High-precision CubeSat sun sensor coupled with infrared Earth horizon detector

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Abstract. This paper presents a novel miniature module of orientation sensors for CubeSat nanosatellites. A high-precision sun sensor and a detector of the Earth horizon are located in one small module body. A two-axis digital sun sensor built into the orientation module is based on the registration of the sunspot formed on the matrix CMOS image sensor when the sun's rays pass through a pinhole in the front mask. A commercially available miniature array of infrared thermometers is used as the Earth horizon sensor. The paper is mainly devoted to the development of the sun sensor. For laboratory tests, a prototype of the orientation module was developed. Laboratory tests and sun sensor calibration confirmed the sun sensor field of view of 120° and made it possible to determine its angular resolution of ±0.015°. The final accuracy of determining the direction to the Sun by the sensor that was calibrated using the existing experimental setup is ±0.15° with 95% confidence. It is possible to improve the accuracy of the sun sensor by improving the experimental setup for its calibration.

1. Introduction

An important component of the satellite attitude determination and control system (ADCS) is the sensor system, which provides information about the relative position of the satellite in space. As a rule, when solving problems of orientation and positioning of very small satellites (nanosatellites) of the CubeSat class, the main reference points of orientation are the Sun and the Earth. Knowledge of orientation relative to the Sun and the Earth allows in most cases to provide a three-axis orientation of the satellite. In recent years, several miniature precision low-power sun sensors have been developed for use in CubeSat nanosatellites [1-6]. Direction to the Earth was determined using a commercially available miniature array of infrared (IR) thermometers [7]. This paper presents a miniature orientation module for CubeSat satellites, developed in the Division for Atmospheric Research of Novosibirsk State University, in which the sun sensor and the Earth horizon detector are located in one small body. This combination of two sensors in one package simplifies the placement of orientation sensors on the satellite, reduces the load on the main processor of the satellite orientation determination and control system, and simplifies the calibration of the ADCS as a whole.

A two-axis sun sensor built into the orientation module is based on the registration of the sunspot formed on the matrix CMOS image sensor when the sun's rays pass through a round hole in the front mask. The task of development was to create a sensor with an accuracy of determining the direction to the Sun not worse than ±0.1° with a field of view of 120°, that is, no worse than the known CubeSat sun sensors, which are based on the same principle [4, 6]. The Melexis MLX90640 32×24 array of IR
thermometers with field of view of $110^\circ \times 75^\circ$ [8] is used as the Earth horizon sensor. The horizon of the Earth is determined on a thermal image obtained by the IR matrix sensor as the boundary between the warm Earth (about 300 K) and the cold space (about 2.7 K).

This paper focuses on the development of a sun sensor. The paper presents the orientation module and the sun sensor design, briefly describes the algorithms of the sun sensor and presents the preliminary results of the sun sensor calibration. A detailed description of the Earth horizon sensor will be given in the next paper.

2. Design of the orientation module and the sun sensor
The working principle of the sun sensor is shown in Figure 1a. The optical system of the sun sensor is based on a conventional pinhole camera [9]. The incident sunrays, passing through the pinhole in the mask, create an inverted image of the Sun on the surface of the recording photodetector. A commercially available monochrome CMOS matrix NOIL1SM0300A-QDC is used as a photodetector [10]. The matrix resolution is 640×480 pixels, the optical active area of the matrix is 6.34×4.75 mm, and the pixel size is 9.9×9.9 μm. When using this matrix, the distance $L$ of 1.37 mm between the matrix and the thin mask with a pinhole provides the sun sensor's field of view of $120^\circ$.

![Figure 1](image)

**Figure 1.** (a) Working principle of the sun sensor. (b) The influence of the shape of the hole in the mask on the formation of a light spot on the matrix.

Usually in sun sensors, the hole in the mask has the shape of a cylinder. In this case, the walls of the cylindrical hole affect the formation of a light spot on the matrix [6] and limit the field of view of the sensor (Figure 1b). Part of the sunlight falling at a non-zero angle $\theta$ does not pass through an obstacle formed by the walls of the hole, and the shape of the light spot on the matrix changes. To reduce the effect of the pinhole walls on the formed image of the Sun, we used a conical pinhole in our sensor (Figure 1b). The conical pinhole used in the solar sensor allowed us to minimize the loss of sunlight and increase the field of view with the same pinhole diameter $d$. The use of a conical pinhole also made it possible to increase the thickness of the mask, which simplified its manufacturing technology.

Figure 2 shows (a) a 3D model of the orientation module and (b) a photograph of the developed module prototype (without a sensor case). The module consists of a printed circuit board and a sensor body. The board contains a CMOS matrix of the sun sensor, an infrared matrix of the sensor of the Earth's horizon, and electronics with a connector. The optical system of the sun sensor is located inside the sensor body. The main element of the optical system is a round aluminum mask with a calibrated conical pinhole 80 μm in diameter. To protect the hole from external influences, a protective sapphire glass is provided in the design of the sensor. The mask and the sapphire glass are fixed in the sensor body with the help of a locking ring through fluoroplastic sealing rings. The dimensions of the module are $42.5 \times 17.5 \times 11$ mm, and the mass is about 10 g.
Figure 2. The orientation module design: (a) a 3D model and (b) a photograph of the developed module prototype (without a sensor case).

The functional block diagram of the module control board is shown in Figure 3. The main computing device of the module is the STM32F410CBU microcontroller, which manages the module power consumption and the configuration of the MLX90640 and NOIL1SM0300A matrices. The sensor power management is organized as follows. In the background, the matrices are physically disconnected from the power supply, and the microcontroller is in standby mode. When a command comes from the main ADCS processor, the microcontroller activates the matrix settings, receives images from them, calculates directions, sends the necessary information to the ADCS via the EIA485 interface, and then returns to sleep mode. The module supply voltage is 3.3 V. The power consumption in active mode is about 215 mW, and in standby mode, it is less than 0.5 mW.

Figure 3. Functional block diagram of the orientation module.

3. Sun sensor algorithm
To find the direction to the Sun, it is necessary to determine the coordinates of the center of the image of the solar disk on the recording matrix in the coordinate system of the solar sensor shown in Figure 1a. The algorithm for determining the coordinates of the sunspot center is based on processing the intensities of each pixel of the image. The first stage of image processing is filtering to remove the pixel noise of the matrix. For this, a 2D moving median filter is used. Each pixel at the output of the filter contains the median value in the 3×3 neighborhood around the corresponding pixel in the input image. Figure 4 illustrates the operation of the filter.

After noise reduction, the coordinates of the sunspot center are calculated. Only pixels with an intensity level greater than 10% of the maximum image intensity are used in the calculations. This is necessary to prevent errors associated with possible glares, and to reduce the amount of computation. The coordinates $x_c$ and $y_c$ of the center the sunspot are determined by

$$
x_c = \frac{\sum_i I_i x_i}{\sum_i I_i}, \quad y_c = \frac{\sum_i I_i y_i}{\sum_i I_i},
$$

where $x_i$ and $y_i$ are the coordinates of the $i$-th pixel, $I_i$ is the image intensity of the $i$-th pixel, the summation is performed on the pixels selected by the intensity level.
Figure 4. Results of image filtering to reduce CMOS matrix noise. (a) The processed image from the matrix near the sunspot. (b) The relative intensity of pixels depending on the horizontal coordinate X at Y = 244 pixel.

To find the direction to the Sun, it is also necessary to know the coordinates of the center of the sunspot with normal incidence of solar radiation on the sensor \( x_0 \) and \( y_0 \). The design of the sensor provides that with a normal incidence of solar radiation, the image of the sun should be in the center of the matrix. The exact values of \( x_0 \) and \( y_0 \) are determined during sensor calibration in the laboratory. Then the azimuth angle \( \varphi \) and the zenith angle \( \theta \) of the direction vector to the Sun in the coordinate system defined in Figure 1 are determined by

\[
\varphi = \arctan \left( \frac{y - y_0}{x - x_0} \right), \quad \theta = \arctan \left( \frac{R}{L} \right)
\]

(2)

where

\[
R = \sqrt{(x_c - x_0)^2 + (y_c - y_0)^2}.
\]

(3)

4. Sun sensor calibration

An experimental setup was developed for testing and calibrating the sun sensor, which includes a sun simulator and an angular positioning system. The positioning system has five degrees of freedom. Two rotary devices of the system provide a randomly defined orientation of the sensor relative to the sun simulator. Three translational move devices provide displacement of the solar sensor in height and in the horizontal plane of the optical table. The solar simulator is located at a distance of 1 m from the sensor. At this distance, the angular size of the light spot from the sun simulator, visible by the sensor, is 0.5°, which corresponds to the angular size of the Sun when it is observed from the Earth.

At the first stage of the sun sensor calibration, the position on the CMOS matrix of the origin of the coordinate system associated with the sun sensor \( (x_0, y_0) \), which is defined in Figure 1, was determined. This point corresponds to the center of the sunspot with normal incidence of solar radiation on the sensor. The error in the alignment of the optical axis of the sun sensor on the calibration setup with the direction to the sun simulator is about 0.03°. This means that the values of \( x_0 \) and \( y_0 \), determined under such conditions, will lead to a systematic error in determining the direction to the Sun about 0.03°.

At the second calibration stage, the dependence between the zenith angle \( \theta \) and the distance \( R \) from the center of the sunspot to the center of the sun sensor coordinate system was determined. The measurements were carried out in the range of zenith angles \( \theta \) from 0° to 60° with a step of 2° at two azimuthal angles \( \varphi \) at 90° and 120°. Three measurements were made for each direction on the sun.
simulator. The measurement results are shown in Figure 5a as a function of $\theta$ versus $R$. Also shown is a calibration function approximating the obtained dependence by a polynomial of the sixth degree:

$$\theta = \sum_{i=0}^{6} a_i R^i.$$ 

(4)

The coefficients of the polynomial are shown in Table 1. From Figure 5a it can be seen that the measurement data is very well described by the calibration function.

![Figure 5. (a) Calibration function (blue curve), which approximates the measured dependence of the zenith angle $\theta$ on the distance $R$ from the center of the sunspot to the origin of the coordinate system of the sun sensor (red asterisks and blue squares). (b) Histogram of the deviations of the measured zenith angles $\theta$ from the calibration curve and its approximation by the Gauss function.](image)

Table 1. Calibration function coefficients.

| $a_0$       | $a_1$        | $a_2$        | $a_3$        | $a_4$        | $a_5$        | $a_6$        |
|------------|--------------|--------------|--------------|--------------|--------------|--------------|
| -7.3778·10^{-1} | 4.0220·10^{-1} | -3.9465·10^{-5} | -5.7361·10^{-6} | 1.4519·10^{-8} | 1.3344·10^{-11} | -6.4053·10^{-14} |

Figure 5b shows a histogram of the deviations of the measured zenith angle from the calibration curve. Also shown is the approximation of the obtained histogram by the Gauss function. The standard deviation $\sigma$ of this distribution is 0.077°, and the distribution has an offset from zero of 0.033°. The latter value agrees well with the above accuracy of the initial installation of the sun sensor relative to the sun simulator on the calibration setup. The value $\sigma = 0.077°$ means that the accuracy of determining the direction to the Sun of our sensor, calibrated using the existing experimental setup, is ±0.15° with 95% confidence.

It is important to know the main factors that determine the accuracy of the solar sensor. Is it an imperfection of the sensor itself or an imperfect calibration technique? We conducted a large number of measurements at different fixed angles of incidence of radiation on the sensor. Ten measurements were made at every angle. In all series of measurements, there was observed a scatter in the measured data of no more than ±0.015° relative to their average values. This value of ±0.015° can be interpreted as the angular resolution of the sun sensor and as the maximum sensor accuracy that can be achieved by calibrating the sensor on the equipment that ensure the proper necessary accuracy of pointing the sensor at the sun simulator. Since the obtained resolution of the sensor is an order of magnitude better than the experimentally obtained accuracy of the sensor, it can be argued that the latter is almost completely determined by the calibration setup used.
The accuracy of our sun sensor achieved so far corresponds to the characteristics of the best sun sensors for CubSat satellites. The angular resolution of these sensors lies in the range from 0.01° to 0.026° [1, 4, 6], and the achieved accuracy is 0.11° [2] and 0.15° [3]. The sun sensor [5] has a better angular resolution of 0.007° and an accuracy of 0.03°, but its dimensions of 69×52×14 mm are much larger than dimensions of our sensor, and therefore it is not very suitable for use on CubeSat nanosatellites.

5. Conclusion

In this paper, we presented a novel miniature module of orientation sensors for CubeSat nanosatellites. A high-precision sun sensor and a detector of the Earth’s horizon are located in one small module body. This combination of two sensors in one package simplifies the placement of orientation sensors on the satellite, reduces the load on the main processor of the satellite attitude determination and control system, and simplifies the ADCS calibration as a whole. The developed prototype of the orientation module has dimensions of 42.5×17.5×11 mm and a weight of about 10 g. The power consumption in active mode is about 215 mW, and in standby mode, it is less than 0.5 mW.

The paper is mainly devoted to the development of a high-precision sun sensor built into the orientation module. This two-axis sun sensor is based on the registration of the sunspot formed on the matrix CMOS image sensor when the sun's rays pass through a round hole in the front mask. Laboratory testing and sensor calibration confirmed the sensor's field of view of 120° and demonstrated an angular resolution of the sensor of ±0.015°. The final accuracy of determining the direction to the Sun by our sensor, calibrated using the existing experimental setup, is ±0.15° with 95% confidence. These values correspond to the angular resolution and accuracy of the best CubeSat solar sensors.

The main reason limiting the accuracy of the sun sensor in our case is the imperfection of the experimental setup used to calibrate the sensor. In the near future, we plan to automate the experimental setup for calibrating sun sensors in order to improve the accuracy of pointing the sensor to the sun simulator. As a result, we expect to significantly improve the accuracy of the sun sensor and bring it closer to the angular resolution of the sensor, as defined in this work, ±0.015°.

Acknowledgments

This work was supported by the Ministry of Science and Higher Education of the Russian Federation under Project RFMEFI57517X0154.

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