Design and Simulation on Position and Attitude Measurement System of Astronaut Assistant Robot

Lihong Dai¹,², Jinguo Liu¹(✉), Zhaojie Ju³, Yang Gao⁴

¹ Shenyang Institute of Automation, Chinese Academy of Sciences, Shenyang 110016, China
dailihong@sia.cn, liujinguo@sia.cn
² University of the Chinese Academy of Sciences, Beijing 100049, China
³ Intelligent Systems & Biomedical Robotics, School of Creative Technologies University of Portsmouth, UK
zhaojie.ju@port.ac.uk
⁴ the Surrey Technology for Autonomous Systems and Robotics Laboratory, Surrey Space Center, Guildford, GU27XH, UK
yang.gao@surrey.ac.uk

Abstract: Manned space program in China has entered the space station stage. Space astronauts have very limited time. In order to free space astronauts from some routine repetitive tasks, various free-flying robots in space appear. The measurement of their position and attitude is the premise of their autonomous flight and remote operation. Thus, the position and attitude measurements system of Astronaut Assistant Robot (AAR) is designed. Because of the limitation of the cabin space, with the movement of the robot, sometimes only the local image of targets can be captured by camera. So how to carry out the local image tracking and pose calculation is a difficult point. The paper proposes an integration method of target feature template and local search to track moving target in real time, so that the position and attitude of the camera is calculated by using PnP algorithm, which has solved the problem stated above. The position and attitude measurements system is modeled and simulated. Furthermore, a series of measures are taken to improve the real-time performance, and the accuracy is verified. The simulation results show that the measurement system meets the requirements of real time and precision.

Keywords: Astronaut Assistant Robot; Position and Attitude Measurement System; Target Feature Template; Local Search; PnP Algorithm

1 Introduction

China's manned space program has entered the space station phase (Gao, Zhao, & Gu, 2015). Compared with the ground laboratory, the space station can provide unique microgravity environment for science research to obtain the results which are difficult to get from the ground station. Astronauts in the space shuttle have limited time. Robots in space can help astronauts to do some repetitive work and provide support for astronauts. And free-flying robots in space normally do not touch the capsule, so there is no mechanical vibration, which can provide a kind of microgravity environment. On the one hand, only small power is needed to control their operation. On the other hand, microgravity environment needed for the scientific experiment is provided. It can be seen that the free-flying robots in space play an important role in the space cabin. There are various free-flying in-cabin robots, such as SPHERE developed by the university of MIT, and the PSA, Smart SPHERE(Fong et al., 2013) developed by the NASA AMS research center, and Astrobotte(Bualat et al., 2015) developed recently; SHB developed in Japan; SCAMP
developed by the university of Maryland in the United States; Mini AERCam developed at NASA Johnson space center; and AAR(Gao, Liu, Tian, & Li, 2017) developed by Shenyang institute of automation, Chinese academy of sciences. The picture of the second generation AAR (AAR-2) is shown in figure 1. There are few detailed descriptions of the pose measurement system on robots in space in literatures. However the measurement of their position and attitude is the premise of their autonomous flight and remote operation. So, the pose measurement system on AAR-2 is designed in the paper.

![AAR-2](image)

Fig.1 The picture of AAR-2

Methods based on magnetic field and those based on machine vision are used in position and attitude measurements. Compared with methods based on magnetic field measurement, those based on machine vision have attracted much attention because they are not interfered by electromagnetic field. Machine vision is mainly classified as monocular vision and binocular vision. Monocular vision measurement system, in which only one camera is needed, has the advantages of simple structure, low cost, convenient operation, easy calibration, simple algorithm and fast calculation speed. So it is suitable for the real-time application, and avoids the problems for binocular vision such as the small field, short measuring distance, and difficult stereo match of feature point (Wang, & Chen, 2015). In this paper, the method based on monocular vision is used in position and attitude measurement system.

A camera is mounted on an AAR-2, so it moves with AAR-2. The target is installed in the inner wall of the cabinet or sealed cabin, with known feature point distribution patterns. The image of target is acquired in real-time by the camera. Because of the limitation of the cabin space, with the movement of the robot, sometimes only the local image of targets can be captured by camera. And target images are composed of the same size of dots, so how to carry out the local image tracking and pose calculation is a difficult point. The paper introduces an integration method of target feature template and local search to track moving target, and their world coordinates are updated in real time, so that the position and attitude of the camera are calculated by using PnP algorithm, which has solved the problem of tracking target and pose calculation when only local image of target is captured by the camera. In addition, a series of measurement is taken in order to improve the
performance of real-time. Furthermore, the system is simulated and verified by the powerful HALCON visual software, and the simulation results show that the system meets the requirements of real-time and precision.

2 Pose Measurement System

The schematic diagram of pose measurement system of AAR-2 robot is shown in figure 2.

![Diagram of Pose Measurement System]

Fig.2 Schematic diagram of the pose measurement system

The system mainly can be divided into four sections: camera calibration, image acquisition, image processing and pose calculation. The purpose of the camera calibration is to calculate the interior camera parameters, which provide the basic data for pose calculation of camera. After image acquisition, image processing and feature extraction are carried out. Image processing mainly includes image preprocessing and image segmentation. And feature extraction mainly includes edge extraction, elliptical fitting and coordinate extraction of target center. On the basis of 2D image coordinates of target circles centers and their 3D space coordinates, the position and attitude parameters of the camera relative to cooperative target are calculated with PnP algorithm, which are saved
to a file, and provide the foundation for better control and operation of the AAR-2.

2.1 Camera Calibration.

In order to calculate the position and attitude more accurately, it is necessary to calibrate the camera first. The camera calibration model is set up, the method of camera calibration proposed by Zhang Zhengyou is employed, and the process of the camera calibration is realized by virtue of the HALCON software.

2.1.1 Camera Calibration Model

Firstly, when the distortion of camera lens is not considered, the camera model is the ideal small pinhole imaging model, and its coordinate system is shown in figure 3.

The model is divided into four coordinate systems:

1. World coordinate system \((x_w, y_w, z_w)\), user-defined three-dimensional space coordinate system;
2. Camera coordinate system \((x_c, y_c, z_c)\), with camera optical center \(O_c\) as the origin, and the camera optical axis perpendicular to the image plane as \(z_c\) axis, \(x_c\) axis and \(y_c\) axis parallel to the image plane;
3. Image plane coordinate system \((x, y)\), with the origin of which is the intersection point \(O\) (also known as the principal point) of the camera's optical axis and the image plane, and the unit is mm;
4. Image pixel coordinate system \((u, v)\), with \(O_0\) in the upper left corner of the image as the origin, and the unit is pixel.

The conversion process of 3D world coordinates to 2D image pixel coordinates is obtained through the camera model, in which the parameters of the camera is involved. The camera calibration process is that of determining the camera parameters.

The 3D camera coordinate system is transformed to the image pixel coordinate system, which can be written as
\[
\begin{bmatrix}
u \\
v \\
1
\end{bmatrix} = \lambda A \begin{bmatrix} r_1 & r_2 & r_3 & t \\
x_w \\
y_w \\
z_w \\
1
\end{bmatrix}
\]  
(1)

where \( \lambda = \frac{1}{z_c} \), \( R = \begin{bmatrix} r_1 & r_2 & r_3 \end{bmatrix} \) and \( A = \begin{bmatrix} f & 0 & u_0 \\
0 & f & v_0 \\
0 & 0 & 1
\end{bmatrix} \).

\( A \) is the matrix of interior camera parameters. The interior camera parameters includes the focal length \( f \), the principal point coordinates \((u_0, v_0)\), the physical dimension per pixel of the sensor, namely \( du \) and \( dv \). \( \lambda \) is the scaling factor. \( R \) and \( t \) are rotating transformation and translational transformation respectively.

2.1.2 Camera calibration method

Then, in the plane template calibration method proposed by Zhang Zhengyou (Zhang, 2000), the world coordinate system is set on the plane of the calibration plate, namely \( z_w = 0 \). Then

\[
\begin{bmatrix}
u \\
v \\
1
\end{bmatrix} = \lambda A \begin{bmatrix} r_1 & r_2 & r_3 & t \\
x_w \\
y_w \\
z_w \\
1
\end{bmatrix}
\]  
(2)

The interior camera parameters and the distortion coefficient obtained are computed as the initial values. And the parameters with high final accuracy are obtained by the method of levenberg-marquarat nonlinear optimization. The performance function is

\[
J_{\text{min}} = \sum_{i=1}^{n} \sum_{j=1}^{m} \left\| m_{ij} - M \left( A, R_i, t_i, k_1, k_2, W_j \right) \right\|
\]  
(3)

where \( n \) is the number of images, \( m \) is the number of feature points in each image, \( m_{ij} \) is the actual feature points detected, and \( M \) is reprojection mapping relationship for the world coordinate \( W \). The optimal objective function denotes that the distance between the image feature point and the reprojection point of world coordinate point is the minimum. By minimizing the optimization objective function, the optimal solution of the interior and exterior camera parameters can be obtained.

2.1.3 Camera calibration process

HALCON has been recognized as the most effective machine vision software in industry in Europe and Japan. It provides some assistants and visual tools, as well as programming hints, which make programming and modification easy,
development cycles short, and development costs low. It is widely used to develop visual system, such as in the literatures (Li, & Chen, 2017, Wang, Zhao, Sun, & Chen, 2015). The program flow chart of camera calibration is shown in figure 4.

2.2 Image Acquisition, Processing and Feature Extraction

2.2.1 Image Acquisition

The image acquisition assistant in HALCON can be used for real-time image acquisition, as can be seen from figure 5. If you connect the camera to the computer via the USB port, and then click “the image acquisition assistant” in the assistant menu, an image acquisition window will pop up. Under the resource tab, the camera can be detected by clicking on “the image acquisition interface” radio button. And under the connection tab, the connected camera device can be seen. Furthermore, under the code generation tab, if you click “insert code” button, image acquisition code can be generated automatically, which makes programming easy.
2.2.2 Image Processing

(1) Image Preprocessing.

In order to improve the anti-interference ability of the image, and filter the noise in the image, image often is preprocessed. Most of image signal or energy concentrates in low frequency and medium frequency amplitude spectrum, while at higher frequencies, useful information is often submerged by noise, and so the filter which decreases high frequency amplitude can reduce noise. Gaussian filtering is essentially a low-pass filter, which is widely used in image denoising and is very effective in suppressing the noise that obeys normal distribution. The image was pretreated with function named gauss_image in HALCON.

(2) Image Segmentation

The gray threshold segmentation method is most applied in image segmentation. It is a method to separate the object from the background by threshold value, whose advantages are simple calculation, high efficiency and
fast speed. It is widely used in real-time system. Because the actual target image has a single background, and the difference between foreground and background is obvious, there is no need for complex threshold segmentation method, and the global threshold can be set for image segmentation. Threshold selection can be made by means of gray histogram in HALCON, shown in figure 6.

(3) Morphological Image Processing.

The methods constantly used in morphological image processing are dilation operation, corrosion operation, open operation and closed operation. The dilation operation makes object larger and is used to fill the holes and narrow gaps in the objects. In contrast, Corrosion can be used to eliminate small and meaningless objects. Open operation is dilation after corrosion, and its effect is similar to that of corrosion, which reduces the object. It has less effect on object reduction than corrosion operation. Closed operation is corrosion after dilation, and its effect is similar to that of dilation operation, which makes the object bigger. It has less effect on object expansion than dilation operation.

In order to better extract the edge of the circle in the target image, the closed operation is used to increase the circle area appropriately. The function named “closing_circle” in HALCON is used. Because the extracted objects are circles, the structure element is chosen as circle.

2.2.3 Feature Extraction

After image preprocessing and image segmentation, the image of marker circle is determined. Next, edge detection is needed to obtain the edge of marker circles. And then they are fitted into ellipse in order to determine the coordinates of the circles center.

(1) Image Edge Detection.

Edge of image is set of pixels whose grey value take on step change, so we can detect the image edge by calculating the maximum value of first-order derivative. Gradient operator commonly used based on the first derivative includes Sobel, Roberts, Prewitt. In addition, image edge can be detected by zero crossing of second derivative. Operator frequently used based on the second derivative is Laplacian of a Gaussian. These operators are on the basis of local window, so their algorithms are simple and easy to implement. However, if these algorithm are adopted, some information on the edge will be lost, the system is sensitive to noise, and edge detection effect is not very ideal.

In 1986 John Canny proposed a new edge detection operator (Canny, 1986). The operator is with the optimization idea, which has a large signal-to-noise ratio and a higher detection precision. It is currently considered as the most ideal edge detection method, and widely used (ElAraby, Madian, Mahmoud, Farag, & Nassef, 2016; Nikolic, Tuba, & Tuba, 2016). The process of Canny edge detection is as follows.

① The image is smoothed with a Gaussian filter to remove noise and interference. One-dimensional Gaussian function is used as filter. The original image \( f(x,y) \) is convolved by row and column respectively. The image after smoothing is \( I(x,y) \). The Gaussian filter and \( I(x,y) \) are given by
\[
G(x) = \frac{\exp\left(-\frac{x^2}{2\sigma^2}\right)}{2\pi\sigma^2}
\]

\[
I(x, y) = [G(x)G(y)]^* f(x, y)
\]

where \(\sigma\) is the standard deviation of Gaussian, which is used to control the smoothness.

② For the smoothed image \(I(x, y)\), the finite difference of first-order partial derivatives is calculated, and the amplitude \(M\) and the direction \(\theta\) of the gradient are obtained, given by

\[
\begin{aligned}
P_x[i, j] &= (I[i+1, j] - I[i, j] + I[i+1, j+1] - I[i, j+1])/2 \\
P_y[i, j] &= (I[i, j+1] - I[i, j] + I[i+1, j+1] - I[i+1, j])/2 \\
M[i, j] &= \sqrt{P_x[i, j]^2 + P_y[i, j]^2} \\
\theta[i, j] &= \arctan\left(\frac{P_x[i, j]}{P_y[i, j]}\right)
\end{aligned}
\]

③ Non-maximum suppression is carried out. The image is scanned along the image gradient direction, and if pixels are not part of the local maxima they are set to zero.

④ Double threshold algorithm is used to detect and connect edges. High and low thresholds are set. The point where the gradient is greater than the high threshold is considered to be the real edge of the image, so it is retained. One where the gradient value is less than the low threshold is not edge and is removed. For the point between the two thresholds, those adjacent to the edge point are retained as edge, otherwise deleted.

Because Canny edge detection is better than other methods, it is used to detect the edge of the target circle. The instruction in HALCON is `edges_sub_pix(ImageReduced, Edges, 'Canny', 4, 20, 40)`.

(2) Elliptic Fitting

Edge detection is used to extract edges, which reduces the amount of data, eliminates irrelevant information, and retains the important structural attributes of the image. Because the result of edge detection is a collection of edge pixels, it is also necessary to select the contour as a whole. The function used in HALCON for contour selection is `select_contours_xld`.

In order to calculate the centers of the target circles, their contours need to be fitted with an ellipse. Compared with the edge detected, the data is reduced. The function of the elliptic fitting contour in HALCON is `fit_ellipse_contour_xld`.

2.3 Moving Target Tracking

In the literature (Pan, Liu, & Fu, 2017), a review of various tracking methods is given. Based on these methods, we propose a method combining target feature template with local search to track the moving target in real time. The target
tracking method can be divided into the following three parts: feature selection and representation of the moving target; template matching and updating of target feature; prediction and tracking of moving target.

(1) Feature Selection and Representation of Moving Target

Moving targets often have various features: the perimeter, center of mass, contour, texture, and color, etc. In order to meet the real-time requirement, all features cannot be extracted, because it takes a lot of time to extract multiple features. Therefore, according to the actual application situation, salient features need to be selected for quick extraction, tracking and positioning.

The feature selected here is the center of the target circle, which is represented as the coordinates of the center. When the target is initialized, all marker circles in target image are extracted and positioned. Because AAR-2 carrying the camera moves constantly, the camera sometimes can only take local image including at least four circles distributed in two rows and two columns. Thus four circles are chosen as our tracking target. From the perspective of probability, the camera is most likely to take the center circle, so the four circles in the center, top, left and upper left are selected as the target feature template.

(2) Matching and Updating of Target Feature Template

After determining the feature template of the moving target, moving target needs to match with the feature template. Similarity measures are often used to match feature templates. Similarity measures commonly used are Euclidean distance and weighted distance.

For the four circles of the target template, the first circle need to be determined which is located at the center of the extracted marker circle area. Then, based on Euclidean distance formula, the one above and closest to the center circle is chosen as the second. After that, the one on the left and closest to the center circle is chosen as the third. Finally, the circle on the left and the nearest from the second one is selected as the fourth circle. Target feature template is shown in figure 7.

![Figure 7 Target feature template](image)

With the movement of camera, the feature points tracked originally may be out of the sight of the camera. If target feature template is not updated, target will be missing inevitably, which will lead to the failure of the target tracking. Therefore, when the feature points tracked reach the edge, the target feature template needs to be updated in real time. When the first circle tracked reaches the lower edge, the circle above it will be selected as the first circle, and then the other three circles are determined. When the first circle tracked reaches the upper
left edge, the circle in its lower right is chosen as the first circle tracked. It is similar when the first circle tracked reaches the other edges.

(3) Predicting and Tracking of Moving Targets

In order to reduce the search area of feature matching and improve the real-time performance, the most likely target area is often selected to predict the target trajectory. Prediction methods commonly used is that of fixed search window radius, whose size is based on the tracking target.

Because the target images taken may be local images, the local search method is adopted. Rectangular area include the center circle instead of the surrounding circles is chosen as local search box to ensure that only the first circle is within the search area. Because the camera moves at a slower speed of about 1 mm/s, the first circle tracked in next frame image will still be in the search box, so as to achieve real-time tracking of moving targets. The search box tracked is shown in figure 8.

![Figure 8 Search box tracked](image)

2.4 Pose Calculation

Based on the mathematical model of the camera and the known camera interior parameters, pose calculation is to establish the relationship between 3D space coordinates of target features and 2D coordinates of image features, so as to determine the relative position and attitude between camera and target.

The commonly used features include point features, linear features, etc. Among them, the problem of pose calculation using point feature is called PnP (perspective-n-point) problem. When n of point number is less than or equal to 2, known condition is insufficient, so the pose parameters of the target cannot be determined. When n>5, the problem can be solved linearly. When 3≤n≤5, the PnP problem is usually nonlinear, and there are possible multiple solutions. Due to the requirement of real time in practical application, points between 3 and 5 are often selected to calculate the position and attitude.

The P3P problem can be described as follows. The known conditions are that angles between two of three rays starting from a vertex O are α, β, γ, and
three sides of a triangle are $c$, $b$, $a$, respectively. The distance between the vertex $O$ of rays and three vertex of the triangle $ABC$, namely $d_1$, $d_2$, and $d_3$, will be calculated. Description of P3P problem is shown as figure 9.

![Figure 9 Description of P3P problem](image)

By using cosine theorem, we have

$$
\begin{align*}
\begin{cases}
d_1^2 + d_2^2 - 2d_1d_2 \cos \alpha = c^2 \\
 d_1^2 + d_3^2 - 2d_1d_3 \cos \beta = b^2 \\
 d_2^3 + d_3^2 - 2d_2d_3 \cos \gamma = a^2
\end{cases}
\end{align*}
$$

Suppose

$$
\begin{align*}
\begin{cases}
d_2 = xd_1 \\
 d_3 = yd_1
\end{cases}
\end{align*}
$$

Substitute (5) into (4), we can derive

$$
\begin{align*}
\begin{cases}
d_1^2 (1 + x^2 - 2x \cos \alpha) = c^2 \\
 d_1^2 (1 + y^2 - 2y \cos \beta) = b^2 \\
 d_1^2 (x^2 + y^2 - 2xy \cos \gamma) = a^2
\end{cases}
\end{align*}
$$

If two of the ones in (6) are taken, and $d_1$ is eliminated, we can obtain

$$
\begin{align*}
\begin{cases}
a^2 (1 + y^2 - 2y \cos \beta) - b^2 (x^2 + y^2 - 2xy \cos \gamma) = c^2 (1 + y^2 - 2y \cos \beta) - b^2 (1 - 2x \cos \alpha)
\end{cases}
\end{align*}
$$

Connecting two equations of (7) and removing $b^2x^2$, it is not difficult to derive that

$$
\begin{align*}
a^2 (1 + y^2 - 2y \cos \beta) - b^2 (y^2 - 2xy \cos \gamma) = c^2 (1 + y^2 - 2y \cos \beta) - b^2 (1 - 2x \cos \alpha)
\end{align*}
$$

Extracting $x$ from (8), we can obtain

$$
x = \frac{a^2 + b^2 - c^2 + (a^2 - b^2 - c^2)y^2 - 2y(a^2 - c^2) \cos \beta}{2b^2(\cos \alpha - y \cos \gamma)}
$$

Substituting (9) into the lower equation of (7), a quartic equation about $y$ is obtained as

$$
a_4y^4 + a_3y^3 + a_2y^2 + a_1y + a_0 = 0
$$
Four sets of solutions for y can be found. Substituting the solution of y into (9), the value of x can be obtained. According the above equation of (6), we have

\[ d_i = \sqrt{c^2 / (1 + x^2 - 2x \cos \alpha)} \]  

Thus d1 can be calculated. According to (5), d2 and d3 can also be obtained. From the process derived above, it can be seen there are at most four solutions to the P3P problem. For P4P problem, when four control points are coplanar, there is only one solution to the problem. Any three points can be selected to determine the pose, and then the fourth point is used to verify it (Wang, Dong, & Wang, 2017). Since the actual target image is coplanar, four control points are used to determine the pose. The instruction of pose calculation in HALCON is vector_to_pose.

3 Performance Evaluation

The MV-500SM CMOS camera, and the M1620-MPW2 optical lens produced by Computar company are used in the system to carry out the simulation experiment. The resolution is 2592*1944 pixels. Its pixel size is 2.2 \( \mu \)m. And the output mode is USB2.0.

3.1 Real-time Performance

In order to meet the real-time demand of the system, the operation efficiency of the system can be improved by simplifying the algorithm, reducing the complexity of image processing and transformation, and reducing the storage space. There are two main methods: one is to reduce the amount of data to be processed; the second is to adopt a simple or simplified algorithm. Reducing the amount of data to be processed plays a major role in real-time image processing algorithms.

The measures to reduce the amount of data to be processed are taken to improve the operation efficiency of the program in the paper.

(1) The function of image zooming is applied to reduce the size of the image from 2592*1944 to 1024*768, which lifts the speed of the program. The corresponding instruction in HALCON is zoom_image_size (Image1, Image, 1024, 768, 'constant').

(2) By setting the interest area or selective region, the data volume of image processing is greatly reduced, and the operation efficiency is dramatically improved. The corresponding instruction in HALCON is reduce_domain (Image, ROI_Rectangle, ImageReduced1), where ROI_Rectangle is the area of interest, which include 9 circles and margin region with the size of the interval between circles, shown as figure 10.

Figure 10 Region of interest
(3) The kernel size of the Gaussian filter is reduced from 5 to 3 which makes the running time reduced. The corresponding instruction in HALCON is
\texttt{gauss\_image (Image, ImageGauss,3)}.

By taking these main measures, the running time of the program is reduced from above 200ms to less than 100ms, which satisfies the system's requirement for real-time performance.

3.2 Accuracy Verification

The \textit{x} and \textit{y} axes are fixed on the target plane, and the \textit{z}-axis is in the direction from the camera to the target. Because the error in \textit{z} direction is larger than \textit{x} and \textit{y} direction, the camera is translated along the \textit{z}-axis to verify the accuracy. The experimental equipment of pose measurement system is mainly composed of the following three parts: 1 Monocular camera, 2 Scale horizontal bar, 3 Tripod, shown in figure 11, in which two monocular cameras are provided to improve reliability. When one camera works, the other is free.

![Figure 11 Experiment device in pose measurement system](image)

From the camera to the target range of 350 mm-250 mm, the experiment was carried out with the accuracy verification of 21 times from far to near, which simulated the process that all the target circles can be captured in the initial location, with the movement of AAR-2, local images can be captured. The camera took an image in the original position of 350 mm at first. Then the camera moved 5 mm on the scale bar every time to take the corresponding image after the camera moved. The PnP algorithm was used to calculate the pose including the corresponding coordinates in the \textit{Z} direction. The difference between the coordinates in the \textit{Z} direction before and after the two adjacent movements is the calculated value, which is compared with the 5mm of measured value, and the difference between the measured value and calculated value is the error. The experimental data are shown in table 1.
<table>
<thead>
<tr>
<th>Number</th>
<th>Z</th>
<th>Calculated Distance</th>
<th>Measured Distance</th>
<th>Error</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>349.6628693</td>
<td>4.59321018</td>
<td>5</td>
<td>0.40678982</td>
</tr>
<tr>
<td>1</td>
<td>345.0696591</td>
<td>4.494626055</td>
<td>5</td>
<td>0.505373945</td>
</tr>
<tr>
<td>2</td>
<td>340.5750331</td>
<td>4.547248267</td>
<td>5</td>
<td>0.452751733</td>
</tr>
<tr>
<td>3</td>
<td>336.0277848</td>
<td>4.77574492</td>
<td>5</td>
<td>0.522425508</td>
</tr>
<tr>
<td>4</td>
<td>331.5502103</td>
<td>4.590145559</td>
<td>5</td>
<td>0.409854441</td>
</tr>
<tr>
<td>5</td>
<td>326.9600648</td>
<td>5.092004352</td>
<td>5</td>
<td>-0.092004352</td>
</tr>
<tr>
<td>6</td>
<td>321.8680604</td>
<td>4.845546052</td>
<td>5</td>
<td>0.154453948</td>
</tr>
<tr>
<td>7</td>
<td>317.0225143</td>
<td>4.702797723</td>
<td>5</td>
<td>0.297202277</td>
</tr>
<tr>
<td>8</td>
<td>307.7308526</td>
<td>4.8886402</td>
<td>5</td>
<td>0.41113598</td>
</tr>
<tr>
<td>9</td>
<td>303.0578504</td>
<td>4.673002237</td>
<td>5</td>
<td>0.326997763</td>
</tr>
<tr>
<td>10</td>
<td>298.4752949</td>
<td>4.58255492</td>
<td>5</td>
<td>0.417444508</td>
</tr>
<tr>
<td>11</td>
<td>293.8001815</td>
<td>4.675113351</td>
<td>5</td>
<td>0.324886649</td>
</tr>
<tr>
<td>12</td>
<td>289.2168651</td>
<td>4.583316396</td>
<td>5</td>
<td>0.416683604</td>
</tr>
<tr>
<td>13</td>
<td>284.4893814</td>
<td>4.727483701</td>
<td>5</td>
<td>0.272516299</td>
</tr>
<tr>
<td>14</td>
<td>279.3836344</td>
<td>5.105747028</td>
<td>5</td>
<td>-0.105747028</td>
</tr>
<tr>
<td>15</td>
<td>274.6252666</td>
<td>4.758367836</td>
<td>5</td>
<td>0.241632164</td>
</tr>
<tr>
<td>16</td>
<td>269.6612653</td>
<td>4.964001307</td>
<td>5</td>
<td>0.03598693</td>
</tr>
<tr>
<td>17</td>
<td>264.9363722</td>
<td>4.724893107</td>
<td>5</td>
<td>0.275106893</td>
</tr>
<tr>
<td>18</td>
<td>259.8427129</td>
<td>5.093659205</td>
<td>5</td>
<td>-0.093659205</td>
</tr>
<tr>
<td>19</td>
<td>255.0538112</td>
<td>4.78890175</td>
<td>5</td>
<td>0.21109825</td>
</tr>
<tr>
<td>20</td>
<td>250.1573274</td>
<td>4.896483796</td>
<td>5</td>
<td>0.103516204</td>
</tr>
<tr>
<td>21</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

On the basis of the experimental data, the error value is drawn, as shown in figure 12.

![Figure 12 Error value of 21 experiments](image-url)
The following conclusions can be drawn in accordance with the experimental results.

(1) When the target is relatively close to the camera distance (250-320 mm), better results can be obtained, and the position accuracy can be better than 0.5mm.

(2) When the target is far away from the camera (320-350 mm), the position accuracy is better than 0.6mm.

(3) The correctness of the pose calculation algorithm is verified.

4 Conclusion

The pose measurement system of AAR in space is modeled and simulated. In the paper the camera calibration model and its principle are expounded. After image of cooperation target is captured in real-time, image preprocessing, image segmentation, edge extraction and ellipse fitting process are carried out to extract the centers of target circles. Then, according to the 3D coordinates of cooperation targets feature points, their corresponding 2D image coordinates, and the interior camera parameters, the position and attitude of camera relative to the target are calculated with PnP algorithm.

Moreover, the moving target is predicted and tracked in real time by the integration method of target feature template and local search. At the same time, when the search box reaches the various edges, the target feature template is updated, and the world coordinates of the moving target are updated in real time, so as to calculate the position and attitude, which solve the pose calculation problem when the camera only takes the local image.

In addition, a series of measures to improve the real time are taken, such as reducing the image, setting the interest area and reducing the kernel size of the Gaussian filter. The system is simulated by virtue of HALCON software, and the running time is less than 100ms, which meets the real-time requirement. The accuracy of the system is verified, and the error is less than 0.6mm, which meets the requirement.

References


