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Recognition of FAST reflector nodes based on Canny operator

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Abstract The reflector system of Five-hundred-meter Aperture Spherical radio Telescope (FAST) is designed as 4450 rigid panels supported by a flexible cable-net structure. We use 10 total stations to measure 2225 nodes of the cable-net and then control the shape of the reflectors. Every time, it takes at least 35 minutes to finish the calibration of the whole cable-net once. It is indeed far too inefficient. Thus, we developed a set of highly efficient instrument CRRS (CCD Rotation Ranging System). It is based on photogrammetry and can finish the measurement in 1 minute. However, the target we used in CRRS is active target, and it has serious electromagnetic interference problems to affect the use of FAST. Take the above reasons into consideration, we plan to identify the nodes by taking the gap between the reflector panels as the feature condition. The new method can take the place of active targets to finish the measuring task. The present work focuses on the following aspects. First, combined with the characteristics of FAST reflector images, the representative algorithms of image edge detection are discussed. Second, the process of node extraction is introduced in detail so that we know that it works. In addition, experimental results are given to draw a conclusion so that Canny algorithm was used for continuous research of reflector edge detection.

Key words: telescopes — Astronomical Instrumentation — Methods and Techniques — methods: data analysis

1 INTRODUCTION

The Five-hundred-meter Aperture Spherical radio Telescope (FAST) is the largest single-aperture radio telescope that we built in the world. The working frequency of FAST is between 70 MHz and 3 GHz, the resolution can reach $2.9'$ and the pointing accuracy can reach $8''$ (Nan & Peng 2000; Nan et al. 2003). Overview of the FAST telescope is shown in Figure 1. According to the working principle of FAST (illustrated in Fig. 2), the supporting structure of the reflector system should be capable of forming a parabolic surface from a spherical surface (Nan et al. 2003; Nan et al. 2011). As one of the most important parts of FAST, the reflector system is composed of girders supported around. The cable-net comprises 6670 steel cables, 4450 reflector panels and approximately 2250 cross nodes. The cross nodes of the cable-net are used as control points. Each control point is connected to an actuator by a down-tied cable (Li et al. 2001; Luo et al. 2000; Ren et al. 2001; Lu & Ren 2007). In total, 2225 measurement targets are installed on the cross node used for measurement. By controlling the actuator using feedback from the measurement and control system, the positions of the cross nodes can be adjusted to form an illuminated aperture having a diameter up to 300 m. This illuminated aperture moves along the spherical surface according to the zenith angle of the target objects (see S1 and S2 in Fig. 1) (Qian et al. 2005a; Qian et al. 2005b).

It is necessary to measure the position of the cross nodes in real time to ensure the accuracy of the reflector panels, no matter if it is in the shape of parabolic surface or a spherical surface (see the nodes in Figs. 3 and 4). We now use 10 total stations to carry out the calibrating measurement and the tracking measurement of reflector nodes. However, there are several shortcomings while using total station measurement system: (1) The measurement precision should be superior to RMS 1.5 mm during the calibrating measurement. It takes about 90 minutes for 10 total stations to finish the calibration task of the whole cross nodes once. Its efficiency is indeed low. (2) The measurement precision should be superior to RMS 2 mm during the

Fig. 1 Overview of the FAST telescope.

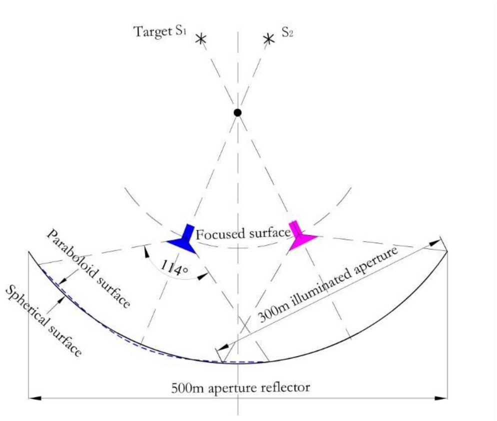

Fig. 2 Geometric optical principle of FAST.

Fig. 3 Cross nodes in day.

Fig. 4 Cross nodes at night.

tracking measurement. During the tracking measurement, 700 cross nodes located within the range of 300-meter in diameter should be measured while the reflectors are in the paraboloid state. It takes about 25 minutes or even more to complete one tracking measurement task. The reflectors need less than 5 minutes to form a parabolic surface from a spherical surface, which means (strictly speaking) that the measurement method that we are using now is different from real-time measurement.

Taking above problems into consideration, an efficient measuring system is needed to measure the reflector nodes.

2 THE CRRS AND ITS CHALLENGE

Taking these reasons into consideration, we developed a CCD Rotation Ranging System (CRRS) with high precision based on photogrammetry (Zhu et al. 2008). CRRS consists of three sets of digital positioning units (DPU) (The shape of DPU is shown in Fig. 5). The measurement range of DPU can reach to 250 meters and the precision is superior to RMS 1 mm. It can measure more than 1000 points in the measuring area in one minute. The CRRS makes the real-time measurement of reflectors possible in such giant radio telescope (Hu et al. 2013). Previous work has focused on the following aspects. First, the composition and principle of the CRRS. CRRS has the characteristic of high speed, high accuracy and large range, so that we can use it not only in FAST but also in other areas. Second, the calibration method, especially the specificity that we used in CRRS. In addition, all functions of CRRS are achieved to increase the observation efficiency of FAST.

DPU is designed for the requirements of reflector measuring tasks. It combines a precision rotating platform and a code plate with photogrammetry, which can increase the efficiency and the range of measurement. Each DPU is mainly composed of the frame and swivel (illustrated in Fig. 5).

The lights from the measurement target enter the lens by the reflection of the mirror reflector while measuring. Finally, CCD receives the light and spots the images on the camera. Under the drive of two motors, the swivel changes its posture with two freedoms of horizontal and pitch rotation, and gets the angle of the rotation in two directions from the encoders. This combination can achieve the transformation of the measuring area. At the same time, the controller itself calculates its orientation and attitude accurately. The zoom motor drives the camera to move in a straight line, and the encoder shows us the accurate dis-

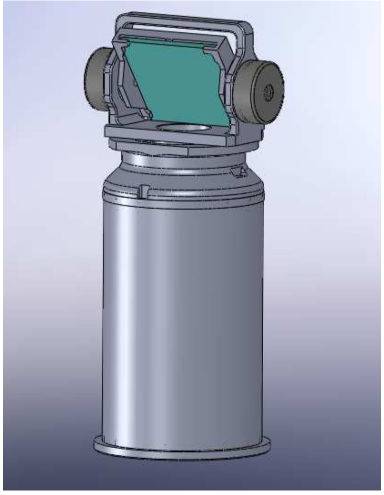

Fig. 5 3D visualization of DPU.

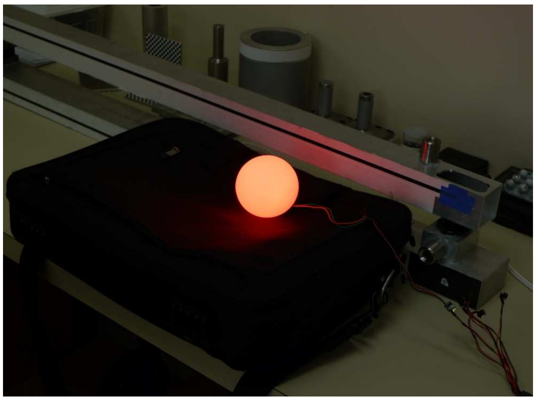

Fig. 6 The globose active target in room.

placement. The measurement of the camera zoom lens is then achieved.

According to the measurement scheme, DPUs are installed in the edge of reflectors. Different DPUs measure the same area at the same time based on 3-dimensional method. It is very important to make sure that the consistency of the geometrical center while observing from different angles. Taking these factors into consideration, we choose the spherical target with diameter of 152.4 mm but not the planar target. The source of light is a narrowband LED, and the narrowband pass filter is matched while receiving light source. We can see the condition while the globose target is in the room (illustrated in Fig. 6).

If we use the CRRS and the globose targets to perform the measurements of the FAST reflector, 2225 globose targets are needed to be installed around every cross nodes. Two problems arise with this approach. First, the requirement of electromagnetic shielding in FAST project is much stricter than that of GJB151A. The electrical components of FAST (CRRS included) should meet the shielding requirement according to the recommendation of ITU for radio astronomical interference protection limit. The 2225 targets that we used as an active target create serious electromagnetic interference problems and will inevitably affect the usage of FAST. Second, the 2225 targets to be installed on the cable network nodes are several meters to hundreds of meters high from the ground. Considerable maintenance difficulties will arise once the targets are out of gear.

Based on the structural characteristics of FAST reflector itself, This paper tries to identify and extract the location of nodes by using the gaps between the panels of reflector as the feature condition, so as to achieve the measurement tasks. Meanwhile, identifying the location of nodes by the gaps feature can also avoid the problem of target maintenance and the problem of electromagnetic interference at the same time.

3 EDGE DETECTION AND CANNY OPERATOR

The image edge contains most of the information of the image, which mainly exists between different objects, objects and backgrounds, and objects and targets. Traditional image edge detection methods mostly extract edge information from high-frequency components of the image, and differential operation is the main means for this. All of the traditional edge detection operators (.e.g., Roberts, Sobel, Prewitt, Kirsch and Laplacian) are gradient operators of local windows, and the effects are not so good when they are used for real image processing because they are sensitive to noise. With the development of signal processing, fuzzy mathematics, geometry and other basic theories in recent years, new technologies have increasingly been applied into edge detection area. In 1986, John Canny proposed that the edge detection operator should be satisfied with criteria: (1) signal-to-noise ratio criterion; (2) location accuracy criterion; (3) response for single edge criterion. He deduced the Canny operator as the best edge detection operator based on above criteria at the same time. By using Canny operator, the process of image edge detection can be divided into three stages as described in the following subsections.

3.1 Smooth Image by Gauss Filter

The image is smoothed by convoluted with Gaussian smoothing filter before processed by Canny operator. The purpose of filtering is to eliminate noise that corresponds to the high-frequency part of the image. To eliminate the influence of noise in the frequency domain, we have to reduce the frequency component of this part.

The Canny edge detection algorithm is the best approximation operator for the product of signal-to-noise ratio and location accuracy. By using Canny algorithm, the image is smoothed by the first derivative of the two-dimensional Gauss function, assuming that the two-dimensional Gauss function is satisfied with Equation (1):

$$G(x,y) = \frac{1}{2\pi\sigma^2}\exp(-\frac{x^2+y^2}{2\pi\sigma^2}). \tag{1}$$

In this equation, stands for the distributed parameters of the Gauss filter, is used for control the smoothness of the image. Its gradient vector is satisfied with Equation (2):

$$\nabla G = \begin{pmatrix} \partial G/\partial x \\ \partial G/\partial y \end{pmatrix}. \tag{2}$$

To increase computing speed and decrease processing time, the two filter templates of are decomposed into two one-dimensional row filters. The expressions are satisfied with Equations (3) and (4):

$$\partial G/\partial x = kx\exp(-\frac{x^2}{2\sigma^2})\exp(-\frac{y^2}{2\sigma^2}), \tag{3}$$

$$\partial G/\partial y = ky\exp(-\frac{x^2}{2\sigma^2})\exp(-\frac{y^2}{2\sigma^2}). \tag{4}$$

The output image $I(x,y)$ is obtained by convoluting the two one-dimensional filters with the image $f(x,y)$ respectively, which can be shown in Equations (5) and (6):

$$E_x(x,y) = \frac{\partial G}{\partial x}f(x), \tag{5}$$

$$I(x,y) = \frac{\partial G}{\partial y}E_x(x,y). \tag{6}$$

In this equation, the width of the Gauss filter is determined by the constant k and the distribution parameter σ of the Gauss filter, which also control the the smoothness of the filter. For filters with small value σ, the location accuracy is high but the signal-to-noise ratio is low. When the value of σ increases, the results suggest the opposite.

3.2 Calculate the Magnitude and Direction of Gradient and Suppress Non-maxima

We use Canny algorithm to calculate gradient magnitude and gradient direction of smoothed image by using finite difference of first-order partial derivative in 2×2 neighborhood. The two arrays $P_x[i,j]$ and $P_y[i,j]$ of partial derivatives in X and Y directions are satisfied with Equations (7) and (8):

$$P_x(i,j) = [I(i,j+1)-I(i,j)+I(i+1,j+1)-I(i+1,j)]/2, \tag{7}$$

$$P_y(i,j) = [I(i,j)-I(i+1,j)+I(i,j+1)-I(i+1,j+1)]/2. \tag{8}$$

The gradient magnitude and gradient direction of the pixels are calculated by the transformation formula from rectangular coordinates to polar coordinates, and the gradient magnitude is calculated by the second-order norm which satisfied with Equation (9):

$$M(i,j) = \sqrt{P_x(i,j)^2 + P_y(i,j)^2}, \tag{9}$$

and the gradient direction is satisfied with Equation (10):

$$H(i,j) = \arctan\left[P_y(i,j)/P_x(i,j)\right]. \tag{10}$$

If the gradient magnitude $M(i,j)$ of a pixel (x,y) is greater than or equal to the gradient magnitude of two adjacent pixels along the gradient direction, then the point is determined to be a possible edge point.

3.3 Detecting and Connecting Edges by Double Threshold Method

The Canny algorithm uses double threshold method to detect and connect edges from candidate edge points. First, the double threshold method determines high value threshold Th and low value threshold Tl, and then detects candidate edge points. If the gradient amplitude at the point (x,y) is higher than the high threshold Th, then the point is considered to be the edge point. Correspondingly, if the gradient amplitude at the point (x,y) is lower than the low threshold Tl, then it is considered that the point is not an edge point.

The strong edge image composed of points whose gradient amplitude is higher than the high threshold value does not contain false edges, but the edge is not good at continuity. To make the edges continuous, the point where the gradient amplitude of the pixels is higher than the low threshold value Tl in the eight neighborhoods of the edge points is also regarded as the edge point. The gap between the edges is connected until the edges become continuous after that.

4 EXTRACTION OF REFLECTOR NODES

4.1 Hough Transform

The edge information obtained by Canny operator is an important information of reflector, which are used to synthesize straight lines by Hough transform on this basis. Hough transform uses the transformation between two coordinate spaces, and map a straight line with the same shape in one space to a point in another coordinate space. A peak value formed after that. Thus the problem of detecting straight line is transformed to the problem of peaking statistical. The HoughlinesP method based on statistical probabilities can not only perform efficiently, but can also detect two endpoints of a line. The points in the image are transformed from space (x,y) to probabilistic voting space (r,θ). The minimum voting numbers, the minimum length of line segments and the tolerance of distance between lines are set to achieve accurate line detection. The relation of r and θ are satisfied with Equation (11):

$$r = x\cos(\theta) + y\sin(\theta). \tag{11}$$

Here, r represents for the distance between the straight line and the origin in the image space, and θ represents for the angle between the straight line and the x axis.

4.2 Node Extraction Process

The information of reflector nodes are concentrated at the intersection of every six reflectors. The capacity of each reflector image captured by DPU is large. To improve the processing velocity, image data are sampling down before processing. By using Canny operator to detect the edge of reflector, the adjacent edges are fitted into straight lines, and the intersection point is determined by two intersecting lines. The intersection point that we get is just the position of the node that we need. During the process of extraction, we may get many false extraction points. We can use the algorithm to eliminate those false points to get an accurate node location relatively in that case.

Finally, we traverse the region near each node with region of interest (ROI) technique in the original image for all nodes, and then get the accurate location of the node in the original image. The position that we get is determined as the final node position of the reflector panel. The steps of node detection and extraction are as follows:

(1) Sampling down. The original image of the reflector panel collected by DPU is too large, which takes up too much memory space and processing speed is slow. By sampling down the image, the pixel of the original image is reduced but the overall shape of the original image has not changed, which greatly improves the calculation speed of the image without affecting the experimental results. The sampling ratio of the algorithm in this article is 0.1.

(2) Image binarization. The key of image binarization is to select the appropriate segmentation threshold, so as to achieve the noise removal in the image. Because the gray level of the line to be extracted is in a dynamic range, a dynamic threshold algorithm based on histogram is proposed.

(3) Edge detection. This algorithm is based on the feature lines. Before extracting the feature lines, we need to detect the edge of the image. There are three steps for edge detection: filtration, enhancement and detection. We can get the edge detection image after that.

(4) Lines detection. After image edge detection, the feature lines need to be extracted to provide the basis for the subsequent extraction of the feature nodes of the reflector panel. The idea of Hough transform is to get a

Fig. 7 Reflector photos to be processed.

set of transformations corresponding to a specific shape as Hough transform result by calculating the local maximum value of the accumulated result in parameter space. The PPHT (Progressive Probabilistic Hough Transform) is used here.

(5) Remove redundant lines. We can get many lines after lines detection. Because of the gradual change of pixels, many interference intersections will be found later, which will affect the accuracy of node extraction. Traverse the detected lines and calculate the angle difference between each two lines. When the absolute value of the angle difference is less than 7.5 degrees, the two lines are considered to be parallel. When the distance between two parallel lines is less than 70, the two lines are considered to be coincident. According to the coordinates of the end points, the expression of the line is obtained by least-square method.

(6) Intersections extraction. Traverse all the lines after the duplication, calculate the pixel coordinates of all intersections and record.

(7) Remove redundant intersections. Use the ROI technique to traverse the reflector image especially the location of the area around each intersection to get more accurate information of the intersection location and replace the point previous.

5 EXPERIMENTAL RESULT

Based on CRRS measurement system and Open CV platform, the photographs of reflector panel are taken and processed (see reflector photograph in Fig. 7). The process and results are shown in Figure 8.

According to the experimental statistics, the accuracy rate of node recognition is more than 80% for the 40 m $\times$ 40 m field of view. To verify the accuracy of the extraction algorithm, we can get a perfect result with precisely control of the view field. We fix the most common binocular camera with the view field of 20 m $\times$ 20 m in the measurement basement (see in Fig. 9), get the reflector images under the

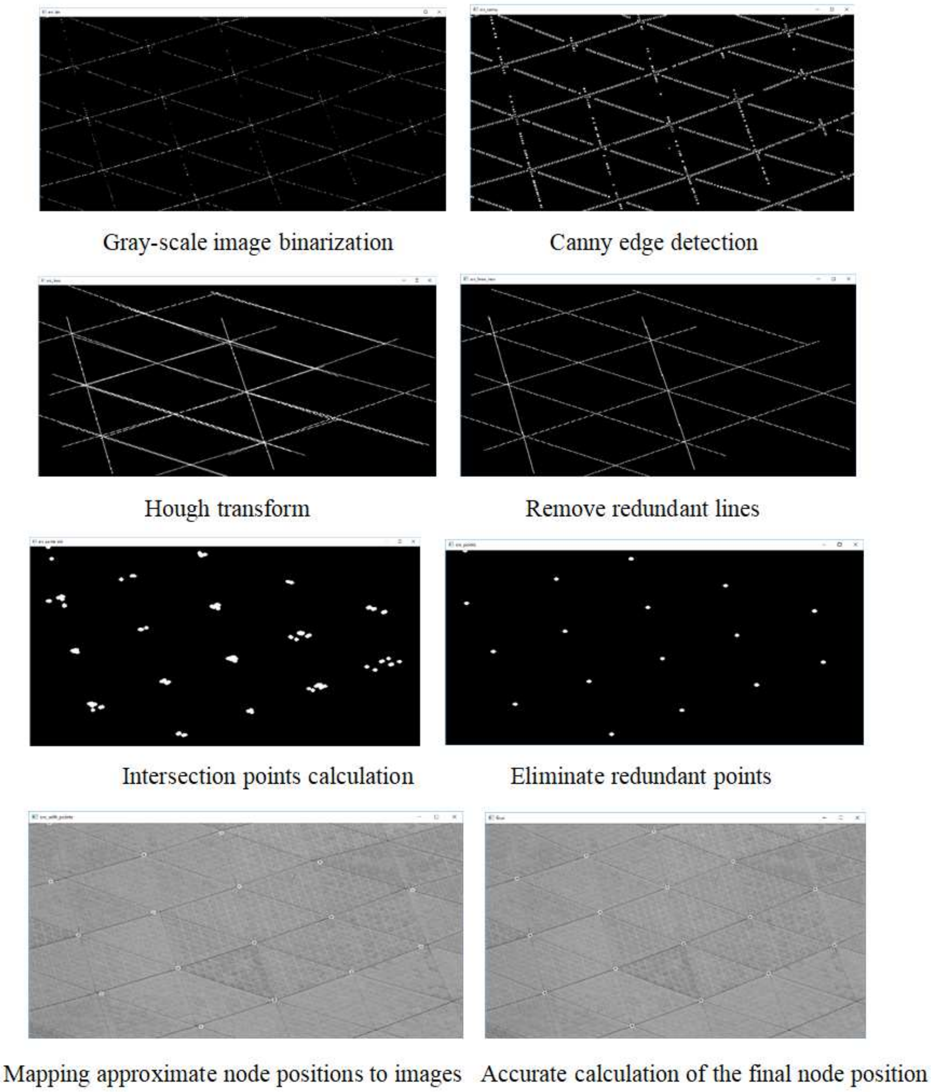

Fig. 8 The processing of reflector photo.

premise of different exposure time. The accuracy of node recognition can reach 100%, as shown in Figure 10.

6 CONCLUSIONS

Based on the requirements of the reflector measurement and electromagnetic shielding, a new way to identify the reflector nodes is established in this paper. The following contributions were made according to the research of Canny detection.

(1) The principle of edge detection and Canny algorithm are discussed. Combined with the characteristic of FAST reflector images, Canny algorithm plays an important role in detection edges.

(2) The process of node extraction is introduced in detail so that we know that it works. Based on Canny edge detection algorithm and Hough transform algorithm, we can get the approximately position of reflector nodes at first and then use the ROI technique to get more accurate position. The method to detect edges seems feasible.

(3) Finally, we examined the accuracy by outside experiments with different equipment in FAST. Through the experiment, we found that the accuracy to extract the nodes was within the zone of reasonableness. The result was much better when under correct view field. We can draw a conclusion that Canny algorithm can be used for continuous research of reflector edge detection.

We still have a lot of problems to solve before the CRRS can be applied to FAST for the reflector measurement. The following work can be divided into three parts, as follows.

(1) We have a way to calibrate the DPU. The DPU uses zoom camera, hence a way to define the intrinsic parameters in different focal lengths should be found because it affects the accuracy badly.

Fig. 9 The process of experiment.

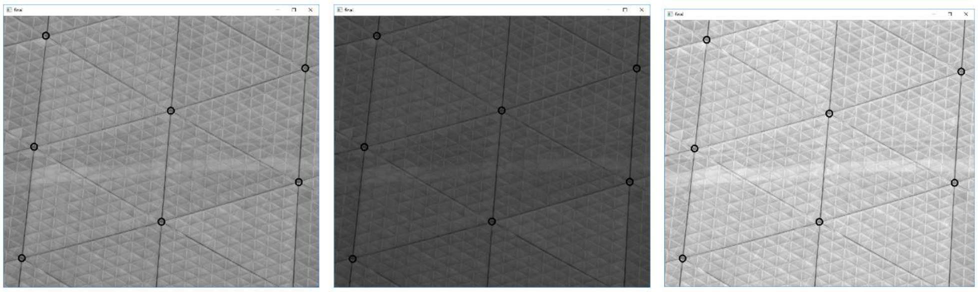

Fig. 10 Node extraction results at exposure time of 1 ms, 2 ms and 3 ms.

(2) We need at least two DPUs to carry out the measurement task because a single DPU can only tell us the angle of the measurement target relative to itself but it gives no distance information. With two DPUs, we can reconstruct three-dimension (3D) of the measurement targets. With three DPUs, we can improve the accuracy of measurement targets by redundant information. Therefore, a 3D reconstruction algorithm needed to be researched.

(3)The CRRS is a successful product in the laboratory but the environment of FAST is complex and changeable. Does the CRRS have the ability to get used to the environment? And will it perform steadily while in the true environment? Does the CRRS hold its accuracy while the targets, the environment and other factors change? All these factors should be taken into consideration and the best solution should be found.

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