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Development of Star Tracker for Satellite

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Abstract**—**Much attention is paid to the development of space branch in Kazakhstan at present. Two Earth remote sensing satellites of Kazakhstan have been launched successfully. Many projects related to the development of components for satellite are carried in Kazakhstan, in particular the project related to the development of star tracker experimental model. It is planned to use the results of this project for development of star tracker prototype in the future. This article describes the main stages of development of star tracker experimental model.

Keywords**—**Development, prototype, satellite, star tracker.

I. INTRODUCTION

STAR tracker is a high-tech device for highly accurate attitude determination of satellite. At present star trackers are developed in the countries implementing their space programs related to the creation of space systems for different purposes. As example one can consider such popular companies as the Institute of Space Research of the Russian Academy of Science (Russia) developing the unit of determination of star coordinates (BOKZ), SODERN (France) developing autonomous star devices SED16, SED26, SED36 and HYDRA, Jena-Optronik (Germany) producing three models of autonomous star devices: ASTRO 10, ASTRO 15 and ASTRO APS etc. [1]. Currently, Kazakhstan has passed to a new level of progress of space branch and also started the development of own components for satellite due to the progress of scientific and technical base and cooperation with countries developing satellites and their components.

It is planned to develop the star tracker in Kazakhstan by force of domestic specialists. At the first stage it was developed an experimental engineering model of the star tracker which has the following characteristics: field of view - 20 degrees, accuracy of attitude determination around optical axis - 50 arcsec, in XY plane – 15 arcsec, update rate - 2 Hz, exclusion angle - 40 degrees, mass - 1.435 kg.

Present article describes the main stages of design and development of star tracker experimental model and its software.

II. DEVELOPMENT OF OPTICAL SYSTEM AND HOOD FOR STAR TRACKER EXPERIMENTAL MODEL

Optical system of star tracker must provide the required size of star image on the detector and the required number of stars in the frame of the star tracker for accurate attitude determination with the help of its software. Thus, the main requirements for optical system of star tracker are formed on the base on demands of software.

The following requirements were used in the process of development of optical system for star tracker experimental model:

- Full field of view must be no less than 20 degrees to ensure the appearance of no less than three stars in the frame of star tracker;
- The maximum star magnitude for a given field of view is 5.5;
- The minimum angle between the optical axis of star tracker and the Sun, which provides the functional characteristics of device is 40 degrees;
- The image of each star must be defocused to a spot with the diameter of 5-6 pixels;
- Point spread function (PSF) is chosen so that the spot diameter with 85% of energy covered about 3 pixels. It allows determining the position of the star's center of mass with sub-pixel accuracy.

These requirements made it necessary to consider the multiple-lens system as a variant of optical system. Three variants of optical system were considered for selection of the optical scheme: seven-lens, six-lens and five-lens optical systems. Design and calculation was carried out for each variant with the help of ZEMAX software system. The change of point spread function, the form and diameter of spot of confusion for various FOVs and concentration of radiant energy in the spot of confusion was studied in the process of calculations. The best results were obtained for six-lens optical system (Fig. 1) with spherical surfaces and diaphragm located at the first surface. This variant was used as the base for development of optical system for star tracker experimental model.

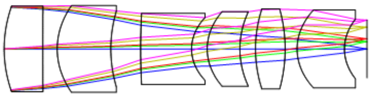

Fig. 1 Six-lens optical system

Designed optical system was manufactured by the specialists of the Institute of space technique and technology. It is shown in the Fig. 2 [2]. A relatively small number of lenses and absence of aspheric surfaces are the main advantages of the developed optical system in comparison

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with other such systems. It simplifies the assembly of optical system and reduces the manufacturing costs.

Fig. 2 Optical system of star tracker experimental model

Optical glass of various foreign companies was used for manufacturing the lenses of optical system of star tracker. The shadow device, auto collimating instrument, instrument for skew measuring, thickness indicator were used for quality control of lens polishing, control of compliance with geometrical parameters and control of installation accuracy of elements of the optical system. Tolerances for glass that was used for the manufacturing of lenses were held. Thus, the manufactured optical system must have suitable characteristics.

The measured values of manufactured optical system have been analyzed in the software ZEMAX. The results of analysis are shown at Fig. 3. Analysis of Fig. 3 shows that manufactured optical system as well as designed optical system meets the requirements for the size of spot of confusion [3].

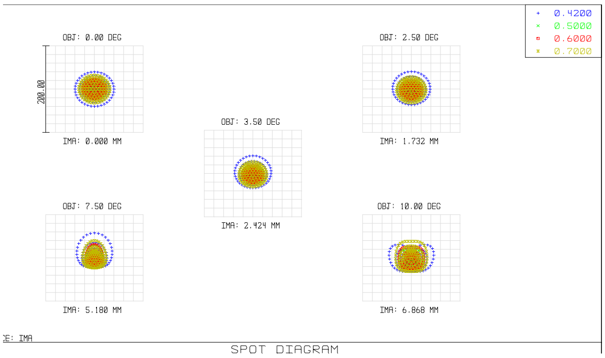

Fig. 3 Images of the point source obtained by the manufactured system in dependence on the FOV angle

Hood of the optical head of star tracker is designed to minimize the unwanted exposure of the detector by the Sun or the sunlight reflected from the Earth.

To design the hood of star tracker experimental model it was carried out the modeling of unwanted exposure due to the Sun for the ultimate exclusion angle of 40 degrees.

Since the surface of the hood was divergent the Monte Carlo method was used when modeling (the direction of the further spread of "photon" after next reflection was chosen randomly with a distribution of direction probability depending on the properties of the coating surface). According to the results of simulation analysis it was manufactured the hood for optical system which is shown at Fig. 4.

Fig. 4 Experimental model of star tracker with the hood

III. Development of Software for Experimental Model of Star Tracker

Software of star tracker experimental model is based on the algorithms of preliminary image processing, star identification and attitude determination. Its general scheme is given in Fig. 5.

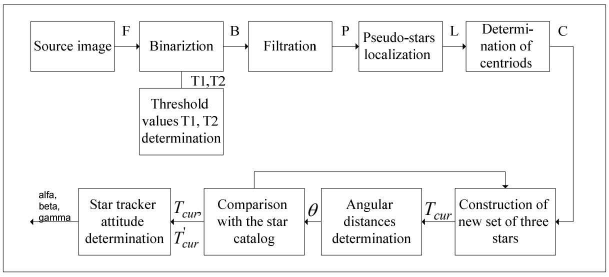

Fig. 5 General scheme of the software for star tracker experimental model

After the source image acquisition its binarization is carried out which transforms the source image into the binary image in accordance with (1):

$$\mathrm{B} = b(x,y) = \begin{cases} 1, & f(x,y) \in [T_1, T_2], \\ 0, & \mathrm{f}(x,y) \in [0, \mathrm{T}_1) \cap (T_2, 255], \end{cases} \qquad (1)$$

where $x = 1..m,\ y = 1..n$; $f(x,y)$ is the pixel intensity of source image with coordinates x, y; T_1, T_2 are threshold values of binarization.

Threshold values of binarization allow excluding the excessive information on the image and allocating the objects contours. Search of threshold values is performed on the basis of image histogram analysis, analysis of average value and root-mean-square error of pixel intensity on the whole image.

At the following stage the image filtration with the use of median filter [4] is performed in accordance with (2). It provides smoothing, maximal preservation of the image contours and noise elimination of different nature:

$$P = p(x, y),$$
$$p(i, j) = \begin{cases} 1, \ S_{W_{ij}} \geq \dfrac{h^2}{2}, \\ 0, \ S_{W_{ij}} < \dfrac{h^2}{2}, \end{cases} \qquad (2)$$

where $p(i, j)$ is the image pixel after filtration having position i, j; $S_{W_{ij}}$ is the quantity of non-zero pixels of the binary image in the filter window generated around the pixel with coordinates i, j; h is the size of filter window (odd number).

Then localization of pseudo-stars is performed which involves the allocation of connected regions by traversing the image with help of special eight-coherent mask. After that determination of centriods (coordinates of centers of mass) of pseoudo-stars is performed.

Here it is necessary to note that binarization, filtration and localization of pseudo-stars is executed on EPLD since these operations require high-computing power. When pseudo-stars array is formed it is sent to CPU where the stars identification is performed by its comparison with star catalog.

Generally star identification is performed by some pseudo-stars configurations [5]. In our case the set of three pseudo-stars T_{cur} were used for identification. For each pair of pseudo-stars that were the part of T_{cur} the angular distance θ was calculated which was compared with the angular distances of stars in star catalog by means of the K-vector method [6]. K-vector method passed successful verification on spacecrafts and has much better performance in comparison with traditional search methods, for example, method of binary search.

As a result of identification it becomes known the coordinates of three stars in the coordinate system of star tracker and corresponding to it inertial coordinates in star catalog. Attitude determination of star tracker in the inertial frame of reference was performed on the basis of correlation in the form (3) connecting the coordinates of identified stars in the field of view of star tracker and corresponding star coordinates in star catalog:

$$X = Ax, \qquad (3)$$

where $X[3 \times 1]$ is the vector of star's coordinates in star catalog, corresponding to the identified star in the field of view of star tracker, $x[3 \times 1]$ is the vector of coordinates of identified star in the field of view of star tracker, $A[3 \times 3]$ is the matrix of affine transformation.

IV. ASSEMBLY AND TESTING OF STAR TRACKER EXPERIMENTAL MODEL

When all the basic components and software of star tracker experimental model were developed its assembly was carried out. The results of assembly are shown at Fig. 4.

The image sensor Cis1910 with the dimensions of 1920x1080 (pixel size is 6.5x6.5 micrometers) was used as the detector for star tracker experimental model.

Testing of star tracker experimental model consisted of three key stages: optical system verification, hood verification, software testing.

Verification of optical system of star tracker experimental model was carried out by taking pictures of the night sky at high altitude (height above sea level of about 2700m) without the influence of outside exposure. The various parts of the night sky at different exposures (0.2-0.8 sec) were surveyed. After that the analysis of size of star images on the focal plane was carried out. Result of analysis is shown at Fig. 6.

Fig. 6 provides a point spread function corresponding to one of the stars with medium brightness.

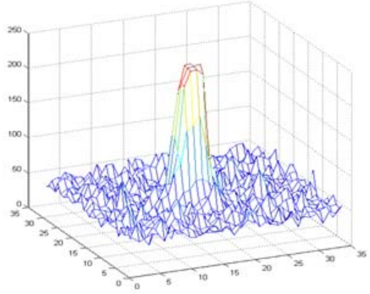

Fig. 6 PSF of one of the stars with medium brightness. Z-axis corresponds to the intensity of the received radiation, plane XY corresponds to the pixels of matrix

The diameter of given PSF is 10-12 pixels and after binning 2x2 it will be 5-6 pixels that is close to the optimal value. Thus, the analysis of tests results showed its full compliance with the results obtained by modeling.

Verification of the hood was carried out to assess the stability of the star tracker to the flare light from the outside light sources (mainly from the Sun and the Earth). General scheme of hood verification process is given in Fig. 7.

A light source (LED) was placed in the focus of the lens of a relatively large diameter which gives a fairly uniform and parallel luminous flux. In the process of verification the light source was moved to different angular distances (alpha) relative to the optical axis of the star tracker and at the same time this light source was surveyed in the conditions close to the conditions of the space environment, i.e. in a maximally dark room where the effect of any secondary light sources (e.g., LED reflections from the walls) in the field of view of the optical system was minimized. Effectiveness of flare light suppression for each angle alpha or illumination level of detector in dependence on the angular distance of light source from optical axis of star tracker was determined on the base of verification results.

It was determined that resulting level of detector exposure for the angle alpha equal to 40 degrees satisfied the requirements to the hood of star tracker.

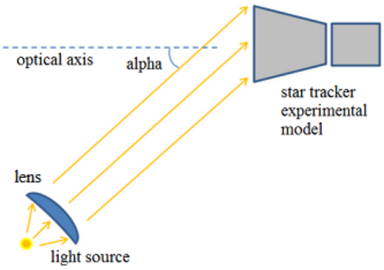

Fig. 7 Verification scheme for the hood of star tracker experimental model

The special software was developed for testing the software of star tracker experimental model. This software allows simulating the image acquisition process of star tracker with account of clutter and noise caused by operation of detector and optical system errors and also with account of star tracker dynamics. This software allowed comparing the calculated attitude of star tracker with its attitude obtained by means of dynamics simulation. As a result of comparison the assessment of attitude determination accuracy of star tracker was carried out. It was obtained that the accuracy of optical axis attitude determination was 18, 5673 arcsec, accuracy of determination of rotation angle around the optical axis was 21, 4973 arcsec. These results correspond to the requirements to the star tracker and by that testify the adequacy of its software functioning.

V. CONCLUSION

Main stages of development of star tracker experimental model were considered in this article. Test results showed the acceptable quality of development of star tracker experimental model and its software that gave a reason to use it as a basis for the development of star tracker prototype.

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