PROCEEDINGS OF SPIE

SPIEDigitalLibrary.org/conference-proceedings-of-spie

Design and simulation of a novel APS star tracker

Feng Wu, Weimin Shen, Jiankang Zhou, Xinhua Chen

Feng Wu, Weimin Shen, Jiankang Zhou, Xinhua Chen, "Design and simulation of a novel APS star tracker," Proc. SPIE 7156, 2008 International Conference on Optical Instruments and Technology: Optical Systems and Optoelectronic Instruments, 71561S (28 January 2009); doi: 10.1117/12.806698

Event: International Conference of Optical Instrument and Technology, 2008, Beijing, China

Design and simulation of a novel APS star tracker

Feng WU[*a,b] , Weimin SHEN[a], Jiankang ZHOU[a], Xinhua CHEN[a]
[a] Jiangsu' Key Lab of Modern Optical Technology, Soochow University, Suzhou ,215006,China;
[b] Changzhou Institute of Technology, Changzhou, 213002,China

ABSTRACT

Star trackers determine attitude by identifying stars imaged on the image sensor via an optical system whose performance is required to meet the star identification algorithm. The method to determine parameters of the optical system is proposed based on the identification algorithm. These parameters include focal length, aperture, and field of view (FOV). Aberration correction requirements are also analyzed. Pyramid identification algorithm utilized in this paper is investigated. Some improved approaches are presented for star map processing, onboard catalog organization and star identification. A link table construction is designed to save brightness from the programmed APS sensor which decreases data effectively and enhances the ability to calculate star positions in star maps. A method is developed to organize the onboard catalog which avoids searching and comparing similar star pairs but makes for rapid and unique identification. When performing star identification with Pyramid identification algorithm, only X brightest stars are chosen from star maps to acquire high signal to noise ratio and decrease spikes. Star number statistics is fulfilled all over the sky with any orientations by varying FOV and limited magnitude. Base on the requirement of the identification algorithm, parameters of the optical system are determined with the given STAR1000 APS sensor by analyzing their feasibility in optical design. According to these determined parameters, a star camera is designed. An onboard catalog on which star identification relies is produced. Star identification simulation is implemented. Simulation result proves that the designed system gets a satisfactory performance.

Keywords: Optical design, Aberration correction, Star identification, APS, Star tracker, Pyramid identification algorithm

1. INTRODUCTION

Modern spacecraft expects accurate orientations when performing complicated space missions. Star trackers have been developed for this purpose in recent decades which offer very high accuracy attitude knowledge superior to conventional attitude determination systems such as sun sensors, gyros and so on[1]. New generation of star trackers are autonomous which need no apriori attitude estimate and work in the lost-in-space mode [2~5]. Nowadays, they trend to be smart with small size, light weight and low power when using active pixel sensor (APS) as the imager replacing charge coupled device (CCD), and become more attractive in space explorations[6~10]. In general, a star tracker is composed of a star camera (the optical system and the imaging device) and a spacecraft computer. The optical system images stars in its field of view (FOV) onto the focal plane where the imaging device, CCD or APS is placed. The computer stores programs for star identification and attitude determination in its chips, and a guide star catalog (the mission catalog) and another catalog derived from the guide star catalog and compiled before launch supporting fast star recognition. After stars are extracted from the star maps obtained from the image sensor, the computer runs the identification algorithm to identify stars by searching data in the catalogs. Based on the positions of identified stars the spacecraft orientations can be determined [11, 12]. Therefore, the performance of the optical system is required to meet the star identification algorithm which is expected to be robust and fast. The design of the optical system and the star identification algorithm for star trackers makes an important role in developing star trackers.

In this paper, we study the design of APS star camera and related identification algorithm. In section 2 the relationships between parameters of the optical system and the identification algorithm are discussed. These parameters include focal length, aperture, and field of view. The method to determine these parameters is introduced. Aberration correction requirements are analyzed. In section 3 Pyramid identification algorithm utilized here is investigated. Some improved approaches are presented for star map processing, onboard catalog organization and star identification. In section 4, after

*dermensheng@yahoo.com.cn; phone 008651265113796

2008 International Conference on Optical Instruments and Technology: Optical Systems and Optoelectronic Instruments
edited by Yunlong Sheng, Yongtian Wang, Lijiang Zeng, Proc. of SPIE Vol. 7156, 71561S · © 2009 SPIE · CCC code:
0277-786X/09/$18 · doi: 10.1117/12.806698

star number statistics is fulfilled all over the sky with any orientations by varying FOV and limiting magnitude, the aperture size and focal length of the optical system are calculated with the given STAR1000 APS sensor by analyzing their feasibility in optical design. According to these determined parameters, a star camera is designed. An onboard catalog on which star identification relies is produced. Some star identification simulations are implemented. And identification results are given out. We draw some important conclusions in section 5. At last an acknowledgement is made.

2. OPTICAL SYSTEM AND STAR IDENTIFICATION ALGORITHM

2.1 Determination of the optical system parameters

In the cosmos, stars have relative stable positions in spite of their slow proper motion which can be neglected within years. Thus, stars are chosen as excellent references to determine attitude in space missions better than other references such as the earth, the sun and so on. Star trackers are developed based on this notion. The characteristics of stars utilized to estimate attitude mainly include their brightness and positions which are described completely in the master star catalogs such as SAO (Smithsonian Astrophysical Observatory) Catalog and SKY2000 Catalog. Most star identification algorithms are brightness independent because brightness is difficult to be measure very accurately by star trackers [13, 14]. Master catalogs are very large and contain some data we don't need. The optical system which serves as an eye to acquire star maps is only sensitive to stars bright enough so that quite a few faint stars can't be observed. So a guide star catalog should be established beforehand which selects stars brighter than a cut-off magnitude from the master catalog. In particular, the guide star catalog can't include variable stars and double stars which will cause ambiguous recognition. In this paper stars are selected from SAO which includes stars as faint as M_v=9 and is sufficient for identification. In SAO the star location is established on the celestial sphere and represented by right ascension and declination, i.e. (α,δ). However it is described as a unit vector ***V*** in the guide catalog. The celestial sphere coordinate is shown in Fig.1, which is called the inertial coordinate, where the origin can be set to the center of any observers. ***V*** can be calculated from (α,δ) as shown in Eq.(1). While, another coordinate system called body fixed coordinate is build up on the star tracker. Its origin is the center of the exit pupil in the optical system, the *Z* axis is chosen as the optical axis, and *X* and *Y* axes are parallel to the image plane.

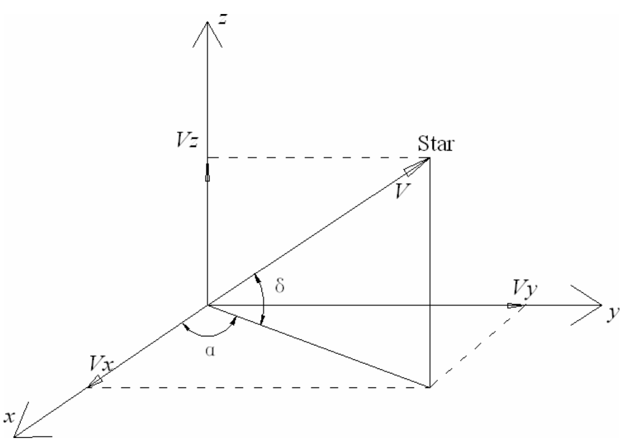


Fig. 1. Inertial coordinate system

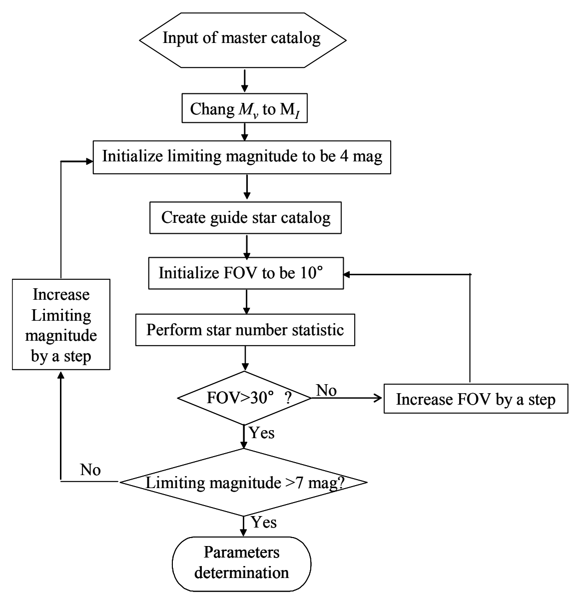


Fig. 2. Flow chart of optical parameters determination

$$V = \begin{bmatrix} Vx \\ Vy \\ Vz \end{bmatrix} = \begin{bmatrix} \cos\alpha\cos\delta \\ \sin\alpha\cos\delta \\ \sin\delta \end{bmatrix} \tag{1}$$

Star identification includes two steps. In the first step, the locations of candidate stars in the image plane are acquired by centroiding techniques. Then their vectors in the body fixed coordinate are calculated. And their features will be deduced such as star pair angular separations. In the second step, the measured stars are matched with the guide stars according to their features. Therefore, stars in FOV can be recognized. Attitude of star trackers can be inferred from positions of these recognized stars in the body fixed coordinate as well as in the inertial coordinate.

Centroiding algorithms claim that a star should be imaged to be a spot in order to achieve high position accuracy. Identification algorithm requires at least a certain number of detected stars exist in order to deduce star features. One class of identification algorithm is based on polygon features. That is, stars in the map make up of a polygon whose sides stand for the angular separations of star pairs. For example, the triangle identification algorithm is the simplest which demands at least three stars be imaged by the camera. Suppose the least star number that ensures successful recognition is n.

Parameters of the optical system consist of the focal length, aperture, and FOV. If the width and height of a square detector are A and B respectively, the focal length and FOV are restricted by Eq.(2).

$$tg\frac{w_A}{2}=\frac{A}{2f} \text{ and } tg\frac{w_B}{2}=\frac{B}{2f} \tag{2}$$

where f stands for the focal length, and FOV is $w_A \times w_B$.

With a given detector, the system with a larger aperture can be sensitive to darker stars. That means more stars will be observed. The total number of photons from a m M_v star coming into the aperture of the optical system per second can be calculated by Eq.(3).

$$n_p=5\times10^{10}\times10^{-\frac{2}{5}m}\times\frac{1}{4}\times\pi\times D^2 \ \ photos/sec \tag{3}$$

where D is the diameter of the optical system aperture measured in meters. Suppose the system transmission rate is η. The star spot covers M pixels. It is analyzed that the centroid algorithm achieves a high accuracy when the spot size covers 3×3 pixels [15,16]. The fill factor and quantum efficiency of APS are FF and QE. The exposure time is t. Therefore, the number of the photoelectrons transformed by a APS pixel is

$$n_e=\frac{n_p\times\eta\times QE\times FF}{M}t \tag{4}$$

Some kinds of noise exist during APS imaging, including the dark current noise, photo shot noise, dark current non-uniformity noise, photo response non-uniformity noise, fixed pattern noise, $1/f$ noise, read noise and reset noise. They are equivalent to some amount of photoelectrons, n_{DC}, n_{PS} ,n_{DCNU}, n_{PRNU}, n_{FPN}, $n_{1/f}$,n_{RN} and n_{KTC} respectively. The total noise is

$$n_{APS}=\sqrt{n_{DC}^2+n_{PS}^2+n_{DCNU}^2+n_{PRNU}^2+n_{FPN}^2+n_{1/f}^2+n_{RN}^2+n_{KTC}^2} \tag{5}$$

Then the signal to noise ratio is $$S/N=\frac{n_e}{\sqrt{n_{DC}^2+n_{PS}^2+n_{DCNU}^2+n_{PRNU}^2+n_{FPN}^2+n_{1/f}^2+n_{RN}^2+n_{KTC}^2}} \tag{6}$$

According to the S/N requirement and the given APS, the relationship between of the aperture size and the cut-off star magnitude can be determined.

Equations above illustrate that as for the same S/N, the system with a larger aperture will detect fainter stars and capture more stars. However to design an optical system with a very large aperture is difficult. And the FOV of such a system is sure not to be very wide. Larger aperture results in narrower FOV. The guide star catalog will become so large that star identification becomes very complex, and usually more facilities need to be equipped. As a result, star tracker turns to be heavy and power consuming. For example, ASTROS(Advanced Stellar and Target Reference Optical Sensor) tracker developed by JPL in 1985 is capable to track stars with visual magnitude up to 8.2 and has a 2.2°×3.5°FOV. It weights

41kg and consumes 43 watts [17]. It is not appropriate for real time work. On the contrary, the optical system designed to have a moderate aperture and a wide FOV is perfect. In addition, increasing the limiting magnitude causes more bright stars appearing in the FOV and higher signal to noise ratio of star maps which is benefit for star identification.

The method to determine aperture, FOV and *f* is described as follows. Firstly, the visual magnitude (M_v) of every star in the master catalog should be changed into its instrumental magnitude (M_I) according to the spectral responsibility of APS. Then guide star catalogs with different limiting magnitudes are created where variable and double stars are excluded. Then the star distribution should be investigated around the whole sky. As shown in Fig.1, α varies from -180° to 180°, and δ changes from -90° to 90°.The boresight sweeps the sky and its orientation of right ascension and declination varies 1°once. Note that less orientation intervals lead to more accurate investigation. In every orientation, we count the star number in the FOV. As for one limiting magnitude, FOV size should meet the demand that the probability of more than *n* stars appearing in the FOV reaches 98% all around the sky. Based on the statistical results, we choose suitable limiting magnitude and FOV. Then the aperture size according to Eqs.(3) ~ (6) can be determined. With the given APS, according to Eq.(2), the focal length can be obtained. Fig.2 illustrates the procedure determining these parameters. Note, the circular FOV is chosen in stand of square FOV because star images in the corner of the image plane have greater amount of aberrations. FOV varies form 10° to 30°.Too wide FOV is not practical for design. The step size of the limiting magnitude is chosen as 0.1Mv. As for FOV a trick to relieve calculation burdens is that at first FOV varies 5 deg once. Then decrease the step gradually in the suitable range.

2.2 Aberration correction consideration

As described above, centroiding algorithms are implemented to calculate the star positions in the star maps. The widely used centroiding algorithm is given by Eq.(7).

$$x = \frac{\sum x_i f(x_i, y_i)}{\sum f(x_i, y_i)} \quad \text{and} \quad y = \frac{\sum y_i f(x_i, y_i)}{\sum f(x_i, y_i)} \tag{7}$$

where $f(x_i,y_i)$ stands for the intensity at the *i*th pixel whose coordinate is (x_i,y_i).

Stars are so far away that they can be regarded as a point light source. The star image energy distribution is considered as the point spread function (PSF) of the optical system. If the star camera is designed to be near diffraction limited, a star will be imaged into a spot smaller than a pixel in the image plane. Hence, the position accuracy of the star image won't be better than one pixel which is limited by the detector resolution. So the star image spot should be expanded to cover several pixels by defocusing the camera to achieve sub-pixel position accuracy based on Eq.(7). However, the image can't become very large otherwise the intensity at the pixel will be below the sensitivity limit. In general, the image spot covers 3×3 pixels.

In order to ensure that every star image in the focal plane has the same vector as the original star, the defocused image with a single wavelength should keep symmetric and has a near Gaussian distribution. The star image spot needs to be circular. Furthermore, all over the spectral range of the starlight, the centroid of any monochromatic image remains the same.

According to the image quality analyzed above which are required by the star recognition algorithm, firstly unsymmetrical aberration i.e. the coma aberration must be corrected. Star spot will not be circular because of astigmatism. As a result of field curvature, the image doesn't adhere to the image plane, and star image spots won't keep circular either. Lateral color needs to be eliminated to get a common star image centroid to each wavelength within the spectral range. Then control spherical aberration and chromatic aberration to obtain an appropriate star image size. Although the distortion resulting in the position changes of star images can be adjusted by digital processing, it can't be so large. Therefore, coma, astigmatism, field curvature and lateral color aberrations are demanded to be corrected. Spherical, chromatic aberrations and distortion can't be too large.

3. IMPROVED PYRAMID IDENTIFICATION ALGORITHM

A successful star identification algorithm should be robust, reliable and fast to recognize stars. First of all, star trackers work in a full of debris environment which requires the identification have the ability to resist the disturbing from other bright objects. Secondly, spacecraft rotation around the earth implies the identification algorithm should output recognition results at a high speed. Otherwise, images taken by the camera will be smeared by each other.

As described in section 2, the star extraction is the basis of the star recognition. Star maps are processed to acquire star positions in the image plane by star extraction algorithm. During star recognition, identification algorithm is fulfilled. Daniele Mortari proposed the pyramid identification algorithm which needs at least 4 stars [18]. As shown in Fig.3, they are labeled as S1, S2, S3 and S4. Sides of the pyramid stand for interstar angles. Only when at least five among the six angular separations i.e.θ_{12}, θ_{13}, θ_{14}, θ_{23}, θ_{24} and θ_{34} match those in the onboard catalog, the identification is regarded to be successful. Because five interstar angles in a pyramid including a spike can seldom be all matched, this algorithm is robust and reliable. In addition, it offers a useful way to recognize spikes. Daniele Mortari presented K-vector method to speed the star recognition [19]. Accordingly, a K-vector catalog is produced by compiling star data in the guide star catalog. Star extraction algorithm, star identification algorithm and an appropriate onboard catalog are three indispensable parts in the star identification. In this section, we improve these three aspects and get a more fast and reliable star recognition.

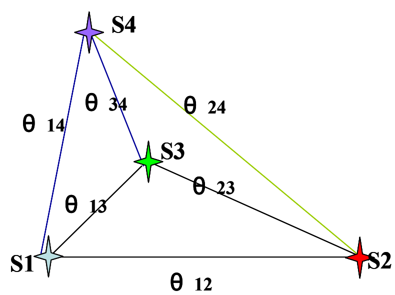


Fig. 3. Pyramid structure

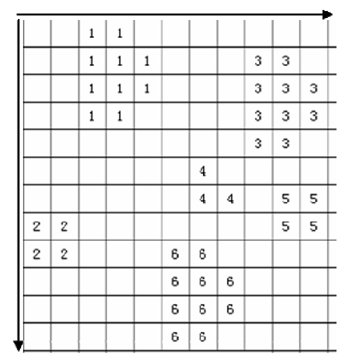


Fig. 4. Star extraction by scanning the full image

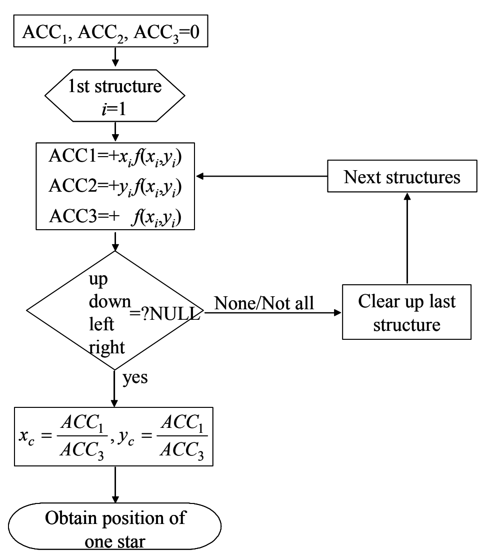


Fig. 5. Star extraction via link table structures

K	I	J	K	I	J	K	I	J
64191	22930	7229461	63966	51221	71643	61027	195400	216926
64192	93950	93954	63967	56840	57006	61028	110456	110583
64192	171317	171549	63969	196059	196240	61028	182857	182883
64193	193944	193965	63970	93932	94043	61030	24384	24563
64193	25597	25771	63970	90065	90075	61030	90065	90214
64194	26618	26784	63971	232091	232203	61034	38768	38924
64195	128572	147041	63972	85921	86003	61036	196643	196857
64196	11751	12038	63974	251472	251664	61036	124661	143324
64196	90075	90214	63975	150237	150416	61037	223753	223960
64197	197171	197277	63977	195952	196061	61037	108732	108878
64200	136899	137035	63978	236339	236693	61037	191554	191687
64201	22554	37665	63978	184068	184221	61037	236181	236368
64202	159330	159335	63979	71086	71165	61037	224317	241047
64204	253554	253756	63980	219186	219502	61038	100252	100374

Fig. 6. An example illustrating successful triangle identification

3.1 Star extraction strategy

To get a sub-pixel centroid accuracy, a star is imaged by the defocused star camera to get a blurred star image covering a few neighboring pixels constituting a connected region. Different stars occupy separated regions. And the rest pixels standing for the sky background appear darker than those representing stars. The centroid acquisition of a star first needs to separate its covering region from other regions. It is important to judge which bright pixels are connected together. The simplest way is to scan every pixel line by line and from left to right. Pixels connected to each other are marked by a same integer as shown in Fig.4. A brightness threshold is given out before scanning to distinguish stars from the background. During scanning, if the gray value of the current pixel is greater than the threshold, it is regarded as a part of a star. At that time , it should be considered whether its top, left or top left pixels are brighter than the background , and whether it should be marked by a new integer or inherit one of these pixels. This method should scan a full image frame. And if the marking integers of connected pixels are found different, the further uniformization is completed. It is time consuming. Another scheme is region growing algorithm in which a few brightest pixels are selected as seeds. Around each seed, according to the gray levels of the neighboring pixels, they are added to the same region if they are similar to the seed. Then the similar pixels are chosen as new seeds. This method avoids scanning the whole map. However, it is unavoidable to check pixels around the seeds, and uniformization still is necessary if two separated regions are connected to a same new bright pixel.

These two methods above require the star tracker transmit a full frame of the star map to the spacecraft computer on which most of the computational burdens are put. However, in star maps, bright pixels only occupy a small portion. That means most of the bandwidth are wasted to transmit the dark pixels. In modern CMOS APS chips every pixel is programmable [20]. Our strategy is that APS pixels are all programmed. During operations, every pixel is compared with a programmable threshold. Only those pixels whose values are greater than the threshold, their coordinate addresses (x,y) and values $f(x,y)$ are transmitted to the computer, and stored in the computer RAM via a three-column matrix SmArray. This strategy saves bandwidth and transmission time. Each row of this matrix records the x and y of a bright pixel in the star map, and the pixel value. A link table structure StarNode is introduced which is defined by Eq.(8) with Visual C++ program language. By scanning the SmArray, each bright pixel is recorded by such a structure and four pointers indicate whether there are bright pixels around it in its left, right, up and down directions. If no bright pixel exists in that direction, the corresponding pointer is equal to NULL. Otherwise, this pointer points to another link table structure recording next bright pixel.

```
struct StarNode { int x; int y; float value;
        StarNode *up; StarNode * down; StarNode * left; StarNode * right;};          (8)
```

Thus star extraction is achieved by searching the link table structures which is illustrated in Fig.5. Three accumulators ACC_1,ACC_2 and ACC_3 are presented to calculate $\sum x_i f(x_i,y_i)$, $\sum y_i f(x_i,y_i)$ and $\sum f_i(x_i,y_i)$, and initialized to be zeros. The search begins from the first link table structure. The accumulators then add $x_1 f(x_1,y_1)$, $y_1 f(x_1,y_1)$ and $f_1(x_1,y_1)$ respectively. By checking the pointers, neighboring pixels in the left, right, top and bottom of the first pixel will be found. The pointers and the value of the first structure are cleared up. Then the search goes from next structures. Their coordinates and values are inputted to the accumulators. Once further new pixels are found according to their pointers, these pointers are set to be NULL, and values of these structures are set to be zeros. Thus searching goes on likewise until the pointers of current link table structure is NULL. These operations to clear up the searched link table structures can avoid repeated search. When there are no new pixels, the search of this connected region ends. And the centroid of this region is calculated. Then another star search begins for rest structures until all link table structures are void.

3.2 Improved Pyramid identification algorithm

After the locations of the star images are determined, the identification algorithm is implemented to match the observed stars with those in the guide catalog according to their features. In Pyramid identification algorithm, 4 stars constitute a polygon with six sides standing for the six angular separations between any two stars. If interstar angles of 4 observed stars uniquely measure those of the cataloged stars within a certain accuracy threshold, they are identified to be those cataloged stars. Thus the basic matching procedure is to compare angular separations of star pairs.

K-vector technique offers a search-less method [19]. Accordingly, a K-vector catalog is produced. K-vector method calculates the angular cosine of every star pairs in the guide star catalog probably appearing in the FOV. Those star pairs closer than the accuracy limit are ignored. These cosines are sorted in descending order and an integer K is used to displace each cosine. In the K-vector catalog, only the integer K values and the corresponding ID numbers of star pairs are recorded which reduces memory expenditures. During star pair matching, an angular distance is related to the K values from K_{start} to K_{end}. It is not necessary to search the catalog and is beneficial for the identification. However, star pair matching has redundant results and may leads to wrong identifications. Therefore, the triangle identification algorithm is usually utilized which selects 3 stars and has more bounded requirements [21]. It still applies K-vector method. Three interstar angles are related to three candidate parts of the K-vector catalog respectively. If the identification is successful, a true star ID number will appear twice in these parts. As illustrated in Fig.6 where I and J are ID numbers of stars, candidate stars are identified to be stars with ID numbers 90065, 90075 and 90214 in the guide catalog. However, this identification still has a high probability of misidentification. Thus 4 stars are combined to form a Pyramid with more restrained requirements. Pyramid identification algorithm is more robust and reliable. The conventional Pyramid identification algorithm chooses the first identified three stars to form a basic triangle. Any other star is combined with two stars selected from this triangle to form a new triangle for identification using the triangle identification algorithm. If one of these new triangles is identified to be unique, the new star is identified successfully.

In this section, the Pyramid identification algorithm is improved. Firstly, in the star map, if the total of observed star n is greater than X, only X brightest stars are selected for identification. Although more identified stars will lead to more accurate attitude identification based on the attitude determination algorithm, time consuming calculation is unavoidable. The attitude accuracy increases imperceptibly when the identified stars are more than a certain number. In addition, selecting brightest observed stars can filter dim objects which may be considered as good stars and leads to invalid searching. In section 3.1, the brightness of stars read from ACC_3 is stored for brightness comparison. Secondly, when more than 4 stars are identified, besides the three stars from the basic triangle, all determined stars join the identification of the rest stars. Only when the triangle including the new candidate star and any two identified stars is proved unique, the new star is identified successfully. This measure makes use of the confirmed stars to determine as more new stars as possible.

The procedures of the improved algorithm are as follows.

Step 1 If n=3, stars are labeled to be S1, S2, and S3. The triangle identification algorithm is utilized for identification. This procedure is successful if the triangle is unique.

Step 2 If $n>X$, stars are compared according to their brightness, only X brightest stars are selected. Otherwise, all stars are reserved.

Step 3 When n>3, 3 candidate stars are firstly selected from the star maps and form a triangle. Then the triangle identification algorithm is implemented. If they are recognized uniquely, then a fourth star S4 is chosen. Otherwise, a new triangle is established by discarding at least one star and adding other new stars. This procedure continues until the unique recognition is achieved. Then go to step 4.Otherwise, the recognition is failed. The recognized triangle is called the basic triangle.

Step 4 Combining any two determined stars with S4 leads to a new triangle, i.e. △124, △234 or △134. If one of the three triangles is unique, and those two stars except S4 are identified the same as those in the basic triangle, identifying S4 is accomplished. For example, △124 is recognized unique, S1 and S2 are identified as the same as those in step 3. Although checking △234 or △134 may be a failure, S4 is considered to be determined. If none of the three triangles satisfies the demand, S4 are selected from rest stars, and the former S4 is never used.

Step 5 After 4 stars are recognized, other observed star S5 is selected from the rest stars. Two stars are selected from the former identified stars. Then go to step 4 for new identification. If all triangles of any combination are unsuccessful, the failure occurs. Then other rest star identification is implemented likewise.

3.3 Organization of the star catalogs

Based on the identification algorithm described above, an appropriate onboard catalog should be established. This catalog should have the ability to enhance the performance of star identification although creating it probably spends lots of time. At least 4 stars are required to appear in the FOV. However the catalog including too many stars brighter than the cut-off magnitude will result in its large size and long time searching. The catalog is expected to have a uniform star distribution all through the sky. So, some stars distributing too densely need to be picked up from the guide star catalog. This measure is coincident with the improved identification algorithm.

Before creating the guide star catalog, a reference catalog is prepared which only records the necessary data of stars such as ID number of stars in the master catalog, right ascension and declination (α,δ) as well as their magnitudes for further use .The stars fainter than the limiting magnitude, double stars and variable stars are discarded. These data are sorted according to δ in ascending order from -90° to 90°.With the given FOV, we expect only X brightest stars around the center star are recorded in the guide star catalog according to the identification algorithm. Thus, we place every star in the reference catalog to the center of the FOV, and compare stars around it within the FOV. Suppose the center star is *i*, the compared star is *j*. Because in the reference catalog neighboring stars are listed closely because of the δ ascending sort, the compared star should satisfy Eq.(9) which shortens the search time. Then check whether star *j* falls within the FOV. If the number of stars in the FOV exceeds *X*, the fainter stars are discarded, and only *X* brightest stars are reserved. If the center star is excluded from these *X* stars, it is also gotten rid of. Then in the next step, only those reserved stars in the previous round of comparisons need to be checked.

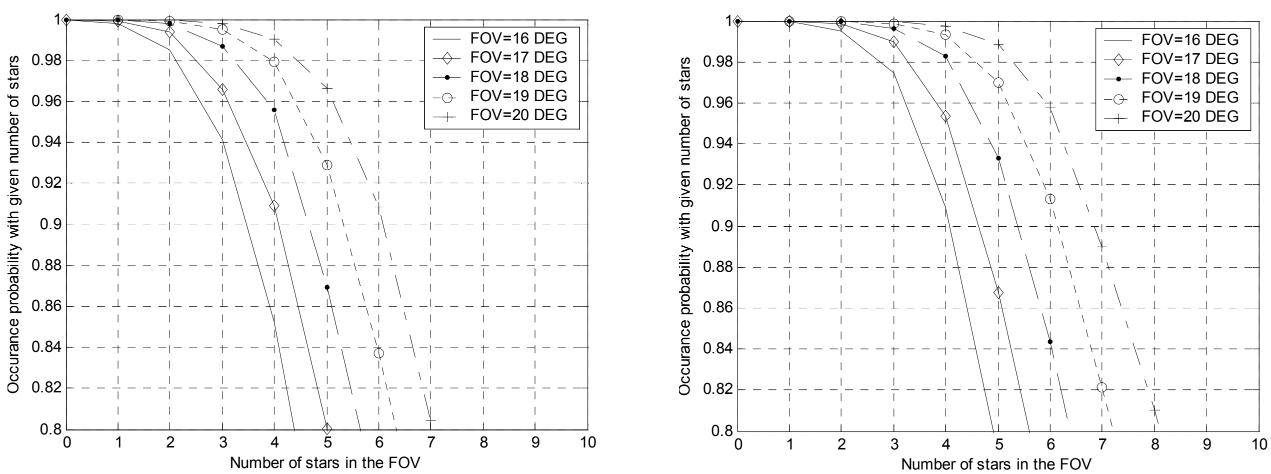
$$|\delta_i - \delta_j| < \frac{1}{2}\mathrm{FOV} \tag{9}$$

As for those reserved stars, their α and δ are converted into vectors according to Eq.(1) which are stored in the guide star catalog as well as the corresponding ID numbers. Then, according to the guide star catalog, K-vector catalog is produced.

4. OPTICAL DESIGN AND STAR IDENTIFICATION SIMULATIONS

4.1 Design of the optical system

Pyramid identification algorithm requires the probability of 4 stars appearing in the FOV reaches 98%. Fig.7 shows when the limiting instrument magnitude is 5.1 and 5.2 magnitude, the probability distribution of various numbers of stars appearing in FOVs from 16° to 20°.In Fig.7(a) , the probability demand is met when FOV is greater than 19°. While in Fig.7(b) , when the FOV is 19°,the probability of observing 4 stars simultaneously reaches 99%. In order to guarantee identification success, cut-off M_I is chosen as 5.2 magnitude, and FOV is 20°.



(a) (b)

Fig. 7. Probability of various star numbers in FOVs when (a) M_I =5.1 magnitude and (b) M_I =5.2 magnitude

We chose Star 1000 APS developed by Cypress Semiconductor Company as the detector. Its parameters are listed in Table 1. According to Eq.(2), the focal length is determined to be 43.56mm. And according to Eqs.(3)and (4), if D is 20mm, n_p=130653photos/sec.We chose the optical system transmission rate η is 0.75 and 85% of the star image energy is contained within an area of 3×3 pixels. Because of the attitude update rate, the exposure time is 0.2 second. Therefore, n_e is 370*e* and noises can be calculated as shown in Table 2. Thus, the S/N is 3.0. So, larger aperture is necessary to obtain higher S/N. The desired aperture is 27.3mm and the related S/N is 5.5.

Therefore, the parameters of the optical system are determined. *f*=43.56mm, D=27.3mm. The star image spot is required to be of near Gaussian distribution, and covers 3×3 pixels where 85% energy is enclosed. The maximum FOV is 20°.The spectral range is chosen from 400nm to 800nm. The central wavelength is 600nm. Such a system has a wide FOV and medium aperture, its F/# is 1.6. During the system design, correction of off axis aberrations can be realized by utilizing a few lenses in the system. The optical system as shown in Fig.8 is designed with the aide of ZEMAX optical design program. It contains 7 lenses. The distance between the edge of the last optical surface and the image plane is over 10 millimeters which offers a sufficient space to equip the APS. Six FOVs are selected to evaluate the performance of this system, and their half FOVs are 0°,3°, 5°,7°,8° and 10°respectively. In Fig.9, approximately 90% energy is contained within an area with the radius of 22.5um. The spot diagram as shown in Fig.10 are nearly circular. The maximum distortion is about 2.5%. Thus the further digital correction is indispensable.

Table 1. Parameters of Star 1000 APS

Image sensor format	1024×1024 pixels
Pixel size	15×15 um
Spectral range	400~1000nm
Full well capacity	135000*e*
Saturation capacity	99000*e*
Quantum efficiency*Fill factor	20%
Conversion gain	11.4*uv*/*e*
KTC noise	47*e*
Dark Current signal	3135*e/s*
ADC	10 bits
Fixed pattern noise	0.3% of full well
Photo response non-uniformity at Sat/2(RMS)	0.67% of full well

Table 2. Noises of Star 1000 APS when *D*=20mm

Noises	Equivalent photoelectrons
n_{DC}	$\sqrt{627}e$
n_{DCNU}	$\sqrt{56}e$
n_{PS}	$\sqrt{370}\ e$
n_{PRNU}	$\sqrt{905}e$
n_{FPN}	$\sqrt{405}e$
$n_{1/f}$	27 e
n_{RN}	100e
n_{KTC}	47e

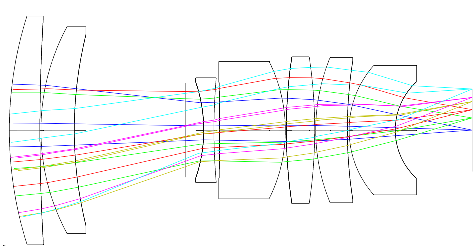


Fig. 8. Designed optical system

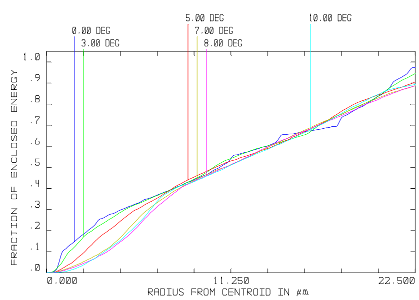


Fig. 9. Energy distribution

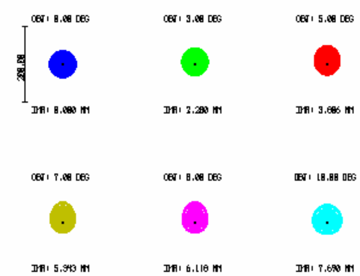
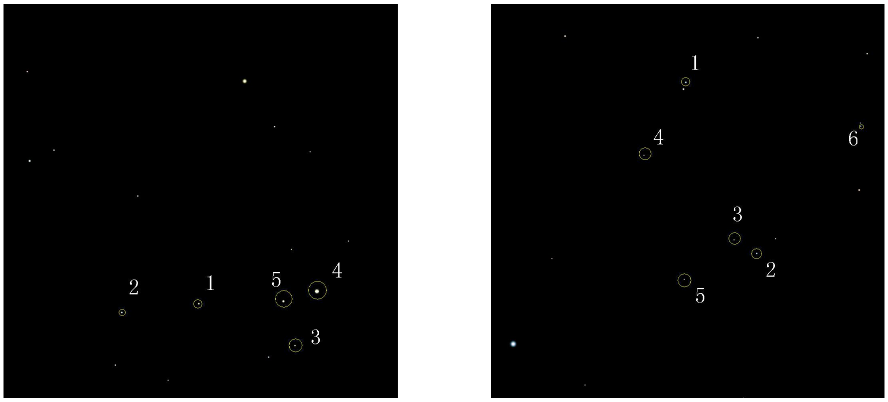


Fig. 10. Spot diagram

4.2 Star identification simulations

According to the proposed algorithm, only 1067 stars brighter than 5.2 M_I are selected. The size of the K-vector catalog is about 1M bytes. We chose several ideal star maps to simulate their imaging via the designed optical system with the aid of ZEMAX. Stars in the maps are identified by the identification algorithm. As shown in Fig.11, two ideal star maps (Star map A and B) and their identification results are given out as examples. In Fig.11, the identified stars are labeled by numbers. In these two maps, only 15 brightest stars are selected to be candidate stars. The interstar angle accuracy is chosen as 0.1 degree. Identification results are shown in Table 3 where the coordinates of the identified stars are presented too. The simulation is implemented using MATLAB6.5 in the computer equipped with a 1.7GHZ CPU.

The average identification time is near 1 second. However, the update rate will be improved when the program is executed by Visual C++ program compiler.



(a) Star map A (b) Star map B

Fig. 11. Ideal star maps and their simulations identification results

Table 3. Simulation identification results

Star map	A			B		
Result	x	y	ID	x	y	ID
1	-4.03	267.40	164346	15.64	-307.82	229646
2	-204.07	290.20	164132	200.03	136.81	245834
3	245.64	376.23	164593	140.96	101.57	245921
4	302.68	235.27	164644	-93.28	-118.15	229751
5	215.59	261.18	164560	11.40	204.18	246055
6				470.54	-193.81	229092

5. CONCLUSIONS

APS star trackers are the developing trend of modern star trackers in virtue of its advantages superior to conventional CCD. The star identification algorithm determines the performance requirement of the star camera. The first step in the star identification is to extracting stars from star maps by centroid technique. It requires stars should be imaged to be defocused spots whose energy is of Gaussian distribution. Thus aberration corrections in optical design are considered. Coma, astigmatism, field curvature and lateral color aberrations are demanded to be corrected. Spherical, chromatic aberrations and distortion should be limited. In this paper, an improved method is used in star extraction which takes advantages of the programmable ASP pixels. A link table structure is proposed to decrease data transmission and accelerate star acquisition. The Pyramid identification algorithm is improved to obtain a guide star catalog with a uniform star distribution all over the sky which shortens the match time. By performing star number statistic with given FOV and cut-off magnitude, FOV is chosen as 20°and limiting star magnitude is $5.2M_I$. According to the selected Star 1000 APS, the focal length and aperture are determined to be 43.56mm and 22.7mm respectively. A star camera is designed. The star identification simulations are implemented to test the identification algorithm and designed star camera. It proves that the designed star tracker achieves a good performance.

ACKNOWLEDGEMENT

This work on this topic is sponsored by JiangSu′ Key Lab of Modern Optical Technology under Grant No. KJS0732 in China.

REFERENCES

[1] A.Read Eisenman, Liebe C.C., "The Advancing State-of-the-art in Second Generation Star Trackers", IEEE Aerospace Conference Proceedings 5,243-253(1998).

[2] Liebe C.C., "Star trackers for attitude determination," IEEE Aerospace and Electronics Systems Magazine 10(6), 10-16(1995).

[3] Liebe C.C., "Accuracy performance of star tracker-a tutorial," Transactions on Aerospace and Electronic Systems 38(2), 587-599(2002).

[4] R. W. Armstrong, D. A. Staley, "A survey of current solid state star tracker technology," Journal of the Astronautical Sciences 33, 341-352(1985).

[5] Eisenman R, Liebe C.C, Joergensen J.L., "The new generation of autonomous star trackers," Proc. SPIE 3221, 524-535(1997).

[6] Hopkinson G.R., Purll D.J., Abbey A.F., et al, "Active pixel array devices in space mission," Nuclear Instruments and Methods in Physics Research A 513, 327-331(2003).

[7] R.C. Stirbl, B.Pain, T.J. Cunningham, et al, "Next Generation CMOS Active Pixel Sensors for satellite hybrid optical communications/imaging sensor systems," Proc. SPIE 3498, 255-264(1998).

[8] Liebe C.C., Dennison E.W., Hancock B.R., Stirbl R.C., Pain B., "Micro APS based star tracker, " IEEE Aerospace Conference Proceedings 5, 2285-2300(2002).

[9] Dong Ying, Xing Fei, You Zheng., "An APS based autonomous star tracker," Proc. SPIE 5633, 225-233 (2005).

[10] Brian Shucker., "A Ground-Based Prototype of a CMOS Navigational Star Camera for Small Satellite Applications," Proceedings of the 15th AIAA/USU Conference on Small Satellites (2001).

[11] T. Lee, A. Sanyal, M. Leok, and N. H. McClamroch, "Deterministic global attitude estimation," Proceedings of the. IEEE Conference on Decision and Control 3174~3179(2006).

[12] LIN Yurong, DENG Zheng Long, "Star-sensor-based Predictive Kalman Filter for Satellite Attitude Estimation," SCIENCE IN CHINA(Series F) 45(3),189~195(2002).

[13] Servidia, P.A. Sanchez Pena, R.S., "New robust star identification algorithm," IEEE Transactions on Aerospace and Electronic Systems 42(3), 1127-1131(2006).

[14] Meng Na, Peifa Jia., "A survey of all-sky autonomous star identification algorithms," ISSCAA 2006 1st International Symposium on Systems and Control in Aerospace and Astronautics 896~901(2006).

[15] LI Chun-yan , XIE Hua ,etc, "Centroiding algorithm for high-accuracy star tracker, " Opto-Electronic Engineering 33(2),41-44(2006).

[16] Hancock B.R., Stirbl R.C., Cunningham T.J., "CMOS Active Pixel Sensor Specific Performance Effects on Star Tracker imager Position Accuracy," Proc. SPIE 4284,43-53(2001).

[17] Shalom E., Alexander J. W., Stanton R. H., "Acquisition and track algorithms for the Astros star tracker," Guidance and Control Proceedings of the Eighth Annual Rocky Mountain Conference 375-398(1985).

[18] Mortari D., Samaan M.A., Bruccoleri C., and Junkins J.L., "The Pyramid Star Identification Technique," The Journal of Navigation 51(3), 171-183(2004).

[19] Mortari D., "Search-less algorithm for star pattern recognition," The Journal of the Astronautical Sciences 45(2), 179-194(1997).

[20] Liebe C.C., "Aclive Pixel Sensor (APS) based Star Tracker," IEEE Proceedings 1,119-127(1998).

[21] Ju, G., "Autonomous star sensing, pattern identification, and attitude determination for spacecraft: An analytical and experimental study," PhD. Graduate Thesis of Texas A&M University 119~124(2001).