A Fast Reconstruction Method for Antenna Sub-reflector Position (Postprint)

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Abstract

To rapidly acquire the position of the sub-reflector as it varies with the antenna elevation angle, and to improve the overall antenna performance by correcting the sub-reflector position through an adjustment mechanism, a virtual binocular vision measurement method is proposed. Through a virtual binocular vision system composed of a high-speed camera and a plane mirror, simulation experiments are conducted on the sub-reflector position during antenna observation. Images of position variations of the object under test caused by spatial movement of the experimental platform are acquired, and operations such as preprocessing, denoising, edge detection, and feature point extraction are performed on the images. The three-dimensional motion of the object under test with the movement of the experimental platform is reconstructed. The reconstruction results show errors of less than 1% in all three directions, demonstrating that the method exhibits high measurement accuracy and can effectively reconstruct the position status of the sub-reflector.

Full Text

Research on a Fast Reconstruction Method for Antenna Subreflector Position

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Abstract

To rapidly obtain the position of the subreflector as it varies with the antenna' s elevation angle and improve overall antenna performance by correcting the subreflector position through adjustment mechanisms, this paper proposes a virtual binocular vision measurement method. Using a virtual binocular vision system composed of a high-speed camera and plane mirrors, we conducted simulation experiments on subreflector position during antenna observations, acquiring images of position changes as the measured object moved with the experimental platform. Through image preprocessing, denoising, edge detection, feature point extraction, and other operations, we reconstructed the three-dimensional motion of the measured object as it moved with the experimental platform. The reconstruction errors in all three directions were less than 1%, demonstrating that the method offers high measurement accuracy and can effectively reconstruct the subreflector position.

Keywords: Antenna subreflector; Virtual binocular vision; Position; Reconstruction

Introduction

With the advancement of science and technology, radio telescope observation techniques have made substantial progress, significantly promoting the development of astronomy. Concurrently, the aperture and frequency bands of large dual-reflector antennas continue to increase, demanding higher pointing accuracy, gain, and other performance indicators. The matching between the subreflector position and main reflector position plays a crucial role in antenna pointing accuracy. However, during actual antenna operation, the subreflector position is affected by wind load, gravity, temperature, and other factors, causing changes that lead to mismatch between the main and subreflector positions. This degradation reduces the antenna' s overall performance and affects its efficiency and pointing accuracy. Therefore, the ability to rapidly, accurately, and in real-time reconstruct the antenna subreflector position is of great significance for improving antenna pointing accuracy.

To obtain high-precision subreflector position data, Wang Jinqing et al. derived and simulated the analytical relationship between subreflector pose and holographic aperture phase, calculating the variation of the subreflector pose with elevation angle for the Shanghai Tianma 65m Telescope (TM65m) using aperture phase data. Xu Qian et al. reconstructed the subreflector pose by collecting strain values from the subreflector support legs and the subreflector itself based on strain sensors and modal superposition principles. Martin Süss et al. employed photogrammetry to measure the subreflector position changes with elevation angle, obtaining position variation curves in the x, y, and z directions. However, this method generates large data volumes, requires high-performance computing systems, and cannot obtain real-time subreflector positions. Tonino Pisanu et al. and Jiang Yongchen et al. both used the PSD method to measure subreflector position changes in the x and y directions with elevation angle. While this method can achieve high-precision positions in the x and y directions, the z-axis position must be obtained through other means. Hou Yulei et al. used a laser tracker to measure the subreflector pose under conditions of 0° and 45°

for the subreflector adjustment mechanism. Although this method offers high precision and works well for high-precision calibration of antenna subreflector adjustment mechanisms, it is too costly. Yin Hang et al. solved the problem of large subreflector swing in large radio telescopes that prevents precise positioning based on inertial measurement and embedded technology. However, this method uses inertial measurement technology, which causes error accumulation and increasing systematic errors over time, requiring timely adjustment.

This paper adopts a virtual binocular measurement system to simulate and measure the three-dimensional position of the antenna subreflector during spatial movement, obtaining three-dimensional motion curves of the target object in space. This method only requires a single capture of the target object to obtain three-dimensional information of the subreflector at that position, without needing complex procedures and without causing error accumulation.

2. Principle of Virtual Binocular Vision

Convergent binocular vision solves for the three-dimensional spatial position of an object based on its parallax in two images and the translation and rotation relationships between the two cameras. Its principle is shown in Figure 1 [Figure 1: see original paper]. To reduce costs while improving capture synchronization, two plane mirrors and one high-speed camera are used to form a virtual binocular vision system. This method follows essentially the same principle as convergent binocular vision, as shown in Figure 2 [Figure 2: see original paper].

As shown in Figure 2, P(x, y, z) is an arbitrary point in space that will form images on both the left and right mirrors. The high-speed camera captures these images, and through image segmentation, two images of point P(x, y, z) are obtained, equivalent to two virtual cameras capturing point P(x, y, z). Its analysis method is basically the same as that of real binocular vision analysis.

Let *Ow-XwYwZw* be the world coordinate system, *O1-X1Y1Z1* be the left camera coordinate system, and *O2-X2Y2Z2* be the right camera coordinate system. P1 is the image point of spatial point Pw in the left camera image, and P2 is the image point of spatial point Pw in the right camera image.

In binocular vision measurement, the relationship between the world coordinate system and the camera coordinate system is described by the camera model, where the intrinsic matrix **K** (comprising parameters such as focal length and principal point coordinates) and extrinsic parameters (rotation matrix **R** and translation matrix **T**) must be determined through calibration.

If camera calibration is completed and the pixel coordinates of image points P1 and P2 are obtained, then from Equation (1) we can derive Equations (2) and (3) for the two camera views. By splitting these equations and eliminating the unknown depth values, we can obtain a system of four linear equations about xw, yw, zw:

Solving this system using the least squares method yields the accurate three-dimensional coordinates of the target point in space.

3. Experiments and Image Processing

The measurement system is shown in Figure 3 [Figure 3: see original paper], consisting of a high-speed camera, two plane mirrors, a checkerboard calibration board, a high-precision four-dimensional platform, and a computer. The computer controls the platform' s movement in the X, Y, and Z directions, while the high-speed camera captures images of the moving object and transmits them to the computer via a data cable for processing and calculation. The experimental images obtained are shown in Figure 4 [Figure 4: see original paper].

After acquiring the experimental images, we segment them to obtain images from the left and right virtual cameras, and use Zhang Zhengyou' s calibration method to calibrate the camera. With the camera' s intrinsic and extrinsic parameters determined through calibration, the target object can be tested. During the capture process, imaging quality is affected by equipment limitations and environmental factors such as noise and lighting, which degrade image quality. Therefore, after obtaining the images, a series of processing steps are required to improve image quality and approximate the true conditions of the target object as closely as possible.

Taking one image as an example, Figure 5 [Figure 5: see original paper] image (a) shows the image obtained by the virtual camera. First, using the camera calibration parameters, the image is corrected for distortion, and a mask is applied to the corrected image to preserve the pixel information of feature points while setting pixel values outside the feature points to 0. This process is called image preprocessing, and the processed image is shown in Figure 5 image (b).

Next, the image is filtered to remove the effects of ambient light during capture, mainly salt-and-pepper noise and Gaussian noise. Gaussian filtering can largely preserve the edge information of the image. The filtered image is shown in Figure 5 image (c).

For the filtered image, edge detection is performed to extract locations where pixel values change abruptly, and the resulting curve constitutes the edge of the feature points. The edge detection result is shown in Figure 5 image (d).

For the processed image, the center coordinates of the feature points are extracted, and the left virtual camera coordinate system is used as the world coordinate. From the linear equation system, the three-dimensional coordinates of the feature points in space can be obtained.

The simulation experiments were conducted in two groups. In the first group, the two plane mirrors were approximately 0.5 m from the measured object, and in the second group, approximately 2 m from the measured object.

In the first simulation experiment, the step size was 5 mm in the x-direction, 1 mm in the y-direction, and 6 mm in the z-direction. The three-dimensional position coordinate reconstruction results of the feature points are shown in Table 1 . The motion plots in the x, y, and z directions drawn from the three-dimensional coordinates are shown in Figure 6 [Figure 6: see original paper].

Knowing the platform' s movement step sizes in the x, y, and z directions, the error between the calculated results and the actual movement distance can be determined from the difference between adjacent point coordinates. The error between the calculated results and the actual movement distance is shown in Table 2 .

To exclude data randomness, different step sizes were selected for the second group of experiments: 3 mm in the x-direction, 1 mm in the y-direction, and 7 mm in the z-direction. The three-dimensional position coordinate reconstruction results of the feature points are shown in Table 3 . The motion plots in the x, y, and z directions are shown in Figure 7 [Figure 7: see original paper].

The error between the calculated results and the actual movement distance for this simulation experiment is shown in Table 4 .

From the coordinate change diagrams in the x, y, and z directions from both groups of simulation experiments, we can see that the calculated coordinate changes in the x, y, and z directions have a good linear relationship with the experimental platform' s movement in three dimensions. By calculating the error between the results and the actual movement distance, we can see that the error between the distance of adjacent points and the actual platform movement distance is less than 1%, which well matches the real situation. Moreover, when the distance between the two plane mirrors and the measured object is 0.5 m, the error is less than 1%, and when the distance is 2 m, the error is also less than 1%, proving that the algorithm has good stability.

4. Comparison Between Virtual Binocular Vision and Real Binocular Vision

To evaluate the accuracy gap between virtual binocular vision and real binocular vision and assess the feasibility of virtual binocular vision, real binocular vision was used to measure the three-dimensional position of the measured object. The distance between the two cameras and the measured object was approximately 2 m, and the experimental platform moved with step sizes of 5 mm, 1 mm, and 6 mm in the X, Y, and Z directions, respectively. Through image processing and a series of calculations, the three-dimensional position of the measured object in space was obtained as shown in Table 5 .

The error between the calculated results and the actual movement distance is shown in Table 6 .

Comparing the calculation errors of virtual binocular vision and real binocular vision, both are less than 1%, and the difference between virtual binocular vision and real binocular vision is only about 0.3%, indicating that virtual binocular vision can achieve accuracy comparable to real binocular vision and demonstrating the good feasibility of this method.

Through research on the principles and system composition of virtual binocular vision, this paper conducted simulation experiments on the position changes of the antenna subreflector in space with elevation angle changes using a virtual binocular vision system composed of a high-speed camera and plane mirrors. The three-dimensional motion of the measured object moving with the experimental platform was reconstructed, and the results well matched the real situation. At the same time, a comparison between virtual binocular vision and real binocular vision shows that the method has good feasibility, providing an effective approach for rapid reconstruction and correction of antenna subreflector position.

6. Application Vision

This research method addresses the problem of subreflector position changes in large-aperture telescopes under different operating conditions, which leads to decreased antenna pointing accuracy and efficiency. By providing real-time measurement of subreflector pose, it offers important support for subsequent corrections. In this measurement system, a target will be fixed on the antenna subreflector, two plane mirrors will be fixed on the antenna main reflector, and the high-speed camera will be fixed on the subreflector support leg. The angle between the two plane mirrors and their relative positions to the high-speed camera will be adjusted to ensure that the target can be fully presented in both mirrors and that the high-speed camera can record the imaging conditions in both mirrors. Experimental verification shows that the measurement accuracy reaches the 0.01 mm level. Due to the system' s simplicity and mature data processing methods, the system has high long-term reliability and can well meet the overall technical requirements of the antenna.

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Note: Figure translations are in progress. See original paper for figures.