The angle adjustment method of the cleaning end effector for the surface of rocket tank based on machine vision

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Abstract. According to the actual engineering needs, the angle adjustment method of cleaning end effector for the surface of rocket tank was studied. In this paper, the PID control model was established to adjust the angle. Through the image processing algorithm, the angle between the robot cleaning end plane and the rocket tank surface was measured. Taking the angle as the control target, the angle θ measured by the visual real-time is used as the feedback information, and the PI algorithm is used as the angle adjustment method. The experimental platform for angle measurement is built. After experimental verification, the method of angle measurement based on machine vision can meet the actual demand and the angle adjustment method is feasible, which is of great significance for realizing the cleaning automation of rocket tanks. This method can greatly improve the cleaning efficiency for the rocket tank surface.

1. Introduction

The rocket tank is the core component of the liquid rocket's internal storage propellant fuel. The storage tank stores low-temperature fuel such as hydrogen and liquid oxygen. Therefore, it is necessary to carry out the coating work of the heat insulation layer in the production process to maintain the temperature of the tank. Before painting, in order to ensure the coating effect of the insulation layer, it is necessary to clean the surface of the rocket tank. In order to improve the cleaning efficiency, the industrial robot is used to hold the cleaning end effector to complete the cleaning operation. Studies have shown that, the angle between the cleaning end effector and the surface of rocket tank has a great influence on the cleaning effect. How to make the angle meet the predetermined demand is of great significance to the cleaning efficiency.

The visual PID servo is a method of processing an image or video by using a computer to correct the control error by the recognition, detection, perception and understanding of the two-dimensional or three-dimensional scene to improve the control precision [1]. At present, machine vision has been widely used in measurement and monitoring [2]. The servo method based on machine vision has the advantages of high speed, precision and non-contact.

In order to meet the requirements of automatic attitude adjustment of the rocket tank cleaning automatic line and cleaning end, this paper proposes a visual PID-based method for adjusting the angle between the rocket tank surface and cleaning end effector. The measuring of angle is the key for adjustment. According to the deviation between the measuring angle and the desired angle, the cleaning end effector is adjusted to meet the requirement. The key of visual processing is to find the baseline of the end effector and the contour of the tank surface, to further identify the relationship between the baseline and the surface of the rocket tank, and calculate the angle.
2. System composition and principle

2.1. System composition

As shown in Figure 1, the image of the cleaning end effector and the rocket tank surface is captured by a CCD camera mounted on the side of the tank. As shown in Figure 2, after the servo system acquires the target image through the CCD camera, the PC processes the image, calculates the relative positional relationship between the cleaning end effector and the surface of the rocket tank, and sends the control signal to the robot controller to control the robot runs to the specified attitude to satisfy the angular relationship between the cleaning end effector and the tank surface.

2.2. Angle servo adjustment method

Simplify the model of cleaning end effector and rocket tank, as shown in Figure 3. Assume that the contact point between the cleaning end effector and the tank surface is fixed point \( m \). There are four contact forms: the effector is separated from the tank surface, the effector is tangent to the tank surface, the angle between the effector and the tank surface are positive, the angle between the effector and the tank surface are negative. This paper mainly studies the latter three cases—the angle \( \theta = 0 \) (P1 attitude in the Figure 3), \( \theta > 0 \) (P2 attitude in the Figure 3), and \( \theta < 0 \) (P3 attitude in the Figure 3).

\[
\cos \theta = \frac{d}{r} \quad (1)
\]

\[
\theta = \arccos \left( \frac{d}{r} \right) \quad (2)
\]
In equation (1) and (2), \(d\) represents the distance between the cleaning end effector and the center of the rocket tank, and \(r\) represents the radius of the rocket tank. The numerical value of \(\theta\) can be obtained by the equation (2). It is stipulated that \(\theta\) is positive when the line segment of the cleaning end effector is on the right side of the line segment \(om\), and negative when it is on the left side.

After obtaining the angle in real time, the vision-based PID servo method shown in Figure 4 can be used to control the angle between the cleaning end effector and the rocket tank surface [3]. The image servo is used to control the angle \(\theta(t)\) between the end effector and the rocket tank.

\[
\theta = K_p (e(t) + \frac{1}{T_i} \int_0^t e(t)dt + T_d \frac{de(t)}{dt})
\]

In equation (3) and (4), \(\theta_d\) represents the desired angle, \(\theta(t)\) represents the angle of feedback after image processing, \(e(t)\) represents the angular deviation, \(K_p\) represents the proportional coefficient, \(T_i\) represents the integral time constant, and \(T_d\) represents the differential time constant.

Set the sampling time interval to \(T\), discretize equation (3), and obtain the PID based on the image servo angle \(\theta\) at time \(k\):

\[
\theta(k) = K_p e(k) + K_i \sum_{n=0}^{k} e(n) + K_d (e(k) - e(k-1))
\]

In equations (5), \(K_i = K_p T/T_i\), \(K_d = K_p T_d/T\).

Since the image processing algorithm has a certain delay, it is difficult to guarantee the rapidity of the system in principle. Therefore, the PI control algorithm is used as the servo control method to ensure the system's steady state deviation and overshoot. The control equation is shown in equation (6):

\[
\theta(k) = K_p e(k) + K_i \sum_{n=0}^{k} e(n)
\]

3. Image processing method

![Image processing method diagram](image)

Figure 5. The process of image detection.
3.1. Image preprocessing and feature extraction

In order to reduce the contour interference of the background environment, the background of the image acquisition environment needs to be simple. First, the camera is calibrated to obtain the camera's internal parameter matrix $K$ and distortion parameters $K_1, K_2, K_3, P_1, P_2$ to correct image [4-5]. Due to the rotation of the rocket tank during the cleaning process for the rocket tank, the robot cleaning end position is basically fixed. Therefore, only extracting the robot cleaning end and the tank portion as the region of interest to reduce time of image processing. Gaussian filtering is used to remove local noise from the image.

The edge detection algorithm is used to acquire the contour. Edge detection is mainly based on the first-order and second-order derivatives of image intensity. In this paper, the Canny operator is used to calculate the edge of the image contour [6]. The Canny edge detection operator has low error rate, high localization, and minimum response characteristics. The edge-detected image is morphologically expanded to fuse adjacent edges. A straight line in the graph is detected by using a Hough transform of a straight line range. Then, the detected straight lines are clustered by clustering algorithm, and adjacent straight lines are aggregated to obtain an optimally fitted straight line [7].

Since the area of the rocket tank in the image is relatively fixed and the size is almost unchanged, a circular template search algorithm can be used to achieve circular fitting. First, expand the image at the bottom right of the image and use the OpenCV contour matching operator “matcTemplate” to search for the best circularity in the image [8]. The circular template is scanned along the line in the image, and the template circle is merged with the target circle. The circle with the best fit is selected as the fitted circle. To improve the matching speed, pyramid acceleration is used.

3.2. Angle $\theta$ calculation

Set the fitted line equation (7) be as follows:

$$Ax + By + C = 0$$

$$\theta = \arccos\left(\frac{(Ax_0 + By_0 + C)(A^2 + B^2)^{\frac{1}{2}}}{r}\right)$$

In equations (8), the $\theta$ can be calculated, and $(x_0, y_0)$ represents the center of circle.

As shown in Figure 3, the line segment $om$ is rotated around the $m$ point. When $om$ coincides with the baseline of cleaning end effector, the matching is stopped, and the matching rotation angle is recorded as $\alpha$. When $\alpha < 180^\circ$, $\theta > 0$, and if $\alpha > 180^\circ$, $\theta < 0$.

Specific algorithm:
- Calculate the Euler distance $d$ from the fitted straight line to the center of the circle;
- Find the intersection of the fitted straight line and the fitted circle, and obtain the coordinates of point $m$;

Figure 6. The original image. Figure 7. Fitted line and circle.
Construct a polar coordinate system \((\rho, \gamma)\) with \(m\) as the origin point, and obtain the linear equation \(\rho \cos \gamma + \rho \sin \gamma = 0\) of the line segment \(om\);

- Calculate the value of \(\theta\) according to equation (8);
- Increase the value of \(\gamma\), make the straight line \(om\) rotate around point \(m\), and find the intersection of the fitted line and the line \(om\). When the intersection is maximum, the two lines are coincident and calculate the rotation angle \(\alpha\) of \(om\). When \(\alpha < 180^\circ\), \(\theta > 0\), if \(\alpha > 180^\circ\), \(\theta < 0\).

4. Experiment and result

The key of this adjustment method is the accuracy of the angle recognition of the cleaning end effector and the surface of the rocket tank, which is verified by the following experiment.

4.1. Experiment platform

The experimental platform used in this paper includes: 600mm diameter aluminum tube (simulated rocket tank), ASUS PC, Mindvision camera(MV-GE131GC-T).

By setting 10 sets of angles to be detected (0°, 10°, 20°, 30°, 40°), each group was measured for 5 times, and the results were averaged.

4.2. Experimental result

| Target angle | Number of measurements | Measuring angle | Measurement deviation |
|--------------|------------------------|----------------|-----------------------|
| 0°           | 5                      | 2.2°           | 2.2°                  |
| 10°          | 5                      | 12.4°          | 2.4°                  |
| 20°          | 5                      | 22.8°          | 2.8°                  |
| 30°          | 5                      | 33.2°          | 3.2°                  |
| 40°          | 5                      | 42.6°          | 2.6°                  |

It can be seen from the Table 1 that the deviation of the angle \(\theta\) between the cleaning end effector and the rocket tank surface detected by the image processing algorithm is not more than 3.5°, and the detection algorithm is effective.
5. Conclusion
In this paper, the angle $\theta$ between the cleaning end effector and the surface of the rocket tank is calculated by visual image processing. The angle $\theta$ measured by the visual real-time is used as the feedback information, and the PI algorithm is used as the angle adjustment method. After experimental verification, the angle $\theta$ deviation from the image detection is less than 3.5°, which can meet the actual needs. The image-based angle control method proposed in this paper is of great significance for realizing the cleaning automation for the rocket tank, which can greatly improve the efficiency of cleaning.

Acknowledgements
This thesis was supported by the major sub-item of “High-Grade CNC Machine Tools and Basic Manufacturing Equipment” of the major science and technology project “Aerospace Lightweight Structures Complete Manufacturing Equipment Demonstration Line (2017ZX04005001).”

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