RETRACTED ARTICLE: On-orbit calibration of sun sensor’s central point error for triad

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ABSTRACT
In this paper, a novel sun sensor which has been applied on orbit since 2018 is introduced. The remote data transmitted from the satellite is analyzed to show its performance. In the lighting area, the sun sensor can give the sun vector which used for the attitude determination. From the data, the center point error is found to be the most significant factor that affects the accuracy of the sun sensor. In the “Sun pointing” work mode, the real output of the sun sensor is different from the theoretical output. The data from the star sensor is used for compensating the center point error based on ellipse fitting. The triad algorithm is affected by the center point error of the sun sensor. The simulation only considers this kind of error. And the result shows that it can decrease the Euler angle errors, so that improves the accuracy of triad algorithm.

Introduction
Sun sensor is an important type of satellite sensors. Although the application of the star sensor improves the accuracy of satellite attitude measurement, almost all the ADCS (Attitude Determine and Control System) are equipped with sun sensors to improve the reliability of satellite. Compared with other attitude sensors like star sensors or infrared earth sensors, the sun sensor has many advantages such as simple structure and low cost. In addition, due to the high brightness of the sun, the positioning process of the sun sensor is hardly interfered by other celestial bodies. The star sensor cannot give stable useful data also when the angular velocity of satellite is more than 3°/s. In these cases, the sun sensor is important for the ADCS, is can use with magnetometer in triad algorithm as the backup method for attitude determination, thus increase the reliability of the system.

Sun sensors can be divided into two types according to accuracy: coarse sun sensor and fine sun sensor. But more conventionally used categories of sun sensors: analog and digital types. When the satellite does not require high accuracy, ADCS always choose analog sun sensors. Photodiodes, which generate current as required, are the most basic type of sun sensor. Therefore, this kind of sun sensor can achieve the highest accuracy of the sun sensor. Without the mask, there is no diffraction in this sun sensor. The phenomenon called the “black sun” is presented. The phenomenon in image sensor known as the “black sun” caused by electron overspill at a oversaturated pixel (Saleem et al., 2017). Another miniature sun sensor is based on the L-shape slit above the chip extends beyond the borders of the chip which can avoid the case when the input beam entirely overlaps along on pixel array (Farian et al., 2017). But both slit and hole are under the effect of diffraction.

In recent years, a sun sensor using a phenomenon called the “black sun” is presented. The phenomenon in image sensor known as the “black sun” caused by electron overspill at a oversaturated pixel (Saleem et al., 2017). Compared with the sun sensor with holes mask, this sun sensor simplified optical system design and reduce the complexity of data processing. Without the mask, there is no diffraction in this sun sensor. Therefore, this kind of sun sensor can achieve high accuracy and precision.

In the mission of “Ladybeetle-1” satellite by COMMSAT company in 2018, two sun sensors usually use more advanced components than photo-diode, such as CCD or CMOS. Compared with photodiodes, the number of basic detection units has been increase from several to hundreds, or even thousands, which greatly improves the ability of sun sensors to get the solar orientation. A lot of digital sun sensors utilize an imaging device as the detector plane with a mask placed in front of it (Wei et al., 2017). A low-cost sun sensor which consists of precisely machined pinhole with a 10 µm circular aperture is introduced and a model is developed in order to account for the geometrical deviations and deformations of the pinhole-projected light-spot (Antonello et al., 2018). Another miniature sun sensor is based on the L-shape slit which extends beyond the borders of the chip which can avoid the case when the input beam entirely overlaps along on pixel array (Farian et al., 2017). But both slit and hole are under the effect of diffraction.
based on “black sun” are used in ADCS. This system also includes two different star sensors, two sun sensors, one magnetometer, two MEMS, four reaction wheels and three magnetorquers. These two sun sensors together with one star sensor are made by TY-space company. The total number of star sensors sent into space made by TY-space is more than one hundred till 2020. The sun sensor inherits part of the design of the star sensor. The two sensors have the similar camera and data processing mode, but the sun sensor does not have hood like star sensor. Those photos are shown in Figure 1, 2 and 3.

Before the satellite launched into space, the sensor had better to be calibrated in the lab. But for various reasons, those two sun sensors did not calibrate with star sensor in the lab. Only the star sensor was calibrated with the body coordinate of the satellite. Therefore, on-orbit calibration was necessary. The photos of the satellite in the lab and on orbit are shown in Figure 4 and 5.

In fact, on-orbit calibration is necessary even it had been done in the lab. Because the structure is affected by the impact of the rocket, the calibration parameter will change after launch. Although the scale factor can be estimated from pre-flight calibration, photodiodes are known to degrade on-orbit due to radiation, and previous flight experience demonstrates that this has a significant effect on the scale factor (Springmann &
In addition, other sensors include magnetometer and gyros also need on-orbit calibration. And they always use similar methods. EKF (Extended Kalman Filter) is always used in on-orbit calibration. Ali Rahdan (Rahdan et al., 2020) proposed a novel attitude independent error model for SS-411 sun sensor. This model includes the central point of the CCD array, installation error, filter thickness and sensor misalignment. Compare with the worst case, the accuracy improvement of about 17° is achieved by the developed calibration algorithms with EKF and UKF.

The biggest difficulty for on-orbit calibration is the lack of accurate information of the real sun angles during flight (Wu & Steyn, 2002). Sensors like magnetometers were used for on-orbit calibration of sun sensor. But the accuracy of angles from
magnetometer is always worse than CMOS sun sensor. The accuracy of calibration is mainly limited by the availability of the attitude reference. It’s better to use higher accurate sensor to calibrate other sensors. Fortunately, the data from the “Ladybeetle-1” shows that ADCS works stable on orbit. The tele-measurement data from the star sensor is accurate enough to calibrate sun sensor. In this paper, we present the on-orbit performance of a novel sun sensor, and use data from the star sensor to calibrate the center of CMOS array. The process of calibration also needs the whole ADCS data include orbit extrapolation algorithm. We design a work mode called “Sun pointing” of satellite. In this mode the output data of sun sensor can be simplified as the error model. An algorithm of ellipse fitting is used to obtain the center of CMOS array. After compensation of the central point error, we analyze the triad error model with sun sensor and magnetometer. Finally, the simulation show that the three axes pointing accuracy can be improved effectively by compensation.

Design of “Sun pointing” work mode

“Ladybeetle-1” is a satellite without SADA (Solar Array Drive Assembly). It weights 100 kg and it needs more than 500 W electric power in special work modes. In order to maximize the charging efficiency, a work mode called “Sun pointing” is designed. In this work mode, the normal vector of the solar array, which defined as $-Z_s$ always points to the sun. The vector is the opposite direction of the body axis $Z_b$, the relationship between the two axes is shown as below

At the same time, the body of the satellite spin around $-Z_s$. The geometric model is shown in Figure 6.

In Figure 7, $r_{sm}$ is the vector pointing to the sun. The three axes of destination coordinate are $X_s$, $Y_s$, and $Z_s$. $Z_o$ is the vector from the center or satellite pointing to the center of the earth. In inertial frame, the defined destination coordinate can be written as
Where the second line of Equation (1) determines the attitude. This mathematical constraint comes from the consideration of effectiveness of the star sensor. It should avoid the sun light and earth atmosphere light. This constraint maximizes the effectiveness of the star sensor in this work mode. Because the sun vector and the earth vector change all the time in the orbit, so the \( \mathbf{X} \) spins around \( \mathbf{Z}_s \).

“Ladybeetle-1” works on the 10:30 a.m. SSO (Sun Synchronous Orbit). Equation (1) can be calculated in inertial coordinate. Using GPS to get the accurate position of the satellite is also important. Then the satellite can calculate the vector \( \mathbf{r}_o \) in inertial frame by the orbit extrapolation algorithm. The other vector is \( \mathbf{Z}_o \). This vector can be written in orbit frame as

\[
\mathbf{Z}_o^i = \begin{bmatrix} 0 & 0 & 1 \end{bmatrix}^T \tag{2}
\]

\( \mathbf{Z}_o^i \) is the vector \( \mathbf{Z}_o \) written in inertial frame. It is given by

\[
\mathbf{Z}_o^i = \mathbf{C}_o^i \mathbf{Z}_o^o \tag{3}
\]

Where \( \mathbf{C}_o^i \) is the transformation matrix from orbit coordinate to inertial frame which also can be obtained by the orbit extrapolation algorithm. The
destination attitude is determined and then the angular velocity can be deduced. Since the ADCS controls the body frame follow the Equation (1) to keep the solar array perpendicular to the sunlight.

Without error form measurement and control, the projection of the sun vector should be a point on the CMOS array of the sun sensor. Before the calibration of sun sensor, the ADCS use star sensor to determine attitude. So the data from star sensor can be used to calibrate sun sensor. And at the same time, the date from sun sensor also can show that the ADCS performance on orbit.

Figure 9. Sun sensor original output (tan α).

Figure 10. Sun sensor original output. (tan β)
Figure 11. $e_\alpha$ and $e_\beta$ in One figure.

Figure 12. Ellipse fitting.
Sun sensor calibration and triad

Analyze the output from the sun sensor

According to the height of the satellite, the sun sensor can not give useful data in the umbra. After filter, we have 856 sets of data which can be analyzed. Each set contained two variables: $\alpha$ and $\beta$ in the sensor frame. The angles $\alpha$ and $\beta$ represent the rotations along the $x$ and $y$ axes respectively. These two angles are determined from the coordinates of black sun image center on the CMOS array. The relationship between the coordinate $x_m$, $y_m$ and max FOV is shown in Figure 8. Where $x_0$, $y_0$ are the center coordinate of the CMOS plane. The angle $\alpha$ can be written as

$$\alpha = \arctan \left( \frac{x_m - x_0}{f} \right)$$

Where $f$ is the focal length of the camera system. The angle $\beta$ can be written as

Figure 13. Roll error and $\theta_{12}$.

Figure 14. Pitch error and $\theta_{12}$. 
\[ \beta = \arctan\left( \frac{y_m - y_0}{f} \right) \]  \hspace{1cm} (5)

The telemetry data contains \( \tan \alpha \) and \( \tan \beta \). The data can be shown in Figure 9 and 10.

The output of the sun sensor can prove that the sun light orientation is not accuracy. In the sunlight the ADCS control the satellite spin around the vector \( Z_b \). In Figure 9 and 10 we can obviously know that this vector does not coincide with the sun vector. In the “Sun pointing” work mode, the ADCS accuracy depends on the orbit extrapolation algorithm and star sensor. The elliptic curve on the CMOS plane can be analyzed to obtain an error model, which give the on-orbit performance of the ADCS.

Two kind of error would cause the inaccurate result shown in Figure 11. First, the central point error of sun sensor. Second, the calculation error of the sun vector by orbit extrapolation algorithm.

\[ \text{Figure 15. Yaw error and } \theta_{12}. \]

\[ \text{Figure 16. Root mean square of three Euler angles and } \theta_{12}. \]
**Central point error**

According to Equations (4) and (5), the center of the CMOS plane is $x_0$ and $y_0$. Since there is no calibration after installation on the satellite, the error of $x_0$ and $y_0$ is the main error which affects the accuracy of the sun sensor. The central location of the ellipse can be calculated and it can be compared with the projection of the sun vector given by the star sensor and orbit extrapolation algorithm.

The GPS can get the location, velocity and the UTC time of the satellite. According to calculation algorithm (Fernández-Ahumada et al., 2017), the sun vector depends on the UTC time. The sun vector calculated by the UTC time is denoted as $\mathbf{r}_{sun}^i$ in inertial frame. The rotation matrix from inertial frame to body is denoted as $\mathbf{C}_b^i$, which given by star sensor.

$$\mathbf{r}_{sun}^b = \mathbf{C}_b^i \mathbf{r}_{sun}^i$$  \hspace{1cm} (6)

Where $\mathbf{r}_{sun}^b$ is the calculated sun vector in body frame. Rotate $\mathbf{r}_{sun}^i$ to the sun sensor frame, we can get a reference location of the sun vector. The reference vector can be written as

$$\mathbf{r}_{sun}^i = \mathbf{C}_b^{sun} \mathbf{r}_{sun}^b = \begin{bmatrix} r_{x}^{sun} \\ r_{y}^{sun} \\ r_{z}^{sun} \end{bmatrix}$$  \hspace{1cm} (7)

Where $\mathbf{C}_b^{sun}$ is the installation matrix.

$$\mathbf{C}_b^{sun} = \begin{bmatrix} 0 & -1 & 0 \\ -0.7314 & 0.6820 & 0 \\ -0.6820 & 0 & -0.7314 \end{bmatrix}$$  \hspace{1cm} (8)

On the CMOS plane, the location can be written as

$$\tan \alpha_c = \frac{r_{y}^{sun}}{r_{z}^{sun}}$$  \hspace{1cm} (9)

$$\tan \beta_c = \frac{r_{x}^{sun}}{r_{z}^{sun}}$$  \hspace{1cm} (10)

Therefore, the angles $\alpha_c$ and $\beta_c$ is calculated easily, which can be compared to the $\alpha$ and $\beta$. The differences between the calculated angles and measured angles can be written as

$$e_\alpha = \tan \alpha - \tan \alpha_c$$  \hspace{1cm} (11)

$$e_\beta = \tan \beta - \tan \beta_c$$  \hspace{1cm} (12)

These above two errors can be drawn in Figure 12.

The error looks like an ellipse curve. The central location of the ellipse can reflect the real center after calibration. The center point error can be described as the center of the ellipse. We can represent a general conic by an implicit second-order polynomial (Kesániemi & Virtanen, 2017)

$$\mathbf{F} = \mathbf{A} \cdot \mathbf{X} = ax^2 + bxy + cy^2 + dx + ey + f = 0$$  \hspace{1cm} (13)

Where $\mathbf{A} = [a \ b \ c \ d \ e \ f]^T$ and $\mathbf{X} = [x^2 \ xy \ y^2 \ x \ y \ 1]^T$. The fitting of a general conic may be approached by minimizing the sum of squared algebraic distances

$$D(\mathbf{A}) = \sum_{i=1}^{N} F(\mathbf{X}_i)^2$$  \hspace{1cm} (14)

Consider that the constraints are all linear, there can be a quadratic constraining $\mathbf{A}^T \mathbf{C} \mathbf{A} = 1$, where $\mathbf{C}$ is a $6 \times 6$ constraint matrix. The quadratic constraint can be expressed in the matrix as

$$\mathbf{A}^T \begin{bmatrix} 0 & 0 & 2 & 0 & 0 & 0 \\ 0 & -1 & 0 & 0 & 0 & 0 \\ 2 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 \end{bmatrix} \mathbf{B} = 1$$  \hspace{1cm} (15)

Now the ellipse fitting problem can be reduced to minimizing $E = || \mathbf{DA} ||^2$ which subject to Equation (15), where $\mathbf{D} = [\mathbf{X}_1 \ \mathbf{X}_2 \ \ldots \ \mathbf{X}_N]$. We can introduce a Lagrange multiplier

$$2\mathbf{D}^T \mathbf{DA} - 2\lambda \mathbf{C} \mathbf{A} = 0$$  \hspace{1cm} (16)

The above equation also can be written as

$$\mathbf{S} \mathbf{A} = \lambda \mathbf{C} \mathbf{A}$$  \hspace{1cm} (17)

Where $\mathbf{S} = \mathbf{D}^T \mathbf{D}$. Equation (17) can be solved by the generalized eigenvectors. Suppose that $(\lambda_i, \mathbf{u}_i)$ solves Equation (16), there is $(\lambda_i, \mu \mathbf{u}_i)$ for any $\mu$ and from Equation (15). We can get the value of $\mu_i$ as $\mu_i^2 \mathbf{u}_i^T \mathbf{C} \mathbf{u}_i = 1$.

$$\mu_i = \frac{1}{\mathbf{u}_i^T \mathbf{C} \mathbf{u}_i}$$  \hspace{1cm} (18)

Now we can get $\mathbf{A}_i = \mu \mathbf{u}_i$. Finally the parameters of the second-order polynomial can be given as

$$\mathbf{A}_i = [a \ b \ c \ d \ e \ f]^T$$  \hspace{1cm} (19)

This algorithm is realized and the result is shown in Figure 12.

The center of the ellipse (Li, 2019) can be written as

$$X_C = \frac{be - 2cd}{4ac - b^2}$$  \hspace{1cm} (20)

$$Y_C = \frac{bd - 2ae}{4ac - b^2}$$  \hspace{1cm} (21)

Now the central point error is $e_\alpha = X_C$, $e_\beta = Y_C$, which can be compensated to Equations (11) and (12).

**Effect of compensation in triad**

When the satellite works in the lighting times, it uses the sun sensor and magnetometer to determine the
attitude of the system. The algorithm is triad which use two reference vector, one is calculated sun vector in inertial frame, the other is calculated magnetic field vector. The current UTC time of the satellite can be known from the GPS. Then the sun vector \( \mathbf{r}_{\text{sun}} \) can be calculated by the UTC time (Fernández-Ahumada et al., 2017). The magnetic field vector also can be calculated by GPS data. The magnetic field which used on “Ladybeetle-1” is IGRF 12. Then we can get the second reference vector \( \mathbf{r}_{\text{mag}} \).

After two reference vectors are obtained, the measurement vector can be got by sun sensor and magnetometer. The sun vector in the sun sensor frame can be written as

\[
\mathbf{r}_{\text{sun}}^s = \frac{1}{\tan^2 \alpha + \tan^2 \beta + 1} \left[ \tan \alpha \quad \tan \beta \quad 1 \right]^T
\]  

(22)

This sun vector in the body frame can be written as

\[
\mathbf{r}_{\text{sun}}^b = \mathbf{C}_{\text{sun}}^b \mathbf{r}_{\text{sun}}^s
\]  

(23)

The three-axis magnetic field strength measured by the magnetometer can be directly converted into a magnetic field vector, as shown in the following equation

\[
\mathbf{r}_{\text{mag}}^i = \frac{1}{Bx^2 + By^2 + Bz^2} \begin{bmatrix} Bx & By & Bz \end{bmatrix}
\]  

(24)

This magnetic field vector in the body frame can be written as

\[
\mathbf{r}_{\text{mag}}^b = \mathbf{C}_{\text{mag}}^b \mathbf{r}_{\text{mag}}^i
\]  

(25)

According to Ref (Soken & Sakai, 2020), (Robinson & Richie, 2016), the convert matrix between the inertial frame and the body frame can be calculated by the triad algorithm. The brief process is as follows:

\[
\mathbf{v}_1 = \mathbf{r}_{\text{sun}}^i \mathbf{v}_2 = \frac{\mathbf{r}_{\text{sun}}^i \times \mathbf{r}_{\text{mag}}^i}{\left| \mathbf{r}_{\text{sun}}^i \times \mathbf{r}_{\text{mag}}^i \right|}, \quad \mathbf{v}_3 = \mathbf{v}_1 \times \mathbf{v}_2
\]  

(26)

\[
\mathbf{w}_1 = \mathbf{r}_{\text{sun}}^i \mathbf{w}_2 = \frac{\mathbf{r}_{\text{sun}}^i \times \mathbf{r}_{\text{mag}}^i}{\left| \mathbf{r}_{\text{sun}}^i \times \mathbf{r}_{\text{mag}}^i \right|}, \quad \mathbf{w}_3 = \mathbf{w}_1 \times \mathbf{w}_2
\]  

(27)

The conversion matrix can be written as

\[
\mathbf{C}_{ij}^b = \begin{bmatrix} w_1 & w_2 & w_3 \end{bmatrix} \begin{bmatrix} v_1 & v_2 & v_3 \end{bmatrix}^T
\]  

(28)

From Equations (26) and (27), an important pre-requisite for dual vector pose determination can be obtained, and the two dual vectors cannot be collinear. If the sun vector and magnetic field vector are collinear, the three-dimensional orthogonal coordinate system can’t be stretched. Since there are also measurement errors existent in the systems, the reference vectors and measurement vectors are not completely coincident. The two vectors \( \mathbf{r}_{\text{sun}}^b \) and \( \mathbf{r}_{\text{mag}}^b \) are on the cone surface with \( \mathbf{r}_{\text{sun}}^i \) and \( \mathbf{r}_{\text{mag}}^i \) as the axes, and the cone angles can be written as \( \theta_{\text{sun}} \) and \( \theta_{\text{mag}} \). These two error angles will be small. Suppose the angle between the sun vector and the magnetic field vector is \( \theta_{12} \), the error relation can be written as follows.

\[
\left| \mathbf{r}_{\text{sun}}^i \times \mathbf{r}_{\text{mag}}^i \right| \approx \left| \mathbf{r}_{\text{sun}}^b \times \mathbf{r}_{\text{mag}}^b \right| \approx \sin \theta_{12}
\]  

(29)

\[
\mathbf{r}_{\text{sun}}^i \cdot \mathbf{r}_{\text{mag}}^i \approx \mathbf{r}_{\text{sun}}^b \cdot \mathbf{r}_{\text{mag}}^b \approx \cos \theta_{12}
\]  

(30)

Construct two vectors \( \mathbf{r}_3^b \) and \( \mathbf{r}_3^i \), where \( \mathbf{r}_3^b \) is perpendicular to \( \mathbf{r}_{\text{sun}}^b \) and \( \mathbf{r}_{\text{mag}}^b \), and \( \mathbf{r}_3^i \) is perpendicular to the \( \mathbf{r}_3^b \) and \( \mathbf{r}_{\text{mag}}^i \). The angle between \( \mathbf{r}_3^b \) and \( \mathbf{r}_3^i \) can be written as \( \theta_3 \). Analyzed with rotation vector method, we have

\[
\sin \frac{\phi_3}{2} = \frac{1}{2} \left( \sin^2 \frac{\theta_{\text{sun}}}{2} + \sin^2 \frac{\theta_{\text{mag}}}{2} + \sin^2 \frac{\theta_3}{2} \right)
\]  

(31)

Using the above relations, we can deduce the \( \theta_3 \) can be written as

\[
\cos \theta_3 = \frac{\mathbf{r}_3^i \cdot \mathbf{r}_3^b}{\sin \theta_{12}} = \frac{1}{\sin \theta_{12}} \begin{bmatrix} \left( \mathbf{r}_{\text{sun}}^i \cdot \mathbf{r}_{\text{mag}}^i \right) - \left( \mathbf{r}_{\text{sun}}^b \cdot \mathbf{r}_{\text{mag}}^b \right) \\ - \left( \mathbf{r}_{\text{sun}}^i \cdot \mathbf{r}_{\text{mag}}^b \right) + \left( \mathbf{r}_{\text{sun}}^b \cdot \mathbf{r}_{\text{mag}}^i \right) \\ - \left( \mathbf{r}_{\text{sun}}^i \cdot \mathbf{r}_{\text{mag}}^i \right) + \left( \mathbf{r}_{\text{sun}}^b \cdot \mathbf{r}_{\text{mag}}^b \right) \end{bmatrix}
\]  

(32)

Therefore, the angle between the sun vector and the magnetic field vector determines the accuracy of the dual vector attitude determination. In the SSO of the “Ladybeetle-1”, the sun vector and the magnetic field vector overlap (\( \theta_{12} = 0 \)) or reverse (\( \theta_{12} = 180 \)) in each orbit cycle. The simulation in the subsequent subsections can explain the improvement of the accuracy of triad after compensating for the sun sensor central point error.

**Simulation**

To illustrate the improvement the attitude determination accuracy caused by central point compensation of the sun sensor, only the measurement vector of sun sensor is considered in the simulation of triad, and the influence of the magnetometer measurement error is ignored in simulation. The triad can give the attitude data in the lighting times of the satellite. Figures 13, 14, 15 and 16 shows the result when there is no compensation of the central point error of the sun sensor, and compared results after compensation.
Table 1. Comparison table before and after improvement.

|                  | Roll (°) | Pitch (°) | Yaw (°) |
|------------------|----------|-----------|---------|
| RMS with no compensation | 1.9375   | 5.2840    | 6.6091  |
| RMS with compensation  | 0.1600   | 0.4986    | 3.6590  |
| Improvement percentage | 91.74%   | 90.56%    | 34.77%  |

According to the statistical analysis of the above data results, the three-axis Euler angle RMSs error before the compensation of the central point error and the RMS error after compensation are shown in the following table. There is also the angle $\theta_{12}$ in Figures 16. It can be seen from the results that the change of the errors is related to the change of the angle $\theta_{12}$. The smaller the angle is, the greater the errors are. The data statistics table is shown in Table 1.

Conclusions

Since the sun sensor only can be used in the lighting area, the data of it cannot be processed in a whole orbit circle. The common averaging method is not suitable for this occasion. In this paper, considered with the “Sun pointing” work mode, we analyze the data from the novel sun sensor base on “black sun effect” of “Ladybeetle-1” satellite on orbit. Then the error compensation method using ellipse fitting is designed according to the using mode and characteristics of the data. Since the sun sensor is the key equipment of triad algorithm, the process of triad is introduced, and simulation only considers the zero-point error of the sun sensor. The result shows that this method improve the accuracy of triad. The three Euler angle error are all improved in the simulation. This method is also suitable for other satellite. The premise is the satellite has star sensor and can control the attitude towards the sun, and the system has good control performance.

This novel sun sensor can achieve high accuracy because there is no interference on CMOS. The on-orbit performance shows that the central point error is the main factor influencing the accuracy of attitude determination. The angle between the two vectors of triad algorithm is also a factor. The accuracy of the magnetometer and calculation of magnetic field both affect the triad accuracy. The satellite prefers to use the star sensor to get good performance, but the star sensor is easily interfered by the sun or the earth. Therefore, the sun sensor is irreplaceable for satellite, and on-orbit calibration is important for its application.

Disclosure statement

No potential conflict of interest was reported by the authors.

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