Development of Star Tracker for Satellite

S. Yelubayev, V. Ten, B. Albazarov, E. Sarsenbayev, K. Alipbayev, A. Shamro, T. Bopeyev, A. Sukhenko

***Abstract*—**Currently in Kazakhstan much attention is paid to the development of space branch. Successful launch of two Earth remote sensing satellite is carried out, projects on development of components for satellite are being carried out. In particular, the project on development of star tracker experimental model is completed. In the future it is planned to use this experimental model for development of star tracker prototype. Main stages of star tracker experimental model development are considered in this article.

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

I. Introduction

STAR tracker is a high-tech device for autonomous determination of satellite angular position with high accuracy. Currently development of star trackers are engaged first of all in the countries implementing their space programs on creation of space systems for different purposes, for example Institute of Space Research of the Russian Academy of Science (Russia), developing the block of determination of star coordinates (BOKZ), SODERN (France), releasing autonomous star devices SED16, SED26, SED36 и HYDRA, Jena-Optronik (Germany), producing three models of autonomous star devices: ASTRO 10, ASTRO 15 and ASTRO APS and etc. [1]. However, progress of scientific and technical base and cooperation with countries developing spacecrafts and their components allowed Kazakhstan to pass to a new level of progress of space branch and to begin development of own components.

The own star tracker is being developed in Kazakhstan by the force of domestic specialists. At the initial stage it has been developed its experimental model 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 deals with the description of main stages of design and development of star tracker experimental model components and its software.

S. Yelubayev, K. Alipbayev, A. Shamro, and T. Bopeyev are with the AALR "Institute of space technique and technology", Republic of Kazakhstan, 050061 Almaty, Kislovodskaya st. 34 (e-mail: elubaev.s@istt.kz, alipbayevk@gmail.com, a_shamro@mail.ru, bopeyev.t@mail.ru).

V. Ten, B. Albazarov, and E. Sarsenbayev are with the CA "Kazakhstan Garysh Sapary", Republic of Kazakhstan, 010000, Astana, Orynbor st. 8, Ministry House, 4-th entrance (e-mail: vladimir.ten@gmail.com, b.albazarov@gharysh.kz, seebox@mail.ru)

A. Sukhenko is with the AALR "Institute of space technique and technology", Republic of Kazakhstan, 050061 Almaty, Kislovodskaya st. 34, (phone: +7(727) 2762167; e-mail: anna.sukhenko@gmail.com).

II. Development of Optical System and Hood for Star Tracker Experimental Model

Optical system of star tracker must ensure the required size of the star on the detector of star tracker and the required number of stars in the frame of the star tracker for accurate determination of its angular position with the help of software. Thus, the software of star tracker forms the main requirements for its optical system.

In the process of development of optical system for star tracker experimental model it was guided by the following requirements:

- 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 the 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 center of mass with sub-pixel accuracy.

To determine the optical scheme for optical system three variants of optical system were considered: five - lens system, six - lens system, seven - lens system.

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.

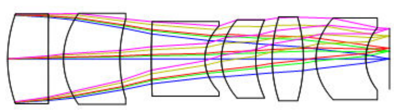

Fig. 1 Six-lens optical system

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 advantages of the developed optical system in comparison 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 for star tracker. The shadow device, auto collimating instrument, instrument for skew measuring, thickness indicator were used for quality control of lens polishing, compliance with geometrical parameters and accuracy of the optical system elements installation. In result of measurements it was defined that tolerances of specifications for the manufacture of glass lenses were held.

The measured values of manufactured optical system have been analyzed in the software ZEMAX. 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].

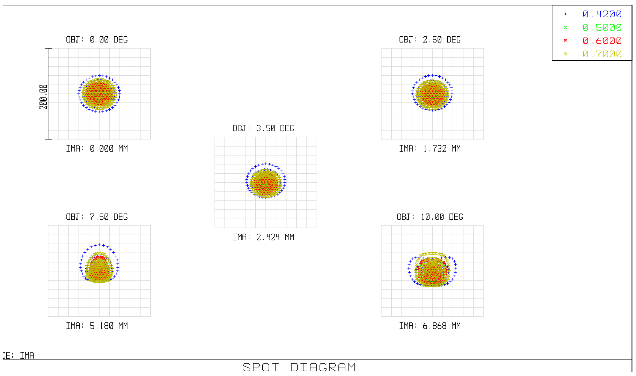

Fig. 3 Images of the point source obtained with manufactured system in dependence on the FOV angle

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

To design the hood 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 is divergent the Monte Carlo method was used when modeling - the direction of the further spread of "photon" after next reflection is chosen randomly with a distribution of direction probability, which depends 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 the Fig. 4.

Fig. 4 Experimental model of star tracker with the hood

III. Development of Mathematical Support and Software for Experimental Model of Star Tracker

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

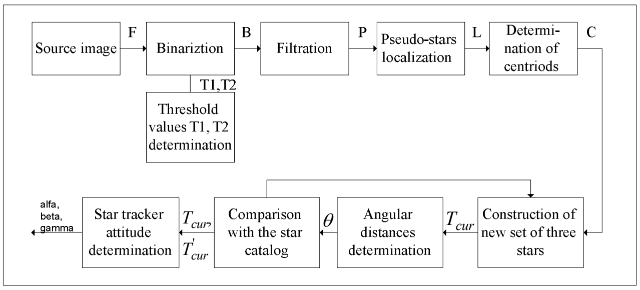

Fig. 5 General scheme of mathematical support and software of star tracker

After the source image acquisition its binarization is carried out which transforms source image into binary 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 to exclude the excessive information on the image and allocate 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 after binarization image filtration with the use of median filter is performed [4] in accordance with (2). It provides smoothing and maximal preservation of 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 binary image in 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 pseoudostar centriods (coordinates of its centers of mass) is performed.

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

Generally identification is performed by some pseudo-stars configurations [5]. In our case for identification the set of three pseudo-stars are used (T_{cur}). For each pair of pseudo-stars, incoming to the set of three, the angular distance (θ) is calculated which is compared with 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 is 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 coordinates in star catalog, corresponding to the identified stars in the field of view of star tracker, $x[3\times 1]$ is the coordinate vector of identified stars 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 is 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) is used as the detector for star tracker experimental model.

Testing of star tracker experimental model consists 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 a pictures of the night sky at high altitude (height above sea level of about 2700m) without the influence of outside exposure. Survey was carried out for various parts of night sky at different exposures: 0.2-0.8 sec. Analysis of size of star images on the focal plane was carried out.

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

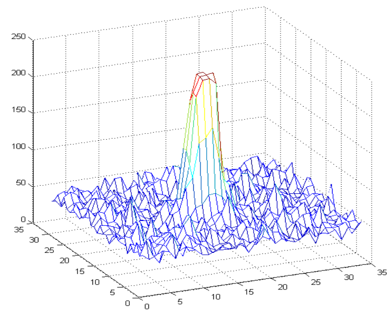

Fig. 6 PSF of one of the stars with medium brightness. Z-axis correspond to the intensity of the received radiation, plane XY correspond to the pixels of matrix

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

Verification of 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 below (Fig. 7).

A light source corresponding a LED placed in the focus of the lens of a relatively large diameter, which gives a fairly uniform and parallel luminous flux was used as the equipment for verification. 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 it were made the pictures of this light source in the conditions as close as possible to the conditions of the space environment, i.e. in a maximally dark room, where all measures are assumed to minimize any secondary light sources (e.g., LED reflections from the walls) in the field of view of the optical system. 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 in the process of hood verification that resulting level of detector exposure for the angle alpha equal to 40 degrees satisfy the requirements to the hood of star tracker.

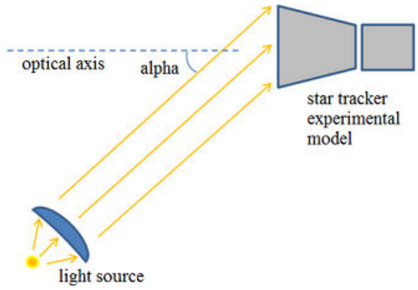

Fig. 7 Verification scheme for the hood of star tracker experimental model

Program simulation complex was developed for testing the mathematical support and software of star tracker. This complex allows to simulate 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 program simulation complex allowed to compare the star tracker attitude obtained by means of its software with star tracker attitude obtained by means of star tracker dynamics model designed-in simulation complex. As a result of comparison the assessment of attitude determination accuracy of star tracker by means of its software was carried out. Accuracy of star tracker optical axis attitude determination is 18, 5673 arcsec, accuracy of determination the rotation angle around optical is 21, 4973 arcsec. These results correspond to the requirements to star tracker and by that testifies the adequacy of work of its software.

V. Conclusion

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

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