Distortion measurement for shipboard radar antenna by photogrammetry

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Abstract. An approach based on photogrammetry has been developed for the measurement of shipboard radar antenna deformation. In the proposed approach, the images of the radar antenna with diagonal reflecting mark points are captured at a few (at least two) different orientations by the calibrated cameras. Then, the mark points in different images are detected and matched automatically with the information of reference points. At last, the optimum spatial coordinates of diagonal marks and measuring cameras external parameters are achieved via bundle adjustment algorithm. The theoretical analysis indicates that the proposed method precision can reach 1.0mm and has the advantages of high precision, convenient and flexible operation. This method can also be employed in deformation measurement of other large deployable structures.

1. Introduction

The antenna is a key component of the whole radar device, which has important effect on the overall performance of it. The precision of antenna reflector surface affects the quality of the received echo pulses of radiation directly. And if there is a big reflector surface errors, the antenna gain would decrease, which thereby affecting the radar range and resolution [1–3]. The radar system is installed on the moving platform, such as airborne radar, ship-based radar and vehicle-borne radar, affected by vibration, gravity deformation in the process of movement and other factors, which leading to inevitable deformation [4]. Therefore, to ensure the radar performance is in good condition, high precision measurement of the radar antenna surface must be carried out regularly [5, 6].

The three-dimensional laser scanning is a common method for deformation measurement of large structures [7], but it needs a stable benchmark, which limits the application in airborne, ship-based and vehicle-borne radar antenna deformation measurement. This paper proposes a method for the radar antenna deformation measuring based on videometrics, implementing real-time deformation monitoring of ship-based radar antenna. The proposed method has the advantages of simple equipment, convenient measurement, high precision and automation, and low requirements on environmental conditions.

2. Measurement principle

The basic principle of videometrics is shown in Figure 1, multiple cameras(or a camera in the different position) image the space object point P, point P is the intersection of the rays composed by
designated $C_i$ and the corresponding image points $p_i$. Given the internal and external parameters of the camera, the object three-dimensional position can be calculated via line-line intersection.

![Figure 1. the basic principle of line-line intersection.](image)

Known the internal and external parameters of each camera, defining the corresponding image point of space object point $P(X, Y, Z)$ captured by the camera $i$ is $p_i(x_i, y_i)$, and the ideal image point is $(\tilde{x}_i, \tilde{y}_i)$ after aberration correction. Hence, the collinear equation can be transformed into linear equations with regard to the unknown $P$’s coordinate $(X, Y, Z)$.

\[
\begin{align*}
[(\tilde{x}_i - C_i)_{i_1} - F_{i_1}]X + [(\tilde{x}_i - C_i)_{i_2} - F_{i_2}] Y + [(\tilde{x}_i - C_i)_{i_3} - F_{i_3}] Z + [(\tilde{y}_i - C_i)_{i_1} - F_{i_1}]X + [(\tilde{y}_i - C_i)_{i_2} - F_{i_2}] Y + [(\tilde{y}_i - C_i)_{i_3} - F_{i_3}] Z = 0
\end{align*}
\]

Equation (1) is a Diophantine Equations which therefore has no unique solution. In fact, eq.(1) identifies a spatial line through the camera optical center and the image point, namely a line in collinear equation. When the $n(n \geq 2)$ cameras are used in line-line intersection, the equations number like eq.(1) increases to $2n$ while the unknown parameters are still three. So it’s convenient to solve the linear equations by least square method.

### 3. Measurement Scheme

The measurement scheme is shown in Figure 2, two cameras were installed above the antenna for binocular intersection measurement; Set the diagonal reflecting mark points as shown in Figure 3 in the antenna and other parts to measure the deformation during the antenna motion. Ignoring the deformation of high stiffness and high strength parts of the antenna base, and with three reference points in the high stiffness and strength parts of the antenna base, the reference coordinate system is established, as shown in Figure 4.

![Figure 2. Schematic diagram of measurement scheme](image)
Figure 3. Schematic diagram of diagonal reflecting mark

Figure 4. Schematic diagram of the layout of reference diagonal marks

The algorithm process of antenna deformation estimation is presented in Figure 5. First, extract the image coordinate of diagonal targets using Harris corner detection algorithm\cite{8}; Second, calculate the initial values of the measuring cameras external parameters via pose estimation algorithm\cite{9} with the above three reference points and corresponding image points; then, according to the camera external parameters, carry out the points matching of other diagonal marks via epipolar constraint matching method\cite{10}; finally, obtain the optimum spatial coordinates of diagonal marks and measuring cameras external parameters via bundle adjustment algorithm\cite{11}.

Figure 5. The flow chart of data processing

4. Error Analysis

The position precision of measured antenna is related to physical spatial resolution, image quality, corner detection, calibration of camera parameters and 3D intersection angle. The layout of cameras and the antenna in the static measurement is shown in Figure 6.
Define the baseline direction between the two cameras as the $Y$ axis and the depth direction as the $Z$ axis respectively. Letter $B$ composed of $B_1$ and $B_2$ is the baseline while $H$ is the distance between cameras and the antenna. $\alpha$ and $\beta$ represent the stereo cameras’ ideal observation angles. The error of observation angles $d\alpha$ and $d\beta$ caused by corner extraction error can be expressed as follows.

$$d\alpha = d\beta = \delta dv$$

(2)

Where $dv$ represent the camera angle resolution, which is the ratio of camera angle of view and image resolution. $(z_0,y_0)$ is the ideal result of stereo intersection, and $(dz_1,dy_1)$, $(dz_2,dy_2)$, $(dz_3,dy_3)$, $(dz_4,dy_4)$ represent the maximum error of target position error. According to the analytic geometry, equations can be attained as follows.

$$\left\{ \begin{array}{l}
\frac{B_1-dy_1}{H+dz_1} = \cot(\alpha + d\alpha) \\
\frac{B_2+dy_1}{H+dz_1} = \cot(\beta + d\beta) \\
\frac{B_1+dy_2}{H+dz_2} = \cot(\alpha + d\alpha) \\
\frac{B_2-dy_2}{H+dz_2} = \cot(\beta + d\beta)
\end{array} \right.$$

(3)

Combine the above equations,

$$\left\{ \begin{array}{l}
dz_1 = \frac{B_1+B_2-H}{k_1+k_3} \\
dy_1 = \frac{k_3B_1-k_1B_2}{k_1+k_3} \\
dz_2 = \frac{B_1+B_2-H}{k_2+k_3} \\
dy_2 = \frac{k_3B_1-k_1B_2}{k_2+k_3}
\end{array} \right.$$

$$\left\{ \begin{array}{l}
dz_3 = \frac{B_1+B_2-H}{k_2+k_4} \\
dy_3 = \frac{k_4B_1-k_2B_2}{k_2+k_4} \\
dz_4 = \frac{B_1+B_2-H}{k_1+k_4} \\
dy_4 = \frac{k_4B_1-k_2B_2}{k_1+k_4}
\end{array} \right.$$

(4)
Where \( k_1 = \cot(\alpha + d\alpha), k_2 = \cot(\alpha - d\alpha), k_3 = \cot(\beta + d\beta), k_4 = \cot(\beta - d\beta) \).

In the vertical direction, the error of intersection measurement \( dX \) is the actual deviation of the target point extraction error, and will not increase the error due to the intersection error, so it is less than the error in the \( Z \) axis and the \( Y \) axis direction,

\[
dX = \max\left( \frac{H}{\sin\alpha} \tan(d\alpha), \frac{H}{\sin\beta} \tan(d\beta) \right)
\]

The layout of cameras and the antenna in the static measurement is shown in Figure 6. Two phantom Flex4k cameras are installed 6m in the distance of antenna, its focal length is 75mm and resolution is 4096×2048 pixels with pixel pitch of 6.75\( \mu \)m. The horizontal angle of field of view is about 20.9°, then the view angle of the unit of the camera is 20.9° /4096=5.10×10^{-3} degrees per pixel which is also called resolution of view angle of cameras \( dv \). Supposed that \( H = 6m \) and baseline of stereo cameras \( B = 5m(B_1=2.5m) \), the observation angle \( \alpha, \beta \) can be calculated. According to the experience of the algorithm, the image point error of the target is 0.8 pixel, then the observation error is:

\[
d\alpha = d\beta = 0.8 \times 5.10 \times 10^{-3} = 0.0041^\circ
\]

Combine eq.(6) and eq.(4), the maximum error in the direction of \( Z \) axis and \( Y \) axis can be calculated, and the maximum error in the direction of \( X \) axis can be attained according to eq.(5). The maximum errors of the depth, horizontal and vertical direction are as follows: (0.94mm, 0.51mm, 0.47mm).

Therefore, the position of the system can reach 1.0mm without considering atmospheric disturbance and other factors.

5. Conclusion

This paper proposes a videometrics based method for measuring the deformation of the radar antenna which can implement implementing real-time and dynamic deformation monitoring of ship-based radar antenna. The theoretical analysis indicates that the proposed method precision can reach 1.0mm and has the advantages of high precision, convenient and flexible operation. This method can also be employed in deformation measurement of other large deployable structures.

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