitude reference error provide by INS platform.

Due to the drift error is small angle, so:

$$\begin{bmatrix} X \\ Y \\ Z \end{bmatrix} = \begin{bmatrix} 1 & \gamma & \beta \\ -\gamma & 1 & \alpha \\ \beta & -\alpha & 1 \end{bmatrix} \begin{bmatrix} X_C \\ Y_C \\ Z_C \end{bmatrix} \qquad \text{------- (1)}$$

In it: $[X\ Y\ Z]^T$ star theoretical value on CID coordinator.

$[\alpha\ \beta\ \gamma]^T$ attitude reference error of INS platform.

The above $[X\ \ Y\ \ Z]^T$ is determined by initial condition of space shuttle launching and relative connection between CID star tracker and Inertial Navigation platform.

Thus through derivation, we can get :

$$\begin{bmatrix} X \\ Y \\ Z \end{bmatrix} = \begin{bmatrix} \cos\theta_z & \sin\theta_z & 0 \\ -\sin\theta_z & \cos\theta_z & 0 \\ 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} \cos\theta_y & 0 & -\sin\theta_y \\ 0 & 1 & 0 \\ \sin\theta_y & 0 & \cos\theta_y \end{bmatrix}$$

$$\times \begin{bmatrix} 1 & 0 & 0 \\ 0 & \cos\theta_x & \sin\theta_x \\ 0 & -\sin\theta_x & \cos\theta_x \end{bmatrix} \begin{bmatrix} \cos A & 0 & \sin A \\ 0 & 1 & 0 \\ -\sin A & 0 & \cos A \end{bmatrix}$$

$$\times \begin{bmatrix} \cos(90-\varphi) & \sin(90-\varphi) & 0 \\ -\sin(90-\varphi) & \cos(90-\varphi) & 0 \\ 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} -1 & 0 & 0 \\ 0 & 0 & 1 \\ 0 & 1 & 0 \end{bmatrix}$$

$$\times \begin{bmatrix} \cos(tg+\lambda) & \sin(tg+\lambda) & 0 \\ -\sin(tg+\lambda) & \cos(tg+\lambda) & 0 \\ 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} f\cos\delta\cos\alpha \\ f\cos\delta\sin\alpha \\ f\sin\delta \end{bmatrix} \qquad \text{------ (2)}$$

Here are the definition for the above symbols:

f ---- the focal length of optical system in the star tracker

α ---- the star right ascension

δ ---- the star declination

λ ---- the space shuttle launch point longitude

φ ---- the space shuttle launch point latitude

tg ---- Greenwich hour angle

A ---- the shuttle launch angle

$\theta_x, \theta_y, \theta_z$ ---- angle between CID coordinator and platform coordinator

It can be proved, in formula (1), for the error angle $[\alpha \ \beta \ \gamma]^T$, three formulas are correlative. That is the attitude error $[\alpha \ \beta \ \gamma]^T$ is uncertain by tracking only one star. Thus we should consider tracking a group of stars (the number is n). The formula (1) should rewrite like this:

$$\begin{bmatrix} X_1-X_{c1} \\ Y_1-Y_{c1} \\ \cdot \\ \cdot \\ \cdot \\ X_n-X_{cn} \\ Y_n-Y_{cn} \end{bmatrix} = \begin{bmatrix} 0 & -Z_c & Y_{c1} \\ Z_{c1} & 0 & -X_{c1} \\ \cdot & \cdot & \cdot \\ \cdot & \cdot & \cdot \\ \cdot & \cdot & \cdot \\ 0 & -Z_{cn} & Y_{cn} \\ Z_{cn} & 0 & -X_{cn} \end{bmatrix} \begin{bmatrix} \alpha \\ \beta \\ \gamma \end{bmatrix}$$

------- (3)

Where the Z_c is :

$$Z_c = \sqrt{f^2 - X_c^2 - Y_c^2}$$

Thus final result is :

$$\begin{bmatrix} \alpha \\ \beta \\ \gamma \end{bmatrix} = \left(H^T H\right)^{-1} H^T \begin{bmatrix} X_1 - X_{c1} \\ Y_1 - Y_{c1} \\ \cdot \\ \cdot \\ \cdot \\ X_n - X_{cn} \\ Y_n - Y_{cn} \end{bmatrix}$$

--------- (4)

Where the H is :

$$H = \begin{bmatrix} 0 & -Z_{c1} & Y_{c1} \\ Z_{c1} & 0 & -X_{c1} \\ \cdot & \cdot & \cdot \\ 0 & -Z_{cn} & Y_{cn} \\ Z_{cn} & 0 & -X_{cn} \end{bmatrix}$$

-------- (5)

2 . Calculation of attitude error

With accompanied measuring noise existed in formula (4) , the least square error method or Kalman filter algorithm can be used to conduct data processing. The method in which data processing is conducted by adopting Kalman in free orbit can be refereed in reference document (3).

In order to improve calculating speed, a group of necessary stars should be chosen from Navigation star map to carry on calculation. supposing every two stars in Navigation star map is one group.

So formula (3) can be obtained thus :

$$X_1 - X_{c1} = \gamma Y_{c1} - \beta\sqrt{f^2 - X_{c1}^2 - Y_{c1}^2}$$

$$Y_1 - Y_{c1} = -\gamma X_{c1} + \alpha\sqrt{f^2 - X_{c1}^2 - Y_{c1}^2}$$

$$X_2 - X_{c2} = \gamma Y_{c2} - \beta\sqrt{f^2 - X_{c2}^2 - Y_{c2}^2}$$

$$Y_2 - Y_{c2} = -\gamma X_{c1} + \alpha\sqrt{f^2 - X_{c2}^2 - Y_{c2}^2}$$

------- (6)

from the equations (6) , the attitude error $[\alpha \ \ \beta \ \ \gamma]^T$ as follows :

$$\gamma = \frac{(X_1 - X_{c1})K_2 - (X_2 - X_{c2})K_1}{Y_{c1}K_2 - Y_{c2}K_1}$$

------- (7)

$$\beta = \frac{[Y_{c1}\gamma - (X_1 - X_{c1})]}{K_1}$$

------- (8)

$$\alpha = \frac{[(Y_1 - Y_{c1}) + \gamma X_{c1}]}{K_1}$$

------- (9)

Where the K_i is :

$$K_i = \sqrt{f^2 - X_{ci}^2 - Y_{ci}^2}$$

Above four formulas can be obtained by calculating the attitude error of two stars in each group. Therefore, there are various ways of calculation and with different formula, different precision is reached. It can be proved that if the selected two stars has the maximum of angle distance in CID visual space, its calculating error will reach the minimum.

After obtaining the attitude reference error $[\alpha \ \ \beta \ \ \gamma]^T$, according to Eulerian angle θ_x , θ_y , θ_z , thus we can get the drift error angle $[\psi_x \ \ \psi_y \ \ \psi_z]^T$, It is the error angle that Inertial Navigation platform surrounding its three directly intersected axis:

$$\begin{bmatrix}\psi_x\\ \psi_y\\ \psi_z\end{bmatrix} = \begin{bmatrix}1 & 0 & 0\\ 0 & \cos\theta_x & -\sin\theta_x\\ 0 & \sin\theta_x & \cos\theta_x\end{bmatrix}$$

$$\times\begin{bmatrix}\cos\theta_y & 0 & \sin\theta_y\\ 0 & 1 & 0\\ -\sin\theta_y & 0 & \cos\theta_y\end{bmatrix}$$

$$\times\begin{bmatrix}\cos\theta_z & -\sin\theta_z & 0\\ \sin\theta_z & \cos\theta_z & 0\\ 0 & 0 & 1\end{bmatrix}\begin{bmatrix}\alpha\\ \beta\\ \gamma\end{bmatrix}$$

------------ (10)

According to the calculating result in the formula (10) , Inertial Navigation platform drift error angle can be corrected. Thus , precise attitude reference of space shuttle can be obtained.

CONCLUSION

Space transportation system opens up a way to a brighter future for space activities of mankind. In order to guarantee reliability and precision of Inertial Navigation system for Space Transportation system and meet the precise attitude that required by the flight mission, it is very important to develop high-quality CID star tracker and Celestial-Inertial integrated Navigation system to provide high precision attitude reference basis for space transportation system.

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