Fine Digital Sun Sensor (FDSS) Design and Analysis for STSAT-2

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Abstract: We have developed satellite devices for fine attitude control of the Science & Technology Satellite-2 (STSAT-2) scheduled to be launched in 2007. The analog sun sensors which have been continuously developed since the 1990s are not adequate for satellites which require fine attitude control system. From the mission requirements of STSAT-2, a compact, fast and fine digital sensor was proposed. The test of the fine attitude determination for the pitch and roll axis, though the main mission of STSAT-2, will be performed by the newly developed FDSS. The FDSS uses a CMOS image sensor and has an accuracy of less than 0.01 degrees, an update rate of 20 Hz and a weight of less than 800 g. A pinhole-type aperture is substituted for the optical lens to minimize the weight while maintaining sensor accuracy by a rigorous centroid algorithm. The target process speed is obtained by utilizing the Field Programmable Gate Array (FPGA) in acquiring images from the CMOS sensor, and storing and processing the data. This paper also describes the analysis of the optical performance for the proper aperture selection and the most effective centroid algorithm.

Keywords: STSAT-2, FDSS, CMOS-image sensor, Sun sensor, Aperture

1. INTRODUCTION

An attitude determination system for satellites is attained by using data measured from attitude sensors. There are several sensors for attitude determination which are Sun Sensor (SS), Earth Horizon Sensor (EHS), Magnetometer (MAG), Fiber Optic Gyro (FOG) and Star Tracker (ST). Among these sensors, especially Sun Sensors have been used widely for coarse and fine attitude determination. Until now, Satellite Technology Research Center (SATRec) has developed analog sun sensors for KITSAT-1, 2, 3 and Science & Technology Satellite-1 (STSAT-1) over the past decade. Analog Sun Sensor output voltage corresponding to the incident angle of sunlight and have an accuracy of less than 1 degree. STSAT-2, developed by SATRec needs fine sun sensors for the precise attitude determination, sun pointing mission and major technology development projects.

Table 1 The specification of FDSS.

<table>
<thead>
<tr>
<th>Item</th>
<th>Specification</th>
<th>Remark</th>
</tr>
</thead>
<tbody>
<tr>
<td>FOV</td>
<td>20°×20°</td>
<td></td>
</tr>
<tr>
<td>Accuracy</td>
<td>&lt; 0.03° (2σ)</td>
<td>μ-σσσ</td>
</tr>
<tr>
<td>Weight</td>
<td>&lt; 1.0 Kg</td>
<td></td>
</tr>
<tr>
<td>Power</td>
<td>&lt; 1.5 W @nomal</td>
<td></td>
</tr>
<tr>
<td>Operating Life Time</td>
<td>2 years</td>
<td></td>
</tr>
<tr>
<td>Size</td>
<td>150x150x160 mm³</td>
<td></td>
</tr>
</tbody>
</table>

We are developing the Fine Digital Sun Sensor (FDSS) with CMOS image sensors and an accuracy of less than 0.03 degrees. Fig. 1 shows the position of the FDSS, and Table 1 shows the specifications of FDSS for STSAT-2. The Field Of View (FOV) is a 20×20 degrees for each axis.

2. OPTICAL DESIGN OF FDSS

2.1 Basic principles of a FDSS

The principles of the FDSS are as follow. Sunlight passes through the aperture of the FDSS and is projected onto the surface of the CMOS image sensor. Each pixel of the CMOS image sensor converts the sunlight into 10 bit digital signals. Those signals are stored by the FPGA which generates and controls signals. The Micro Processor Unit (MPU) reads the
stored data from the FPGA, calculates the entrance degree of the sunlight ray, and provides calculated entrance degrees for the On-Board Computer (OBC) processing attitude determination and control program.

FDSS is divided into three parts. The first part is an optical part: sunlight passes through aperture, attenuated by the Neutral Density Filter (NDF) and filtered by the Band Pass Filter (BPF). The optical part projects sunlight onto the surface of the CMOS image sensor. The second part is the FPGA: this part generates control signals and provides control signals for the CMOS image sensor. The second part stores data acquired from the CMOS image sensor and communicates with the MPU using data packets. The third part is the MPU: it communicates with the OBC and calculates the incident angle of the sunlight.

2.2 Optical part of FDSS

Fig. 2 describes the schematic of the optical part on the FDSS. The sunlight enters the aperture with the radius of $\phi$, is filtered by the BPF, and attenuated by the NDF. The inside of the optical part is coated with anti-reflection material: that is, it is painted to minimize the reflection of the sunlight. Also, the optics and mechanical structures need to be accurately aligned between the aperture and the CMOS image sensor.

2.3 Diffraction characteristics of the aperture

In the optical system, we need to analyze the characteristics of the sunlight on the surface of the CMOS image sensor. Particularly, the intensity of the sunlight must be decreased so it does not exceed the allowable electrical threshold of the CMOS image sensor. A stable wavelength is chosen for the BPF after considering the diffraction effect [4].

The optical characteristics of the FDSS and the distribution of the energy need to be considered.

$$\tilde{E} = E_0 \frac{e^{i(kx-kR)}}{R} \int e^{i(ky+2z)} dS , \quad (1)$$

$$z = \rho \cos \phi, y = \rho \sin \phi, Z = q \cos \Phi, Y = q \sin \Phi \quad (2)$$

$$I = \int_{\rho=0}^{a} \int_{\phi=0}^{2\pi} e^{i(kq/R) \cos(\phi-\Phi)} \rho d\rho d\phi , \quad (3)$$

and due to the $I \propto E^2 E$. the intensity, $I$ is

$$I = I_0 \left[ \frac{J_1(kq/R)}{kaq/R} \right]^2 . \quad (4)$$

Eq. (4) shows that the diffraction intensity of the sun is evaluated.

$$I = I_0 \left[ \frac{J_1(kaq/R)}{kaq/R} \right]^2 , \quad (5)$$

where $a$ is the radius of the aperture; $b$ is the maximum symmetric distance of the aperture that the sunlight passes through; $\Phi$ is the rotation angle on the $yz$ plane based on the $z$ axis; and $q$ is the distance between the center and the diffraction pattern.

$I_{tot}$ is the total energy which is received from the a circular aperture. The sun constant is

$$I = I_{tot} \int_{0}^{a} \int_{0}^{2\pi} \left[ \frac{J_1(kaq/R)}{kaq/R} \right]^2 qdqd\theta . \quad (6)$$

Eq. (6) shows that $I(q)$ meets zero when $q = 116 \mu m$. This illustrates the fact that $I(q)$ is twice as long as the diameter of the aperture in length.
The energy radiated into the central pixel based on Eq. (9) for 0.1 second is
\[
E_{0,0} = 0.07 \times 0.1 \times \int_{-12.5 \mu m}^{12.5 \mu m} \int_{-12.5 \mu m}^{12.5 \mu m} I(y, z) \, dy \, dz = 1.29 \times 10^{-10} \text{J}
\]
Using Eq. (10), we can calculate where other pixels close to the center pixels exist. The first airy disk is plotted by the pixels as shown in Fig. 7.

Fig. 7  The CCD pixel and the first airy disk.

Electrons are generated by the photo effect. The energy of an electron is \(\frac{1789}{1789}\)
Eq. (12) and (13) show how many electrons are generated.

\[ N(E_{0,0}) = 5.72 \times 10^8 \]  
\[ N(E_{2,0}) = 2.65 \times 10^8 \] (12) (13)

We considered the design of filter for the attenuation of sunlight. The sunlight’s energy needed to be decreased using the NDF because the energy was too strong. Using the above results, Eq. (14) shows the percentage of attenuation that the filter needed.

\[ \frac{311000}{5.72 \times 10^8 \times 100} = 0.0544 \] (14)

Therefore, we must use a 5.44% filter. If the transmittance of the NDF is low, its characteristics tend to decrease. Therefore there needs to be a trade off between the NDF and BPF to obtain optimal performance. An appropriate exposure time and sampling time were also chosen by the designer.

3. CALCULATION ALGORITHM FOR THE INCIDENT ANGLE

The center must be found to calculate the incident angle of the sunlight that passes through the aperture, so a sunlight image was projected onto the pixel of the CMOS image sensor. Among the several algorithms that can be used to find the center, the centroid algorithm is well-known and popular; the formula was presented in Eq. (10).

Fig. 8 shows the size of the CMOS sensor. X and Y are the center coordinates calculated by the centroid algorithm. The graph plots the incident angle error of the sunlight in µm, and shows that the maximum error is less than 2.0E-4 degrees.

\[ X = \frac{\sum_{j=1}^{m} \sum_{i=1}^{n} j \cdot l_{ij}}{\sum_{j=1}^{m} \sum_{i=1}^{n} l_{ij}}, \quad Y = \frac{\sum_{j=1}^{m} \sum_{i=1}^{n} i \cdot l_{ij}}{\sum_{j=1}^{m} \sum_{i=1}^{n} l_{ij}} \] (15)

\( i, j \) : the number of pixels.
\( l \) : the intensity of each pixel.

Fig. 8 Coordinates calculated by the centroid algorithm.

ACKNOWLEDGMENTS

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REFERENCES