An on-line detection technology based on machine vision for micro parts assembly

Zeru An¹, Bingguo Liu⁎, Guodong Liu¹, Binghui Lu¹, Zhitao Zhuang¹, Yongmeng Yang¹
¹ Institute of Optical Measurement and Intellectualization, Harbin Institute of Technology, Harbin, Heilongjiang, 150001, China
⁎ liu_bingguo@hit.edu.cn

Abstract. Target preparation technology is one of the core technologies in ICF research. There are many micro parts on the target, the gap between parts is only a few microns, so it is difficult to assemble and realize automatic detection in the assembly process. In this paper, a three-way orthogonal micro vision system is proposed to detect the real-time position and posture of the through-hole and fill-tube of the parts on the target capsule, so to realize the real-time detection in the assembly process. The optical design of the hollow 45-degree reflector is proposed to solve the contradiction between the positive imaging of the through-hole and the positive insertion of the fill-tube. The scheme design of the detection system and the calculation of the system parameters are completed. The precise calibration of the three-dimensional micro vision system and the unified method of the coordinate relationship are proposed. Finally, the experimental test of the online detection system of the target assembly is carried out. The test results show that the system has the following functions. The accuracy of alignment is better than 1μm, and the accuracy of angle alignment is better than 0.2°. It realizes the automation and high-precision detection of the assembly process of small parts, which provides a reliable basis for the automatic assembly of targets for ICF experiments.

1. Introduction

Target preparation technology is one of the key technologies in Inertial Confinement Fusion (ICF) research. ICF target is the key component of laser fusion system[1]. Among them, the structure of cryogenic target is often complex, which is usually assembled by many very small parts. The size of large parts is several millimeters, while the size of small parts is only tens of microns. When assembling, all parts need to be assembled together according to certain accuracy requirements and order. The assembly process is tedious, which requires high requirements for assembly operators. At the same time, it needs to ensure high assembly efficiency to meet the requirements of ICF experiment. At present, it is the development trend to combine machine vision technology with precision control technology to realize automatic target assembly.

Target assembly is an important part in the precision assembly of ICF cryogenic target. The goal of a target is to insert a fill-tube with an outer diameter of about 10μm into the inflation hole with a diameter of about 12-15μm on the target (an outer diameter of about 0.5mm). The wall thickness of the target is about 10μm to 50μm[2-5]. Because the target and the fill-tube are very fragile, a little deviation during assembly will cause damage to the target and the fill-tube. The matching accuracy of each part is required to be better than 3μm, and the angle error is within 0.5°[6]. In order to ensure the assembly accuracy, efficiency and success rate, it is necessary to develop a high-precision detection
system to detect the position of the through-hole and the fill-tube in real time during the assembly process and feed back to the motion control actuator to achieve high-precision and efficient automatic assembly.

At present, the cryogenic target used in Lawrence Livermore National Laboratory (LLNL) is developed by GA[7]. The company has developed a semi-automatic precision assembly system for the fill-tube of the target. Because the position of the through-hole and the fill-tube cannot be observed directly, the system requires the operator to visually observe the docking of the through-hole and the fill-tube through a number of microscopes placed on the side, repeatedly aim, and confirm that they are fully aligned in space. The whole operation process is tedious and the assembly efficiency is not high.

Under the guidance of China Academy of Engineering Physics, some domestic universities and research institutions have also begun to conduct in-depth research on ICF target precision assembly technology, such as Tianjin University, Dalian University of technology, Institute of automation of Chinese Academy of Sciences, etc., and have made a lot of research results, but research on detection technology related to the assembly of target and fill-tube is less[8].

To sum up, at present, the assembly system of foreign target assembly is generally tested online by two or more imaging microscopes. The fill-tube is inserted from above, and the imaging system can only tilt a certain angle from the side viewing hole and tube. Due to the limitation of the depth of field of the imaging system, the imaging of the fill-tube and the through-hole is not very complete and clear due to the side viewing. Finally, the operator is required to conduct visual observation realignment, low detection efficiency, and high experience requirements for operators, unable to achieve automatic assembly. In order to improve the accuracy and efficiency of assembly and meet the increasing demand of ICF experiment for targets, it is urgent to develop automatic target assembly and online detection technology.

2. Online detection scheme of target assembly
For the assembly of the fill-tube of a certain target, the fill-tube should be inserted into the through-hole of the target at a certain depth and then fixed with glue. As shown in figure 1 below, the clearance between the fill-tube and the through-hole is only a few microns, and the parts will be damaged if there is a slight deviation during the assembly.

![Figure 1. Photo of CFTA assembly.](image)

The main difficulties in the assembly of the inflation tube of the target are as follows:
- The fit clearance is small, and the clearance between the tube and the hole is only a few microns;
- Detection position of the pipe shelter hole when inserting;
- It is necessary to detect the spatial pose of the tube and the hole at the same time.
If the through-hole can be observed in a real-time forward direction without blocking the forward insertion of the tube, it is a difficult problem for the on-line precise detection of target assembly. Based on this, this paper proposes a detection scheme as shown in figure 2. In this scheme, the upper vision system is observing the through-hole in a positive direction. In order to avoid blocking the fill-tube, the upper vision system is placed horizontally by turning the light path through a 45-degree reflector, and the center of the reflector is perforated to facilitate the fill-tube to pass through.

![Figure 2. Up inspecting diagram for capsule hole.](image1)

At the same time, in order to determine the space pose of the fill-tube, two mutually orthogonal imaging systems are placed in the middle path.

Finally, the system is composed of three micro vision systems, as shown in figure 3. The upper part of the target and the through-hole are detected by the upper part of the 45-degree reflector. When the target is placed on a three-dimensional displacement platform, it can move precisely in three directions, while the displacement system of the vision system can realize the displacement and focusing of the camera. The fill-tube is inserted into the through-hole under the reflector through the vertical hole in the middle of the 45-degree reflector, and does not affect the imaging of the upper vision system.

![Figure 3. System composition diagram.](image2)

The point light source is used as the coaxial light source through the micro lens light source jack, and the upper side of the target is illuminated by a 45-degree reflector to provide illumination for the upper micro vision system. The telecentric light source (not shown in the figure) is used as two side
lenses to provide backlight illumination, which can realize good illumination of the target and the fill-tube, so as to make the CCD image the target outline and the fill-tube clearly.

3. System parameter calculation

In the whole system, the lens and CCD are the most critical units in the whole imaging structure, which are directly related to the imaging effect, final detection accuracy and assembly accuracy. According to the design requirements, the positioning accuracy is better than 2μm, and the resolution of the imaging system is required to be high.

Firstly, the CCD camera is selected, the positioning accuracy is required to be better than 2μm, so the camera resolution is at least better than 2μm, the target diameter is about 500μm, so the object field of view is greater than 0.5mm. In this paper, the CCD camera is selected as 2/3 inch, its diagonal size is 11mm, the target size is 8.8mm × 6.6mm, the imaging magnification should be about 10 times, its field of view meets the requirements of greater than 0.5mm, and the size of a single pixel is 4.65μm.

Secondly, select the micro lens, the target hole size is very small, so the higher magnification microscope should be selected; in addition, the whole system assembly space is limited, and the assembled target is located between the lens and the imaging surface, so we should choose the lens with a larger working distance, leaving enough operation space, and determine the magnification by combining the above parameters. In addition, according to the resolution requirements and the cost performance of the lens of relevant brands, 10 times telecentric micro lens is selected. The numerical aperture of the lens is NA = 0.23mm. According to the spectral characteristics of the camera, 532nm green light is selected for illumination, and the optical resolution of the system can be calculated:

\[ \sigma_i = \frac{0.61\lambda}{N_A} = \frac{0.61 \times 0.532}{0.23} = 1.4\mu m \]  

(1)

According to the above parameters and CCD camera parameters, calculate the pixel resolution of the imaging system:

\[ \sigma_z = \frac{6.45}{\beta} = 0.645\mu m \]  

(2)

According to the calculation results: \( \sigma_i < \sigma_z < 2\mu m \), both the optical resolution and the pixel resolution are better than 2μm, which can initially meet the assembly accuracy requirements. Moreover, through further image subdivision algorithm, the imaging resolution and positioning accuracy can be further improved.

The on-road micro vision system is imaged by a hollow reflector. In consideration of meeting the requirements of light passing aperture, the outer diameter of the reflector should be as small as possible to ensure the compact structure, and the middle hole should be as small as possible when meeting the requirements of the fill-tube.

Considering that the size of the mirror is as small as possible, the working distance of the selected microscope lens is 55mm, the numerical aperture of the microscope is \( N_A = 0.23\text{mm} \), according to the calculation formula \( N_A = n \times \sin \theta \), so the object aperture angle of the microscope is \( 2\theta = 2 \times \sin^{-1} N_A = 26.6^\circ \).

After optimization design, under the condition of ensuring reasonable installation space and making the structure as compact as possible, the parameter design results are as shown in figure 4. The distance between the center of the mirror and the target ball is 20mm, the diameter of the mirror is \( \Phi 10\text{mm} \), and the diameter of the center opening of the mirror is \( \Phi 3\text{mm} \). At this time, the through-hole in the center of the mirror will reduce the aperture of the light and affect the imaging quality. According to the model calculation shown in figure 4, the aperture of the mirror is less than 1/3 of the total aperture of the light, and the loss of light energy is about 10%, which has little impact on the imaging quality.
Figure 4. Mirror imaging model of up visual system.

The image collected by the three-way micro vision system is shown in figure 5 below. It can be seen from the figure that the image acquisition system realizes the forward imaging of the target hole and the inflation tube, and the edge imaging of the inflation tube and the target is clear. The opening has little impact on the imaging quality of the upper road. Through the corresponding image processing algorithm, the rapid and automatic positioning of the target hole and the inflation tube can be realized.

Figure 5. Images of the micro visual system.

4. Coordinate system and calibration principle

The three-way micro vision system respectively collects the images of the fill-tube of the target, in which the micro vision system 1 observes the position of the fill-tube on the target, and the micro vision system 2 and micro vision system 3 observe the spatial position and posture of the fill-tube in two directions. Three vision systems cannot simultaneously observe the through-hole and the fill-tube, and the spatial coordinate system relationship is shown in figure 6 below. Before assembly, the spatial coordinate system relationship of the three micro vision systems need to be accurately calibrated.

To calibrate the three micro vision systems, it is necessary to observe the target simultaneously by the three systems and fix the position of the three vision imaging systems after calibration. In this paper, the external profile of the target is used as the calibration reference.

The calibration principle of the system is as follows: after the installation of the system, the coordinate transformation relationship of the target coordinate system \(x_0y_0z_0\), the three-way microsystem coordinate system \(x_1y_1z_1, x_2y_2z_2, x_3y_3z_3\) and the fill-tube coordinate system \(x_cy_cz_c\) is...
determined by the precise calibration technology based on the external contour of the target. Finally, the coordinate relationship between the through-hole and the fill-tube is unified.

The calibration process is shown in figure 7. Firstly, the target is placed in the center of the three cameras, and each imaging path is clear by adjusting the precision displacement adjustment table. Then, the edge of each target is detected several times, and the center position and average value are obtained. As the calibration reference points of three cameras (these three points are the projection of the ball center of the target on three CCD's, and the same point in space). When the top of the fill-tube moves to the calibration point in any two lenses, it can be considered that it moves to the calibration point in the space. By moving the center of the fill-tube and the target hole to this position, the alignment between the center of the inflation tube and the through-hole is realized. At the same time, the space angle of the fill-tube is detected, and the insertion depth is controlled, so the assembly can be completed.

![Figure 7. Three visual systems coordinate calibration.](image)

### 5. Results and discussion

#### 5.1. Positioning accuracy experiment of through-hole and fill-tube

After several assembly tests, the assembly accuracy is verified, and the experimental results are shown in table 1. From table 1, it can be seen that the repeatability error of micro vision system 1 for through-hole is $0.08\mu m$ ($3\sigma$).

| Serial number | Position ($\mu m$) | Radius ($\mu m$) |
|---------------|-------------------|-----------------|
| 1             | 532.95            | 6.01            |
| 2             | 532.96            | 6.01            |
| 3             | 532.98            | 6.01            |
| 4             | 532.99            | 6.00            |
| 5             | 533.04            | 6.01            |
| 6             | 533.07            | 6.01            |
| 7             | 532.95            | 6.01            |
| 8             | 533.06            | 6.02            |
| 9             | 533.05            | 6.02            |
| 10            | 533.04            | 5.99            |
| Mean value E  | 533.01            | 6.01            |
| $2\sigma$     | 0.08              | 0.02            |
From table 2, it can be seen that the positioning repeatability errors of micro vision system 2 and micro vision system 3 are 0.18μm and 0.22μm (2σ) respectively, and the angular positioning repeatability errors are 0.12° and 0.16° respectively.

| Serial number | Position (μm) | Angle (°) |
|---------------|--------------|-----------|
|               | Forward direction | Side direction | Forward direction | Side direction |
| 1             | 804.6         | 810.9      | -7.3          | 4.1           |
| 2             | 804.80        | 811.09     | -7.17         | 3.97          |
| 3             | 804.80        | 811.09     | -7.17         | 3.97          |
| 4             | 804.72        | 810.78     | -7.30         | 4.09          |
| 5             | 804.92        | 811.12     | -7.16         | 3.93          |
| 6             | 804.78        | 811.04     | -7.21         | 4.10          |
| 7             | 804.78        | 811.06     | -7.21         | 3.96          |
| 8             | 804.74        | 811.11     | -7.22         | 3.90          |
| 9             | 804.73        | 811.07     | -7.31         | 4.09          |
| 10            | 804.81        | 811.17     | -7.16         | 3.86          |
| Mean value E | 804.76        | 811.05     | -7.22         | 3.99          |
| 2σ            | 0.18          | 0.22       | 0.12          | 0.16          |

During assembly, the through-hole and the fill-tube need to be positioned respectively, and the positioning error is:

\[ \sigma_{\text{position}} = \sqrt{0.08^2 + 0.18^2 + 0.22^2} = 0.3\mu m \]  \hspace{1cm} (3)

Angle positioning error of fill-tube is:

\[ \sigma_{\text{angle}} = \sqrt{0.12^2 + 0.16^2} = 0.2^\circ \]  \hspace{1cm} (4)

5.2. Calibration error

According to the calibration method in Section 3 of this paper, the three-way imaging system is based on the contour of the same target. The calibration error is mainly composed of the processing error of the target contour and the image processing error when the three-way system obtains the center of the target contour. Among them, the actual processing error of the target sphere outline is better than 0.2μm, and the actual measuring error of each image measuring system for the target sphere outline is better than 0.2μm (2σ).

So the total calibration error is:

\[ \sigma_{\text{calibration}} = \sqrt{0.2^2 + 3 \times 0.2^2} = 0.4\mu m \]  \hspace{1cm} (5)
5.3. Mechanism motion error
According to the assembly process of the fill-tube of the target, first determine the position of the through-hole of the target, and then insert the fill-tube downward by the moving mechanism. During the insertion process, the two-way measuring system at the middle and side tracks the fill-tube in real time and corrects the position. The movement error of the mechanism has little effect on the assembly accuracy, which can be ignored.

5.4. Environmental error
The environmental error includes vibration error and error introduced by changes on temperature. Considering that the assembly experiment environment is better, it has constant temperature and vibration isolation measures. According to experience, the error is less than 0.5μm.

Synthesize the above errors, and the total error of the position detection of the online detection system is:

$$\sigma_{\text{total}} = \sqrt{0.3^2 + 0.4^2 + 0.5^2} = 0.71\mu m$$  \hfill (6)

The final three images of the successful assembly of the fill-tube of the target are shown in figure 8. The experimental results show that the system realizes the online detection task of the assembly of the fill-tube and the target, and realizes the automatic tracking and positioning in the assembly process.

6. Conclusion
Aiming at the problem of automatic assembly of ICF target and fill-tube, a new scheme based on multi-dimensional micro vision on-line detection is proposed. The two horizontal vision systems are used to detect the position and orientation of fill-tube, the 45-degree hollow reflector is used to detect the position of the through-hole in the forward direction of the upper vision system, and the precise calibration of the three vision systems is realized through precise calibration. After calibration, the relative spatial position of the target and the fill-tube can be accurately determined, so that the automatic detection of the assembly process of the target and the fill-tube can be realized. At the same time, the automatic tracking and detection of the assembly process can be realized through the image matching tracking algorithm. Finally, the development of the on-line detection system for the assembly of the target and the fill-tube is completed. After the on-site assembly test, the total error of the system position detection is better than 1μm, and the total error of the angle error detection is 0.2°.

The experimental results show that the system meets the requirements of the assembly of the target and the fill-tube. The development of the system provides a solid foundation for the automatic assembly of the target and the fill-tube.

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