Star Sensor Layout Design Based on PSO

ZHA Micheng, ZHAO Liping

Technology and Engineering Center for Space Utilization, Chinese Academy of Sciences, System design laboratory, Beijing, 100094

zhamiceng17@mails.ucas.ac.cn

Abstract. Incident light, such as sunlight and atmosphere-earth light, will interfere with the viewing field of star sensor, and the accuracy and precision of star sensor will decrease. A design method based on PSO algorithm and STK software to solve layout problems efficiently is applied. The star sensor layout problem is described as the problem of finding the global optimal solution in three-dimensional space. The results show that this method can solve the problem of satellite sensor layout quickly and effectively and the method has certain engineering application value.

1. Introduction

Star sensors are high-accuracy optical sensors. In order to capture more targets, a large field of view angle needs to be designed. However, it should try to avoid the incident light that affects the precision and accuracy of star point extraction, such as sunlight and atmosphere-earth light, entering the star sensor field of view. The design of the hood structure and the incident light filtering algorithm can improve the anti-incident ability. Optimizing the design of the star sensor installation layout position and the direction of the field axis also reduces incident light effects. In order to ensure the effectiveness of the star sensor, the installation layout of the star sensor should be analysed in detail in the design stage of the whole star scheme [1]. An et al. took the incident light suppression performance of the star sensor as the research focus and they used STK to analyse the angle change between the optical axis of the star sensor and the solar vector in a typical time [2]. Du et al. provided the conditions for incident light to enter the viewing field of the star sensor. They proposed an analysis method for the viewing field of star sensors based on STK and they simulated incident light entering the viewing field [3]. Zhang et al. established a mathematical model for the incident light in the viewing field of the star sensor. They used STK to simulate the field of view of incident light entering the star sensor, and gave the time period, duration and other information [4]. On the basis of studying the geometric position of Sun-Earth-Lune-Star, Zhao Lin et al. analysed the influence of sunlight on the view of star sensor during the process of satellite on orbit operation by combining the installation position of the star sensor and the viewing field [5].

The above several types of the viewing field analysis are only based on STK software, and the layout position needs to be designed repeatedly and iteratively. It is difficult to find the optimal layout quickly and the efficiency is low. In order to avoid the influence of incident light, the orientation of the satellite sensor installed on the satellite was analysed and optimized to ensure the effectiveness of the satellite sensor in orbit. Particle swarm optimization algorithm (PSO) is a population-based stochastic optimization technique. In this paper, the conditions of incident
light entering the viewing field of star sensor are analysed and the viewing field analysis model of star sensor is established. Combined with the data provide by STK tool and PSO algorithm, the validity of the layout method is verified by simulation.

2. Coordinate System Establishment
In this paper, geocentric inertial coordinate system J2000 is used to describe the position relationship among earth, satellite and satellite orbit and to determine the satellite position and velocity parameters. The stability of the satellite attitude usually adopts three modes: three-axis stability, spin stabilization, and gravity gradient stabilization. In this paper, the three-axis attitude stabilization method is selected, which is suitable for satellites with various pointing requirements. The zero-attitude schematic diagram of the satellite and the ontological coordinate system are shown in figure 1. The center of mass is the origin O of the coordinate system. The X-axis is constrained by the direction of inertial velocity, and the Z-axis always points to the Nadir.

![Satellite body coordinate system.](image)

Figure 1. Satellite body coordinate system.

3. Analysis of incident light entering the viewing field
Incident light which makes the background noise of CCD camera increase, enters the viewing field of star sensor. Incident light reduces the level of the entire image surface and deteriorates the sharpness. In severe cases, the target image or signal may be completely overwhelmed by incident noise. Incident light will seriously affect the accuracy and reliability of star point extraction [6].

The suppression angles of sunlight and ground-gas light in the star sensor are $\gamma_s$, $\gamma_m$, $\gamma_e$. $S_S$ is the sun direction vector in the star sensor coordinate system. The angle between the vector $S_S$ and the boresight direction of star sensor is $\beta_{ss}$, as shown in figure 2.

![Angle relationship between the sun vector and the visual axis vector of the star sensor.](image)

Figure 2. Angle relationship between the sun vector and the visual axis vector of the star sensor.

3.1. Conditions for sunlight to enter the viewing field
Due to the distance between the earth and the sun, the solar diffusion angle observed from the earth is only about 30 ', so sunlight can be thought of as parallel light. The angle between the sun direction vector and the satellite position vector is $\alpha_{ss}$. The radius of the earth is $R_e$. The
tangent line between the sun's rays and the earth intersects with the satellite's flight orbit at points L1 and L2, as shown in figure 3.

![Diagram of sunlight-earth-satellite relationship](image)

**Figure 3.** Location relationship analysis of sunlight-earth-satellite

According to figure 4, it can be analysed:

1. When the satellite enters the ground shadow area, i.e. $\alpha_{ss} < \arcsin \left( \frac{R_e}{|O_eL_1|} \right)$, there is no direct sunlight in the viewing field, so this region is not considered.
2. When $\alpha_{ss} \geq 90^\circ$, the satellite is illuminated by the sun. Moreover, when $\beta_{ss} \leq \gamma_s$, sunlight enters the viewing field of the star sensor.
3. When $90^\circ - \arcsin \left( \frac{R_e}{|O_eL_1|} \right) \leq \alpha_{ss} < 90^\circ$ and $\beta_{ss} \leq \gamma_s$, sunlight into the viewing field.

### 3.2. Conditions for the entry of atmosphere-earth light into the viewing field

The earth's surface is covered with an atmosphere more than 1000 kilometers thick. The atmospheric system is a space system with the upper surface of the earth as the lower limit and the upper boundary of the atmosphere as the upper limit. The earth can be regarded as a blackbody with a temperature of 300K. And its radiation peak wavelength is about 10 μm [7]. In the study of the influence of atmosphere-earth light on the irradiance of star sensor, the irradiance of the reflected sunlight on the earth's surface is mainly studied, regardless of the influence of the earth's own radiation. Due to the reflection and scattering of sunlight from the atmosphere, the atmosphere-earth light becomes a strong incident light source which affects the normal operation of the star sensor. The atmosphere-earth light seriously interfered with the working process of the satellite sensor on the LEO orbit satellite [8].

When the satellite enters the sunlit area, the atmosphere-earth light will cause interference. When the satellite is in the shadow area, there is no atmosphere-earth light interference. Therefore, only the satellite in the solar exposure area was analyzed. Suppose that the earth's atmospheric system is spherical, the atmospheric thickness is $d_a$ and the satellite's center of mass is $O_t$. The atmosphere-earth light exists in the cone with satellite centroid as the apex, $O_t A$ as element, $O_t O_e$ as central axis and $\alpha_{se}$ as semi-cone Angle. The angle between the atmosphere-earth light and the visual axis of the star sensor is $\beta_{se}$, which is the angle between the conical surface and the visual axis outside the conical surface, as shown in figure 4.
Figure 4. Atmosphere-earth light into the field of view analysis

According to the earth shadow model in figure 5, the conditions for atmosphere-earth light to enter the viewing field of the star sensor are as follows:

1. When \( \alpha_{se} \geq \arcsin \left( \frac{R_e}{|O_eL_{1}|} \right) \), the satellite is under the sunlight. And when the visual axis of the star sensor is within the semi-cone angle \( \alpha_{se} \), the atmosphere-earth light enters the viewing field;

2. When \( \alpha_{se} \geq \arcsin \left( \frac{R_e}{|O_eL_{1}|} \right) \), the satellite is under the sunlight. And when \( \beta_{se} \leq \gamma_e \), the atmosphere-earth light enters the viewing field.

3.3. Comprehensive conditions of incident light entering the field of view of star sensor

Based on the above single incident light analysis, the specific process of determining whether the field of view of the star sensor is exposed to atmosphere-earth light and sunlight is shown in figure 5.

Figure 5. Flow field of incident light entering star sensor

According to this flow chart, it is specifically determined whether the viewing field of the star sensor is affected by stray light. During the orbiting of the satellite, the direction of the boresight only needs to satisfy \( \beta_{se} \geq \gamma_e \) to avoid the atmosphere-earth light. When the visual axis direction of the star sensor satisfies the conditions of \( \beta_{ss} \geq \gamma_s \), sunlight and moonlight can be prevented from entering the field of view.
4. Simulation model establishment

In the previous chapter, the influence of incident light on the different positions of the star sensor is analysed in detail, and the conditional model of incident light entering the star sensor is described. In this chapter, the satellite toolkit STK and MATLAB are used to analyse the influence of incident light on the viewing field of the star sensor. Developed by analytical graphics, STK is a leading business analysis software in the aerospace field. It supports the entire process of space missions, including design, test, launch, operation and mission applications, and provides analytical results in the form of diagrams and texts.

4.1. Add target satellite model

This article starts by creating a scenario in STK. The angle between the earth-sun line and the orbit plane in a year is the smallest on the summer solstice. At this time, the angle between the star sensor and the sunlight is the smallest, which has the greatest influence on the star sensor. Therefore, only the worst case is considered in the simulation modelling [8]. Therefore, the day with the smallest solar incidence angle in a year was selected, and the simulation time is set as 21 Jun 00:00:00 UTCG - 22 Jul 00:00:00 UTCG.

Use the "Orbit Wizard" method to add a target satellite $S_c$ with a circular orbital height of 400 km and an orbital inclination of 42°. Ideally, the satellite attitude angle is (0°, 0°, 0°). The pose type is the direction of the nadir and the direction of the velocity vector under the ECF. The Z axis points to the bottom of the sky, and the X axis is constrained by the direction of the fixing speed. The orbit prediction method is J4Perturbation. The suppression angles of the sun and the atmosphere-earth light of a star sensor are respectively 25° and 25°.

4.2. Output report

STK software provides a standard set of data reports to summarize key information, and all reports can be exported to popular spreadsheet tools in industry standard formats. In this paper, the required information includes the solar vector based on the satellite's ontology coordinate system, the time when the satellite enters and exits the illumination zone, and the duration of the illumination zone.

By using the vector geometry tool, I build a solar vector based on the satellite ontology coordinate system, which points from the centre of the sun to the centre of the satellite, and the size is the true distance from the satellite to the sun[9]. The report tool is used to output the solar vector report of every moment in the simulation period under the satellite body coordinate system. The Sun item in the Report tool is used to calculate the visit to the Sun, and the time when the satellite enter and leave the illumination area and the duration in the illumination area are obtained.

4.3. Design of star sensor layout based on PSO

In practice, it is necessary to determine the orientation of the optical axis vector of the star sensor in the satellite body coordinate system and specify the specific installation position according to the specific satellite structure. Therefore, it is assumed that the starting point of the optical axis vector of the star sensor coincides with the centre of mass of the satellite body. The layout problem of star sensor is simplified to the problem of finding the best vertex coordinate of the optical axis vector in the satellite body coordinate system [10].

The starting point of the optical axis vector of the star sensor is coincident with the centre of mass of the satellite body. Taking the origin of the satellite body coordinate system as the centre, a three-dimensional sphere with the radius as the unit length is made. The vector formed from the origin to any point on the surface of the sphere is the apparent axis vector of the star sensor layout, forming a potential layout vector set. First, I remove the vector whose angle with the positive direction of the z-axis is less than the atmosphere-earth light suppression angle of the star sensor. Then the particle swarm optimization algorithm is used to calculate the mean value of the angle between the layout vector and the solar vector in the light time, and it is the optimal layout vector. Therefore, the star sensor layout problem is described as the problem of finding the global optimal solution in three-dimensional space.
4.3.1. Avoiding atmosphere-earth light interference. In the satellite body coordinate system, the conical plane, which takes the origin as the center of the circle, takes the positive direction of the z-axis as the central axis, and takes $\alpha_{se}$ as the semi-cone angle, intersects the unit sphere. Part of the spherical cone surface contains I area can be considered to be an accessible area of atmosphere-earth light [11].

![Figure 6. Unit sphere schematic diagram.](image)

4.3.2. Obtaining the sun and moon exposure time of the satellite. Based on the Sun report from the STK output, I used MATLAB to filter out the set of sun vectors $b_j$ under the sun’s illumination time.

4.3.3. Using particle swarm optimization algorithm to obtain the optimal position. In order to reduce the interference of the direct sunlight on the star sensor, it is necessary to make the angle between the solar vector and the star sensor optical axis vector larger than the sun sensor suppression angle $\gamma_s$ of the star sensor. According to the solar vector under the illumination time, the angle between the star sensor optical axis vector $a_i$ and the vector $b_j$ at a certain moment is:

$$\theta_{ij} = \arccos\left(\frac{a_i \cdot b_j}{\|a_i\| \|b_j\|}\right)$$

The coordinate points on the secure efficient sphere constitute the solution space of particle swarm optimization. The mean angle between the optical axis vector $a_i$ of the star sensor and the solar vector $b_j$ at a certain time in the period is taken as the evaluation index. Fitness function $f$ of the algorithm is shown as follows, where $k$ is the maximum moment in the cycle:

$$f = \frac{\sum_{j=0}^{k} \arccos (a_i \cdot b_j)}{k}$$

PSO initializes a group of random particles, namely random coordinate points on the safe and effective sphere. In each iteration, the position of the particle is updated by tracking the optimal solution found by the particle itself and the optimal solution found by the whole population. Calculate the best layout vector $a_{i, \text{best}} = [-0.9280 -0.2984 0.2229]$, which is equivalent to a star sensor with an azimuth of $-34^\circ$ and an elevation angle of $-40.5^\circ$. The layout orientation on the satellite is shown in the figure below.

![Figure 7. Star sensor installation angle diagram](image)
4.4. **Simulation Analysis of Incident Light Interference Based on STK**

The Sensor1 is added into the scene created before. The sensor type is a simple cone. The pointing type is Fixed in Axes and the azimuth way is azimuth-elevation Angle (Az-El: -34°, -40.5°). The reference frame is the satellite body coordinate system.

4.4.1. **The semi-cone angle is set to 25°.** And Line of Sight and Field of View are selected from the basic properties of the constraint. By using the output report function, the change of the angle between the apparent axis of the star sensor and the solar vector is calculated. As shown in the figure below, the minimum angle is 39.4°. At all times, the angle meets the condition of \( \beta_{ss} \geq \gamma_s \), without interference from sunlight.

![Figure 8](image)

**Figure 8.** Change of the Angle between the apparent axis of the star sensor and the solar vector.

4.4.2. **The semi-cone angle is set to 25°.** Using the output report function, the change of the angle between the direction of the apparent axis and the earth vector is statistically calculated. And The Angle is always 130.5°. At all times, the angle satisfies the condition of \( \beta_{se} \geq \gamma_e \). There is no earth-gas-light interference.

![Figure 9](image)

**Figure 9.** Change of Angle between the apparent axis of star sensor and the earth vector

5. **Conclusion**

In this paper, the model of incident light entering the viewing field of star sensor is established. Based on STK and PSO, the optimal position of star sensor is designed. The rationality and validity of this layout method are verified by STK. This method is applicable to the viewing field analysis of optical sensors on satellites of any orbital type. It can be used to design and optimize the placement of the star sensor on the spacecraft quickly and it meets the requirements of rationality and effectiveness of on-orbit work.

**Reference**

[1] CHEN C M, LI Y X, ZHOU W, GAO Y X. 2003. An Observation Study on the aviation Budget Characteristics for Earth atmospheric System. *Journal of Zhongshan University*. 42(1): 88-89

[2] AN M, ZHANG J, WANG X H and HAN B. 2013. Simulation and Analysis for the Stray Light Suppressing Based on STK. *Tactical missile technology*. (3): 59-66
[3] Li X Y, DU W and MO F. 2013. Simulation Analysis on View Field of Star Sensor Based on STK. *Spacecraft engineering*. 22(2): 27-31

[4] ZHANG H, HAO Y J. 2013. Simulation and Analysis for the Stray Light Suppressing Based on STK. *Computer simulation*. 2(7): 83-86

[5] ZHAO LIN, SU Z H, HAO Y. 2013. Research on star sensor layout based on geometric position analysis. *Transducer and Microsystem Technologies*. 32(12): 34-37

[6] IAO Y, LIU G M and WEN Y L. 2006. Research on Modeling and Simulation for View Field of Star Sensor. *Journal of system simulation*. 40(1): 38-40

[7] LIAO Z B, FU R M and ZHONG X Y. 2011. Design of specular baffle of star sensor. *Infrared and Laser Engineering*. 40(1): 66-69

[8] TANG Y, LU X and HAO C Y. 2004. Star Sensor Stray Suppression Analysis. *Aerospace Control*. 22(3): 58-61

[9] XIANG S H, ZHANG T. 2007. Calculation of Solar Direct Radiation on the Satellite External Surface Using STK. *Infrared Technology*. 29(9): 508-511

[10] XU K, CHEN Z G, ZHAO J H, DAI L and LI F. 2011. Layout design method of star sensor based on particle swarm optimization algorithm. *Journal of Jilin University (Engineering and Technology Edition)*. 49(3): 927-978

[11] YANG Y, WANG H L, LU J H. 2016. Analysis of Impact of Earth and Atmosphere Radiation on Star. *Optoelectronic Engineering*. 43(4): 8-14