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Algorithm Design and Test of the Solar Guide Telescope

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Abstract The Solar Guide Telescope (SGT), an important solar attitude sensor of the SST (Space Solar Telescope, a space solar observing instrument being developed in China), can accurately produce pointing error signals of the SST for attitude control at high speed. We analyze in detail the error algorithm of the heliocentric coordinates and the edge judging of solar images. The measuring accuracy of ±0.5 arcsec of the SGT is verified by experiments on the tracking of the Sun and by testing a sun simulator. Some factors causing the pointing errors are examined.

Key words: Solar Guide Telescope — telescopes — techniques: image processing

1 INTRODUCTION

The spacecraft systems of the SST (Space Solar Telescope) are designed to be highly automatic and independent in space. The attitude control is three-axis stabilization. The high angular resolution of 0.1 arcsec of the SST is dependent on the high accuracy of the attitude control. The pointing accuracy in pitch and yaw to the Sun is better than ±6 arcsec, and the accuracy around the roll axis is better than ±40 arcsec. Compared the other solar explorers working in space, the pointing accuracy of the SST is high. Table 1 lists the pointing accuracies of some satellites working in space (Bernhard et al. 1995; SLISR 1994; Xi 2003).

Table 1 Pointing Accuracy of Some Space Satellites

Satellites	(ETS) - VI	Resource-1	SOHO	TRACE
Country	Japan	China & Brazil	U.S.A	U.S.A
Pointing accuracy	$0.05° \sim 0.15°$	$0.2° \sim 0.3°$	$10''$	$< 20''$

The attitude accuracy of a satellite is determined largely by the measuring accuracy of its attitude sensors. Until now the common goal of sun sensor development is to have a broad field of view (FOV) and a high measuring accuracy. Table 2 lists the measuring accuracies of some sun sensors (Bernhard et al. 1995; SLISR 1994; Xi 2003). The present available sensors cannot meet the demands of the SST.

The high accuracy attitude control of the SST needs a sun sensor with a measuring accuracy as low as in hundreds of milliarcseconds. In addition, the Gyros, which control the pointing attitude of the SST, need the sensor to provide the attitude parameters at high speed. Hence the SGT (Solar Guide Telescope) is developed. The SGT has an APS (Active Pixel Sensor) with a 2048 × 2048 resolution. Its FOV is 60 arcmin, the measuring accuracy is ±0.5 arcsec, and the update frequency of attitude data is better than 30 Hz.

Table 2 Measuring Accuracy of Some Sun Sensors

Sun sensor	TNO_TPD	Astro-1	FY-2	TRACE
Country	Holland	China	China	U.S.A
FOV	120°	1.2°	28°	90″
Measuring accuracy	±0.02°	±0.03°	±2.16′	±20″

2 MEASURING ALGORITHM OF SGT

2.1 Basic Measuring Principle

When the SGT points to the Sun, if the whole solar disk is in its FOV all the time, the position of the edge of the solar image can be detected by the row or column line pixels of APS. The coordinates of the line pixels of the APS are in line with the pitch and yaw axes. So the edge positions can be used to reckon the two position errors between the center of the Sun and the attitude center of SGT. Thus, the two position errors can be used as the attitude parameters when adjusting the pointing. Figure 1 shows the measuring process of the SGT.

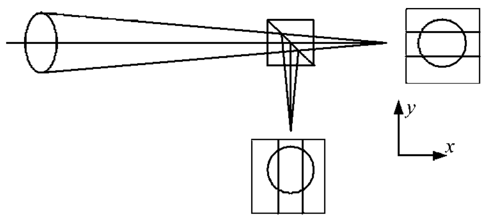

Fig. 1 Schematic drawing of measuring process of SGT.

2.2 Pointing Error Algorithm of SGT

Generally, the coordinates of the center of the image can be obtained by processing the signals of the whole image. However, a disadvantage of this method is that a large amount of data has to be collected and processed, taking very long computing time. For example, if the SGT processes the information of a whole solar image, the output frequency of the center errors will be about only 5 Hz, far below the 30 Hz demanded by the attitude control system. The target of the pointing error algorithm introduced in this paper is to overcome such difficulties—it can improve effectively the computing speed without reducing the measuring accuracy.

Take Fig. 2 for illustration. Suppose the solar image is perfectly round, and two predefined line pixels of the solar image on the SGT and two scan lines (AB and CD) lie across the image, the edge positions of AB and CD can be computed by the edge-judging algorithm. The coordinates of A, B, C and D are known. Because the coordinates of the two scan lines are immutable, the relative positions between the center of the solar image and the two lines have four equivalent states. Thus, only one of the states will be discussed in the following.

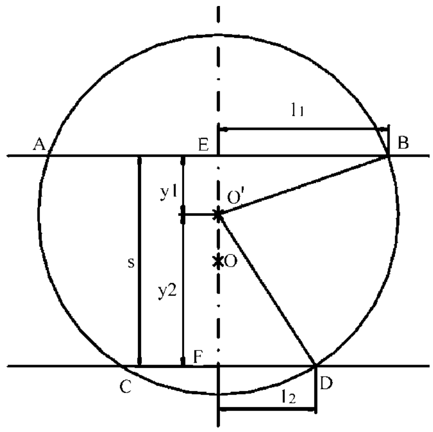

Fig. 2 Schematic drawing of pointing algorithm.

Take point o' as the center of the Sun, point o the one on the center line of the Sun with equal distance to the parallels AB and CD, then the distance between AB and CD is

$$s = y_1 + y_2 \,. \tag{1}$$

Suppose the length of AB is $2l_1$, the length of CD is $2l_2$, the radius of the solar image is R, the distances between point o' and the parallels are given respectively by

$$\begin{aligned} y_1^2 &= R^2 - l_1^2 \,, \\ y_2^2 &= R^2 - l_2^2 \,, \end{aligned} \tag{2}$$

or

$$y_2^2 - y_1^2 = l_1^2 - l_2^2 \,. \tag{3}$$

With Eqs. (1) and (2), we obtain

$$\begin{cases} y_2 - y_1 = \frac{1}{s}(l_1^2 - l_2^2) \,, \\ y_2 + y_1 = s \,, \end{cases} \tag{4}$$

or

$$\begin{cases} y_1 = \frac{1}{2}(s - \frac{1}{s}(l_1^2 - l_2^2)) \,, \\ y_2 = \frac{1}{2}(s + \frac{1}{s}(l_1^2 - l_2^2)) \,. \end{cases} \tag{5}$$

The heliocentric coordinate error Δ, which is the distance between point o and point o', can be obtained from

$$\Delta = \frac{1}{2s}(l_1^2 - l_2^2) \,. \tag{6}$$

Finally, the distance between the center and the two parallels AB and CD is given by

$$\begin{cases} y_1 = \frac{s}{2} - \Delta \,, \\ y_2 = \frac{s}{2} + \Delta \,. \end{cases} \tag{7}$$

So if the parallel coordinates (AB or CD) are known, the Y-direction of the heliocentric coordinate can be obtained by Eq. (7).

As for the X-direction coordinate of the solar image, it can be obtained from two scanning lines perpendicular to the direction of AB and CD, with the same computation as the Y-coordinate.

The radius of the solar disk is not present in Eq. (6), so the errors caused by a change of the radius of the solar disk are excluded when computing the coordinate errors of the solar images.

2.3 Edge Judging Algorithm of Solar Images

The computing precision of the errors of the center of the solar images depends on how accurately the edges of the images are detected. The brightness of a solar image in the image sensor of SGT is nonuniform from the center to the edge. The highest resolution of original image data obtained from the image sensor is restricted by the size of one pixel, the corresponding angular resolution is about $2''$. The result is too far from what we demanded, and cannot be used to compute the coordinates of the solar image. So the original image has to be reprocessed.

2.3.1 Picking Up the Edges

From the point of view of information optics, the edges of images are represented by the elements of high frequency, which can be obtained by difference processing (Yuan 2001). In this paper, the solar image can be treated as a plane graph, whose data are not vectors. Therefore, in the difference processing only the magnitude of the image will be considered. A scalar function of difference processing is given as:

$$G\left[f(x,y)\right] = \max\{grad[f(x,y)]\} = \left[\left(\frac{\partial f}{\partial x}\right)^2 + \left(\frac{\partial f}{\partial y}\right)^2\right]^{\frac{1}{2}} \quad . \tag{8}$$

In computations, the image data are discrete. So Eq. (8) is given in terms of discrete differences as:

$$G\left[f(x,y)\right] \approx \{[f(x,y) - f(x+1,y)]^2 + [f(x,y) - f(x,y+1)]^2\}^{\frac{1}{2}} \quad . \tag{9}$$

Considering the convenience of processing in computers, Eq. (9) is approximated by the form:

$$G\left[f(x,y)\right] \approx |f(x,y) - f(x+1,y)| + |f(x,y) - f(x,y+1)|. \tag{10}$$

Figure 3 shows the effect of discrete difference processing of a solar image in SGT. After the difference processing, the edge of one line of the solar image is picked up clearly.

2.3.2 Edge Sharpening

Because difference processing can only yield coarse edges to within 3∼5 pixels, sharpening the edges is necessary, Actually this can be made by finding out the brightest position of the edges of the solar image. So the true edges are weighted edge data, given by

$$W = \frac{\int xf(x)dx}{\int f(x)dx} \quad , \tag{11}$$

which can be approximated by

$$W = \frac{\sum nf(n)}{\sum f(n)} \quad , \tag{12}$$

where W is the position of the edge.

Because in the edge sharpening of SGT only the data at the edges are computed, so much processing time is saved. After the processing, the precision of the edges can be as high as 0.1 pixels.

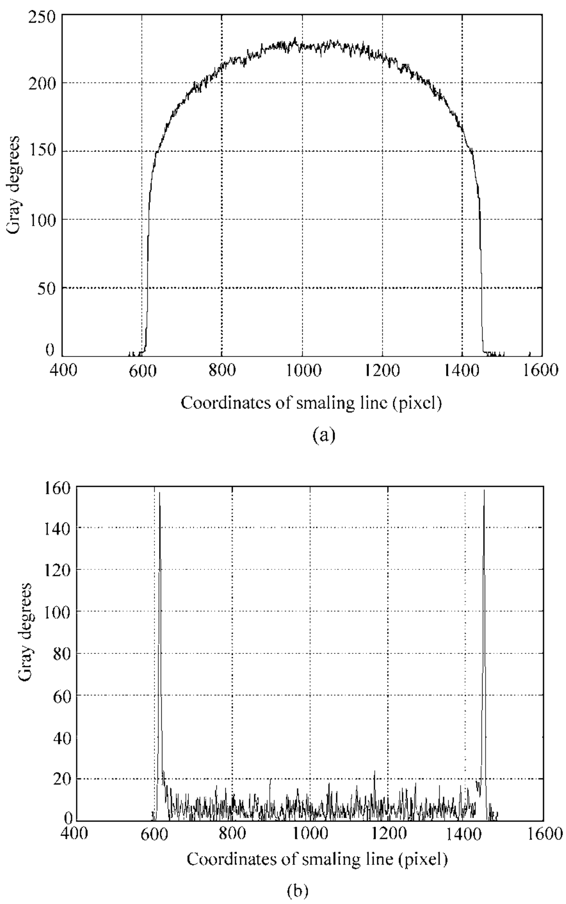

Fig. 3 Schematic drawing of picking up the Edge. (a) Original curve of one line pixel across a solar image; (b) The result curve of difference processing.

3 Experiments and Results

3.1 Tracking the Center of the Sun

This experiment was made to test the scale of the errors when the SGT detects the center of the Sun. The SGT is mounted on a tracker with transit instruments, so the central path of the Sun can be observed. Because of the disturbing effects of sunspots on the edge, more scanned lines of APS are chosen in an observing period, and the results of error computation are averaged. Following the methods discussed in the above sections, the errors between the actual and measured coordinates of the Sun and the measured center coordinates of SGT can be obtained.

In Fig. 4 the two curves represent respectively the center coordinates errors in the X-direction and Y-direction. It can be seen that these error curves fluctuate in a range of about ± 0.25 pixels. The resolution of one pixel of image sensor of SGT is about $2''$, therefore the relative errors of SGT tracking are within $\pm 0.5''$.

This experiment shows that the measuring algorithm of the SGT is adequate, and the measured results will satisfy the demands of the attitude control system.

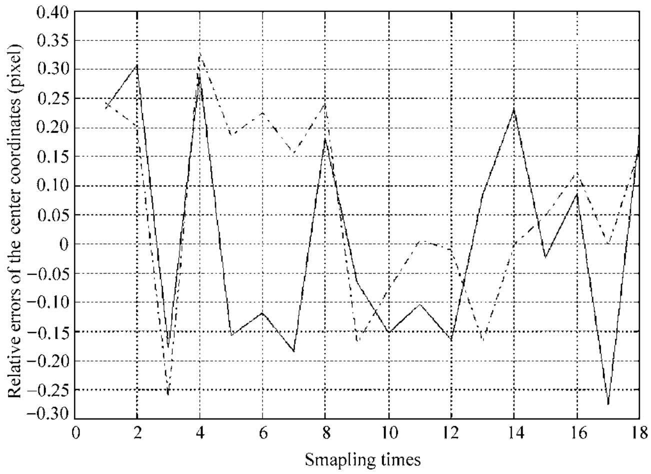

Fig. 4 Error curves of actual heliocentric coordinates and measuring center of SGT. The solid line presents X-direction and the dotted line presents Y-direction.

3.2 Checking the Sun Simulator

According to the specifications of physical emulation of SST attitude control system, the SGT should be used to measure the angular errors of the solar simulator, i.e., the capability of the sun simulator must be checked by the SGT. Because the sun simulator is a man-made light source, its stability, uniformity and linearity are not exactly the same as the Sun, the indexes of measuring error accuracy relative to the sun simulator are adjusted to $\pm 1.5''$ in 3σ. During the experiment, the positions of the sun simulator and the SGT are fixed. The SGT measures the center of the sun simulator periodically. Figure 5 shows the relative error curves of the imaging center of the sun simulator we obtained using the SGT.

After the statistical reduction, we have the following results: For the X-coordinate of the center of the sun simulator, the mean value μ_x is 520.15, the mean square deviation is 0.374 and the relative error $3\sigma_x$ is $1.96''$; for the Y-coordinate, the mean value μ_y is 508.79, the mean square deviation is 0.40 and the relative error $3\sigma_y$ is $2.1''$. The results show that the errors are outside the control value of $1.5''$. It is found that long-period drift of the light source of the sun simulator causes some data values to go beyond the range ($3\sigma \leq 1.5''$). As a result, we conclude that the sun simulator tested did not meet the requirement of the physical emulation and must be improved.

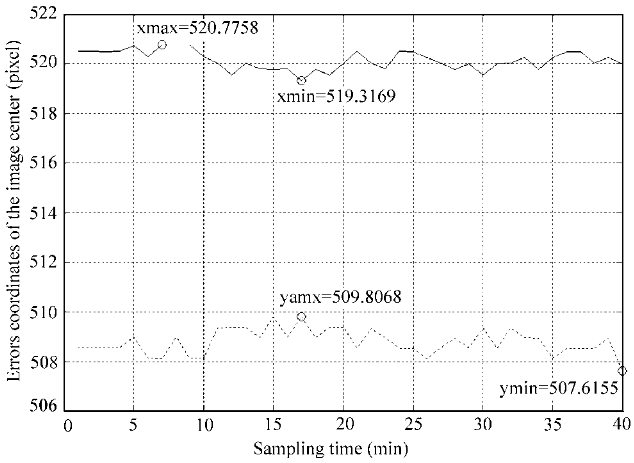

Fig. 5 Data curves of checking the sun simulator. The solid line presents X-direction and the dotted line presents Y-direction.

4 FACTORS AFFECTING THE MEASURING ERRORS OF SGT

4.1 Computing Accuracy Influenced by the Positions of Scanning Lines of APS

The edge positions of solar images are determined by the positions of scanning lines. Differential processing Eq. (5), when

$$l_1 = l_2,$$

we obtain

$$dy/_y = 0.$$

The computing accuracy of the Y-coordinate is maximum. So when computing the errors, it is better to choose parallel scanning lines whose length errors are minimum. Considering the influence of sunspots at the edge of the solar images on the error algorithms, the integration time of the APS should be appropriately increased. Moreover, the final result of the errors should be the average over groups of the sampled data. In the range of the same errors, random errors may be reduced. So, it is obvious that the more times the work is repeated, the less the errors will be.

4.2 Optical Accuracy of SGT

By analyzing the results of the experiments, it can be found that errors are larger at the edge of the APS than at the center. This is because of the influence of optical aberration of the SGT and the deficient mounting accuracy of the APS on the SGT.

However, here optical aberration is almost inevitable because the system of SGT is composed of three groups of lenses. This system can only be adjusted to correct part of the chromatic aberration. On the other hand, the mounting accuracy is related to the manufacture accuracy of the camera on the SGT. Thanks to the large focal length of the SGT, the influence of mounting accuracy can be corrected effectively.

4.3 Noise of APS

The major flaws of the APS are large readout noise, low-sensitivity and being highly susceptible to the ambient temperature (Prull et al. 1999). During our experiments, the sunlight was very strong. Although the sunlight was attenuated to 10% by the filters, the error of gray degree between the foreground and background was still as large as 80. So the readout noise of the APS can be ignored, and only its working temperature be noted.

4.4 Gray Degree of the Image

The accuracy of the measuring algorithm is related to the steepness of the edges of the solar images, and the latter, in turn, is under the influence of quantization errors of the computers. The output digital signals of the APS are 8 bits, that is, the digital images are 256 gray degrees. The range of quantization error E_r of each pixel with fixed-point binary is

$$-2^{-8} < E_r \leq 2^{-8},$$

where E_r is less than 0.39% of the saturation value of one pixel. So we may find the higher the degree of saturation of pixels is, the smaller the quantization errors are; and the better the steepness degree of the edge of the solar image is. When the SGT is in operation, the filters will not be changed. The brightness of the solar image is adjusted mostly by the integration time of the APS. Indicators of integration time will depend on more complete and more detailed experiments in the future.

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