

Research on Three-dimensional Tracking Technology of Aviation Plugs and Design of Auxiliary Soldering Systems

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ABSTRACT

Aviation plugs are characterized by safety, reliability, waterproof and dustproof, and have been widely used in various industries. Aviation plugs are mainly welded manually at present, and this method has low welding efficiency and high error rate. Three-dimensional tracking technology of aviation plug is the key to the realization of aviation plug auxiliary welding system, this paper proposes an improved three-dimensional tracking method based on the vision SLAM framework: the position estimation method based on the fusion of the direct method and the CMT feature point method, and the fast closed-loop detection method based on the model of the back-end. On this basis, the development of the aviation plug assisted welding system was launched, and finally experimental validation was carried out on a self-made dataset to test and evaluate the system functions. The results show that the aviation plug auxiliary welding system can, to a certain extent, solve the various problems occurring in manual welding, and has certain research significance in improving both welding accuracy and welding efficiency.

KEYWORDS

Aviation Plugs; Three-dimensional tracking technology; Soldering Systems

1. INTRODUCTION

The aviation plug consists of a shell, an insulation layer and a contact body, the end of which is called the solder cup. Through soldering technology, the inner core wires in the cable can be connected to the soldering cups, and the completed soldered plug is then mated to the socket for efficient data transmission [1, 2]. However, due to its compact design and densely arranged solder cups, problems of inaccurate positioning, incomplete or poor soldering may be encountered during the soldering process, which may affect the functionality of the plug. With the trend toward high-density miniaturization, the increase in the number of solder cups further enhances the difficulty of soldering [3].

In recent years, thanks to advances in image processing technology and machine learning, automated welding technology for aviation plugs has developed significantly [4]. Automated welding not only improves productivity, but also improves welding quality. However, automated welding equipment is more expensive and less mobile, so it is more suitable for the production of large quantities and high-precision requirements [5, 6]. In contrast, although manual welding is better in terms of flexibility and portability, and is suitable for on-site handling of special needs and the production and repair of small non-standard parts, it is prone to weld quality problems caused by operator fatigue. Manual welding offers a more flexible solution for specific situations, but can lead to increased errors after many repetitions [7, 8].

With the emergence and development of MR mixed reality technology, mixed reality technology has basically matured in the fields of production, medical treatment, smart city, etc., and has made several advances in key technologies and applications. In the field of production and manufacturing, the use of mixed reality technology to carry out auxiliary processing, assembly and inspection has also achieved good results [9].

Mixed reality technology is used to assist welding in the manual welding technology of aviation plugs. This kind of auxiliary welding technology can retain the advantages of portable and fast handling of special problems of manual welding, but also can put the image processing and some algorithms of automatic machine welding technology into use, which solves the welding quality problems that are easy to appear in manual welding to a certain extent. Therefore, an in-depth study of the mixed reality-based aviation plug assisted welding technology has important significance and value in terms of aviation plug manual welding technology.

In this paper, an improved 3D tracking method is proposed based on the visual SLAM framework: a position estimation method based on the fusion of the direct and CMT feature point methods and a model-based back-end fast closed-loop detection method. On this basis, the development of an aviation plug assisted welding system was launched, and finally, experimental validation was carried out on a home-made dataset to test and evaluate the system functions. The results show that the aviation plug auxiliary welding system can, to a certain extent, solve the various problems occurring in manual welding, and has certain research significance in improving both welding accuracy and welding efficiency.

2. RESEARCH ON THREE-DIMENSIONAL TRACKING TECHNOLOGY FOR AERIAL PLUGS

As an important technical means, 3D tracking and registration technology realizes its functions through data acquisition, feature extraction and matching, and attitude estimation and updating. The current mainstream 3D tracking and registration technology can be mainly divided into three categories: computer vision-based technology methods, hardware sensor-dependent technology and hybrid tracking and registration technology [10]. According to the detection method with or without markers, computer vision-based tracking and registration can be divided into marker-based 3D tracking and registration methods and marker-free 3D tracking and registration methods. The markerless 3D tracking and registration methods can be further divided into natural feature-based tracking and registration techniques, model-based tracking and registration techniques, SLAM-based tracking and registration techniques, and other techniques [11].

After analyzing the advantages and disadvantages of the above several registration tracking techniques and combining them with the needs of the actual inspection of welding cups, this paper proposes a three-dimensional tracking improvement method based on the SLAM framework.

The visual SLAM algorithm architecture mainly covers three core components: sensor data acquisition, front-end visual odometry, and closed-loop detection [12].

2.1. Position Estimation Based on Fusion Methods

In the SLAM direct method, the computation of the camera positional pose starts with an initial estimate provided by the motion model. Subsequently, this estimate is refined by minimizing the photometric error, which determines subsequent camera poses and constructs the camera's motion path. The accuracy of the initial pose is critical to the effectiveness of the direct method; however, in the presence of camera jitter or other external disturbances, significant differences between the initial two frames may lead to inaccuracies in the initial pose estimation, which in turn affects the entire pose computation process [13].

To address this problem, this section proposes an improved camera pose estimation method that combines the direct method with the feature point method. This method first tries to use the direct method to estimate and evaluate the initial camera position. If the initial pose meets the requirements of the direct method, the computation is continued using the direct method. On the contrary, if the initial position is not accurate enough, the feature point method is used to obtain a more reliable initial position, and then the direct method is applied to refine the adjustment. This method effectively solves the failure problem of the direct method due to inaccurate initial position and enhances the stability and reliability of the system [14].

2.1.1. Initial Position Estimation Based on Direct Method

After receiving an image frame, the number of spatial points in the two neighboring frames should first be evaluated to determine whether the number of spatial points in the two frames is suitable for obtaining a more accurate estimate of the initial bitmap by image alignment. Subsequently, a sparse image alignment technique can be applied to determine this initial bitmap. The process of sparse image alignment is as follows: first determine the projected pixels of the same spatial points in the two frames before and after, and then calculate the gray level difference of all the pixels in the frames before and after the minimization of all the pixels used for solving the pose, so as to estimate the initial change of the pose between these two frames. This is shown in Fig. 1.

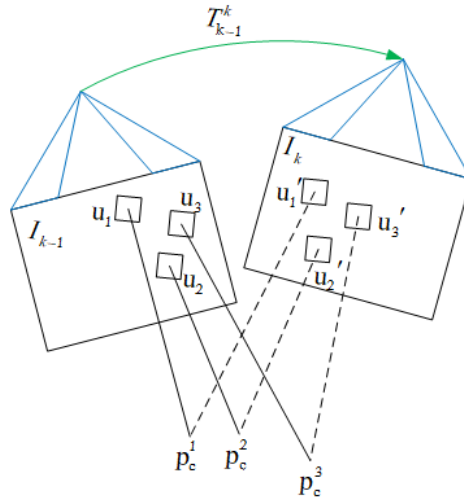


Figure 1. Direct method image alignment

Image alignment is performed using selected pixel points with significant gradients and ignoring those lacking significant gradients. Next, the camera position and pose changes are deduced by evaluating the gray scale difference between the matched pixel points in the before and after frames. The photometric error of point pixels is calculated as shown in Eq. 1:

$$r(\xi) = I_2(p_1') - I_1(p_1) \quad (1)$$

Where, p_1 denotes a pixel point on the previous frame, p_1' denotes a pixel point projected onto the next frame after bitmap optimization calculation, and I denotes the image value.

Based on the assumption of gray scale invariance, it is assumed that the gray scale value of a spatial point is invariant under each viewpoint in the direct method. When there are multiple spatial keypoints, the bit position estimation formula is expressed as:

$$\min_{\xi} r(\xi) = \sum_{i=1}^N e_i^T e_i \quad (2)$$

$$e_i = I_2(p_1', i) - I_1(p_1, i) \quad (3)$$

After obtaining the initial bitmap estimate using the direct method, the pixel points of the subsequent frames can be mapped to the current frame. Next, Eq. 1 is applied to calculate the difference in pixel grayscale values between the two frames and a threshold criterion is set. The accuracy of the initial bit position is evaluated to meet the requirements by comparing the calculated gray level error with the preset threshold [15].

2.1.2. Initial position estimation based on CMT feature point method

When the initial position determined by the direct method does not meet the requirements, the feature method can be turned to estimate the initial position and attitude of the camera. The CMT algorithm has a series of advantages, especially in dealing with small image variations and noise, and shows good robustness, which makes it suitable for real-time video streaming processing and environments with limited computational resources. The CMT algorithm is relatively simple to implement, which makes it easy for rapid prototyping and algorithmic validation and is more intuitive and effective in capturing motion information in images.

The CMT target tracking algorithm integrates keypoint matching and tracking techniques to determine the exact location of an object by voting for the center of the target through a keypoint mapping mechanism. In the process of filtering keypoints, the algorithm utilizes a consistent fusion strategy to reduce the generation of erroneous keypoints. In addition, it is able to estimate the size change and plane rotation angle of the target object based on the current distribution of keypoints. Compared to other algorithms, a distinctive feature of CMT is that it does not rely on the target's appearance information for tracking, which makes it somewhat resistant to tracking errors due to target deformation or attitude changes. Meanwhile, in terms of improving tracking efficiency, the CMT algorithm chooses the FAST feature point detector and the BRISK binary descriptor, a combination that helps to improve the overall processing speed of the algorithm [16].

Principles of the CMT algorithm:

Given a sequence of images I_1, I_2, \dots, I_n and an initial position b_1 in I_1 , the goal of the CMT algorithm is to recover the pose of the target object in each frame of the sequence, or to determine whether the object is invisible. Specifically, the pose of the object is estimated, including its center position μ , scale s , and angle of rotation in the plane α , where s and α are estimated relative to the object's position in the initial frame. To simplify the problem, the initial region is assumed to be an axis-aligned rectangle. In this process, it is assumed that there are already available methods for keypoint detection and description.

2.2. Model-Based Back-End Fast Closed-Loop Detection

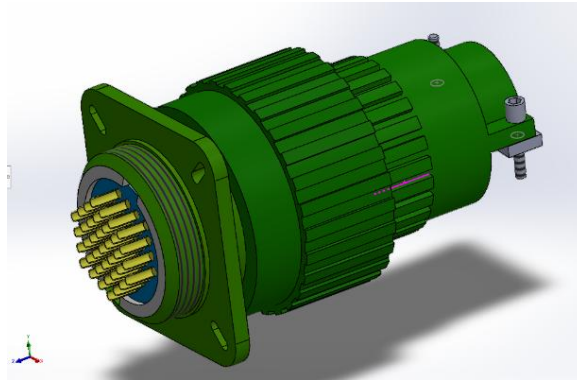
In this section, a fast closed-loop measurement and inspection method based on visual bag-of-words is proposed and a new model-based approach is introduced.

In the offline preparation phase, reference images with multiple angles are generated based on a 3D model of an aerial plug, and these images are trained to extract edge gradients and keypoints, which in turn lead to the construction of feature descriptors. In the online application stage, the LINE-MOD template matching algorithm is applied to quickly find the image most similar to the current viewing angle from the pre-generated reference image library, which supports the back-end system to realize the closed-loop detection quickly [17].

Table 1. CMT Algorithm Flow

| CMT Algorithm Flow: | |
|---|--|
| <i>Input</i> : I_1, \dots, I_n, b_1 | |
| <i>Output</i> : b_2, \dots, b_n | |
| <ol style="list-style-type: none"> 1. $O \leftarrow \text{detect}(I_1, B_1)$ 2. $K_1 \leftarrow O$ 3. for $t \leftarrow 2, \dots, n$ do 4. $P \leftarrow \text{detect}(I_t)$ 5. $M \leftarrow \text{match}(P, O)$ 6. $T \leftarrow \text{track}(K_{t-1}, I_{t-1}, I_t)$ 7. $K' \leftarrow T \cup M$ 8. $s \leftarrow \text{estimate_scale}(K', O)$ 9. $\alpha \leftarrow \text{estimate_rotation}(K', O)$ 10. $V \leftarrow \text{vote}(K', O, s, \alpha)$ 11. $V^c \leftarrow \text{consensus}(V)$ 12. $K_t \leftarrow \text{vote}^{-1}(V^c)$ 13. if $V^c \geq \theta \cdot N^o$ then 14. $\mu \leftarrow \frac{1}{n} \sum_{i=1}^n V_i^c$ 15. $b_t \leftarrow \text{bounding_box}(b_1, \mu, s, \alpha)$ 16. else 17. $b_t \leftarrow \phi$. 18. end if 19. end for | |

The training of target objects is mainly divided into two ways: online and offline. Given that the online learning needs to collect samples manually to construct the training set, the process is more cumbersome, and the greedy algorithm used is difficult to achieve a good balance between speed and stability. Therefore, in this paper, we choose the offline method to generate a multi-view reference image by utilizing the 3D model of the aviation plug. The 3D model of the aviation plug is shown in Fig. 2.

**Figure 2.** Three-dimensional modeling schematic of an aviation plug

In the offline sampling process, each surface of an ortho icosahedron is first subdivided, each face is uniformly divided into four parts and further subdivided through an iterative process. In order to find the optimal balance between computational efficiency and accuracy, two iterations were chosen to be performed, which resulted in the final formation of 16 equilateral triangles on each original face. Next,

in the Unity3D software environment, the 3D model of the object was placed at the center of the ortho icosahedron and it was ensured that the optical axis of the camera always remained through that center point. The sampling perspective is then set on the vertices of each equilateral triangle formed after these subdivisions, and the effect in Unity3D is shown in Fig. 3. The sampling range is from 0° to 360° in the longitude direction, and from 0° to 90° in the latitude direction. For each selected viewpoint, four rotation angles between -45° and +45° are defined to cope with the lack of rotational invariance of the LINE-MOD algorithm, thus improving the inconsistencies that may occur during online matching. This approach ensures more accurate and reliable matching results even at different rotations.

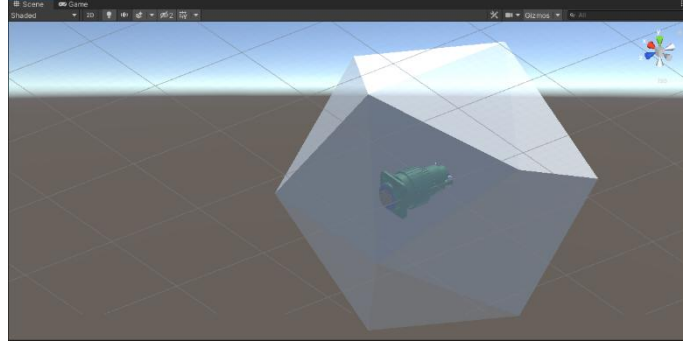


Figure 3. Offline Acquisition Schematic

For each sampled viewpoint, analyze the gradient direction of the edges of the target object in the red (R), green (G), and blue (B) color channels and determine the maximum gradient value at each position. Take the gradient direction of the image I at x position as an example, the formula is as [18] follows:

$$I_g(x) = \text{ori}(\hat{C}(x)) \quad (4)$$

In the offline preparation phase, ORB feature point detection and descriptor generation are used and these feature points are inversely mapped onto the 3D model of the object to determine their exact position in 3D space. Eventually, the pose information associated with each reference viewpoint, the object template, the 2D feature points with their corresponding 3D coordinates, and the ORB descriptors are saved to an XML file.

In the offline preparation phase, the object is trained by fixing the viewing angle. However, when applied in real scenes, the camera may be located at an arbitrary position in 3D space, thus requiring the feature descriptors to be able to maintain not only rotational invariance but also scale invariance. Although the LINE-MOD method realizes rotational invariance, it does not support invariance for scale changes. The similarity validation formula for the LINE-MOD method is:

$$\varepsilon(I, T, c) = \sum_{r \in p} \max_{t \in R(c+r)} |\cos(\text{ori}(O, r) - \text{ori}(I, t))| \quad (5)$$

$$T = (O, p) \quad (6)$$

$$t \in R(c+r) = \left[c+r - \frac{\tau}{2}, c+r + \frac{\tau}{2} \right] \quad (7)$$

Since the position of the object is fixed and known during offline training, the scaling of the template can be obtained from the depth information online by using the above formula calculation.

Next, a sliding window method is used to move step by step over the input image; in this process, the sum of all the matching scores in each position mapping table is calculated to evaluate the degree of similarity between the input image and the reference image. By comparing all the reference images, the one with the highest similarity to the current input image is selected as the key frame to accomplish the back-end fast closed-loop detection of visual SLAM.

3. AUXILIARY WELDING SYSTEM DESIGN FOR AVIATION PLUGS

3.1. Auxiliary Welding System Configuration and System Functional Requirements

3.1.1. System Configuration

a. HoloLens head-mounted display

The device is equipped with an advanced combination of sensors, including an Inertial Measurement Unit (IMU), four Environment Understanding Cameras, a Depth Perception Camera, a 2-megapixel main camera, and microphone arrays. Its core processing power comes from an Intel 32-bit processor and a holographic processing unit (HPU) optimized for mixed reality applications.

b. Server Platform

server is powered by a 12th Gen Intel (R) Core (TM) i5-12490F processor with NVIDIA GeForce RTX 4060 graphics. Memory is configured with 8GB of DDR4 RAM, and storage combines a 256GB SSD for fast reads and writes and a 500GB HDD for greater data storage.

3.1.2. System Functional Requirements

Good interactivity is essential when designing an assisted welding system for user-oriented applications aimed at performing aerospace plug welding tasks in a mixed reality environment. In order to ensure a smooth and efficient user experience, the system should integrate a range of advanced features to support the operator in performing smooth welding operations.

Based on the requirement analysis and combined with the model designed in this paper, the auxiliary welding system specifically includes the following functions:

Welding cup number display function: the system can provide clear and intuitive welding cup number images and 3D models to help operators quickly and accurately identify the specific location of each welding cup in the aviation plug.

Welding cup database storage and extraction function: The system has a built-in powerful data management mechanism to store the welding cup data of many types of aviation plugs as well as the specific welding cup numbers required for various welding tasks.

Aviation plug target recognition function: using Microsoft HoloLens device, combined with optimized YOLO target detection algorithm, it realizes efficient detection and classification of aviation plugs in the real world.

Aviation plug welding cup positioning function: based on the previously recognized aviation plug type and its 2D position information, plus the specific welding task number, the system will use advanced image processing technology to determine the exact position of each welding cup in the picture.

Cup tracking during the welding process: Throughout the welding process, the HoloLens device continuously tracks changes in the position of the selected cup and maps it to the real aviation plug.

Information Alerts: To keep the operator informed of the welding progress, the system is equipped with a comprehensive information alert mechanism. Whether it's a weld parameter setting, a progress update, or a warning of a potential problem, visual or audible signals are communicated to the user in a timely manner, ensuring that the entire process is smooth and organized.

3.2. Auxiliary Welding System Design

First, in the modeling stage, 3D Max and Flash were used to create a 3D model of the aviation plug and an animated demonstration of the welding process. Subsequently, these models were imported into the Unity3D environment for constructing a comprehensive model library of aviation plugs and a corresponding database of welding tasks, which provided a solid data foundation for subsequent applications.

In terms of target recognition, a target detection module based on the improved YOLO algorithm is developed in Unity3D. The module is able to receive real-time video streams from HoloLens devices, and after the user triggers the start recognition command, it intercepts the current video frame on the server side and starts the target recognition process. Through this process, the system can quickly and accurately recognize various types of aerial plugs appearing in the field of view and obtain their specific location information. Once the target object is successfully recognized, the recognition module will stop running, and at the same time, the recognition results - including the type of aviation plug and its coordinate position - will be fed back to the server.

For the problem of solder cup positioning, a specialized positioning module is also implemented under the Unity3D framework. This module can load the corresponding welding cup parameters according to the task number retrieved from the database. Combined with the previously obtained aerial plug location information, the system automatically intercepts the part of the video frame that contains the aerial plug, and applies a series of image processing techniques for accurate positioning. Ultimately, the system provides the exact position of the solder cups within the video frame to support further operational guidance.

In order to ensure continuous updating of the positional information of the solder cups during operation, a solder cup tracking module has also been designed. This module maintains real-time tracking of the weld cup position throughout the welding process, ensuring highly accurate position information output even in complex backgrounds, which greatly improves the safety and efficiency of welding operations.

Finally, all the above functional modules are integrated into a unified application, and Unity3D's packaging tool is used to generate a UMP application for the HoloLens platform. With the powerful compilation capability of Visual Studio, the application was successfully deployed to HoloLens devices, providing users with an intuitive, interactive and highly practical welding assistance system for aviation plugs.

4. SYSTEM FUNCTIONAL VERIFICATION TESTING

In order to ensure that there are no defects in the prototype system and that the prototype system functions properly, the prototype system was black-box tested in the following ways:

Welding cup number display function: After testing, this function can be displayed normally when the user chooses to view the welding cup number, and the system is able to provide a clear image of the welding cup number and a three-dimensional model, which can help the operator to quickly and accurately identify the specific location of each welding cup on the aerospace plug. The system can provide clear images and three-dimensional models to help operators quickly and accurately identify the specific location of each solder cup on the aviation plug.

Welding cup database storage and extraction function: After testing, when the user completes the welding task, the user can normally enter the information of the completed task, and when different welding tasks are selected, the corresponding welding task information can be automatically retrieved and loaded from the database.

Aviation plug target recognition function: After testing, the module can normally detect and categorize aviation plugs in the real world efficiently. When the aviation plug type is detected, the module will compare the aviation plug type with the task information for judgment. When the welding task is consistent with the aviation plug type, it will stop the target recognition module and call the aviation plug welding cup positioning module.

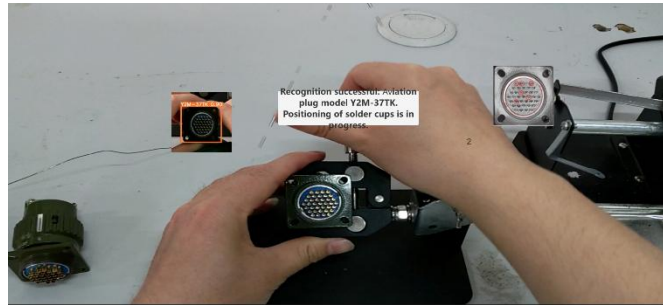


Figure 4. Successful Schematic of Aviation Plug Recognition

Aviation plug welding cup positioning function: after testing, the module can normally identify the aviation plug category after the aviation plug welding cup positioning of the aviation plug accurate position. After completing the positioning of the welding cup, it will start to call the welding cup three-dimensional tracking module.

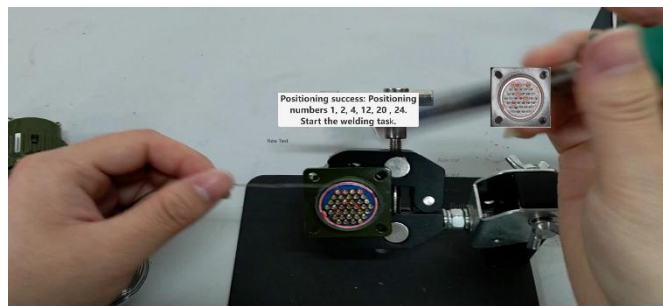


Figure 5. Aviation plug positioning success schematic

Welding cup tracking function during welding: After testing, during the whole welding process, the HoloLens device will continuously track the position change of the selected welding cup and map it to the real aviation plug. And judge the ongoing welding cups, prompting the user to weld correctly or not.



Figure 6. Soldering of aviation plug No.19 solder cup diagram

Information prompting function: After testing, throughout the welding operation, the system is able to properly prompt the user on how to proceed to the next step, and instantly remind the user.

The black box test results show that all the functions of the prototype system can be used normally without obvious defects.

5. SUMMARY

This article discusses in detail the research of the aviation plug assisted welding system based on mixed reality technology. In the technical realization part, the article focuses on describing the application of 3D tracking registration technology and visual SLAM to realize the real-time and interactive capability of the system, ensuring the smooth progress of the welding process. Finally, the article introduces the designed aviation plug assisted welding system, covering the system configuration requirements, functional module design and its implementation details, and verifies the feasibility and effectiveness of the system through a series of functional tests. These research results not only solve the quality problems existing in traditional manual welding, but also retain the advantages of manual operation to flexibly cope with special conditions, which is of great significance for promoting the development of aviation plug welding technology.

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