A Review on Significant Technologies Related to the Robot-Guided Intelligent Bolt Assembly Under Complex or Uncertain Working Conditions

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ABSTRACT In most existing bolt assembling operations, the human-machine collaboration (HMC) is used to guarantee both the operational efficiency and the connection quality. However, the huge labor intensity and costs are still needed when there exist bolts with huge quantity and multiple models in some special working environments, for example locomotive maintenance and automobile assembly. Actually, the robotic application can better solve the above problem. The main reason why this application is limited in the bolt assembly is due to the technological barriers related to the intelligent control. This paper firstly introduces the HMC-based and the robot-guided bolt assembly processes in detail, then summarizes the latest researches related to the significant technologies needed in the robot-guided assembly to show their present status and future trends. Finally based on the technology limitations this paper further presents some suggestions for future studies of each technology, which attempts to help readers broaden their research thoughts and speed up the development of the robot-guided bolt assembly.

INDEX TERMS Automatic bolt assembly, robotic application, technological barrier, intelligent control.

I. INTRODUCTION

Bolt connections have been widely utilized in the industrial and civil/structural fields, such as aerospace, rail transit, and basic equipment manufacturing. The connection quality directly affects dynamic characteristics of the connected structure, for example the sealing of precision parts and the bearing performance. In industries, there exist many kinds of bolts such as ordinary bolts, headless bolts, hexagon fit bolts, studs, screw with small size and so on, as well as three threaded connection modes. The type and application situation decide different bolt assembly processes, which always include a series of operations. For example, a assembly process of an ordinary bolt (without using gaskets) covers the following set of operations: (1) obtain the information of the target and environmental obstacles; (2) select and take the bolt with the correct type and size; (3) move the bolt from the

initial pose to the target pose determined by the connecting hole; (4) control the bolt/hole mating; (5) hold and move the nut from the initial pose to target; (6) control the bolt/nut mating; (7) perform the bolt tightening.

Nowadays the assembly work is completed mainly through the HMC-based and the robot-guided bolt assembly processes. In real applications, the HMC-based process has been widely utilized in situations under complex operational environments and with high requirements of the assembly accuracy and reliability, for example, the automobile engine assembly [1] and the locomotive maintenance [2]. In most HMC-based works, operators hold the automatic tightening device to complete the bolt assembly. With strong vision and force perceptions of the human, the bolt can be accurately and reliably matched to the connecting hole and the nut, which can effectively guarantee the connection quality. Compared to the former process, the latter one is a fully automated assembly, which uses the two/three-dimensional (2/3D) measuring system like cameras, to obtain the information of the
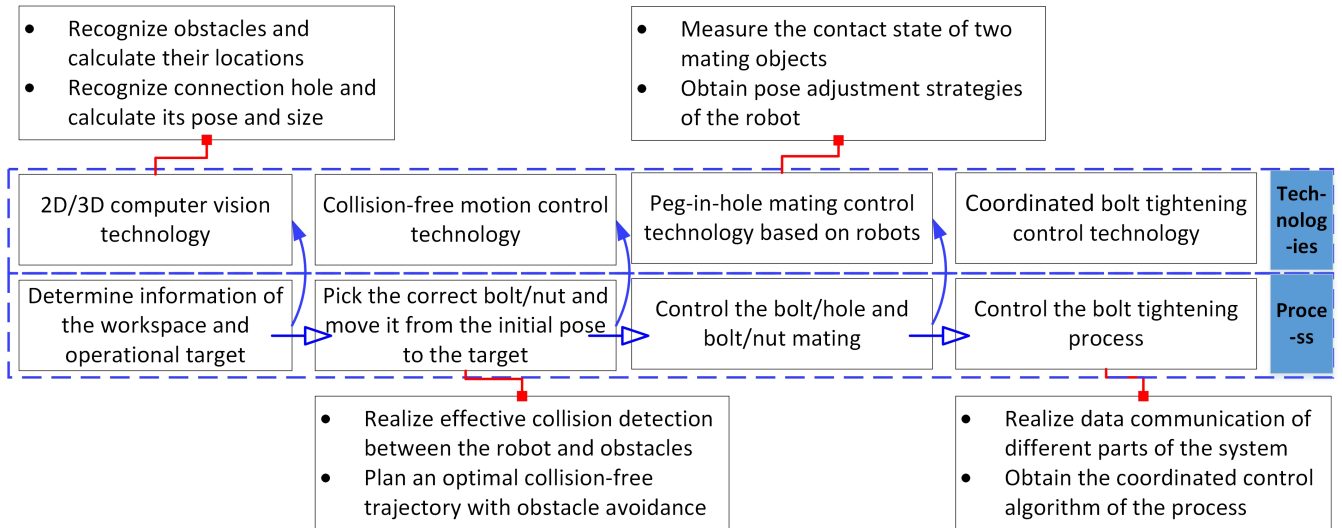
FIGURE 1. Main process and required technologies of the robot-guided bolt tightening as well as specific tasks of each step.

working environment including the target pose and obstacles' locations, and uses the robot to safely take the bolt and nut and also perform the bolt/hole and bolt/nut mating through guiding end-effector motions, and implements the bolt tightening operation based on the coordinated control of robotic joints and tightening device (mounted on the robotic end effector). The robot-guided intelligent system guided by the manipulator has been widely used in the modern assembly with fixed operational spaces and single assembly task [3], [4]. In these cases, the fixed and known operation space provide some known information about the target and obstacles, which means that the 2D pose of the target that can be measured easily and accurately using existing vision technologies. Based on the accurate vision information, the precision and safety of the robotic motion are largely improved in this application.

But while facing multiple bolt assembly tasks existed in complex and uncertain workspaces, it will put forward new challenges to technologies. Figure 1 shows the the main process and required technologies of the robot-guided bolt tightening as well as specific tasks of each step. The following gives the brief explanation of each technology requirement to show new challenges of achieving the fully automated bolt tightening operation of the manipulator.

(1) Computer Vision Technology: Facing multiple tasks and uncertain working environments, both the 3D information of the workspace and operational target, including locations of obstacles as well as the pose and size of the connection hole, need to be measured accurately. But there always exist kinds of mechanical components with different shapes and sizes in the surrounding environment (Figure 2 shows two complex structural cases) for many bolt connections, which need to be separated, recognized, and measured. it puts forward high requirements to the computer vision technology.

(2) Collision-free Motion Control Technology: When robots are utilized to automatically take and move the bolt/nut

(a) Wheel-pair axle box of locomotive system
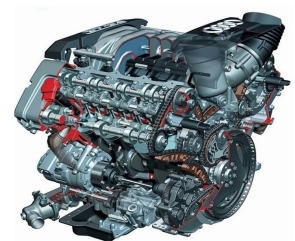
(b) Engine of automobile system

FIGURE 2. Two complex structural cases during the bolt assembly.

from the initial pose to the target, it is significant to plan a collision-free trajectory for the robot according to the 3D information of the target and obstacles obtained using the vision system. However, the collision-free motion control is still an open problem that needs to be firstly solved, for which we need to provide an efficient and reliable collision detection algorithm, and then present an effective collision-free trajectory planning technique for the manipulator.

(3) Peg-in-hole Mating Control Technology: It is known that we cannot obtain the absolutely correct pose of the target due to calibration errors of the vision and robotic systems, as well as the error of 3D location caused by the image processing, which would lead to a relative pose error between the bolt and connection hole, as well as the bolt and nut. This error can directly result in the failure or low quality of the bolt/hole or bolt/nut mating operation. Therefore, the robot-guided mating control, which includes the data processing based on the force or vision sensing systems, as well as the pose adjustment strategy of the robot, is a significant technology in the bolt assembly.

(4) Coordinated Bolt Tightening Control Technology: When the clamping force is applied, some fault conditions are easily happened, such as cross thread, stagnation, slippage and misalignment and so on. Also with too large clamping

TABLE 1. Advantages and disadvantages of three types of cameras.

Depth Camera	Advantages	Disadvantages
BV-based	√ It is insensitive to the light disturbance; √ It also has the long service life and the lowest cost.	× It cannot be used under conditions like dim light, busy background, and partial occlusion; × To obtain the high accuracy, the measuring distance should be less than $2m$, and the image processing algorithm needs to balance the calculation complexity and efficiency.
SLS-based	√ It is relatively mature development, good real-time, and high resolution; √ It needs less computation compared with the BV-based camera.	× The depth information of the metallic material is often missing under strong light conditions, which largely limited its real application in the industrial field; × The structured light emitter is easy to damage under the long monitoring condition; × There exists the conflict between the range and accuracy (its accuracy can reach $0.01 - 1mm$ within a 10-meter range).
TOF-based	√ It is insensitive to ambient conditions, and has good real-time.	× It has features of low resolution, immature development and high cost. Also, the accuracy is largely affected by the systematic and random errors (can only reach the level of centimetre).

force the bolt will yield and even break, and with too small one the connection performance cannot be guaranteed. That is, the bolt tightening control is an important technology for the improvement of the final connection quality. But, the robot-guided bolt tightening machine would be an extremely complicated system composed of the robot, the robotic control unit, the tightening device, the vision and force measurement subsystems, as well as the industrial PC utilized for the digital processing. Then how to realize the data communication of different parts and the coordinated bolt tightening control procedure is one main challenge for this study.

The above content introduces the HMC-based bolt assembly process, the robot-guided bolt assembly process and its related key technologies. The remainder of the paper is then organized to show the present status and future trends of key technologies through listing some representative studies and present their disadvantages in solving practical problems of the real bolt assembly, and finally give some suggestions for future studies in conclusions.

II. COMPUTER VISION TECHNOLOGY
As mentioned above, it is necessary to develop the 3D measuring technology if we want to further expand the robotic application in the assembly work under multiple bolt tightening tasks and uncertain operational environments. For the computer vision technique, the accuracy, efficiency, and reliability of algorithms, as well as the cost of the system are all the indexes that we concerned in previous studies. In general, a computer vision system is mainly composed of the image collecting and processing systems. Figure 3 shows that the number of researches related to the computer vision increases exponentially in general year by year, which means that with the rapid development of artificial intelligence, the computer vision as an important technology access to the external world has always been the research focus of many universities, scientific institutions and enterprises.

In modern automatic industries, 3D information of the environment can be obtained mainly using depth camera based on principles such as binocular vision (BV) [5],
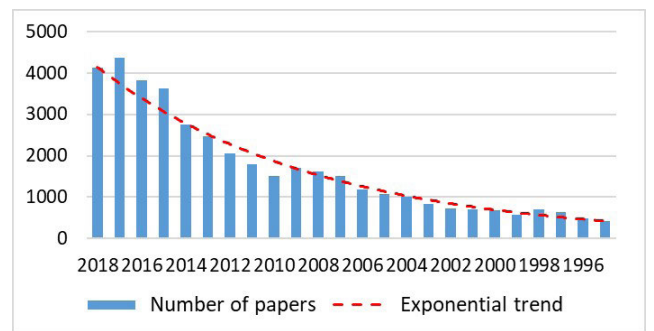

FIGURE 3. Number of researches and the exponential trend about the computer vision in each year. In the paper database of Web of Science paper database, computer vision was used as the subject for retrieval and analysis, and the number of proceeding papers is 25233, which is above 50 percent of the total number of researches (43307).

structured light scanning (SLS) [6] and Time of Flight (TOF) [7]. BV-based camera is the firstly developed approach, and is always used in conjunction with lightening equipment to collect the environmental image. SLS-based camera is widely used to measure the depth information due to its simple principle, high accuracy and reliability [8]. In its system, a projector is utilized to firstly project controllable points, lines or planes of light, then the depth and RGB cameras are used to obtain the objective images, and finally calculate the 3D location of the object based on the information fusion of images [9]. TOF-based camera uses sensor to send out near-infrared light and also receive its reflected light, then obtain the depth information of the object through calculating the time or phase differences between two light, and finally show the 3D configuration of the object using different colors to represent different distances. The latter two have been developed into the mature product like Kinect, which is composed of camera used to obtain RGB color images (or RGB camera), Infrared (IR) emitter and Infrared CMOS camera (or IR camera) [5]. Based on the color and depth images, 3D locations of point clouds can be obtained finally. Advantages and disadvantages of three types of cameras are listed in Table 1.

Digital image processing refers to procedures of determining the environmental information, including the conversion
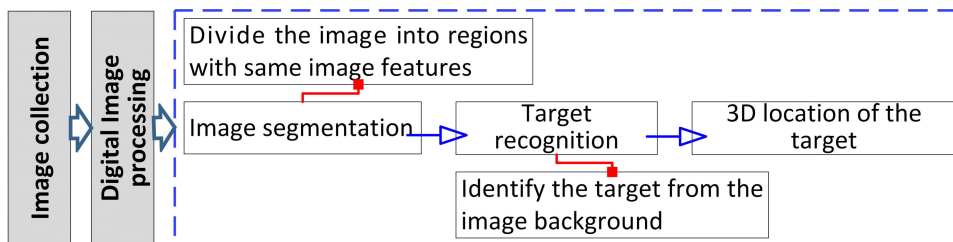
FIGURE 4. Steps of image processing and the purpose of each step.

from the image signal to the digital signal, as well as the digital processing in computer. This technology has advantages of reproducibility, high accuracy, wide adaptability and high flexibility, and has been widely used in fields like aerospace, industry, medical diagnosis and traffic monitoring, etc. It is composed of processing algorithms mainly including image segmentation, target recognition and 3D location of the target, as Figure 4. In real industrial environments, the image acquisition is often unstable due to light interference and water mist occlusion [10], [11], which put forwards the large challenge to the image processing.

A. IMAGE SEGMENTATION

Firstly, as a bridge from the processing to analysis, image segmentation aims to divide the image into several regions according to the image feature, such as grayscale, texture, shape, and color. Existing methods for this problem [12] mainly include the threshold method, edge method, region growth method and clustering analysis, which are summarized as follows.

(1) In the threshold method, the target is separated through dividing the gray histogram into several non-overlapping parts by selecting threshold. It is suitable for the condition with the big difference between the target and background. Aiming to determining the optimal threshold, researchers have proposed some effective methods with objectives like interclass variance (Otsu segmentation [13]), interclass entropy [14], and correlation [15], etc. However, the computing efficiency of these methods will be largely reduced when they are utilized to solve the multilevel threshold determining case [16]. Aiming at this limitation, some nature inspired algorithms have been introduced in the latest researches. For example, El Aziz *et al.* [17] combined the variance-based fitness function and optimization algorithms (Whale and Moth-Flame Optimizations) to determine the optimal threshold values, and validated the accuracy and efficiency of the proposed algorithm by comparing with other algorithms. But the threshold-based method only considers the image gray level, the segmentation may fail if the grayscale difference is small or the gray between classes overlaps.

(2) Edge method [18] achieves the purpose of inter-domain edge detection mainly by analysing the discontinuity and mutation of the gray level of the gray image or the depth value of the depth image. For the gray image, the effect of the edge

method can be largely affected by the image noise or ambient light. And for the depth image, it will fail under cases that the structure light is parallel to the environmental edge and the edge is shaded. Latest studies focus on improving the reliability of the edge method. For example, combining morphological operations and Gaussian Smoothing, Prathusha and Jyothi [19] obtained continuous edges from the image and also removed the false edges using the m-connectivity, and finally verified the effect of the proposed algorithm (it can precisely obtain thick and continuous image edges) by comparing with existing edge segmentations. This work can be helpful in extracting key corners from complex structural environmental images. Wu *et al.* [20] realized the edge representation and extraction of the fuzzy uncertain image caused by illumination and noise using an novel edge method, wherein cognitive physics was introduced to construct a non-linear mapping from image gray space to potential space. Marysela *et al.* [21] presented a supervised, statistical edge-based segmentation method, wherein the edge was located using the image gradient, and the uncertainty of each edge was quantified using maximum likelihood. Also, this method can locate edges between regions with overlapping intensity histograms.

(3) In the traditional region growth method [22], seed points of different regions need to be firstly determined by manual, then all pixel points are classified based on their similarity to seed points. Therefore it is more applicable for the segmentation task of images with uniform regions. However, the image is easily to be over-segmented or under-segmented due to the influence of noise. In addition, the manual selection of seeds largely limits the real application of this method. To solve this problem, some researches [23], [24] combined with the edge method to automatically select the seed by labelling the edge pixel with the maximum probability in the gray histogram analysis. Besides, the region growth method has been further improved based on super-pixel generated by special over-segmentation algorithms, which has advantages of higher computing accuracy and providing more efficient segmentation extraction. For example, Chaibou *et al.* [25] summarized and evaluated existing super-pixel-based image segmentations, pointed out that the main problem is how to efficiently quantify the similarity between super-pixels, and finally presented a robust adaptive multi-scale method to calculate the similarity. This method can provide a significant

TABLE 2. Comparison of the classification accuracy based on different methods [40], wherein SOC means standard operating conditions that require testing conditions and training conditions to be very similar, EOC means extended operating conditions that require huge dissimilarities between the them.

Model	EMACH[43]	IGT[44]	MSRC[45]	MSS[46]	M-PMC[47]	Gao' method [40]
SOC(percent)	88	95	93.6	96.6	98.8	99.15
EOC(percent)	77	85	98.4	98.2	98.2	99.57

foundation for the further semantic segmentation, which is more interesting for real applications.

(4) Clustering analysis [26] is an image segmentation technique based on the K-means algorithm and some advanced methods such as fuzzy theory [27] and neural network [28], [29]. When K-means algorithm is utilized, the value of k largely affects the final segmentation effect. To avoid this limitation, Choy *et al.* [27] presented an unsupervised learning algorithm based on fuzzy theory, which is insensitive to initial parameters. Recently, fuzzy-based algorithms have been largely improved to solve segmentation problems of uncertain and fuzzy images and and mainly applied in some special fields, especially the medical imaging analysis. Latest studies proposed some segmentation methods based on the adaptive feature learning algorithm (FLA) to solve this problem. For example, Hung *et al.* [30] presented a multi-scale feature learning technique to obtain transformations used for the pixel-wise classifications, and validated that it has the better effect than the traditional method. Bargoti and Underwood [31] proposed an adaptive pixel-level segmentation method based on two FLAs including the multi-scale Multi-Layered Perceptron and Convolutional Neural Networks(CNN), which is a special kind of feed-forward neural network or multilayer perceptron. Although with FLA the region growth method becomes applicable in the fully autonomous image segmentation, there still exist some conditions it has poor effect, for example under conditions of under-exposed and over-exposed images.

B. TARGET RECOGNITION

Target recognition aims to identify the target from the image background. Main methods [32] include shape feature method, template matching method, statistical method, etc. Shape features include global features (such as color [33], texture [34] and shape [35]) and local features (such as corner point [36] and extreme point). Image features are easily affected in the image collecting process, which puts forward challenges for the target recognition: Colour depends on light conditions; Texture features are dependent on image resolution and even affected by illumination; Shape features can also be distorted due to viewpoint changes, leading to recognition failure; Corner point where the gray changes sharply with the direction, is sensitive to scale variations. Compared with global features, local features are not easily disturbed by environmental conditions such as illumination and noise, as well as geometrical changes such as translation, rotation, scale and affine. Therefore, some methods, based on local features have been proposed and widely used, such

as SIFT [37], SURF [38], ORB [39], etc. But these methods need to be further studied to improve the robustness and accuracy of the target recognition. Template matching method is realized by comparing the similarity between the template and the tested image. In most existing studies, similarity comparisons were based on gray image description, which has higher recognition rate under the practical scene with the stable light and fixed position of the view spot.

Statistical method recognize the target through training the classification function using algorithms such as support vector machine (SVM), Bayesian, decision making, neural network [40], [41], and their combination [40] based on image feature data. Neural network is quite commonly studied mainly since it can generalize the information from training images far less than the possible images needed in other machining learning methods such as SVM, Bayesian, and decision making. Fei *et al.* [40] combined the SVM and deep conventional neural network (DCNN) to recognize targets, wherein DCNN is utilized to learn and extract features of synthetic aperture radar (SAR) image, SVM is applied to determine output labels based on recognized features. And he also verified the accuracy of the proposed method by comparing with other algorithms (as Table 2). Vodrahalli and Bhowmik [42] summarized studies related to the computer vision based on deep neural network (DNN), and concluded that the information fusion of the color and depth images based on DNN can improve the accuracy of the target recognition, but the execution efficiency of this method is still an open problem for the visual system with the requirement of high real time performance.

To further improve the reliability of the target recognition, researchers proposed the semantic segmentation, which is the combination of the image segmentation and target recognition, aiming to divide the image into regions with certain semantic categories. Garcia-Garcia *et al.* [48] summarized deep learning methods for semantic segmentation based on 2D data (from gray-scale or RGB images), 2.5D data (from RGB and depth images) and 3D data (from 3D point clouds of volumes), and presented three evaluation metrics of execution time, memory usage and accuracy, and also gave the comparison of the accuracy of previous studies under different datasets, which shows that the highest accuracy for 2D-based and 2.5D-based segmentations reach 91.60 IoU [49] and 58.5 IoU [50], respectively (Intersection over Union, which is a metric used to evaluate the segmentation accuracy). The comparison means that the accuracy for the 2.5D data can be further improved for obtaining higher reliability of the next operation. This study finally presented

TABLE 3. Developments and disadvantages of the representative studies related to existing methods for the computer vision.

Methods for computer vision technology		Developments	Disadvantages
Image segmentation	Threshold Ref.13-17	√ Combining with the inspired algorithms, efficiency is largely improved.	× May fail if the grayscale difference is small or the gray between classes overlaps.
	Edge Ref.18-21	√ It is effective if the grayscale difference is small or the gray between classes overlaps.	× Its reliability and efficiency are largely determined by the size and quality of the training data.
	Region growth Ref.22-25	√ Based on super-pixel and adaptive merging criterion, its reliability is largely improved.	× Its efficiency is lower than other segmentation methods due to iterations.
	Clustering analysis Ref.26-31	√ With the use of CNN, its efficiency is largely improved.	× Its effect is more sensitive to the image quality. × Its reliability is largely determined by the size and quality of the training data.
Target recognition	Shape feature method Ref.37-39	√ Considering local features, its reliability can be improved.	× Its reliability is sensitive to the image quality.
	Statistical method Ref.40-47	√ With the use of DCNN and SVM, its reliability is improved.	× Its reliability is largely determined by the size and quality of the training data.
	Semantic recognition Ref.48-50	√ It has been better used to process the fusion data of RGB and depth images.	× Its accuracy needs to be further improved.
3D location of the target	Stereo matching Ref.51-56	√ Its accuracy is largely improved.	× It has lower efficiency due to more computations.
	RGB and depth image registration Ref.58	√ Use of depth camera largely reduces the cost. √ Its efficiency is more higher due to less computations.	× Its accuracy is largely affected by the quality of both depth and color cameras.

several future research directions including some challenges existed in the point-clouds-based semantic segmentation, techniques of finding a trade-off between accuracy and efficiency, as well as techniques of reducing the complexity of the segmentation networks to overcome memory limitations.

C. 3D LOCATION OF THE TARGET
How to determine the 3D location of the target is always the ultimate goal of the image processing in real applications, based on which the pose of the bolt and locations of obstacles can be calculated for the bolt tightening task. Based on different image-collection principles, methods of the 3D location are definitely different for the BV-based, SLS-based, and TOF-based cameras.

For the BV-based camera, stereo matching was developed to realize one-to-one pixel match of a stereo pair located in two viewpoint color images, after which the 3D location of targets can be calculated based on the principle of binocular parallax. According to the optimization theory, stereo matching include the local [51] and global [52] optimization algorithms. The former only performs the matching operation on the small area around the feature point to be matched, it has advantages of the simple calculation and high execution efficiency, but disadvantages of the low robustness and accuracy for images with partial occlusion, weak texture and repeated regions. The latter is to determine differences for all pixels at ones, through estimating the parallax of pixels and deciding the matching result by minimizing the energy cost function, which overcomes defects of the former but also largely reduces the computing speed due to the complex calculation.

Aiming at reducing the uncertainty of the local approach, some adaptive algorithms have been developed in the latest studies. Hong and Kim [51] summarized these methods and pointed out the conflict between the uncertainty reduction and computing efficiency, and for this problem presented a local algorithm based on texture features to determine adaptive weights, which can remove the noise by controlling the edge awareness, and validated the matching accuracy of the proposed method by comparing with several previous local methods including AdaptWeight [53], GeoSup [54], Inforpeamable [55], and CostAggr [56]. For the Kinect camera, the registration of the depth and color images is the most commonly used method of determining the 3D position of the target, wherein the coordinate system conversion is modelled to make frames of two images completely coincide with each other, and then the 3D location of the target can be determined [57]. The conversion is directly related to the resolution difference of two images, which means that the location accuracy is largely affected by the quality of both depth and color cameras.

D. SUMMARY FOR COMPUTER VISION
Through the above descriptions, we can summarize the developments and disadvantages of the representative studies related to existing methods for the computer vision as listed in table 3. From this table, we can conclude the following challenges when existing methods are applied to the proposed applications.

(1) In the proposed applications, complex operating environments bring major challenges for the recognition and location accuracy of the target. For example, under the
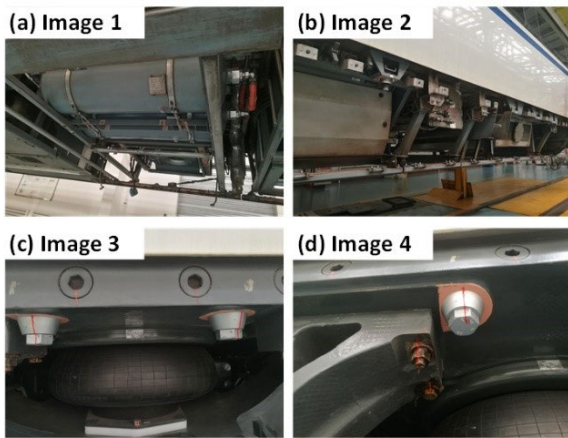
FIGURE 5. Images of bolted structures in the locomotive system.

background of the locomotive maintenance, the image of the bolted structure (images 1 and 2 of Figure 5) always contains the information of many other components except for bolts, which will make the image processing (such as image segmentation and target recognition) much more difficult due to the higher image complexity. In addition, bolts are more densely distributed in most mechanical structures of the locomotive system, which means that we need to separate and locate one more bolts with different types and sizes from the complicated background. That is, the quite complex algorithms will largely reduce the execution efficiency of the image processing system, which means that the absolutely real-time vision feedback cannot be guaranteed using existing methods.

More importantly, the wrong recognition, inaccurate 3D location or delay of the vision feedback will lead to the wrong action of the manipulator, and then the failure of the automatic bolt tightening work, which mostly represents a major accident since it is likely to happen the mechanical damage. In the computer vision system, the image quality can largely affect the recognition rate and 3D location accuracy. However, the high image quality is always difficult to be obtained in the proposed applications. For example, for industrial applications, the connected elements and the surrounding environmental obstacles are mostly metal elements (made of metal like alloy steel or aluminum alloy), which largely limits the use of the depth camera due to the difficulty of avoiding the depth information lose through controlling the light condition according to the actual operating environment. For civil/structural applications, elements and obstacles may be metal elements or concrete structures, the above challenge still exists. Another major problem is the acquisition of high-quality images under the open-air operating environment, which is easily affected by environmental factors such as temperature, light strength, dust, humidity and electromagnetic interference. Therefore, facing these complex environments, one hundred percent of the recognition rate and absolutely accurate 3D location of the target cannot be obtained using the advanced methods, which combined both the color and depth

images or even based on DNN. That is, existing methods are still not reliable or accurate enough for the proposed applications.

(2) For the automatic tightening guided by the robot, we have another task of moving the robotic end effector from the initial pose to the target safely, which means that the information of obstacles existed in the operating environment needs to be determined through the image processing. Obviously, vertexes, edges and planes of the surrounding components of the target bolt are important features of describing the environmental obstacles, but from images 3 and 4 of Figure 5, they are difficult to be separated or even located due to the small grayscale difference and partial occlusion.

III. COLLISION-FREE MOTION CONTROL TECHNOLOGY OF MANIPULATORS

The collision-free motion control of industrial robots aims to guide the safe motion of the robotic end effector from the initial pose to the target pose in workspace. The principal problem associated to this technique is the on-line or off-line collision-free trajectory planning of the manipulator under the complex operating environment. In previous studies, several methods [59] related to this problem have been proposed and developed, mainly including the traditional trajectory planning method (TTPM) [60], Configuration Space Algorithm (CSA) [61], Gradient Projection Method (GPM) [62], Artificial Potential Field Method (APFM) [63], [64], Intelligent Searching Method [65], [66], and sensor/model-based novel methods.

A. TRADITIONAL TRAJECTORY PLANNING METHOD
Existing studies for TTPM of the manipulator concentrate more on the motion efficiency [60], energy consumption [67], motion stability [68], and accuracy [69], but rarely take into account the collision detection or distance calculation between the manipulator and the workspace. Researchers introduced the B-spline and high-order polynomial curves [70], [71] to interpolate the trajectory in joint space, which can largely improve the motion stability through obtaining continuous curves for angular parameters (such as velocity, acceleration, and even jerk), and used intelligent algorithms (like Particle Swarm Optimization (PSO) [69], Ant Colony (AC) [72], Genetic Algorithm (GA) [73], and Neural Network (NN) [74], etc.) to search for the optimal trajectory considering kinematic and dynamic constraints. For example, Gasparetto and Zanotto [75] designed an optimization objective as the weighted sum of the angular jerk and motion time with weighting coefficients determined by practical requirements of the task, aiming to balance the motion stability and efficiency. Gregory *et al.* [76] presented a trajectory planning technique to minimize the energy consumption based on the dynamic modelling under a prescribed path of the robotic end effector determined by obstacles existed in the workspace. With this method, although obstacles located on the end-effector path are considered, we also cannot fully guarantee the safety of the whole system during
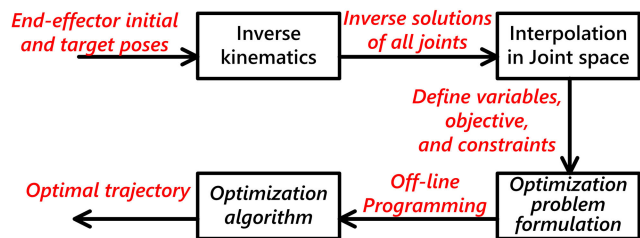
FIGURE 6. Core framework of off-line trajectory planning of manipulators.

the robotic motion. Debrouwere *et al.* [77] proposed a time-optimal trajectory technique taking into account constraints of torque or torque-rate limitations related to angular velocities of joints, which were described by the difference of convex functions to improve the convergence efficiency of the presented optimization method. Abudakka *et al.* [78] introduced a genetic algorithm with parallel populations to search for the optimal-time trajectory with cubic splines, considering constraint limits related to the kinematics (joint velocity, acceleration, jerk), dynamic (torque, power, energy) and payload, which can largely improve the overall performance of the robotic motion, but did not consider the computing cost.

The core framework of the above methods can be expressed as Figure 6, which is significantly helpful for the off-line motion control with obstacle avoidance of robots. In the collision-free trajectory planning, constraints of obstacles is a major problem that needs to be solved in future works [79]. For the constraints of obstacles, methods of collision detection or minimum distance estimation are significant foundations, mainly used to detect the collision occurred between robot and robot, as well as between robot and obstacles, or the potential danger of collision. Note that for the proposed applications, the shortest distance between the manipulator with multiple links and obstacles existed in the workspace needs to be modelled for the absolute safety of the manipulator's motion. In existing studies, researchers used standard geometries (like spheres [80], cylinders, and prisms [81], etc.), convex polyhedrons [82], bounding boxes [83]–[86], and bounding volume hierarchy [87] to describe the simplified model of the manipulator or obstacle, aiming to improve the execution efficiency of the collision detection. The following part briefly summarizes disadvantages of each description method.

The collision detection based on standard-geometry descriptions can greatly improve the efficiency through building simple linear inequalities related to geometric relations [81], but leads to two disadvantages: (1) Over-simplified structures will largely reduce the feasible solution space of robotic collision-free trajectories since collisions might be detected when the minimum distance between the real robot and obstacles is small enough; (2) Since the relative postures between two geometries, for example between two prisms, are extremely complicated, it is difficult to model their minimum distance under different geometric relations.

In earlier studies, Lin-Canny (LC) [88] and Gilbert-Johnson-Keerthi (GJK) [89] algorithms were proposed and widely used to calculate the minimum translational distance between convex polyhedrons. The former searches the nearest feature pair (such as point, edge, and surface) along the object surface and determines it through establishing the vertex-vertex, vertex-edge, vertex-surface criteria. This method needs to traverse all feature pairs and make comparative judgements, which results in a tedious computation and low efficiency. The later was developed based on the convex-polyhedron description and the mesh refinement technique for ease of the representation of non-convex objects. In this method, the distance can be estimated through iteratively searching the closest of two objects with a certain level of mesh refinement. In later studies, some GJK-based methods have been presented to improve the numerical instability and low convergence rate. For example, Montanari *et al.* [90] presented a novel distance algorithm based on signed volumes, and applied to the real collision detection between a Stanford bunny model and eight knots, the total CPU time of the algorithm was reduced by 18 percent (48.1 min) compared with the original algorithm when the number of outer facets was taken by 4.5k. Although GJK is more general and accurate than LC, when it is utilized to the distance estimation between the manipulator and complex workspace with large sizes, a large amount of CPU time and storage are needed during the execution of the algorithm.

To more tightly wrap robotic links or obstacles, hierarchical bounding volumes (HBVs) [87] was developed based on simple bounding volumes including bounding spheres (BV) [83], axis aligned bounding boxes (AABB) [84], oriented bounded boxes (OBB) [85], and discrete oriented polytopes (k-DOPs) [86], which makes it be a geometric description method suitable for both convex and non-convex objects. Its universality and flexibility promote its wide use in the collision detection of manipulators. For BVHs-based methods, the collision between objects can be quickly judged by traversing bounding boxes of nodes and detecting the collision between them, which means that the more refined model can determine the higher detection accuracy but the lower efficiency.

B. CONFIGURATION SPACE ALGORITHM

From the presentation of the collision-free path planning of the manipulator based on CSA [91], the basic idea can be summarized as follows: (1) The configuration space is firstly established by taking the joint coordinate system as the reference frame; (2) The free space is then created through obstacles' mapping and spatial complementary operation; In this step, spatial relations between robotic links and obstacles need to be analyzed, and the boundary function of each joint angle needs to be built by determining its upper and lower critical collision angles. (3) The geometric information of obstacles must be described by defining a data structure to record their occupancy features in the workspace; for this step, skeletal and unit segmentation descriptions were mainly developed to represent the connecting character of the free space and occupancy features of obstacles, respectively.
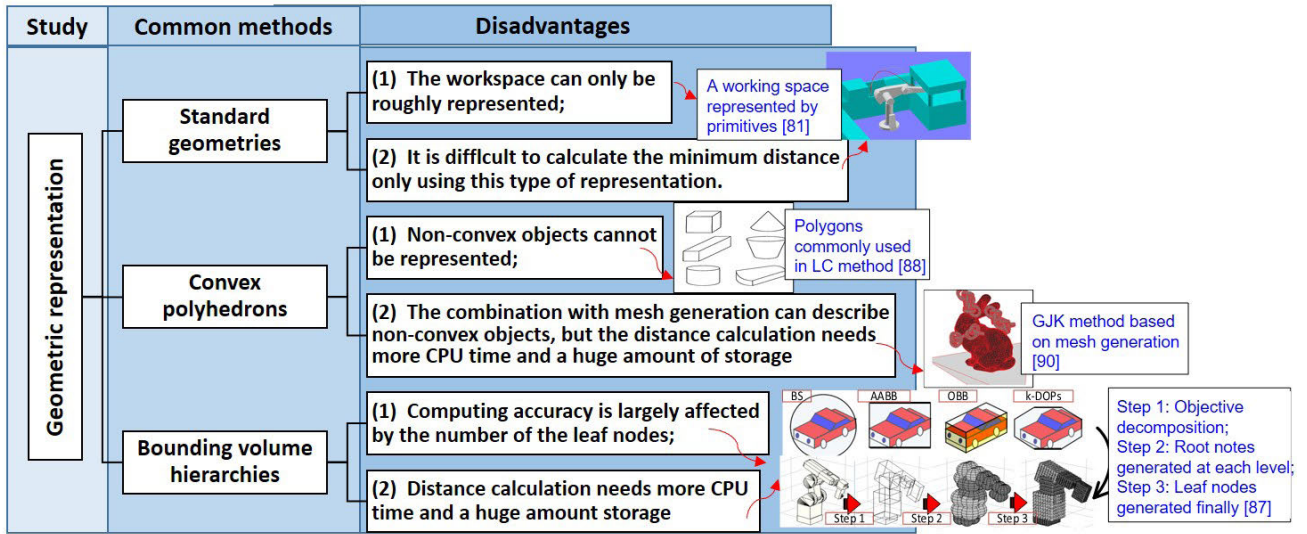
FIGURE 7. Geometric representations of spatial objects used in previous studies and their disadvantages.

(4) Finally, the optimal collision-free trajectory can be obtained using blind and heuristic search algorithms [92].

From these steps, we can obtain two features of CSA: (1) Degrees of freedom (DOFs), configuration of the robot and environmental characteristics can seriously affect the modelling complexity of the free space. Especially, the free space needs to be re-analyzed and re-modelled when the robotic structure and obstacles change, which also limits its application under uncertain operating workspaces; (2) The efficiency and accuracy are directly related to the complexity of the free-space model, the geometric description and search method. For example, the grid method is one type of unit segmentation descriptions most commonly used in previous studies, and it has the lower efficiency but higher accuracy with the smaller grid size. Therefore, this method is unsuitable to be utilized in the collision-free control problem of the robot with multiple bolt tightening tasks under complex and uncertain obstacle environments.

C. ARTIFICIAL POTENTIAL FIELD METHOD

APFM is a method based on the local environmental information, which generate the motion path of the robotic end effector through determining the position increment of the end effector according to the direction of the resultant force of attraction and repulsion defined by the target and the obstacle [93]. Bounini *et al.* [94] summarized the related works of the APFM, and concluded that the traditional method can be easily performed and has the high real-time performance when utilized to the navigation of the mobile robot, but has disadvantages as follows: (1) Under the case of many obstacles, the path search is highly possible to fall into the local minimum, causing the pheromone of robotic oscillation or stagnation; (2) We need to define the minimum distance between the robot and each obstacle to detect the collision and also predict the potential danger in real time. For the first problem, researches have proposed some

improved methods based on some approaches like modifying the potential function, adding virtual targets or obstacles, and combining with intelligent algorithms [63], [64], etc. For the application of this method in the field presented in this work, the true problem is the second one. The real-time estimation of the minimum distance between the manipulator and complex obstacles is extremely difficult, which is the main reason why it is although widely used in the path planning for mobile robots, but limited in the trajectory planning of manipulators with the complex operating environment.

D. GRADIENT PROJECTION METHOD

There exist the infinite inverse solutions for redundant robots under a fixed target position or pose. This flexibility can be utilized to avoid obstacles and singularity in real applications [95]. GPM is an obstacle-avoidance method for redundant manipulators [59], wherein the joint angular velocity was expressed by $\dot{q} = \dot{q}_s + \dot{q}_h = J^+\dot{x} + k(I - J^+J)\nabla H(q)$, $\dot{q}_s, \dot{q}_h \in \Re^n$ are the particular and homogeneous solutions of each joint velocity, respectively, $\dot{x}$ denotes the operating velocity of the robotic end effector, $J \in \Re^{m \times n}$ is the Jacobian Matrix of the robot, $J^+ \in \Re^{n \times m}$ is the Moore-Penrose pseudo inverse of J, $k \in \Re$ is the amplification coefficient, $\nabla H(q) \in \Re^n$ is the gradient of the obstacle-avoidance-index function $H(q)$.

From the principle of GPM, its characteristics include the following points: (1) The obstacle avoidance is realized through the self-motion adjustment of each joint based on a reliable and collision-free path of the robotic end effector; (2) The control needs to a large amount of pseudo inverse computations, and may easily appear problems of divergence and singularity; (3) $H(q)$ is a significant index-model foundation for the collision detection. Indexes commonly used in existing studies (like threshold, minimum distance [96], collision-free area, etc.) can be utilized under point-type or sphere-type obstacles; (4) k controls the

TABLE 4. Advantages and disadvantages of existing methods for the collision-free motion control.

Methods for collision-free motion control	Advantages	Disadvantages
TTPM Ref.67-90	√ The motion efficiency and stability can be both guaranteed. √ Use of the advanced optimization algorithm can largely improve the execution efficiency.	× The reliability of obstacle avoidance and efficiency of the algorithm are largely affected by the constraint modeling of obstacles.
CSA Ref.91-92	√ It is effective and efficient for the manipulator with low DOFs and simple shapes, as well as point-like or sphere-like obstacles.	× It is unsuitable to be applied for high-DOFs manipulator under complex operating environment.
APFM Ref.93-94	√ The local minimum can be avoided effectively by using some advanced methods.	× Except for the above disadvantage, they both cannot control the motion efficiency or stability.
GPM Ref.95-99	√ It can be effectively used to plan the collision-free trajectory for redundant robots.	The same as the above.
Novel methods Ref.100-109	√ The real-time performance can be largely improved by using kinds of novel sensors. √ It can avoid estimating the shortest distance.	× When the manipulator moves with a large velocity, the collision will result in a major damage of the mechanical structure.

changing speed of the obstacle-avoidance index. Its value directly determines the effect of the collision-free trajectory planning; (5) During the execution, both the motion acceleration and operation time are not considered, which means that the motion stability and efficiency of the manipulator cannot be controlled quantitatively during the trajectory planning.

In recent studies, researcher focused on the solution of the third step to improve the generality of this method. For example, Shen and Liu [97] proposed a novel GPM with self-adaptive value of k, which can accelerate the convergence of the optimization problem. Cheng [98] proposed a hybrid index to improve the performance of the obstacle avoidance of the manipulator, evaluating the minimum distance and the collision area under cases that the obstacle is located within and out of the robotic linkage configuration respectively. Combining with the modelling of the minimum distance mentioned above, this method can be suitable to the complex obstacle environments. But for this application, the shortest distance between the manipulator and obstacles needs to be estimated in real time to guarantee the absolute safety of the robotic motion.

E. SENSOR/MODEL-BASED METHOD

In most intelligent assembly applications, the collision-free motion of manipulators can be obtained only based on the accurate poses of 3D obstacles determined by computer vision, as well as the efficient and reliable trajectory control method, which are big challenges for manipulators with complex and unknown environments [99]. To solve this problem, the force/torque sensor [100], [101], micro pressure sensor (electronic skin) [102], and virtual collision sensor [103] have been developed to perceive the minor impact force. Based on the perception of force, the robotic link can adaptively adjust its motion using a closed-loop control method based on the robotic dynamic model [101].

The minor collision can be reliably detected through the dynamics analysis of the robot based on signals measured by the force/torque sensor with the high sensitivity. But the use of the high-quality sensor can largely increase the cost of the

collision-free system. Moreover, the dynamics model used in this approach can be obtained mathematically, but has drawbacks of low generality to robots with different configurations and low accuracy due to simplification and errors of dynamic parameters [104], which will directly affect the reliability of the obstacle avoidance. Many researchers focused on improving the dynamics model by the experimental calibration, which is always a complex and expensive procedure [105]. Also, the complete accurate model cannot be obtained due to the influence of the environmental conditions.

Electronic skin was also developed and has huge potential to change the human-machine interactive way. It can be utilized to perceive the minor force applied on the robotic surface, but its reliability, flexibility and fixed form with mechanical elements must be further improved [106]. With the rapid development of intelligent algorithms such as fuzzy theory [107] and neural network, the non-model-based dynamic model was developed to solve the above drawbacks. Marina *et al.* [103] presented a virtual collision sensor, which detected the collision through comparing a predefined threshold function with a residual term computed based on an robotic internal dynamic model and inputs (motor currents) measured by proprioceptive sensors equipped in joint systems. In this method, the dynamic kinematics of the robot needs also to be analyzed.

F. SUMMARY FOR COLLISION-FREE MOTION CONTROL

Existing methods for the trajectory planning of manipulators and the path planning of the mobile robot are presented and discussed above, based on which table 4 summaries their advantages and disadvantages. From this table, the following conclusions can be obtained considering environmental characteristics of the proposed applications.

(1) For the manipulator, the trajectory optimization has been well developed with objectives such as the operating efficiency, motion stability and accuracy, which can provide a strong foundation for the off-line motion control. In these developments, except for some intelligent optimization algorithms, GPM has also been also developed for searching the

optimal trajectory for the redundant robot. Actually, if the obstacle-avoidance constraint is considered in the trajectory optimization, the problem of the collision-free motion control can be resolved. But from the present status of the modeling of the shortest distance estimation, which is the necessary value of detecting collisions between the manipulator and obstacles reliably, existing methods have their own disadvantages, mainly focusing on the conflict of the computation accuracy and efficiency that determines the reliability and real-time performance of the collision detection respectively. Moreover, from Figure 5 the environmental obstacles are quite complex, which will further limits the application of existing methods. The above discussion means that the shortest distance estimation is still an open problem for the collision-free motion control of the manipulator in the proposed applications.

(2) Some novel collision-detection methods based on force sensors or dynamic modeling have been utilized in the human-robot interaction. These methods will work only when the minor collision happens and their reliability are based on the high sensitivity of the sensor, or the accuracy and efficiency of the mathematical modeling. But, even the minor collision may result in a major accident for the robot or the connected elements. Also the major accident will happen if the feedback of the collision is delayed due to the wrong measurement of the sensor or the wrong prediction of the model. Therefore, these methods are not applicable in the proposed applications at their present status.

IV. PEG-IN-HOLE MATING CONTROL TECHNOLOGY BASED ON ROBOTS

Peg-in-hole mating refers to the process of the peg-hole alignment and accurate insertion. The low precision of the mating may result in the low quality, or even the failure of the bolt tightening, which is the next operation of the bolt assembly. In recent years, the number of researches about the automatic peg-in-hole assembly increases in general (Figure 8), mainly due to the increasing assembly automation in various industries, as well as the rapid developments of technologies of sensors, digital image, and computer. The small amount of papers means that existing results can generally satisfy the basic operating requirements of most modern automated factories, where each robot faces the fixed and simple working environment and performs the single operating task. But, with the extension of the robotic application range, its operating space is getting more complex and uncertain, which will further effectively simulate the development of this technology. Methods [108], [109] including Passive Compliance Control (PCC), Active Control (AC) and Manual Teaching Control (MTC) have been developed to solve the control problem of peg-in-hole mating. For PCC and AC, the mating is achieved by eliminating the deviation between poses of the peg and hole based on the passive and active methods, respectively (Figure 9 [108]). Main previous works are summarized and evaluated as follows.
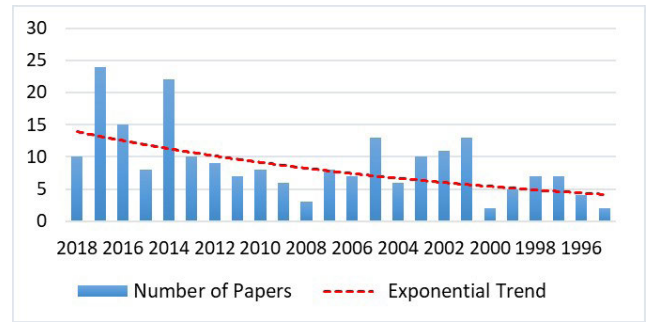

FIGURE 8. Number of researches and the exponential trend about the peg-in-hole assembly in each year. In the paper database of Web of Science paper database, peg-in-hole assembly was used as the subject for retrieval and analysis, and results were mainly focused on four research directions of engineering, robot, automatic control, and computer Science, with a total number of 231.
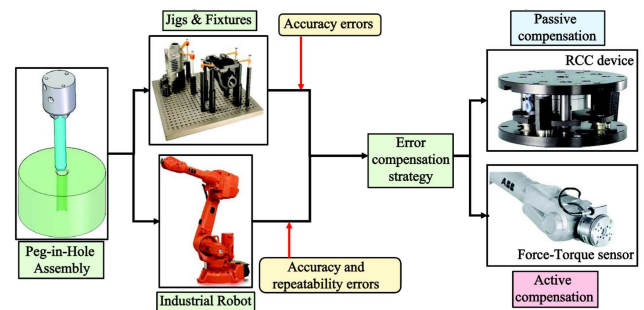

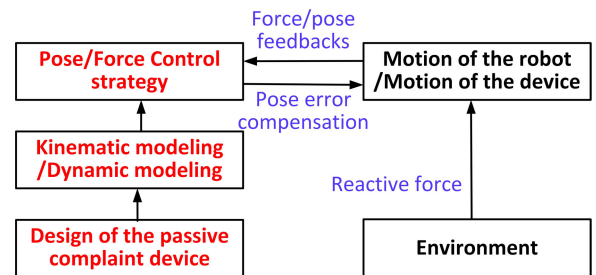**FIGURE 9.** Pose error compensation methods for PCC and AC [108].

FIGURE 10. Main framework of PCC.

A. PASSIVE COMPLIANCE CONTROL METHOD

In the PCC system, a manipulation device with the structural flexibility provided by springs or shear pads is mounted on the robotic end effector, and utilized to naturally accommodate the change of the reactive force caused when contacts is happening between the device and external environments, aiming to compensate the pose error or reduce the mechanical damage during the operation [110]. The main problems for PCC mainly include three points: the design of passive complaint devices, its kinematic/dynamic modeling, and the pose/force control strategy, which are shown in Figure 10.

Whitney developed a remote center compliance (RCC) device with an elastomer shear pad (ESP) (Figure 11a [111]) to solve the peg-in-hole problem. This device can compensate the lateral error through generating the lateral displacement
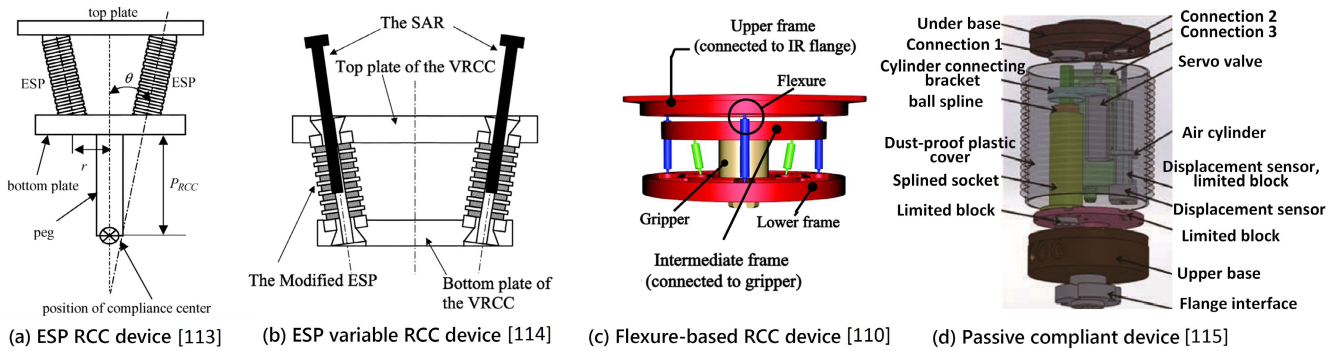
FIGURE 11. Structures of passive complaint structures presented in previous methods, wherein SAR is the stiffness adjustment rod.

(a) ESP RCC device [113] (b) ESP variable RCC device [114] (c) Flexure-based RCC device [110] (d) Passive compliant device [115]

by the force applied on the compliance center. The ESP RCC was then widely used in real assembly line due to its simple structure. But it has the low applicability caused by the fixed position of center and the unchanged stiffness of this device, which largely limits its real applications. To overcome this problem, RCC has been improved in later studies. Lee proposed an ESP variable RCC to adjust the stiffness using a rigid rod passed through the ESP hole (Figure 11b [112]), and validated that the new RCC can easily adjust the position of the compliance center when the operating environment changes. To further improve the mechanism precision, Vaschieri [108] designed a novel RCC device based on flexures (Figure 11c) to reduce the rigid kinematic pairs, which may bring the motion error due to the wear and possible backlash. In this work, he finally analyzed mating processes under different insertion speeds, angular/translational offsets based on the certain friction coefficient through 3D simulations, aiming to show the effectiveness of the proposed device. Since the above designs of RCC increase the flexibility of the system, which make the precise control quite difficult, Huang [113] introduced a passive complaint device (Figure 11d) to realize the force/position control of the polishing robot, which integrated the low-friction cylinder and the displacement sensor. In this system, the passive compliance was provided by the cylinder, which can be adjusted through controlling the air pressure based on the feedback of the displacement variation.

The modeling of the device is a significant theoretical foundation for the precise and efficient mating control, aiming to describe the relation of the pose deviation, insertion speed and parameters of the device, such as the stiffness, damping and inertia. For this problem, researchers have also done some works. Pitchandi *et al.* [114] summarized the previous studies related to this problem, and concluded that the damping property of the compliance material was rarely considered in existing dynamic models. Therefore, he proposed an estimation model of the insertion force for a RCC device, and validated that the proposed model considering damping can effectively reduce the operational vibration and chattering through simulation validations. However, the dynamic model of the RCC device was always conducted based on
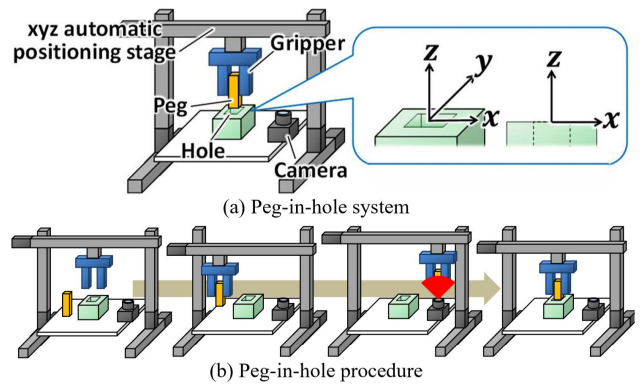

(a) Peg-in-hole system

(b) Peg-in-hole procedure

FIGURE 12. Peg-in-hole system with high applicability and its procedure [115].

the force analysis under different contact stages largely determined by the specific peg and hole, which means it is only applicable to one certain target. To overcome this drawback, Nishimura *et al.* [115] proposed a passive wrist with functions of push, activation and rotation to complete the peg-in-hole mating assembly with different shapes, such as rectangle, circle, hexagon and triangle. In the process, a camera was used to obtain the initial posture of the peg before the mating operation, then an acceleration sensor was utilized to estimate the relative pose of the peg and hole during the mating, finally the contact-state uncertainty was absorbed using the flexibility of the passive wrist. This peg-in-hole system and its control procedure (Figure 12) has the higher applicability to different shapes of pegs and holes.

B. ACTIVE CONTROL METHOD

In existing studies, AC can be completed using two kinds of systems: the active force control (AFC) system and the AC system without the force sensor. In the framework of the traditional AFC system as Figure 13, the force/torque sensor mounted at the robotic end effector is utilized to measure the contact force information; the contact-state monitoring model provides the mapping between the force/torque of the end effector and the pose deviation of two mating objects; the control strategy is designed to adjust the end-effector pose of
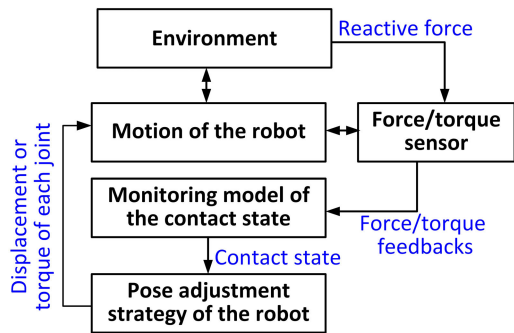
FIGURE 13. Main framework of the traditional AFC system.

FIGURE 14. Dual peg-in-hole assembly system [120].

the robot, which can guide the real robotic motion to complete the peg-in-hole mating. Recently, researchers mainly focus on the contact-state monitoring and the control strategy of the robot to improve the efficiency and reliability of the AFC method.

In recent studies, some theoretical methods have been proposed to estimate the contact state based on the force/torque feedback. Jasim and Plapper [116] proposed a Gaussian Mixture Model (GMM) to determine the peg-hole contact state through monitoring the force/torque sensing information in real time. Subsequently based on the contact state identification, the hole can be found from the search circle with a certain radius using a spiral search method [117]. In this method, the size of the search circle largely affected the peg-in-hole mating time. To overcome the negative influence of the sensor-signal uncertainty on the operating efficiency, Zhao *et al.* [118] introduced the Markov Model (MM) to learn from human skills based on the force/torque information and encode the invisible state of the process, which can largely speed-up the mating assembly. For the same purpose, Tang *et al.* [119] established a mapping between the force/torque feedback and contact states, which were classified into four categories: line contact, single-point contact, two-point contact and three-point contact. Using the same method, Zhang *et al.* [120] provided the mapping model with complex logic computations to estimate the actual contact state for the dual peg-in-hole mating process, and validated the effectiveness through an experimental assembly platform with a force/torque sensor (Figure 14). In this method, the mapping was always obtained based on the force analysis and geometric analysis of all contact states, which relies largely on the specific shape and fit tolerance of the peg and hole. That is, this type of solution has low generality to the problem of the peg-in-hole mating assembly [121], and the complex logic computations will reduce the efficiency of the contact-state monitoring, which may lead to the failure of the mating assembly.

To avoid the contact-state analysis during the mating, Yao *et al.* [122], [123] proposed a six-axis wrist force sensor with the novel prototype to monitor the contact state of the peg and hole directly based on the sensory feedback. The design work of the sensor included the mathematics model and task model of the sensor, models of force and moment
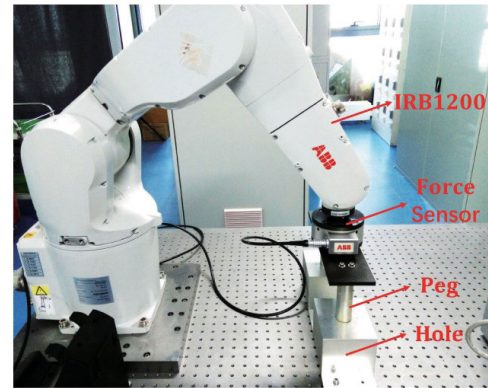
ellipsoids of the sensor, as well as the structural design of the sensor prototype. The experimental results show that the novel sensor was effective in performing the peg-in-hole assembly. However, this sensor has low generality to other assembly tasks, because models of the sensor were established based on the specific task requirements.

Based on the estimation of the contact state, researchers have presented some control strategies to complete the peg-in-hole mating during the through adjusting the robotic pose, mainly including the impedance control and hybrid position/force control [124]. The impedance control of the manipulator can be implemented by firstly establishing the dynamic relation between the pose deviation and the contact force, then based on that controlling the force by updating the displacement or velocity of the end effector based on a desired reference trajectory. This method has the good robustness for disturbances and uncertainties from the operation and data sensing due to the high compliance of the controller, but it cannot precisely control the position and force since the desired reference is difficult to be determined [125]. Song *et al.* [126] used this method to perform the automatic assembly of parts with complex shapes (Figure 15), and concluded that the success rate can reach one hundred percent for the peg-in-hole mating with small orientation errors. As summarized by the reference report [124], an impedance controller alone without position updates can lead to the jamming of two mating parts (especially for that with tight tolerances) when the pose deviation is large. To solve this problem, this work proposed a nested admittance-impedance control controller, wherein the reference state provided for the adaptive controller was firstly determined by theoretical stability bounds obtained using a numeric analysis, then a three-closed-loop controller was designed for the position tracking, the physical coupling and the force tracking. Although this method is effective in solving the peg-in-hole mating problem with large initial pose deviations, its application is limited since the reference state is obtained based on the numeric analysis related to practical assembly boundaries (environmental stiffness and position), which can be different when the operating task changes.
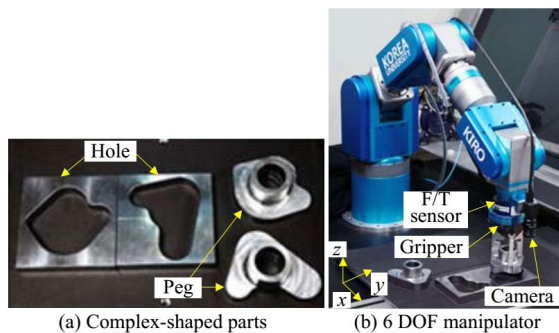
FIGURE 15. Peg-in-hole assembly system with irregular shapes [126].

(a) Complex-shaped parts   (b) 6 DOF manipulator

FIGURE 16. Peg-in-hole assembly system guided by robot with laser tracking device [128].

FIGURE 17. Peg-in-hole assembly system guided by robot with Kinect depth camera [130].

In the hybrid control system, six degrees of freedom of Cartesian space are firstly divided into two categories based on the practical requirement, then for one of them the position control is performed, and for the other one the force control is performed. Wu *et al.* [127] summarized the current research status of this method, which is briefly as follows: (1) Compared with the impedance control, this method can better control the force, and is more suitable for assembly operation with high precision requirements, which has been widely applied by present robot companies (such as KUKA and ABB). (2) This method is still an open problem due to some reasons such as the low response speed and the complex dynamic compensation. And he proposed a control strategy for the high-precision peg-in-hole mating guided by the industrial robot under the high-stiffness environment. But in this work, the complex dynamics analysis is also needed for the gravity compensation and velocity control of the robot, which will affect the reliability and execution efficiency of the controller.

Since high-precision force sensors usually need high cost, some AC systems without the force sensor were also proposed in the previous studies. For some of them, the vision sensor was introduced to measure the relative pose between the peg and hole. For example, Liu *et al.* [128] used the laser tracking system (Figure 16) to accurately measure the relative pose of the peg and the hole, and compensated the pose deviation based on the Jacobian matrix between attitude deviation and joint angles. However, the measurement error of the laser tracking system needs to be analyzed and compensated through several experiments, which limits the practical application of the proposed system. The team [129] proposed another solution for this task, where the laser interference guidance method was utilized to calibrate the geometric feature of the part, and the flexible multi-claw clamping device driven by the stepping motor was designed to grab large parts. This method improved the mating precision, but belongs to PCC, which is disadvantageous to subsequent rigid operations due to the device flexibility. Park *et al.* [130], [131] used a Kinect camera to monitor the pose deviation of two mating objects (Figure 17), based on which the peg-in-hole assembly was then completed through a series of basic unit motions (including pushing, rubbing, wiggling,
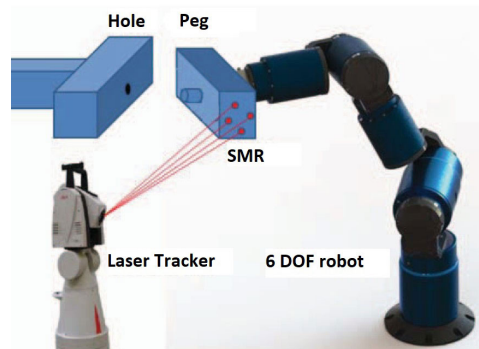
and screwing). But in this work, the controller gain of the system was determined adequately by experimental methods, and its value largely influence the efficiency and reliability of the axial position adjustment, which means that the application of this system will be limited in actual industries. Due to uncertainties of sensors, Cho *et al.* [132] proposed a peg-in-hole control scheme without Cartesian sensor (Figure 18). This scheme designed a disturbance observer by establishing a mapping between force disturbances in joint space and Cartesian space, and adjusted the robotic pose based on joint torques obtained from the current feedback of motors when the contact happens. This scheme largely reduces the cost of the system, but the observer output largely depends on the robotic dynamic model influenced by parameters (like inertia, geometric parameters, structural friction, etc.) of each joint. That is, the inaccurate or complex dynamic model can result in the error or delay of the practical torque prediction, which may lead to the major mechanical damage of the parts.

C. MANUAL TEACHING CONTROL METHOD

In the MTC system, the robotic motion of the peg-in-hole mating is guided by a memory obtained through learning and recording the manual process. Since the force/torque of the end effector directly reflects the contact state of the peg and hole, and the motion trajectory shows the pose adjustment of the peg during the manual assembly, the acquisition of their profiles is important for the successful peg-in-hole mating task. In recent studies, many researchers focus on
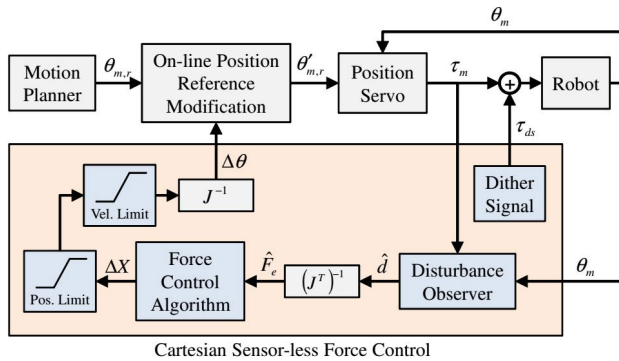
FIGURE 18. Peg-in-hole mating control scheme without Cartesian Force sensor [132].

two problems: how to record the profiles of the trajectory and force/torque during the manual operation, and how to control the robotic motion based on the recorded profiles. Yang *et al.* [109] built a trakstar system to track the Cartesian trajectory, and used the force/torque sensor mounted at the end effector to record the contact states during the operation. To control the robotic motion, he estimated the relative pose of the peg and hole using the vision system, and then adjusted the real robotic trajectory through comparing the force feedback to the recorded reference in real time. Abu-Dakka *et al.* [133] summarized some previous related works and concluded that the vision noise and uncertainties of the grasping action may lead to the failure of the mating operation. In this work, he measured trajectories and forces during the assembly work combining a vision system with force sensors located in the robotic joints, and proposed an approach to iteratively track the learned trajectory to improve the performance of the motion, as well as exception strategies triggered by large force/torque errors, aiming to improve the success rate of the mating. Moreover, experimental results showed that the success rate of the circular peg-in-hole mating task can reach 100 percent.

In latest works, some scholars introduced the intelligent search methods to further improve the adaptability of the mating. For example, Navarro-Gonzalez *et al.* [134] proposed an on-line incremental learning method to overcome uncertainties of sensors (vision system and wrist force/torque sensor), the control system and dynamic model. In this method, the peg-in-hole mating was completed through updating weights of the neural network on-line based on a model criterion and the force data when new situations happened. More importantly, results of several experiments indicated that this method has high adaptability of the mating with different tolerances and geometric features, but the efficiency that largely determined by the evolving level of the controller. Johannsmeier *et al.* [135] provided an overview for the previous studies related to the peg-in-hole assembly, from which we obtained the same conclusion, that is, the use of the adaptive or learning principles can largely improve the generality of the control method, but the efficiency of the operation is affected by the number of trials used for

sampling. In this work, he proposed a novel general operational scheme for the peg-in-hole mating control through combining the skill formalization, meta-learning and adaptive control method to solve this problem. This scheme integrated the process description and quality assessment indicators into an abstract expert knowledge system, which can summarize and evaluate some samples with advanced original parameters. This framework can be utilized to solve the problem of the precise mating, for example that with sub-millimetre tolerances. However, when the condition of the peg-in-hole assembly (like tolerance or geometry) changes, enough operating samples need to be obtained to provide the learning data for the adaptive controller, which means that although the efficiency and success rate of the learning method is quite high, it needs a large amount of time cost before the specific controller is obtained using the proposed learning framework. That is, the MTC based on the learning algorithm cannot solve the problem of the low adaptability of the specific controller, which is determined by a single operating task in the general MTC.

D. NOVEL WORKS RELATED TO PEG-IN-HOLE MATING CONTROL

At present, the haptic virtual reality assembly technology has been rapidly developed [136], [137], mainly based on the tactile sensing, to help users experience and explore the real assembly process in the virtual environment. The development of this technology contributes to the internal law of the peg-in-hole mating process and the exploration of human skills, and provides novel inspirations for further improving and perfecting the automatic assembly.

E. SUMMARY FOR PEG-IN-HOLE MATING CONTROL

By presenting the previous representative studies, the advantages and disadvantages of existing methods for the peg-in-hole mating control are summarized in table 5, from which we can obtain conclusions as follows based on the specific requirements of the proposed applications,

(1) PCC has been developed into an effective and efficient solution for the automated peg-in-hole mating problem with developments of the dynamic modelling and the design of the complaint device. But, when it is utilized to solve the proposed problem, since a device is mounted at the end effector of the robot to tighten the bolt after the bolt/hole and bolt/nut mating, it will be quite difficult to control the great tightening force/torque due to the flexibility of PCC, which means that there still exist big challenges when PCC is utilized in the automated bolt assembly.

(2) Although AFC has been studied in depth, there are still some open problems when it is utilized to solve the peg-in-hole mating problem for the intelligent bolt assembly. (a) For bolts used in different application situations, the type or the fit tolerance may be totally different. But the existing models of the contact-state monitoring, which is a significant step for the traditional AFC strategy as Figure 13, are always proposed for one specific shape. To propose a general monitoring

TABLE 5. Advantages and disadvantages of existing methods for the peg-in-hole mating control.

Methods for peg-in-hole mating control	Advantages	Disadvantages
PCC Ref.112-117	√ The good design and modeling of the complaint device largely improved the effectiveness and efficiency of the mating.	× The force of the end effector is quite difficult to be controlled.
AC Ref.118-134	√ With the development of contact estimation model and control strategy, its reliability and efficiency are largely improved. √ The force of the end effector can be controlled.	× Contact estimation model has the lower generality to bolts with different shapes or fit tolerance. × Methods without force sensors may lead to major collisions.
MTC Ref.135-137	√ Its accuracy rate can reach 100 percent. √ Use of intelligent algorithms improved the efficiency of the mating.	× Use of intelligent algorithms reduced the reliability of the mating.
Novel methods Ref.138-139	√ The haptic virtual reliability can be utilized to explore human skills of the peg-in-hole mating.	× It has not been applied in the real peg-in-hole mating control yet.

method for bolts with an arbitrary shape will be an evaluable work. (b) Although the robotic end effector with the high flexibility (as Figure 15) can be introduced to improve the adaptability of the AFC method, it is limited by the difficulty of the force control in the bolt tightening, which is similar to the use of PCC. (c) In the proposed applications, except for the mating reliability, the mating efficiency is also an important research objective. Both the target search method and the control strategy can be further studied to improve the efficiency of the mating process. (d) High-precision force sensors are expensive, which greatly increase the cost of the assembly system, and can only bear the force/torque less than a certain value. Therefore, the design of the force sensor is also an open problem for the proposed task. (f) To avoid the use of the force sensor, the pose measured by vision sensors, or the torque estimated by the theoretical modeling, is utilized to reflect the real contact situation of the peg and hole in some recent studies. When these methods are applied to the intelligent bolt assembly, the measurement accuracy of the sensor and execution efficiency of the model needs to be further improved to avoid the big mechanical damage due to the error or delay of the feedback.

(3) MTC has been largely developed, and has advantages of high efficiency and high reliability when it is applied to the peg-in-hole mating control under a single operating environment. But in the proposed applications, it is a big challenge to obtain a general and effective controller based on the personnel operating process for multiple tasks with different or uncertain working environment. The haptic virtual assembly technology is an advanced method, and can be used to find and explore human skills of the peg-in-hole process, which will be beneficial for the research of the general control strategy.

V. BOLT TIGHTENING CONTROL TECHNOLOGY OF THE ROBOT-GUIDED SYSTEM

While applying the clamping force in the bolt tightening process, the phenomenon (such as the cross thread, stagnation, slippage, misalignment and so on) is easily happened, which can result in the operational failure. Also, too

small preload cannot satisfy the functional requirement of the connection, and too large preload may lead to the yield deformation or even fracture of bolts. Therefore, to complete the fully automatic bolt tightening is not only based on the high accuracy of pre-actions (visional measurement, robotic motion and bolt/nut mating, etc.) of the tightening, but also the reliability of the bolt tightening control strategy of the robot-guided system. This section firstly presents the bolt tightening process and tightening tools, which are the significant foundations for the revolution from the semi-automatic (HMC-based) to fully automatic operation guided by robots. Then with these foundations, existing control strategies for the automatic tightening procedure are summarized and evaluated.

A. BOLT TIGHTENING PROCESS

The bolt tightening process has always been the research focus in most countries. Important industry specifications have been formed for different usage occasions and working conditions, such as ASME, Garlock, ES and GB/T. Guo *et al.* [138], [139] summarized advantages, disadvantages, and applicable ranges of existing bolt tightening methods commonly used in practical applications, as shown in Table 6. Since the process parameters are important values to guarantee the quality of the bolt tightening, except for values suggested by the specification, a few researchers presented some specific methods to improve the final tightening quality. For example, Zhao [140] took the value for the fit torque of the T/ACM considering the range of the torque sensor, and determined the control range of the torque and angle through the finite element analysis (FEA).

According to the Germany DEUTZ standard, only 10 percent of the external torque can be converted into the clamping force during the bolt tightening. The remaining 90 percent is utilized to overcome the friction between two contact surfaces and between threads [139], which means that the clamping force obtained finally is directly related to the friction coefficient when a certain tightening torque is applied. Since the friction coefficient is largely affected by many factors of the connection such as the machining accuracy of contact

TABLE 6. Comparison of bolt tightening methods commonly used [138], [139], wherein the torque rate means the ratio of the torque and rotating angle, the fit torque is defined to guarantee the sufficient contact between the bolt and the bolt, and it is taken from 25 to 30 percent of the final tightening torque.

Tightening process	Process parameters	Advantages	Disadvantages
Torque control method (TCM)	Preset torque	✓ It is simple and easy to operate; ✓ It can be completed with low cost.	✕ It is largely affected by the torque coefficient; ✕ It needs to control both the accuracy of the tool and the torque coefficient at the same time to guarantee the tightening accuracy (the error can be controlled within about 25 to 40 percent).
Torque/Angle control method (T/ACM)	Fit torque, preset angle or torque rate	✓ It is less affected by torque coefficient; ✓ It has the higher accuracy than TCM.	✕ Its cost is higher than that of TMC; ✕ It is not suitable for segment bolts with small corners, bolts with poor plasticity, and bolts repeatedly used.
Stretch control method (SCM)	Preset elongation or preload	✓ It has higher accuracy than the above two methods (the error is controlled within 10 to 15 percent); ✓ It is suitable for long bolt fastening.	✕ It has higher requirements for the connected structure; ✕ The measurement cost of the bolt elongation is high.
Yield point Control method	Preset torque rate	✓ It has the highest accuracy (the error can generally be controlled within 4 percent)	✕ It may lead to the false yield phenomenon due to the poor surface quality; ✕ It is difficult to be performed due to the unstable change of the torque rate.

surfaces, lubrication, thread quality, and temperature. Some researchers have tried to reveal how these factors affect the clamping force. Hwan-Seon *et al.* [141] analyzed the influence of the temperature ($-10 \rightarrow 50^{o}C$) on the clamping force due to the lubrication effect when the TCM was used to tighten high-strength bolts, finally revealed the linear relation between the ideal clamping force and the temperature. Zhou and Abid [142]–[144] concluded that the SCM can be used to reduce influences of factors on the tightening quality due to the monitor of the bolt elongation.

In real applications, the bolt tightening process can be determined based on existing specifications and studies, synthetically considering factors such as the bolt type, the working condition, the quality requirement of the bolt tightening, and the cost of the control method. But how to determine process parameters of each method is still an open problem for the intelligent bolt assembly.

In the field of bolt assembly, the bolt tightening process is implemented using some tightening devices, such as the manual set-torque wrench, pneumatic wrench [140], and automatic tightening machine, which have advantages and disadvantages listed as Table 7. Compared with the former two, the automatic device has functions of the false torque detection and self-diagnosis, which are realized by the computer control system based on the feedback of torque/angle sensors, and provides the alarm output to effectively avoid the occurrence of unexpected phenomenon. To improve the level of automation, the automatic device has always been designed as a multi-axis system. For example, Wei [145] designed a 3-DOFs tightening system (Figure 19) for the aero engine assembly. At present, it has been widely applied to complete some assembly operations, such as bolting of engines and tires, in the auto-mobile industry of most countries such as Europe, America, Japan and China. The tightening quality of

the device mainly depends on the reliability of the control strategy, the sensitivity of sensors, as well as the reliability of the mechanical system.

B. CONTROL STRATEGIES FOR THE AUTOMATIC TIGHTENING PROCEDURE

In real bolt tightening, uncertainties of sensors and mechanical system can lead to abnormal jointing conditions such as the cross-threading, jamming and slippage of two connected parts, which may largely reduce the connection quality [146]. Therefore, how to reliably detect abnormal conditions and exactly control the process path are significant for the intelligent bolt assembly. In previous studies, some control strategies for manipulators with three or six DOFs have been proposed to solve the above problem. In existing control strategies, the tightening process was always monitored based on the torque or rotating angle measured by sensors during the real operation. For example, the torque rate monitoring was always used under the case with high-accuracy requirements, which can be performed through firstly recording the value of the torque every time rotates a certain angle, and then determining whether the deviation of the torque rate is currently above the tolerance zone determined by the desired torque/angle curve [140]. However, since the sensing data is always unstable due to the dynamic characteristic of the bolt tightening process, some intelligent controllers have been designed to reliably detect abnormal conditions, which can help the connection obtain a precise clamping force and then largely improve the final tightening quality [146]. In the reference report [146], Mrad summarized and evaluated these controllers, including the expert system, fuzzy logic, neural network, as well as self-learning controller and so on, and concluded that the fuzzy logic controller has more simple structure and lower computing complexity than the others.

TABLE 7. Comparison of the proposed IK models and the previous methods.

| Tightening devices		Advantages	Disadvantages
Manual set-torque wrench		√ It is simple to operate.	× Such as high labour intensity, low precision, low efficiency.
Pneumatic wrench Ref.142	Standard	√ Such as low labour intensity, high efficiency, mature technology and corresponding standards.	× Such as short life, high gas consumption and noise, strong vibration and low torque accuracy.
	Hydraulic pulse	√ Hydraulic shock structure and sensor are adopted to overcome shortcomings like short life, high noise and low torque accuracy.	× The clamping accuracy cannot be guaranteed.
Automatic tightening machine		√ Such as low labour intensity, high efficiency, high torque accuracy, low noise.	× Its operational flexibility is relatively low.

(a) Scheme of the automatic bolt tightening system for the aero-engine

(b) Bolt tightening mechanism
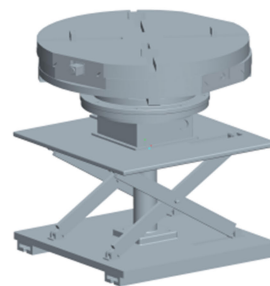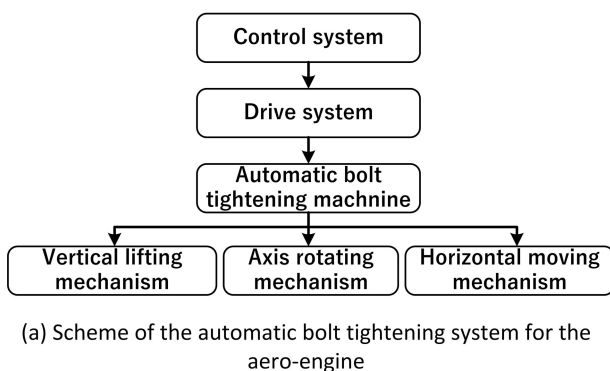
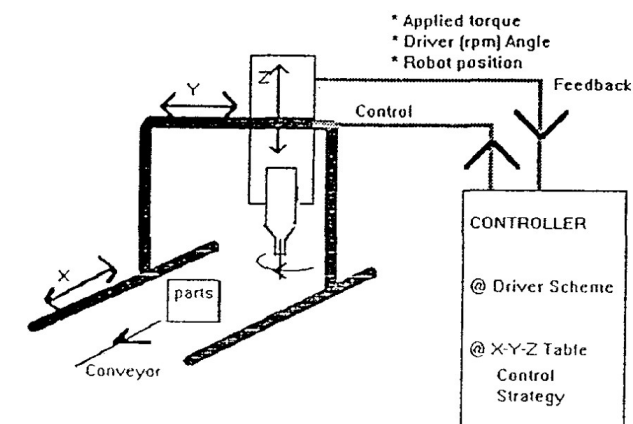**FIGURE 19.** Aviation engine bolt automatic tightening system [145].

FIGURE 20. A 3-DOF manipulator [146], wherein the tightening tool can be precisely positioned in three directions, the drive is equipped with an encoder to provide angular position and angular velocity information of the drive shaft, and the torque sensor is mounted at the end of the drive shaft.

In his work, a closed-loop fastening control strategy was also proposed for the motion control of the 3-DOFs manipulator (Figure 20). Actually, the 3-DOFs manipulators have been well developed into mature products and widely utilized in the real bolt assembly [139], but they cannot be utilized to the assembly task of bolts with the arbitrary spatial pose due to their low kinematic dexterity.

With more DOFs, the 6-DOFs manipulator has the more complex geometric feature and dynamic model, which are

theoretical foundations of the robotic force control. Also, when it is combined with the tightening tool, and applied to the bolt assembly, the coordinated control will be a more complicated problem due to large uncertainties of the mechanical structure and sensing systems. In latest studies, some researchers have tried to solve this problem. For example, Deters et al. [147] presented a model-free fuzzy control strategy for the robot-guided tightening process under the background of the rotor bearing assembly of the wind turbine. This strategy integrates the expertise related to the tightening process and error detection. Müller et al. [148], [149] mounted the manual tensioning cylinder onto the end effector of the robot with sensors such as vision sensor and ultrasonic measurement equipment (Figure 21), and designed an adaptive control method for this assembly system with the same background of Lam's work, and also proposed a technical scheme of avoiding the deviation of the tightening process through analyzing the tolerance chain to further improve the tightening accuracy (Figure 22). Deters et al. [150] presented the self-adjusting proportion-integration (PI) control strategy based on genetic algorithm for the wind turbine bearing assembly.

Compared to other studies, Müller presented the relative complete bolt assembly system with six DOFs, which can be applied to perform the bolt tightening process with the large-torque requirement effectively and accurately. However, from Figure 5 we know that the adaptive tensioning cylinder is a rather complicated system with sensors utilized to monitor
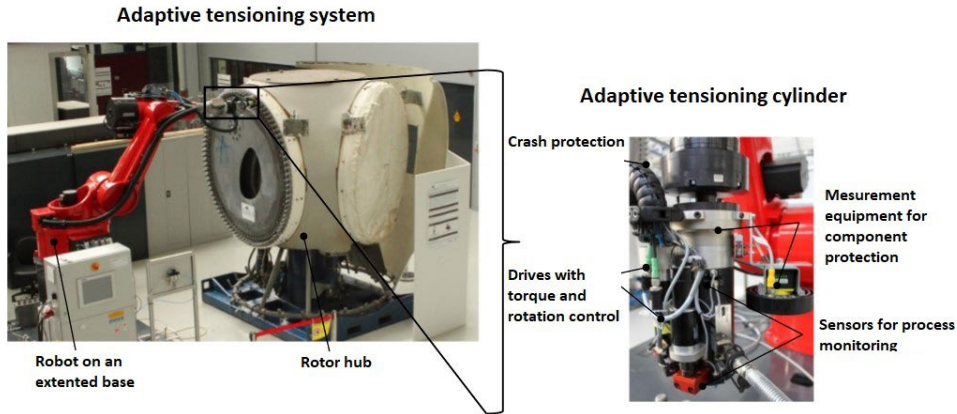
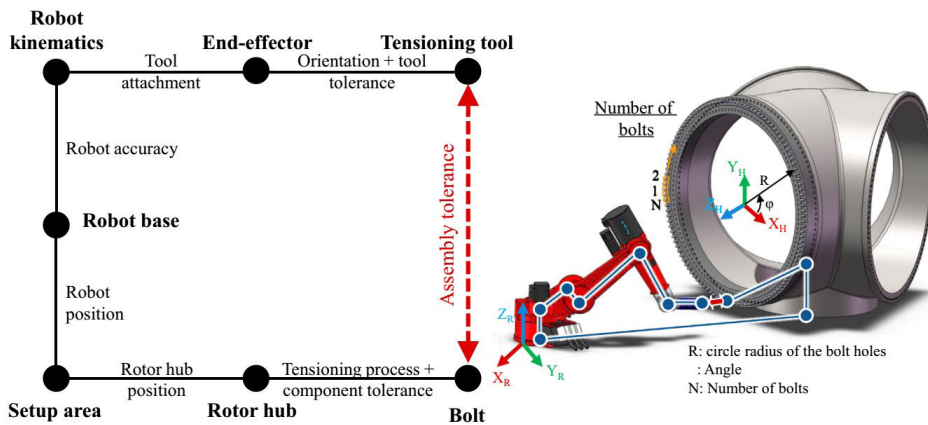**FIGURE 21.** Experimental platform of the robot-guided bolt assembly system [148].

FIGURE 22. Assembly tolerance chain analysis and assembly process parameters [148].

TABLE 8. Advantages and disadvantages of existing methods for the bolt tightening control.

Methods for bolt tightening control	Advantages	Disadvantages
Bolt tightening process Ref.143	√ As a significant foundation, it has been developed into some specifications.	× The effectiveness of existing processes is sensitive to environmental factors.
Semi-automatic bolt tightening Ref.142	√ It is more easier to handle than the bolting guided by manipulators.	× It has lower reliability and operational efficiency.
Bolt tightening guided by 3-DOFs manipulators Ref.147-148	√ It is more reliable and efficient than semi-automatic bolt tightening. √ The control strategy has been well developed and served the real industry field.	× It is not applicable for the bolting under complex environments due to the lower dexterity.
Bolt tightening guided by 6-DOFs manipulators Ref.150-151	√ It is more reliable and efficient than semi-automatic bolt tightening. √ It is more applicable to the bolting under complex environments due to the higher dexterity.	× The bolt tightening system is quite complex. × The control strategy is more difficult than the above methods.

the tightening process and avoid the structural damage, which means that the proposed framework may not be applicable to perform bolting tasks under the complex or small workspace.

C. SUMMARY FOR BOLT TIGHTENING CONTROL

This section presents the existing bolt tightening processes and control strategies. The advantages and disadvantages of existing methods are summarized in table 8, based on which we can conclude that the following problems needs to be further studied to realize the fully automatic bolt tightening procedure.

(1) Bolt tightening processes, as the one direct influence factor of the tightening quality, have been well developed before and formed some specifications for different

applications. However, since the environmental conditions, such as temperature, humidity and vibration interference, can affect the tightening quality, the impacting mechanism of these factors needs to be studied further to help improve the tightening process of bolts under some complex environments.

(2) To improve the efficiency and reliability of the bolt tightening, manipulators with different degrees of freedom (DOFs) were designed and applied to implement the tightening task, and control strategies were developed in previous studies. And only control strategies of bolting manipulators with 3 DOFs have been well developed. But it is largely limited for the proposed applications due to the low dexterity. The control strategy for 6-DOFs bolting manipulators is still an open problem. For example, the bolting device mounted on the robotic end effector is a quite complex system since it needs to connected and communicated to several sensors, which will provide the necessary data for the control strategy.

VI. CONCLUSION AND SUGGESTIONS FOR FUTURE STUDIES

Compared with the general HMC-based bolt tightening, this paper firstly proposes the key technologies of completing the fully automatic bolt assembly using robots, including the computer vision, collision-free motion control, peg-in-hole mating control and coordinated bolt tightening control, and then reviews the latest representative studies of each technology to show their present status, advantages and disadvantages when they are applied to the proposed assembly task. Based on the above summaries and evaluations, this paper further presents the following possible suggestions for future studies, which attempts to help readers broaden their research thoughts and speed up the development of the robot-guided bolt assembly.

(1) From the status of the computer vision, we concluded that existing methods for the image processing are still not efficient, reliable and accurate enough for the vision task of the automatic bolt assembly under complex and uncertain working environments, especially methods based on BV-based system with more complex computations than systems based on the depth camera. To solve this problem, we need firstly design the vision system to obtain the higher-quality images for different applications, considering both the environmental condition of the real application and properties of connected objects. Based on images acquired using the vision system, the combination of the grayscale and depth information can provide a possible way of recognizing and locating the target bolt and obstacles of the operating environment more reliably and accurately.

Besides that, some human experiences of collecting images can be designed to further improve the accuracy of the 3D location. For example, we can approximate the target location using images collected from a remote distance, and then determine accurately its pose using images collected from a close distance. Actually, only the improvement of algorithms cannot make the automatic assembly absolutely reliable.

Since 3D locations of the target and obstacles are measured for control systems of the trajectory motion and peg-in-hole mating, the uncertainty caused by the small location errors can be avoided by designing constraints with the geometric threshold for each control system. In future works, we need also propose some strategies about how to deal with the failure of the target recognition.

(2) From the summary of section 4, it is concluded that existing methods based on the shortest distance estimation (including TTPM, APFM and GPM) are more suitable for the collision-free control problem of high-DOFs (more than six DOFs) robots under complex and uncertain environments. And the shortest distance estimation is still an open problem since an industrial robot has multiple links, as well as environmental obstacles may have complex geometric shapes that can be convex or non-convex. To solve this problem, the combination of the intelligent searching algorithm and BVHs-based distance calculation is one possible way to improve the accuracy and efficiency of the distance prediction. For this way, the intelligent algorithm can be introduced to search for the shortest distance from distances between nodal sets of two objects. The other way of this problem is to establish the shortest distance estimation model based on a certain level of geometric simplifications and mathematical descriptions.

Moreover, compared with 6-DOFs robots the redundant robot has the higher kinematic dexterity, which means that it is more applicable to perform automatic tasks with complex environmental obstacles. For this type of problems, an optimization problem can be formulated to plan an optimal collision-free trajectory for the robot considering both kinematic and obstacle-avoidance constraints.

(3) For the bolt/hole or bolt/nut mating process, the deviation between poses of the mating objects is caused by the measurement error of the vision system and the joint flexibility of the robot. Therefore, we firstly can minimize the initial deviation through the error estimation and compensation of the robotic motion, which can largely reduce the difficulty of the mating control. As summarized in Section 4, although PCC has been well developed, it is still limited in the proposed applications due to its high structural flexibility. For this method, the use of the dual-arm robot is a possible way that can solve the bolt assembly task. Based on the advantage of PCC, in the robotic system one arm can be designed based on PCC to effectively and reliably perform the peg-in-hole mating process, and the other arm can be integrated with the bolt tightening device using a rigid connection to complete the bolting process.

From the summary, we can also concluded that AFC is another possible method that can be utilized to the mating control of the robot with multiple bolt assembly tasks under complex and uncertain environments. But its generality and efficiency need to be further improved by studying the general contact-state model based on the force/torque feedback and introducing some intelligent pose adjustment strategies of the robot. Also, since the force/torque sensor will bear the
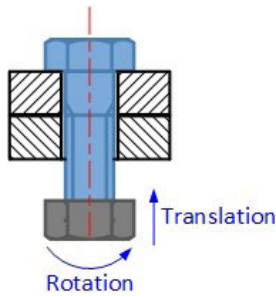
FIGURE 23. Relative motions between the bolt and the nut.

tightening force/torque in the next operation, it needs to be selected considering both the force and torque capacities in the design stage of the bolt assembly system.

(4) In real applications, different types of bolts are used (for example two different types of European pre-loadable bolts [151], HV and HR), and they always have different non-linear behaviours during the tightening operation. The non-linear behaviour of the bolt largely determines the design of the bolt tightening process, which is the main foundation of generating the coordinated tightening control strategy of the manipulator and the tightening device. Therefore, proposing series of control strategies for different bolt types and forming a complete control system for the bolt tightening of different applications can provide a significant theoretical foundation for the intelligent bolt assembly.

Since the bolting process is composed of relative rotation and translation motions between the bolt and nut (Figure 23), the robot-guided system generally uses the robot to implement the translation motion, and the tightening tool to complete the rotation motion, for example systems shown in Müller's works [149], [150]. The work presents two suggestions to improve the tightening accuracy: (1) The translation motion of the robot and the rotation motion of the tightening tool can be planned based on the tightening process. And then the close-loop control method can be designed based on the feedback of the torque rate obtained by monitoring the tightening torque and rotation angle in real time. (2) Since the robotic end effector is under the non-linear and large-load conditions, the motion error caused by the joint flexibility cannot be ignored. In the control system, the estimation and compensation of the motion error can be considered to largely improve the tightening accuracy.

Moreover, we need further improve the applicability of the tightening system to assembly tasks under complex or small workspaces. For example, we can improve the level of integration of the robotic end effector and sensing devices through the design of sensors or the study of assembly methods. We can also reduce the complexity of the tightening system by reducing sensing devices mounted on the end effector by using exact mathematical models of the robotic system. Moreover, the redundant robot can be applied to more flexibly guide the tightening device to the final target pose.

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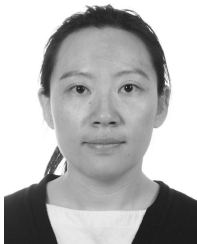
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