Research on Key Technologies of Vision-Based Robotic Shaft Hole Clearance Assembly

Zhaoyang Deng

School of Mechanical Science & Engineering, Huazhong University of Science and Technology, Wuhan, 430074, China
U202110712@hust.edu.cn

Abstract. With the rapid development of intelligent manufacturing, robotic shaft hole assembly is a key link in the manufacturing industry; its accuracy and efficiency are crucial to product quality and production efficiency. Vision-based robotic shaft hole gap assembly technology has become an important means to improve assembly quality and automation level of its advantages of non-contact measurement and real-time feedback. However, traditional research shows that position measurement accuracy is difficult to meet the demand of high-precision assembly, and assembly path planning lacks adaptability to the complex environment. Therefore, this paper investigates the key technologies of vision-based robotic shaft hole gap assembly, covering the aspects of shaft hole feature extraction and recognition, position measurement and matching, assembly path planning and control, etc., and analyzes, integrates, and synthesizes the current situation of robotic shaft hole assembly and puts forward the prospect. The aim hopes to provide a strong reference for future research on shaft-hole assembly, and to facilitate technological breakthroughs and innovative development in this field.

Keywords: Robot Vision, Shaft Hole Assembly, Path Planning

1 Introduction

In transforming and upgrading the modern manufacturing industry toward intelligence and automation, robot assembly technology plays an increasingly critical role. As a typical and basic assembly operation, Shaft hole assembly is widely used in automotive manufacturing, aerospace, electronic equipment, and many other fields. For example, in manufacturing automotive engines, pistons and cylinders, shafts and bearings, and so on are assembled. The quality of the shaft hole assembly directly affects the overall performance and reliability of the product. If the assembly precision is insufficient, it may lead to vibration, noise increase, and other problems during the operation of the equipment, and even lead to premature wear and failure of components, which seriously affects the service life and safety of the product [1].

Today's traditional shaft hole assembly mostly relies on manual operation; although manual assembly than robot assembly has a certain degree of flexibility, it is susceptible to fatigue, emotion, and other factors, the stability of the assembly quality is difficult

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to ensure, and lower efficiency, unable to meet the needs of large-scale, high-efficiency production. With the introduction and promotion of Industry 4.0 and the intelligent manufacturing concept, robot automation assembly has gradually become an inevitable trend in the development of the manufacturing industry; it has the advantages of high positioning accuracy and stable efficiency and can be operated for a long time, which can effectively make up for the shortcomings of manual assembly.

Vision-based robotic shaft-hole gap assembly can use vision sensors to acquire image information of shafts and holes and extract the features of the shaft holes through image processing technology to accurately measure the shaft-hole position and then provide accurate assembly guidance. This technology integrates the knowledge of computer vision, robot motion control, image processing, etc. It has the advantages of non-contact measurement, real-time feedback, rich information acquisition, etc., which provides an effective way to solve the problems of shaft-hole assembly accuracy and stability [2].

This paper adopts literature research and other methods to study the key technology of vision-based robotic shaft hole clearance assembly, mainly from the level of vision technology and path planning technology, to integrate the review and put forward the outlook for the robot vision shaft hole assembly.

2 Analysis of Shaft Hole Clearance Assembly Process and Key Indicators

2.1 Assembly Process

The robot axis hole assembly process is more complex; each link is closely linked. In the camera, the lens selection link needs to be based on the size of the axis hole, assembly accuracy requirements, and working environment lighting conditions. If the size of the shaft hole is small and there are high assembly accuracy requirements, it should be selected with a high resolution, short focal length lens to ensure that the details of the shaft hole are captured in the light of the complex environment, you need to choose a wide dynamic range of cameras, to ensure the quality of the image.

Calibration is an indispensable step, usually done using the Zhang calibration method. The purpose is to obtain the camera's internal and external parameters and achieve an accurate conversion of the image pixel coordinates to the actual physical coordinates, which is essential for the subsequent accurate measurement of the shaft bore position.

When shooting, monocular or binocular vision solutions are selected according to the assembly scene. Monocular vision is suitable for relatively low precision requirements and simple scenes, while binocular vision obtains depth information by the parallax principle and is suitable for high-precision assembly tasks.

The image processing link starts with filtering. Taking Gaussian filtering as an example, it effectively removes Gaussian noise by weighted averaging the neighborhood pixels, making the image smoother and conducive to subsequent processing; median filtering removes impulse noise such as pretzel noise. Edge detection is commonly used in the Canny algorithm, which accurately extracts axial hole contour information through Gaussian smoothing, calculation of gradient magnitude and direction, non-maximum value suppression, and double threshold detection and connection. Image segmentation is used to screen out irrelevant features, e.g., when screening based on color, the color difference between the axial hole and the background can be used to remove the background interference; and based on shape screening, the part that does not conform to the shape characteristics of the axial hole can be eliminated.

Thresholding is a key parameter in image processing, and different thresholds can lead to significant differences in edge extraction results. A suitable threshold value can accurately extract the edge of the shaft hole, laying the foundation for the subsequent position and coordinate system solution. After the edges are extracted, the relevant algorithms are used to solve the shaft holes' position and coordinate system to determine the shaft holes' position and attitude in space.

Finally, it enters the path planning stage, which is commonly used in RRT or RRT algorithms. RRT algorithms are based on random sampling, which can quickly explore feasible paths in complex environments. On this basis, RRT algorithms introduce asymptotically optimal strategies to optimize the paths to meet the needs of the high-precision assembly.

The assembly flowchart is shown in Fig. 1.

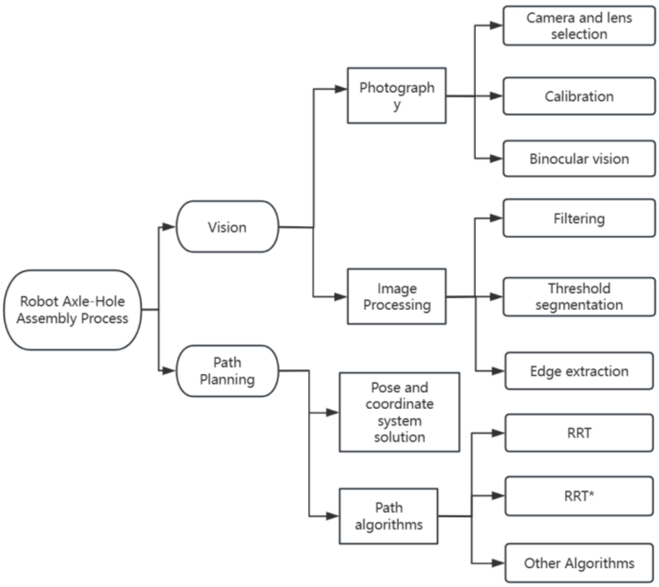

Fig. 1. Robotic shaft hole assembly flow chart (Picture credit: Original).

2.2 Analysis of Key Indicators

The key indexes of the shaft hole assembly include the assembly time, assembly success rate, and force control indexes in the assembly process, in addition to the tolerance requirements, size requirements, and accuracy.

Tolerance requirements determine the degree of tightness of the shaft and hole fit. For example, in the aviation engine assembly, some of the shaft holes have very high tolerance requirements, generally controlled within ± 0.01mm; anything beyond the range affects the engine performance and reliability. Size requirements specify the specifications of the shaft and hole to ensure that they meet the design standards.

Accuracy is an important indicator of assembly quality, covering positional accuracy, attitude accuracy, etc. Positional accuracy affects the degree of alignment between the shaft and the hole, and attitude accuracy determines the accuracy of the angle at which the shaft is inserted into the hole. High-precision assembly can reduce vibration and noise during equipment operation and extend service life.

Assembly time reflects assembly efficiency; shortening the assembly time can improve mass production efficiency. The assembly success rate reflects the reliability of the assembly system; a higher success rate can reduce the rate of defective products and production costs.

Force control metrics during assembly are also critical. Too much assembly force may damage the shaft hole components, while too little force will not complete the assembly. For example, in the assembly of precision shafts for electronic equipment, the force control accuracy should be ±0.1 N to ensure the assembly quality.

3 Vision Technology

In the robotic shaft and hole assembly process, vision technology is the core means to obtain shaft and hole-related information, which is like the robot's "eyes", providing key data support for subsequent accurate assembly. Through the vision system, the robot can sense the shape, position, attitude, and other information of the shaft and hole to control the assembly process. This paper integrates and reviews the camera position measurement technology and image processing technology in the vision technology of shaft hole assembly, and clarifys the specific content of the corresponding technology and relevant application examples.

3.1 Camera Position Measurement Techniques

Camera position measurement technology is a key technology to determine the position and attitude of the camera in space, and its measurement accuracy is directly related to the accurate judgment of the position of the axis hole, which in turn affects the final accuracy of the robot axis hole assembly. In practical application, choosing the appropriate camera position measurement technology is necessary according to different assembly scenes and accuracy requirements. In the following section, this paper talks about monocular vision and binocular vision, and not goes into the details of position measurement with three or more cameras because they are rarely used. As for the position measurement of the depth camera, it can be applied in monocular and binocular camera types, which is the classification of camera types, so it will not be expanded from here.

3.1.1 Monocular vision-based position measurement.

Monocular vision position measurement technology uses a single camera to obtain image information, and the use of geometric constraints and feature point matching to calculate the position of the target object, the technology has the advantages of low cost, simple system, and so on, in the shaft, hole assembly is more widely used.

Xu et al. proposed a robot assembly strategy based on local positional invariance, with the help of monocular vision measurement based on 3-D-2-D matching, which directly reflects 2-D pixel coordinates to 3-D coordinates, and the working schematic is shown in Fig. 2. The advantage of this method is obvious, which is reflected in the ability to achieve monocular camera-guided high-precision assembly, with the axial hole assembly error of less than 0.26 mm over a range of 4 m. However, the method may be poorly adapted to complex and variable environments, which may be overcome by using multi-sensor information [3]. Yang et al. combined robot localization with coaxial machine vision and utilized the monocular camera vision calibration and the multi-degree-of-freedom robot to adjust the eccentric hole position. Degree of freedom robot to adjust the eccentric hole position. The advantage is that it can complete the robot assembly of eccentric holes on complex three-dimensional workpieces under monocular vision. However, there may be a limitation of insufficient adaptability to specially shaped workpieces, which may be overcome by developing a more generalized attitude adjustment algorithm [4]. Ma et al. proposed a deep reinforcement learning approach to achieve different sizes of axial hole assembly by means of global camera monocular vision recognition, Actor-Critic architecture, and hole searching algorithm, which has the advantage of a better assembly capability for different sizes of axial holes. However, its training process may consume a lot of computational resources and time, which may be overcome by optimizing the model structure of the algorithm [5].Chen et al. used a template matching algorithm based on edge information and a position measurement algorithm based on a camera small hole imaging model to achieve force control and preliminary position control for aerospace pipeline docking with the help of a monocular camera and a robotic arm with a six-dimensional force sensor, and the advantage of this approach is that it is suitable for aerospace pipeline docking scenarios. The advantage of this method is that it is suitable for space pipeline docking scenarios. However, it may not be stable enough in the face of the environment with many disturbing factors, which the enhancement of anti-interference filtering algorithms can overcome [6].

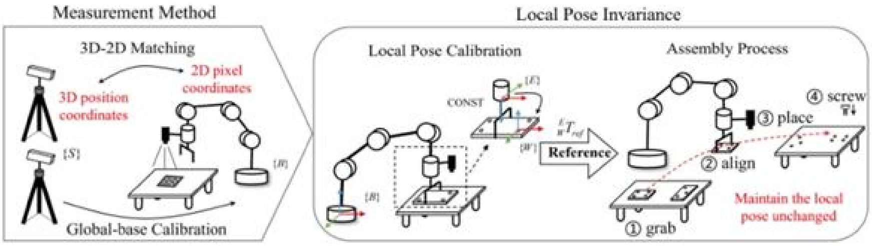

Fig. 2. Working schematic of a high-precision assembly robot system based on 3-D-2-D matched monocular vision measurement [3]

In summary, monocular vision technology can initially position shafts and holes in the robotic shaft and hole assembly. By extracting the edge features of shafts and holes and combining them with geometric constraints, the relative positions of shafts and holes can be quickly estimated, guiding subsequent precise assembly. However, in the process of shaft and hole assembly, monocular vision technology still has certain defects, which cannot obtain depth information well, so its application in complex assembly tasks is limited.

3.1.2 Binocular vision-based position measurement.

Binocular vision position measurement technology uses two cameras to acquire images from different angles. The parallax principle calculates the depth information of the target object and then estimates its position. Unlike monocular vision, binocular vision can provide more accurate depth information, is suitable for position measurement in complex environments, and has corresponding applications in industrial processing, aerospace, intelligent equipment, and other complex assemblies.

Binocular vision-based position measurement techniques are widely used in robotic shaft hole assembly. Zhang et al. developed a binocular vision-based automated robotic thread assembly system and a new method for spatial circular position estimation, which has obvious advantages, as reflected in the significant enhancement of the automation degree of the robotic shaft hole assembly and the precision of the position estimation [7]. Jiang et al. proposed, for the binocular vision technique, a system model and workflow diagram of the calibration strategy applicable to vision-guided large cabin assembly system (LCSS) are shown in Fig. 3. It has been experimentally verified with real data and has a positive effect on aerospace assembly. However, its calibration process may be cumbersome and may be optimized with the help of automated calibration algorithms [8]. Li et al. used binocular vision to identify the coarse and fine localization of perforated workpieces, which meets the demand for efficient workpiece cleaning in rail transportation. However, the localization may not be effective when dealing with workpieces with insignificant surface features, which could be done by combining other feature extraction methods [9].

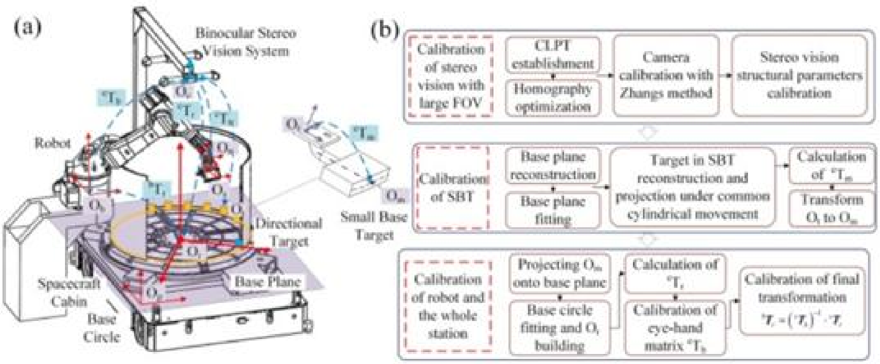

Fig. 3. Model of large nacelle assembly system based on (a) binocular vision technology and (b) workflow diagram [8]

In a robotic shaft and hole assembly, binocular vision technology can be used to accurately measure the relative position and attitude of the shaft and hole. With the in-depth information obtained by the binocular camera, the robot can more accurately adjust the position of the shaft to ensure that the gap between the shaft and the hole meets the assembly requirements. In addition, it can detect small deviations in the assembly and adjust the path in real-time to improve assembly accuracy.

3.2 Image Processing Techniques

Image processing technology refers to the technology of processing and analyzing the images acquired by the camera, which will extract the key information of the axis hole and provide the basis for the subsequent position measurement and assembly path planning, which is an indispensable link in the vision technology, and plays an important role in improving the reliability and accuracy of the robot axis hole assembly. It is an indispensable part of vision technology and is important in improving the reliability and accuracy of robot shaft-hole assembly.

3.2.1 Pre-processing techniques.

Image preprocessing is a key step in vision technology, mainly including image filtering, edge detection, and image segmentation (screening of irrelevant features). Image filtering techniques (such as Gaussian filtering, median filtering, etc.) can effectively remove the noise in the image and improve the accuracy of subsequent processing. Edge detection techniques (e.g., Canny edge detection) extract the contour information in the image, providing the basis for subsequent feature extraction and matching. Irrelevant feature screening techniques (e.g., color or shape-based screening) can reduce the interfering information in the image and improve the accuracy of feature extraction. After the camera captured the shaft hole photo for the above preprocessing before the subsequent hole circle fitting and other operations, improving the quality of the preprocessed image can improve the accuracy of the shaft hole assembly. Therefore, it is very important to choose what kind of filtering method, edge detection method, image segmentation, thresholding, etc. Experiments are needed to determine the optimal solution, and the preprocessing methods used for shaft hole assembly in different environments are often different.

In robotic shaft-hole assembly, image preprocessing techniques are mainly used to extract shaft and hole edge features to pave the way for subsequent feature fitting. Azman et al. proposed a vision-based system solution for the axle-hole assembly problem faced by forklift robots by using image preprocessing such as circular Hough transform (CHT), binarisation, morphological operations and edge detection for real-time images, which enabled the robot to autonomously pick up the spools and insert the central cylindrical shaft into the centre hole of the spools without any problem [10].

3.2.2 Fitting techniques.

Fitting techniques mainly extract geometric features from images with operations such as ellipse fitting and center extraction. Ellipse fitting is often used to extract the contour of the borehole and can fit the geometric center of the borehole by the least squares method. The center extraction technique is used to determine the exact position of the bore, which provides the basis for subsequent position measurement and path planning.

Deep learning-based fitting techniques have been widely mentioned in recent related studies, which automatically extract image geometric features with the help of neural networks, with significant advantages, as reflected in the greatly improved fitting accuracy and efficiency. Taking the research of Guo et al. as an example, they used deep neural network (DNN) with image processing techniques to determine the pose of the hole, and adopted an incremental learning method based on the generalized learning system (BLS) to simulate the human learning ability, and succeeded in deducing the pixel positions and orientations of the target holes in 0.12 seconds, and completed the insertion of the axes with only 1 - 3 adjustments. However, the diversity of the training data may limit this method, and the accuracy may be degraded in the face of the judgment of the whole position attitude under some special working conditions or complex scenes, which may be overcome by expanding the rich and diverse training sample set and combining with the migration learning technique [11]. Jiang et al. obtained the hole position attitude by image processing and hole edge matching methods, and adopted 3D hole reconstruction and spatial circle fitting algorithm, proposed a low-cost position determination method based on the selection of hole edge points, the advantage of this method is that it expands the visual measurement range, improves the local accuracy, and also enhances the degree of robot automation. However, this method may affect the accurate judgment of hole position when dealing with situations such as serious wear and tear or stains obscuring the hole edges [12].

In a robotic shaft and hole assembly, fitting techniques can accurately extract the geometric centers of shafts and holes. With ellipse fitting and center extraction, the robot can accurately determine the position of shafts and holes, providing the basis for subsequent position measurement and path planning.

4 Path Planning Techniques

After completing a series of operations such as position measurement, image processing, etc., the final stage of robotic hole assembly comes to the path planning stage. Path planning is one of the key technologies in vision-based robotic shaft assembly, and its goal is to find an optimal or feasible path for the robot from the initial position to the target position while avoiding collisions and meeting the assembly accuracy requirements. The choice of path planning algorithms directly affects the efficiency and accuracy of assembly, and there are many kinds of algorithms, such as the Rapid Random Tree (RRT) algorithm, Probabilistic Roadmap (PRM) algorithm, Genetic Algorithm, and Particle Swarm Optimisation algorithm, and so on. However, in robotic shaft hole assembly, the rapid exploration random tree algorithm, i.e., RRT, and the derived RRT* algorithm are often used, and the following is a review of these two algorithms and their related research status.

4.1 RRT Algorithm

The RRT algorithm is a random sampling-based path planning algorithm that explores the environment by randomly generating a tree structure, which can quickly find a feasible path in a high-dimensional space. The algorithm is suitable for shaft hole assembly tasks in complex environments and can quickly find a feasible assembly path. By combining the visual feedback in the robot shaft hole assembly, the robot can adjust the path in real time to ensure that the shaft can be inserted into the hole smoothly and accurately.

Xu reviewed the research on improved RRT-based algorithms from 2021 to 2023 in terms of theoretical improvements and application implementations, and the research results have obvious advantages, which are reflected in pointing out that the Rapidly Exploring Random Trees (RRT) algorithm has more potential to generate high-quality paths balancing global and local optimality due to the combination of both searching and random sampling characteristics compared with other path planning algorithms. However, since the RRT algorithm is based on random sampling, in complex and narrow spatial environments, the problems of low sampling efficiency and long path planning time may occur [13]. Wang et al. proposed a path planning method based on a new and improved Rapidly Expandable Random Tree (RRT) algorithm, which has the advantage of searching for collision-free paths in space, and successfully applied it to typical small-object assembly experiments to perfect the It has been successfully applied to typical small-object assembly experiments, which improves the path algorithm related to precision assembly robots. However, this method may have insufficient algorithm adaptability when facing scenarios with frequent changes in assembly tasks, and this limitation may be overcome by designing an adaptive parameter adjustment mechanism to optimize the algorithm parameters in real time according to the characteristics of different assembly tasks [14]. Urrea et al. developed and simulated a path planning approach using the RRT path planner and related coordination algorithms for a precision assembly robot consisting of two Selective Compliance Assembly Machine arm (SCARA) robots. The advantage of this system lies in its ability to anticipate and respond to partner's movements and environmental changes in real-time and complete the corresponding path planning and obstacle avoidance. However, the system may suffer from deviations in the collaborative path planning due to communication delays when multiple robots are working together, which may be overcome by constructing a low-latency and highly reliable communication network architecture and designing prediction-based collaborative compensation algorithms [15].

The RRT algorithm has unique advantages in robotic shaft hole assembly, which can quickly generate a tree structure and explore feasible assembly paths in complex assembly environments, and is especially suitable for scenarios that require high path planning speed. Through the combination of visual feedback, the robot can flexibly adjust the path based on the real-time acquisition of the shaft and hole position information to ensure that the shaft is inserted into the hole smoothly and accurately. However, the algorithm also has certain disadvantages; in the face of high-precision assembly tasks, its generated path may not be optimal, and there is a certain optimization space.

4.2 RRT* Algorithm

The RRT* algorithm is an improved version of the RRT algorithm. It can continuously optimize the paths during the path planning process by introducing an asymptotic optimization strategy to finally find the optimal path. The algorithm is suitable for high-precision assembly tasks, allowing the shaft to be assembled with the holes in the optimal path, which reduces the assembly time and minimizes the error.

Zhang et al. proposed a path planning algorithm for dual-arm robots based on the Improved Rapidly Expanded Random Tree Star (RRT*) algorithm for dual-arm robots for precision assembly tasks, which has significant advantages. By introducing the obstacle detection method, applying the adaptive step length adjustment function and adaptive sampling probability adjustment function, as well as adopting the multi-random tree merger and path smoothing optimization method, the planned path is smoother, and the stability of the robotic arm operation is greatly improved, so that the precise assembly of the axial holes can be achieved and the error can be controlled within 0.1 mm. However, the algorithm may have a certain delay due to the response to the environmental changes when facing the extremely frequent and complex dynamic changes in the obstacle environment [16]. Zhang et al. proposed an offline sampling-based Informed - Bi - Quick RRT * algorithm, which is based on offline sampling to address the problems of the low sampling success rate and the long computation time of the motion planning of the two-arm collaborative system with multi-constraint conditions. The Algorithm, verified by the simulated assembly and handling tasks, has an outstanding ability to handle multi-constraint conditions. Compared with other methods, it has obvious path quality and planning efficiency advantages. However, the algorithm may be limited by the a priori information of the environment that offline sampling relies on, which may lead to a degradation of the algorithm's performance if there is a large deviation between the actual environment and the pre-modeled environment, and this limitation may be overcome by adding an online real-time correction link to dynamically adjust the offline sampling results in conjunction with the real-time sensor data [17]. The improved RRT algorithm proposed by Xu et al. for the six-axis industrial robot assembly obstacle avoidance path motion problem has the advantage of effectively shortening the path length by about 14% compared to the standard RRT algorithm, and it can meet the obstacle avoidance requirements [18].

The RRT* algorithm is an optimized upgrade of the RRT algorithm, and its core strength is the introduction of the asymptotic optimization strategy. During the planning process, it can continuously optimize the path and finally find the theoretically optimal path, which makes it excellent for high-precision assembly tasks. By reducing assembly time and assembly errors, the RRT* algorithm effectively improves the quality of shaft hole assembly. However, the RRT* algorithm has a relatively high computational complexity, which is more demanding on computational resources and time, and the relationship between computational cost and assembly accuracy needs to be weighed in practical applications.

4.3 Other Algorithms

4.3.1 SARSA algorithm.

The SARSA algorithm (State-Action-Reward-State-Action) is a path-planning algorithm based on reinforcement learning. In a robotic shaft hole assembly, it continuously interacts with the environment through an intelligent body that selects an action based on the current state, obtains a reward, and moves to the next state, which updates the strategy.

In a shaft-hole assembly scenario with an unknown environment, the assembly robot can use the SARSA algorithm for path exploration. It starts from an initial position, senses the state of the surrounding environment, and selects a movement action based on the current strategy, e.g., moving a certain distance in a certain direction. If it successfully avoids obstacles and approaches the target hole, it gets a positive reward; conversely, if it collides or moves away from the target, it gets a negative reward. Through continuous trial-and-error learning, the robot gradually optimizes its strategy to find a successful assembly path [19].

The advantage of this algorithm lies in its online learning capability, which can dynamically adjust the path planning strategy in real-time interaction with the environment to solve complex problems and significantly improve assembly efficiency. It is especially adaptable in scenarios where the environmental information is incomplete and difficult to model accurately. However, the SARSA algorithm's learning process relies on many trials, with high initial learning costs and slow convergence speed, which can be a limiting factor in scenarios with demanding assembly time requirements. Moreover, the algorithm's performance is also affected by the design of the reward function, which may lead to a non-optimal learned strategy if the reward function is not set reasonably.

4.3.2 Behavioural dynamics approach.

The behavioral dynamics approach combines the robot's motion behavior with dynamics principles for path planning. In shaft-hole assembly, it fully considers the robot's physical characteristics, the interaction force between shafts and holes, and environmental factors to make the planned paths more in line with the actual motion laws.

When a large robot performs shaft hole assembly, such as a robotic arm installing a crankshaft into the shaft hole of a cylinder block on an automotive engine assembly line, the behavioral dynamics approach takes into account the inertia of the robotic arm, the driving force, the friction between the shaft and the hole, and other factors. By establishing a dynamics model, the force and motion parameters that the robot should apply at different assembly stages are calculated, and a smooth and efficient assembly path is planned [20].

The paths planned by this method are reasonable and can ensure the coordination ability of the robotic arm in the assembly process and ensure stability of movement. In the assembly environment with obstacles, it can better deal with the dynamics between the robot and the obstacles to avoid collision and achieve safe assembly. However, the method relies on an accurate dynamics model, and there are many uncertainties in the actual assembly environment, making accurate modeling difficult, which limits its generality. In addition, the complex dynamics calculation also increases the algorithm's time complexity, which requires high computational resources. The shaft hole assembly path planning performance based on different algorithms is shown in Table 1.

Table 1. Typical performance of shaft hole assembly path planning based on different algorithms

Arithmetic	Performances	Application Scenario	Bibliography
Rapid Expansion of Randomised Tree Algorithms (RRT)	Fast search, flexible path planning, better completeness	Assembly of complex spatial layouts, tasks with high real-time requirements	Xu [11] Wang et al. [12] Urrea et al. [13]
RRT* algorithm	Asymptotic optimality, finding better paths over time; relatively efficient search in complex environments; effective obstacle avoidance	High-quality path planning scenarios, such as in the field of autonomous driving; high-precision robotic arm assembly tasks with high requirements for path smoothness and optimality	Zhang et al. [14] Zhang et al. [15] Xu et al. [16]

SARSA algorithm	Online learning capabilities to solve complex problems and improve assembly efficiency	Assembly in unknown environments, tasks with high success and efficiency for assembly	Jisuanji et al. [17]
Behavioural dynamics approach	Well-planned paths, good coordination and stability	Large robot assembly, assembly environment with obstacles	Wang et al. [18]

Rapid Expansion Random Tree (RRT) algorithm is fast in search, flexible in planning, good in completeness, suitable for complex spatial layout and assembly tasks with high real-time requirements, but the quality of the path is poor; RRT* algorithm has asymptotic optimality, high efficiency in searching for complex environments, obstacle avoidance, and path smoothing, suitable for scenarios with high requirements on the quality of the path, but computationally complex and dependent on sampling; SARSA algorithm has strong online learning capability, which can solve complex problems and improve assembly efficiency. SARSA algorithm has strong online learning ability, can solve complex problems and improve assembly efficiency, and is suitable for unknown environments with high requirements on success rate and efficiency of assembly, with high initial learning cost. The Behavioural Dynamics method has reasonable path planning, strong coordination, and stability and is used for large robots and assemblies with obstacles, and its versatility needs to be improved. These algorithms are based on different principles, each with its own characteristics and applicable scenarios, and the actual application needs to be selected according to the specific situation.

5 Conclusion

Vision-based robotic shaft hole gap assembly technology has made significant progress in recent years; vision and path planning-related technologies have been continuously refined and improved, providing strong support for improving the accuracy and efficiency of shaft hole assembly. In terms of vision, monocular vision and binocular vision have their own advantages and disadvantages. Monocular vision technology is mostly used in some scenes with relatively low precision requirements, while binocular vision has obvious advantages in in-depth measurement and position accuracy, which is suitable for high-precision assembly tasks, but the operation and calculation are not as simple as monocular vision, which is generally chosen according to the precision of shaft hole assembly; in terms of path planning, the RRT and RRT sampling-based algorithms can be used in complex assembly environments to improve the accuracy and efficiency. A* algorithms show good adaptability and planning ability in complex assembly environments, but RRT* is more accurate and has better paths than RRT, while RRT requires less computation than RRT*, which is more concise and convenient.

Many challenges remain in the shaft hole assembly process. On the vision side, complex lighting conditions, occlusion, and the diversity of materials on the shaft hole's surface can affect the vision system's accuracy and stability. In terms of path planning, how to quickly plan stable, high-quality, and short paths under complex dynamic environments is still an urgent problem.

This paper believes that future shaft hole assembly may be considered in the following directions: first, in-depth research on multi-sensor fusion technology, combining visual sensors with force sensors, ultrasonic sensors, etc., to make up for the shortcomings of a single visual sensor and to improve the system's ability to perceive complex environments; second, to further explore the potential of deep learning in vision and path planning, and to take advantage of the strong learning and feature extraction ability, to achieve more intelligent and accurate shaft hole assembly; Third, for the shaft hole assembly needs of specific industries, develop customized algorithms and systems to improve the practicality and relevance of the technology. It is believed that with the development of technology, robotic shaft hole assembly will become more efficient and high precision, play a greater role in intelligent manufacturing, and promote the manufacturing industry to a higher level.

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