Control system of 4-DOF palletizing robot based on improved R control multi-objective trajectory planning

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Abstract
To realize efficient palletizing robot trajectory planning and ensure ultimate robot control system universality and extensibility, the B-spline trajectory planning algorithm is used to establish a palletizing robot control system and the system is tested and analyzed. Simultaneously, to improve trajectory planning speeds, R control trajectory planning is used. Through improved algorithm design, a trajectory interpolation algorithm is established. The robot control system is based on R-dominated multi-objective trajectory planning. System stack function testing and system accuracy testing are conducted in a production environment. During palletizing function testing, the system's single-step code packet time is stable at approximately 5.8 s and the average evolutionary algebra for each layer ranges between 32.49 and 45.66, which can save trajectory planning time. During system accuracy testing, the palletizing robot system's repeated positioning accuracy is tested. The repeated positioning accuracy error is currently 10^{-2} mm and is mainly caused by friction and the machining process. By studying the control system of a four-degrees-of-freedom (4-DOF) palletizing robot based on the trajectory planning algorithm, the design predictions and effects are realized, thus providing a reference for more efficient future palletizing robot design. Although the working process still has some shortcomings, the research has major practical significance.

Keywords
Palletizing robot, trajectory planning algorithm, palletizing function, R control, multi-objective trajectory planning, positioning accuracy, robot control system

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Introduction
With the continuing development of society, the frequency of consumer online shopping has gradually increased, and this has led to accelerated development of the accompanying logistics industry. To increase the support available for logistical functions, palletizing robots have emerged to meet the requirements of the present times. The act of “palletizing” means that, based on the idea of an integrated unit, materials are stacked one by one using a specified pattern, thus allowing logistical activities such as the storage, handling, loading and unloading of materials to be realized

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in a unitary way.\textsuperscript{1} Palletizing robots are mainly used for handling of materials in automated production lines, as illustrated in Figure 1. The palletizing robot is located downstream of the production line and stacks the products delivered from the production line one by one. These products are then transported outward through the production line, waiting for the next logistical operation.

For goods that are small in size, lightweight, nonhazardous and involve a slow production process, manual stacking can be used to achieve the palletizing task.\textsuperscript{2} However, manpower is ultimately limited. When the speed at which the goods are incoming is too high, the manual stacking approach cannot keep up with the pace of production. Improving the speed of manual stacking by investing in more manpower will lead to increased production costs, potential confusion in the production site and increased organizational difficulty, and malpractice leading to production safety accidents will occur more easily. Therefore, the advantages of using automation equipment to stack the materials become obvious, including higher material handling efficiency, lower cost, easier management, material damage reduction, improved forklift truck handling efficiency and a reduced probability of production safety accidents. Traditional automatic palletizing technology uses industrial manipulators, mechanical or hydraulic stackers and similar equipment that can solve the problems caused by manual palletizing well.\textsuperscript{3} However, with the continuing improvements in industrial production efficiency and the increased demand for rapid palletizing and handling, the shortcomings of the traditional automatic palletizers, which include limited working efficiency, singular palletizing capability, large production area occupation and high failure rate, are gradually emerging and demonstrate that this equipment cannot meet the demand for growth in modern production. Simultaneously, the emergence of intensive large-scale material distribution requirements means that palletizing technology with mixed palletizing functionality is needed. These factors have led to opportunities for the emergence and application of palletizing robots. Robot trajectory planning can be divided into joint space trajectory planning and Cartesian coordinate space trajectory planning approaches because of the different planning spaces involved.\textsuperscript{4} Trajectory planning in Cartesian coordinate space requires continuous solution of inverse kinematics problems and the joint value of the joint space must be obtained before planning. Because the trajectory planning for joint space is based on the principles of speed and high smoothness, each joint is required to have the ability to start and stop in a short time and the motion process must be sufficiently stable.

Therefore, based on the application requirements of palletizing robots and the current architectures of algorithmic control systems, a general four-degrees-of-freedom (4-DOF) palletizing robot control system is designed and developed in this work. System palletizing function testing and system accuracy testing of the designed system’s operational performance is carried out and provides a reference and guidance for the development of palletizing robot systems.

\section*{Literature review}

With the ongoing development of the logistics industry, efficiency improvement has become increasingly important. Palletizing robots have flexible operation capabilities that can improve their operating efficiency greatly. Therefore, the research into and design of high-demand palletizing robots has become the top priority for global production line automation. Krug et al.\textsuperscript{4} studied cases of the use of automatic selection and palletizing in 2016 and discussed the lessons learned during the test process for simplification of warehouse settings. Large numbers of experiments were performed to verify their grasping method and an average grasping time of 23.5 s was reported with a success rate of 94.7. Iqbal et al.\textsuperscript{5} studied the applications of robots in 2017 and compared the actual robots used in industry. Their results showed that the food service industry is a new potential application field for robots and that many research opportunities occur through integration of the progress made in different technological fields. Huang et al.\textsuperscript{6} studied the estimation of maximum workpiece flows or part feed rates in multi-robot systems in 2018. Their simulation results were compared with those based on
the Monte Carlo strategy (MCS) and the M/M/1 queue model. The results showed that their method could ensure the efficiency and the task completion rate of the system and the computational time required for the method met the computational time constraint, which was to be less than 1/10 of the time required for the MCS method. Xie et al. proposed a robust cascade path tracking control method to improve the position control performances of networked industrial robots. In a joint task space, a cascade control framework was designed for a robot execution system. The control framework consisted of an inner speed loop and an outer position loop. The results obtained show that this method can improve the dynamic path tracking and robustness of the system under a variety of working conditions.

Experimental procedure

Motion trajectory algorithm

The motion trajectory planning algorithm is the core of an industrial robot control system. A well-designed algorithm not only can make the robot run smoothly and in a co-ordinated manner, but also can optimize the robot’s performance and make up for any hardware defects. At the same time, with the improvements in the hardware performance of industrial robots, it is now possible to use algorithms that could not previously be implemented by these robots because of the high levels of computation required. Therefore, it is necessary to summarize the previous planning algorithms and propose algorithms that offer better planning performance as a result. As the number of trajectory planning algorithms available has increased sharply, it is becoming difficult for the robot trajectory planning process to determine the most suitable algorithm for specific tasks in a specific application process because of the large number of possible algorithms, and thus evaluation of the trajectory planning algorithm is required.

The trajectory planning algorithms for industrial robots must consider many factors, including both static constraints and dynamic constraints. Most of the available algorithms only consider the static constraints, because dynamic constraints require consideration of the real-time nature of the robot, which is highly relevant and brings difficulties in implementation of the algorithm. Depending on the level of analysis required, the constraints are described as follows.

First, it is necessary to consider the basic abilities of the motor. The basic constraints are the motor’s maximum speed and its acceleration capacity, which are given as follows:

\[
\begin{align*}
|v_j(t)| &\leq V_{cj} \\
|a_j(t)| &\leq a_{cj}
\end{align*}
\] (1)

In equation (1), \(j\) represents the \(j\)th joint of the robot, where \(j = 1, ..., N\), and \(N\) is the number of joints in the robot, \(v_j(t)\) represents the speed of robot joint \(j\), \(a_j(t)\) is the acceleration of robot joint \(j\), \(V_{cj}\) is the maximum speed of motor \(j\) that drives the robot joint motion and \(a_{cj}\) represents the maximum acceleration of motor \(j\) when driving the robot joint motion.

In addition, the spatial work of the palletizing robot is another factor that must be considered. Based on the differences in the coordinate space, trajectory planning for a palletizing robot can be divided into joint space planning and right angle space planning. Joint space planning is the motion planning process for one or more joints of a robot. There is no mathematical relationship between the different joint planning quantities. Right angle space planning is the trajectory planning process for the end of the robot and there is a specific mathematical relationship between the final joint planning quantities in this case. From a numerical calculation viewpoint, trajectory planning in right-angled space has more forward and backward kinematics-based solutions than trajectory planning in joint space, while the forward and backward kinematics solutions for the robot are relatively independent parts of the calculation. Therefore, from the trajectory planning algorithm viewpoint, the trajectory planning algorithm for use in right-angled space is consistent with that used in joint space. Therefore, during design of the upper trajectory planning algorithm, the workspaces of the industrial robots can be neglected and only the constraints on specific trajectories should be considered.

Conventional trajectory planning algorithm

Conventional trajectory planning algorithms only consider static constraints, including speed and acceleration. During the trajectory planning calculation process, the position and the velocity of the first and last two points of the trajectory must be satisfied.

The polynomial function programming algorithm is the most commonly used robot planning algorithm. The polynomial function offers the advantages of simplicity, an intuitive nature and ease of calculation, particularly when calculating the derivative of the function. Therefore, it is used widely in trajectory planning for robots. The combined polynomial velocity curve algorithm, which combines multi-segment polynomial functions to form a curve, is used to form a velocity curve to plan the trajectory. The most typical of these curves is the \(s\)-type velocity curve that is generated by combining two quadratic polynomials, while the high-order polynomial velocity curve algorithm uses a high-order polynomial. The acceleration curve is guaranteed to be continuous when higher order polynomials are used to simulate the velocity curve. When the requirements for the motion characteristics of the robot increase, then a
better planning performance is required for the motion planning algorithm. If a higher order polynomial is used, higher orders are required to provide better planning performance. However, improvement of the polynomial order also increases the complexity of the computation and requires more known conditions. The most commonly used method is to use a quintic polynomial as the displacement programming function curve algorithm.

The special function programming algorithm, which uses certain special mathematical functions as speed planning functions, is also applied to robot trajectory planning. During the trajectory planning process for robots, it is a necessary condition that the velocity changes gradually from one value to another and there can be no sudden velocity changes. For example, the trigonometric function velocity curve algorithm and the exponential function velocity curve algorithm are filtered using this necessary condition to determine which velocity function is suitable for robot trajectory planning.

**Dynamic programming algorithm**

The implementation of the dynamic planning algorithm is based on a time division method. The current trajectory planning algorithm only plans the robot’s trajectory from the perspective of the upper algorithm itself, without consideration of the effect of implementation of the lower algorithm on the robot body or of the negative impact of implementation of the lower algorithm on the algorithm itself. In other words, the trajectory planning algorithm above ignores the factors stemming from the robot ontology, such as the influence of the real-time position of the robot on the speed and acceleration in the planning algorithm. The velocity curve for the planned trajectory is fitted using a method of approximation of small straight line segments and the planned velocity curve\textsuperscript{11} is then obtained. Note that the shape of the velocity curve is dependent on the robot’s position and attitude during operation and on the servo motor driving the joint.

**Evaluation model of trajectory planning algorithm**

Common trajectory planning algorithms are generally based on time optimization, path optimization, impact optimization and energy optimization. However, because of the large number of algorithms available during the actual application process, it is unclear which algorithm is most suitable for each specific operation. Therefore, by establishing an evaluation model for the trajectory planning algorithm, different algorithms can be evaluated for specific tasks and the most suitable algorithm can finally be determined.

To date, only a few studies in the literature mention evaluation of the different algorithms, but there are not many types of evaluation algorithm, as shown in Figure 2. The evaluation algorithms have obvious limitations and can only be evaluated with regard to specific constraints. Therefore, it is necessary to establish a general algorithm evaluation model.

**Model of robot electric drive system**

The palletizing robot is coordinated using several servo motors to complete its task. Only the end servo motor can be connected directly to the working mechanism through the reducer, while the other servo motors are fixed on the manipulator. Figure 3 shows a simplified diagram of the palletizing robot structure. Through this simplification, the 4-DOF palletizing robot can be regarded as a complex electric drive system that consists of multiple single-axis electric drive systems.

According to the rotation equation of the uniaxial electric drive system:

\[ T - T_L = J_d \frac{d\Omega}{dt} \quad (2) \]

In equation (2), \( T \) is the output torque of the servo motor, \( T_L \) is the load torque equivalent to that provided by the servo motor shaft, \( J_d \) is the inertia equivalent to that of the servo motor shaft and \( \omega \) is the angular velocity equivalent to the servo motor output.

**Control system model of improved trajectory planning algorithms**

The design of the improved algorithm can be divided into the following steps. The flow chart for algorithm design is shown in Figure 4.
Establishment of the trajectory interpolation algorithm: the various trajectory interpolation algorithms have different effects on the final trajectory of the robot and thus the trajectory interpolation algorithm must meet the kinematics constraints of the robot; Non-dominated Sorting Genetic Algorithm-II (NSGA-II) multi-objective trajectory planning: there are many different objectives in trajectory planning and NSGA-II multi-objective trajectory planning is required to form the solution for the first trajectory on the same level; R-control multi-objective trajectory planning: after the trajectory planning results of the previous step are obtained, the trajectory for the current step is planned according to these results.

System operation test
Based on all the preceding work, the palletizing robot control system was realized and the system was then tested in the production environment. The palletizing test parameters are listed in Table 1.

Results and discussion
In this paper, the algorithm running time and the average evolutionary algebra are used as the performance metrics for the proposed method in the palletizing function test; the results of the system test are shown in Figure 5. In Figure 5(a), the x-axis represents the stacking layer number, where the units are layers, and the y-axis represents the running time, where the units are s. In Figure 5(b), the x-axis represents the stacking layer number, where the units are layers, and the y-axis represents the average evolutionary generation, where the units are generations. According to the design index used in the experiment, the time of the single-step code is 5.8 s. From Figure 5(a), it can be concluded that the time of the single-step code package of the system remains basically stable at approximately 5.8 s. At the same time, Figure 5(b) shows that the average evolutionary algebra result for each layer ranges between 32.49 and 45.66 when using the improved trajectory planning algorithm, which can save trajectory planning time. Therefore, according to the test results, with increasing numbers of stacking layers, the algorithm can always plan the stacking trajectory and control the robot arm to perform the required stacking task and the running time and convergence generation results both remain within an acceptable range, which proves that the proposed method is robust and that it can meet industrial automatic stacking requirements.

In the system accuracy test, the repetitive positioning accuracy of the palletizing robot system was tested. The test results are shown in Figure 6; the x-axis represents the number of stacking layers, where the units are layers, and the y-axis represents the repeated positioning accuracy error, where the units are mm. It can be concluded from the results that the repetitive positioning accuracy errors of the current robots are all within the 10^{-1} mm range; these errors are mainly caused by friction, mechanical processing technology and other factors. Therefore, the accuracy of the proposed system can meet the operational requirements.

Conclusion
The overall scheme and structure of a palletizing robot control system are analyzed in this work. According to the design requirements, the ultimate universality and expansibility of this robot control system are
guaranteed. The novelty and contribution of this paper are described as follows.

First, a B-spline trajectory planning algorithm is used to build the palletizing robot control system and the established system is then tested and analyzed. Second, for optimal trajectory planning for the core problem in the system, other improvements have been made, rather than consider the use of other trajectory information in the palletizing robot operation. In the traditional trajectory planning algorithm, a multi-objective solution method based on R-control is introduced and the trajectory planning results are then input as reference points to influence the direction of the evolution. Third, to improve the trajectory planning speed, R-control trajectory planning is used. If it is found that there are solutions that are larger than a certain proportion near the reference point, the evolution stops and a solution is found in the solution set that can dominate the reference point; this result is then regarded as the result of planning. If it is impossible to find an individual solution that can dominate the reference point, then the individual solution closest to the reference point is found and the target component, which is better than the reference point, is replaced by the reference point, and this reference point is then used for the next evolution. After completion of the algorithm design, simulation experiments were carried out to verify the effectiveness of the algorithm and palletizing function testing and repetitive positioning accuracy testing were also carried out.

In conclusion, the design and analysis of the control system for a 4-DOF palletizing robot in this work have basically achieved the design expectations and the desired effect, which thus provides a reference point for the design of more efficient palletizing robots. However, there are still some shortcomings in the working process. For example, in terms of optimal trajectory planning for robots, the research on the evolutionary algorithm is still insufficient and no improvement or optimization was realized based on the existing algorithm, which means that there is room to improve both the convergence performance and the space search ability. Therefore, the algorithm will be optimized and improved in future work.

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