Design of a Miniature CMOS APS Star Tracker

Penghai Wang, Lidong Lan, Yifei Han, Guanya Wang, and Haiyang Quan
Beijing Microelectronics Tech. Institution (BMTI), Beijing, China
Email: dreamor418@163.com, zhumengzhongke@126.com

***Abstract*—Star trackers are currently the most advanced attitude measuring instruments. They have the advantages of high precision, small quality, no drift, strong anti-interference and autonomous navigation without relying on other navigation systems. This paper proposes the design of a low-quality, small-size and high-accuracy star tracker that is constructed by a self-developed CMOS APS (Complementary Metal Oxide Semiconductor Active Pixel Sensor) image sensor and a microprocessor based on SPARC V8 architecture. Details of the hardware structure, algorithm design and navigation star catalog design are presented. Meanwhile, a control system is developed jointly on Microsoft Visual Studio and Matlab which can be used to configure parameters of the star tracker and display three-dimensionally attitude information. By analyzing the performance of the star sensor, the accuracy of the Euler angles can reach 2.25", 2.25" and 15.97", respectively. And their noise equivalent angles are 2.22", 2.22" and 16.65". Finally, considering the influence of the star tracker itself and the external environment noise, a median filter and a binary linear interpolation compensation method can be used to suppress the noise and improve the accuracy of attitude determination.**

***Index Terms*—star tracker, CMOS APS, attitude accuracy, median filter, binary linear interpolation compensation**

I. Introduction

Star trackers are by far the most sophisticate space attitude measuring devices. They use stars as the frame of reference and provide accurate spatial orientation. A star tracker uses the imaging system for imaging the sky, and then measures the position of stars in the star tracker coordinate system. When the stellar accurate position in the inertial coordinate system is recognized, triaxial attitudes of the aircraft can be calculated. They have the characteristics of high precision, small quality, no drift, strong anti-interference and autonomous navigation without relying on other navigation system. Star trackers have been widely used in remote sensing of the earth, earth mapping, planetary exploration and mapping, interstellar communication, intercontinental ballistic missiles and other aerospace field.

According to the general model of a star tracker formulated by European Space Agency (ESA), a star tracker is composed of an optical unit, a detection unit and a processing unit [1]. Photons emitted by stars in the field of view are collected by the optical unit, and then the detection unit converts optical signals into electrical signals. The algorithms, including star map preprocessing, star target extraction, star pattern recognition and attitude calculation, are running on the processing unit.

Depending on the kind of detection units, star trackers can be divided into three main categories. The detection units of the earliest star trackers were image dissector tubes. The structure of these star trackers was simple, and the number of navigation stars that could be used was small. In the 1970s, with the development of the solid-state image sensor, such as the charge coupled device (CCD) and the charge injection device (CID), researchers begun to use solid-state image sensors as detection units. Due to the characteristics of devices and the development of manufacturing process, CCD star trackers gradually dominated. Another image sensor-CMOS APS (Complementary Metal Oxide Semiconductor Active Pixel Sensor) has been widely used since the 1990s, because of the advent of microelectronic technologies. It has the characteristics of low power consumption, simple sampling circuits and strong anti-radiation performance, etc. [2] Because CCD sensors still have the considerable advantages in sensitivity, noise performance and filling rate, high-precision star trackers are mostly based on them. However, CMOS sensors will replace them with significant reducing of the noise. In addition, the electron multiplying CCD (EMCCD) has been developed in recent years. Due to its high signal-to-noise ratio, simple structure and high dynamic, it has been applied in many aerospace missions, such as ESO telescope and Planck telescope [3]. The main features of three kinds of detectors applied in star trackers are shown in Table I.

TABLE I. Features of CCD, CMOS and EMCCD

Detector	sensitivity	Complexity	Sampling rate	power
CCD	High	Complex	Low	High
CMOS	General	Simple	High	Low
EMCCD	Ext-high	Complex	Low	Ext-high

In this paper, we propose the design of a low-quality, small-size and high-accuracy star tracker that is constructed by a self-developed CMOS APS image sensor and a microprocessor based on SPARC V8 architecture. The details are described in system design description section, including hardware design, algorithm design, navigation star catalog design and control system design. Then the performance and the noise are analyzed, and a median filter and a binary linear interpolation compensation method are used to suppress the noise and improve attitude determination accuracy.

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II. System Design Description

A. Hardware Design

The hardware structure diagram of the star tracker is shown in Fig. 1. It is mainly composed of the optical system, the imaging and control system and the data processing system. The optical system has a great impact on performance of the star tracker, such as the accuracy, sensitivity of detectable magnitude, quality and dimensions. It also indirectly affects the update rate and algorithm performance. Parameters of the optical system include focal length, aperture, field of view, spectral range, the center wavelength, transmittance rate, size of dispersion circles and working temperature, etc. [4] Wherein, the focal length, field of view and aperture are three important factors. And they are interrelated and mutually conditioned. In addition, increases of the focal length would lead to large volume and heavy weight of the star tracker, which couldn't be conducive to miniaturization. The focal length of the optical system can be calculated as follows:

$$f = \frac{L}{2\tan\frac{FOV}{2}} \tag{1}$$

where, L is the total length of all pixels, FOV represents the field of view. As shown in the Table II, the value of L is 15.36mm and FOV is 20 degree. So the focal length of our star tracker is 43.56mm according to the (1).

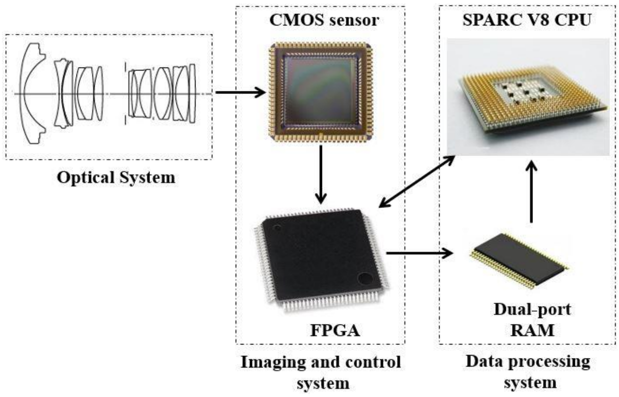

Figure 1. The hardware structure diagram

TABLE II. Parameters of the CMOS Image Sensor

Voltage	3.3V
Sensitive area format	1024*1024
Pixel size	15um*15um
Spectral range	400~1000nm
Pixel output rate	12MHz
Gain	1,2,4,8
ADC	12 bit
shutter	Rolling shutter

The imaging and control system mainly consists of our self-developed CMOS image sensor and Field-Programmable Gate Array (FPGA). The CMOS image sensor converts optical signals into electrical signals that contain the information of navigation stars. It is a radiation tolerant image sensor with 1024 by 1024 pixels on a 15mm pitch. It features on-chip double sampling technique, a programmable gain amplifier (PGA), an analog multiplexer and a 12-bit analog-to-digital converter (ADC). All circuits are designed using the radiation tolerant design rules to allow to a high tolerance. Registers that contain the X- and Y- addresses of the pixels to be read can be directly accessed by the external controller. This architecture provides control of the sampling window size and the starting addresses. The programmable gain amplifier with a gain of 1, 2, 4 and 8 times can realize dual-slope integration, which greatly improves the dynamic range. The mode of the shutter is electronic rolling. Specific parameters of the CMOS image sensor are shown in Table II. The main role of the FPGA is to control the CMOS image sensor, generate the timing-driven sequence, modulate data of the stars and preprocess star maps.

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The data processing system is made up of a microprocessor based on SPARC V8 architecture and a dual-port random-access memory (RAM). The dual-port ram is used to save star maps generated by the CMOS image sensor. The purpose of the microprocessor based on SPARC V8 architecture is to execute the algorithms of star extraction, star pattern recognition and attitude determination. Its operating frequency can be up to 150MHz, and signal and double precision floating-point arithmetic are supported with five pipelines and the high-speed on-chip AMBA bus. The architecture allows for a spectrum of input/output (I/O), memory management unit (MMU), and cache system sub-architectures. SPARC assumes that these elements are optimally defined by the specific requirements of particular systems. They are invisible to nearly all user application programs and the interfaces to them can be limited to localized modules in an associated operating system.

B. Algorithm Design

1) Star map capture

In order to ensure the normal operation of the CMOS image sensor to capture star maps, the FPGA needs to generate the appropriate timing-driven sequence. This can be realized through the Verilog HDL hardware description language. According to the top-down design approach, the sequence is designed using multiple functional modules, and each module is designed and implemented independently. Then a top-level module is designed to connect all individual modules together. The modules after the division are the reset module to generate the control signals of reset operation, the pixel-readout module to produce the timing of the pixel readout sequence and the star-map buffer module that is used to save star map data.to dual-port ram. The reset module and the pixel-readout module are implemented by two finite state machines (FEM). Their state transition diagrams are shown in Fig. 2 and Fig. 3, and the number of states is respectively 4 and 7. When the cycle of pixel readout is 50ns and the integration time is 3.5us, the update rate of star maps can reach 29Hz.

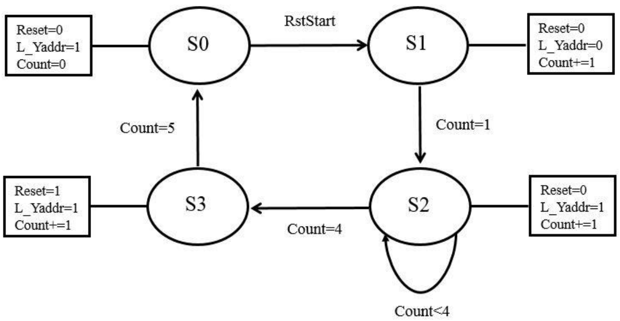

Figure 2. The FEM of the reset module

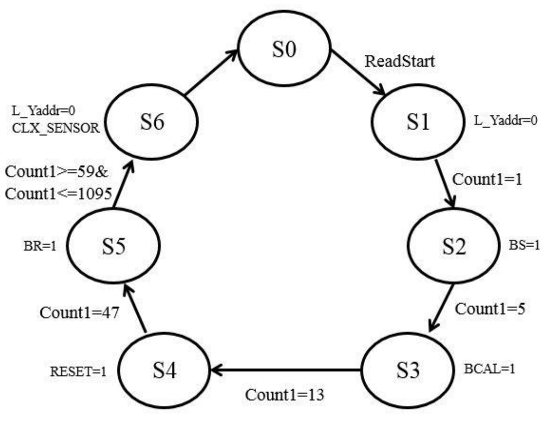

Figure 3. The FEM of the pixel readout module

2) Star map pretreatment

The purpose of star map pretreatment is to suppress noise existed in the background of star maps, to remove the influence of confounding factors and improve the success rate of star extraction. In order that plenty of star map data can be processed in real time, the algorithm must be easy to implement. Since the peak of desired signals is much larger than the average of the noise, we use the adaptive global threshold-segmentation method to pretreat star maps. Its principle is to separate star points from the background noise and identify useful star points. It can be expressed as the formula:

$$s(\mathrm{x},\mathrm{y}) = \begin{cases} 0 \quad , f(x,y) < V_{th} \\ f(x,y), f(x,y) \geq V_{th} \end{cases} \quad (x, y \in L) \tag{2}$$

$$V_{th} = Mean + \alpha D \tag{3}$$

$$Mean = \frac{\sum_{x=1}^{m} \sum_{y=1}^{n} f(x,y)}{mn} \tag{4}$$

$$D = \sqrt{\frac{\sum_{x=1}^{m} \sum_{y=1}^{n} (f(x,y) - Mean)^2}{mn-1}} \tag{5}$$

where, $f(x, y)$ is the gray value of the pixel located at the point (x, y) in a star map, $s(x, y)$ is the gray value of the pixel located at the point (x, y) after the pretreatment, Vth represents the global threshold value and can be counted as (3), *Mean* represents the average of all pixel values of a star map and its formula is shown in (4), D is the variance of a star map, which is expressed as (5), α is a coefficient related to the noise, m and n are rows and columns of pixels.

3) Star extraction

The light of a star is distributed in a plurality of pixels on the photosensitive plane of an image sensor. The objective of star extraction is to get the coordinates of the star targets. The accuracy of attitude determination is directly dependent on the process of star extraction. Star extraction involves two steps: target point analysis and the subpixel interpolation centering. The role of target point analysis is to separate a star target from other objectives. The subpixel interpolation centering is to diffuse a star point to a plurality of pixels with the use of interpolation subdivision technique, so that the precision of star extraction can reach sub-pixel level. Currently, there are mainly two methods: the scanning method and the vector method [5]. When there is large noise in star maps, the vector method can lead to the failure of target point analysis. So the scanning method is adopted for target point analysis.

The main process of the scanning method is as follows. Firstly, coordinates of the pixels after the pretreatment in the same row are analyzed. A star target is made up by the pixels that their row coordinates are adjacent. Secondly, column coordinates of star targets generated in the first step are checked. When the coordinates of the star target i and j have the relationship as shown in (6), the star target i and j are merged into the same star target. Finally, star targets with an isolated pixel or more than 25 pixels are rejected due to the influence of the high brightness isolated point and the false targets.

$$\begin{gathered} \left| y_i - y_j \right| = 1 \\ x_{js} \leq x_{is} \, and \, x_{je} \geq x_{is} \, or \, x_{js} \geq x_{is} \, and \, x_{js} \leq x_{ie} \end{gathered} \tag{6}$$

where, y_i and y_j represent the row coordinates of the star target i and j, x_{is} and x_{js} represent the column start coordinates, x_{ie} and x_{je} represent the column end coordinates.

At present, there are a lot of algorithms about subpixel interpolation centering, such as the centroid method, the threshold centroid method, the Gaussian fitting method, the maximum likelihood method, the square weighted centroid method and so on. Among them, the centroid method is stable, accurate, fast and easy to implement [6]. In order to obtain higher accuracy, we used the threshold centroid method to extract star targets. Its formula is as shown in (7).

$$x_c = \frac{\sum_{x=1}^{m}\sum_{y=1}^{n}[s(x,y)-V_{th}]x}{\sum_{x=1}^{m}\sum_{y=1}^{n}[s(x,y)-V_{th}]}$$
$$y_c = \frac{\sum_{x=1}^{m}\sum_{y=1}^{n}[s(x,y)-V_{th}]y}{\sum_{x=1}^{m}\sum_{y=1}^{n}[s(x,y)-V_{th}]} \tag{7}$$

where, x_c and y_c are exact row and column coordinates of star targets after the subpixel interpolation centering.

4) Star pattern recognition

Star pattern recognition is based on the geometric characteristics between stars to determine the correspondence between observed star targets and navigation stars. It is a key factor in the attitude determination. So far, the algorithms of star pattern recognition mainly include the triangle algorithm, the match group algorithm, and the grid algorithm, etc. In our implementation, we chose the improved triangle algorithm to recognize all the areas of the sky, which rough attitudes of the star tracker could be calculated. Then we adopted the quaternary star pattern recognition [7] to make the local-sky recognition according to the obtained rough attitudes, which could reduce redundant match, accelerate the identification rate and improve recognition accuracy. The identification processing of the triangle algorithm is summarized as follows.

(1) Find the brightest star S_1 from the star map as the host star.

(2) Find two of the brightest stars S_2, S_3 as the companion stars in the area of the ring whose inner and outer radius are R_1 and R_2. Guarantee S_1, S_2 and S_3 in the counterclockwise arrangement using the right hand rule.

(3) Generate a triangle with the vertices S_1, S_2 and S_3, and match the angular distance of three edges with each edge of catalog triangles within the margin of error.

(4) Analyze the matching results.

- When there are no matched catalog triangles, select the second brightest star in the star map as the host star and repeat the above processes.
- When there is the only matched catalog triangle, indicate successful recognition.
- When there are two or more catalog triangles, select the brightest star S_4 in the intersection of the rings whose centers are located in positions of the star S_1 and S_2. Construct another triangle by the vertices S_1, S_2 and S_3, and match it with catalog triangles.

(5) Repeat the above processes. If there are no bright stars in the star map, indicate failure.

When the recognition is successful using the improved triangle algorithm, the initial attitude of the star tracker can be obtained after the process of attitude determination. Based on this initial attitude the approximate range of photographed sky can be determined. So navigation stars that may appear in the field of view of the star tracker can be selected to make the local-sky recognition with the quaternary star pattern recognition. The algorithm is summarized as follows.

(1) Find the four brightest stars S_1, S_2, S_3 and S_4 from the star map, and their magnitude meets the relation: $Ms_1<Ms_2<Ms_3<Ms_4$. Generate a triangle Δ_1 with the vertices S_1, S_2 and S_3 and another triangle Δ_2 with S_1, S_2 and S_4. Then calculate the angular distance and the relative magnitude of all their edges.

(2) Select navigation stars from the star catalog based on the initial attitude.

(3) Match respectively the angular distance and the relative magnitude of three edges of the triangle Δ_1 with ones of the edges generated by the selected navigation stars within the margin of error, and record these matched star pairs.

(4) Determine whether the star pairs can be constituted for triangles.

- If there is only one triangle, indicate success.
- If the number of triangles is greater than one, repeat above the processes to get the star pairs matched with the edges of Δ_2. If the triangles constituted by the two sets of star pairs have a common edge, indicate success.
- If there are no triangles, find the four brightest stars in the remaining stars, and repeat the above processes.

5) Attitude determination

The attitude determination algorithm is used to determine the attitude transformation matrix through the multiple observation vectors. Generally, as long as there are two vectors that are not parallel, the attitude transformation matrix can be calculated. The algorithm is expressed as the (8) [8].

$$W_i = AV_i + \Delta V_i, i = 1, 2, ..., \mathrm{n} \tag{8}$$

where, W_i is a unit vector in the inertial coordinate system, V_i is a unit vector in the star tracker coordinate system, A is the attitude transformation matrix, ΔV_i is the error vector in observation.

In 1965, Wahba proposed the loss function to seek the optimal orthogonal attitude matrix as shown in (9) [8].

$$L(\boldsymbol{A}) = \frac{1}{2}\sum_{i=1}^{n} a_i \left|W_i - \boldsymbol{A}V_i\right|^2 \tag{9}$$

where, a_i is the weighting coefficient.

Currently, one of the most commonly used algorithm to solve the Wahba loss function is the QUEST (Quaternion Estimator) in the practical applications. This algorithm maintains all the computational advantages of a fast deterministic algorithm while yielding an optimal quaternion. And this optimal quaternion satisfies the relationship, which is

$$Kq_{opt} = \lambda_{max} q_{opt}$$
$$K = \begin{bmatrix} S - \sigma I & Z \\ Z^T & \sigma \end{bmatrix}, B = \sum_{i=1}^{n} \alpha_i W_i V_i^T \quad (10)$$
$$S = B^T + B, Z = \sum_{i=1}^{n} \alpha_i W_i \times V_i, \sigma = trB$$

where, q_{opt} is an eigenvector of the matrix K.

When the sequence of rotation axes of Euler angles is z-x-y, the relationship between the attitude transformation matrix and the quaternion is shown in (11).

$$A = \begin{bmatrix} q_4^2 + q_1^2 - q_2^2 - q_3^2 & 2(q_3 q_4 + q_1 q_2) & 2(q_1 q_3 - q_2 q_4) \\ 2(q_1 q_2 - q_3 q_4) & q_4^2 + q_2^2 - q_1^2 - q_3^2 & 2(q_1 q_4 + q_2 q_3) \\ 2(q_2 q_4 + q_1 q_3) & 2(q_2 q_3 - q_1 q_4) & q_4^2 + q_3^2 - q_1^2 - q_2^2 \end{bmatrix} \quad (11)$$
$$q_{opt} = [q_1, q_2, q_3, q_4]^T$$

In summary, the structure chart of our algorithm design is shown in Fig. 4.

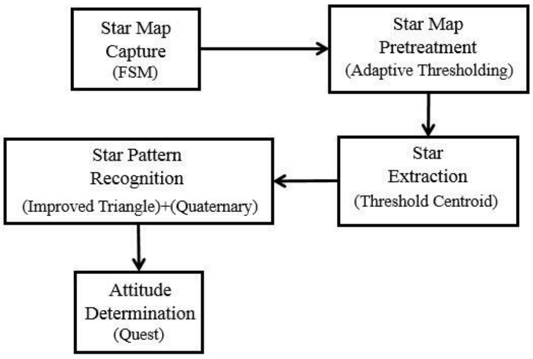

Figure 4. The structure chart of algorithm design

C. Star Catalog Sesign

A navigation star catalog is used to implement the star pattern recognition and attitude determination, which the necessary information of stars for the algorithms is stored in. The capacity, content and storage mode of the navigation star catalog are vital to the performance of a star tracker. Because the existing star catalogs which have been produced for different purposes can't be used directly for star trackers, the star catalog design for star trackers is essential. The following is a brief outline of our design based on the SAO star catalog.

(1) Remove variable stars and double stars in the SAO star catalog. Because the brightness of variable stars changes either irregularly or regularly, their magnitude can't be confirmed. And the double stars can drop the accuracy of the subpixel interpolation centering.

(2) Select navigation stars. According to the optical features of our CMOS image sensor, choose the stars whose visual magnitude is less than 5.5 as the navigation stars. Then select the stars whose visual magnitude is less than 3 as the host stars, which can accelerate the speed of retrieval and reduce the time spent by the recognition.

(3) Construct the navigation star catalogs: the partition catalog, the star pair catalog and the unit vector catalog. In order to make fast and accurate star pattern recognition, divide the celestial sphere into 180 zones by declination. And arrange all the stars in every zone in order of increasing right ascension. Then store the information of these stars in the partition catalog, including starting addresses of these stars in the star pair catalog and total number. When the angular distance calculated between host stars and other navigation stars satisfies a certain error limit, record their ID, the angular distance and relative magnitude into the star pair catalog. For all the unit vectors of navigation stars, store them in the unit vector catalog. The unit vector of a star is expressed as (12).

$$v_u = \begin{bmatrix} x & y & z \end{bmatrix}^T = \begin{bmatrix} \cos\alpha \sin\delta \\ \cos\alpha \cos\delta \\ \sin\alpha \end{bmatrix} \quad (12)$$

D. Control System Design

The control system has been developed on Microsoft visual studio 2008 and Matlab R2011a. Its main functions are to configure parameters of the star tracker via a serial port, control the work mode and display star maps and the corresponding attitude. The graphic user interface of the control system is shown in Fig. 5. Parameters of the star tracker, including the gain, integration time, reference threshold and row and column start addresses of a star map, are configured on the top left graph window. The buttons on the bottom left window are used to control the work mode and save the captured star map. And star maps which have been captured can be injected into the star tracker by our control system. These star maps are displayed on the middle window, and the attitude information is illustrated three-dimensionally on the right window, including Euler angles and the location of the star tracker in the terrestrial coordinate system.

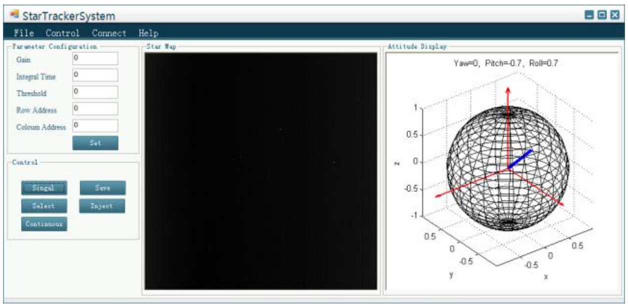

Figure 5. Graphic user interface of the control system

III. Performance Analysis

The single-star measurement precision is the basis of the overall accuracy of a star tracker, and it has the significant impact on attitude measurement. The errors are caused by the optical lens distortion and aberrations, dark current, random noise and shot noise, etc. The single-star measurement precision with the subpixel interpolation centering is expressed by (13).

$$\xi_{simpix} = \frac{FOV}{N} \cdot \frac{1}{m} \quad (13)$$

where, FOV represents the field of view, N is the number of pixels in the diagonal of the photosensitive plane, m is the size of the window used by algorithms.

The size of the window used by the subpixel interpolation centering is 3*3, so the single-star measurement precision of our star tracker is 7”.

The measurement precision of Euler angles, including a pitch angle, a yaw angle and a roll angle, is given by (14).

$$\sigma_{pitch} = \sigma_{yaw} = \frac{2\tan(FOV/2)}{\sqrt{N_S}\cdot m\cdot N}$$
$$\sigma_{roll} = \frac{\sqrt{2}}{\sqrt{N_S - 1}}\cdot\frac{\tan(FOV/2)}{m\cdot N\cdot\theta_S} \quad (14)$$

where, N_s is the number of star targets extracted from a star map, θ_S represents the average angular distance.

When the number of star targets extracted is 10, the precision of the pitch angle, the yaw angle and the roll angle is respectively

$$\sigma_{pitch} = \sigma_{yaw} \approx 2.25"$$
$$\sigma_{roll} \approx 15.97"$$

A noise equivalent angle (NEA) is related with the performance of hardware devices and reflects the static stability of a star tracker. The sources of noise are mainly optical noise, dark current noise and random errors in the attitude determination, etc. The NEAs of a star tracker can be equivalent to error angles of three axes. Error angles of the pitch axe and the yaw axe are calculated by (15). Because the size of the focal length is much greater than the photosensitive plane, the precision of the roll axe is lower. The error angle of the roll axe is expressed by (16).

$$E_{pitch} = E_{yaw} = \frac{FOV\cdot E_{cen}}{N\cdot\sqrt{N_S}} \quad (15)$$

$$E_{roll} = \arctan\left(\frac{E_{cen}}{0.3825\cdot N}\right)\cdot\frac{1}{\sqrt{N_S}} \quad (16)$$

where, E_{cen} is the error of star centroid.

The triaxial noise equivalent angles of our star tracker calculated by (15) and (16) are respectively

$$E_{pitch} = E_{yaw} \approx 2.22"$$
$$E_{roll} \approx 16.65"$$

In summary, the specifications of our star tracker are shown in Table III.

TABLE III. THE SPECIFICATIONS OF THE STAR TRACKER

Weight(no lens hood)	≤1kg
Update rate	≥3Hz
FOV	20°×20°
Sensitive	5.5Mv
Accuracy of the pitch and yaw angle	2.25’’
Accuracy of the roll angle	15.97’’
Resolution	1024×1024

IV. DISCUSSION

Because the noise can lead to the failure of attitude determination, the noise suppression before the star map pretreatment is very significant to improve the performance. The median filter [9] is a nonlinear digital filtering technique and often used to remove noise. It considers each pixel in the image in turn and looks at its nearby neighbors to decide whether or not it is representative of its surroundings. The median is calculated by first sorting all the pixel values from the surrounding neighborhood which is called the “window” into numerical order and then replacing the pixel being considered with the middle pixel value. It is simple to implement and able to suppress effectively noise. The result after the noise suppression satisfies the relationship as shown in (17).

$$g(m,n) = median\{f(m-i, n-j), (i, j)\in W\} \quad (17)$$

where, $f(m\text{-}i, n\text{-}j)$ is the gray value of the pixel located at the point $(m\text{-}i, n\text{-}j)$ in the original star map, $g(m, n)$ is the gray value of the pixel located at the point (m, n) after using the median filter, W represents the window.

In order to reduce the error caused by exterior environmental noise and the CMOS sensor, many scholars have conducted researches on how to reduce the system error of the centroid method and put forward a lot of methods, such as the least squares fitting compensation method and the iteration compensation method. However, these algorithms are difficult to implement in a star tracker system due to large amount of computation. Therefore, another algorithm-the binary linear interpolation compensation method is used to decrease the errors.

Observation vectors and reference vectors used in the algorithm of attitude determination must be accurate enough in order to obtain high-precision attitudes. The attitude update rate of the algorithm based on vectors is low, which can’t satisfy real-time requirements. So the algorithm based on attitude dynamics and the predicted kalman filter can be adopted to estimate the attitudes. By this method the dynamic characteristics can be significantly improved.

V. CONCLUSION

As one of the most advanced attitude sensors, the design of a star tracker involves a wide range of technologies. We have presented the design of a low-quality, small-size and high-accuracy star tracker that is constructed by a self-developed CMOS APS image sensor. The hardware devices mainly include a microprocessor based on SPARC V8 architecture, a FPGA unit, a dual-port ram and so on. The algorithms, including star map capture, star map pretreatment, star target extraction, star pattern recognition and attitude determination, are described in detail. And the control system is designed to configure parameters and display three-dimensionally attitudes. The accuracy of the Euler angles can reach 2.25”, 2.25” and 15.97”, respectively. And their noise equivalent angles are 2.22”, 2.22” and 16.65”. According to the sources of the noise, the median filter and the binary linear interpolation compensation method are used to suppress the noise and errors and improve the accuracy.

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Penghai Wang was born in Shanxi Province, China, in 1990. He received the B.S. degree from the Northwestern Polytechnical University, Xi'an, in 2012. He is currently pursuing the M.S. degree in Beijing Microelectronics Technology Institute. His research interests include MEMS system, digital signal processing, FPGA, and the inertial navigation.