Obstacle Avoidance Trajectory Planning for Manipulators with Rapid Multi-objective Optimization*

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Abstract—The aim of this paper is to propose a planning method which is used to get an optimized obstacle avoidance trajectory rapidly for a manipulator working in narrow space. In this paper, a local search method basing on high order splines is used to generate an optimized obstacle avoidance trajectory which guarantee the trajectory velocity continuous, acceleration continuous in joint space and minimize the traveling time, the length of the joints and the path length of the end effector. We study the performance of the algorithm proposed in the paper with simulation and experiment which indicate that it is indeed of high convenience and efficiency.

Keywords—manipulator; obstacle avoidance; trajectory planning; multi-objective optimization

I. INTRODUCTION

The ultimate requirement of robotics is to create intelligent robotic systems that can operate autonomously and make the best decisions according to its ability. In most industry applications, the motion of robot is programmed determinately, to do repetitious tasks. In the case of autonomous robots, the robot is provided with only descriptions of tasks on an abstract level and it will carry out those tasks without human intervention or explicit teaching ([17] R. Saravanan 2008). Recent years, with the extensive applications of manipulators in aerospace science, underwater exploration and unclear safety, automatic and optimized motion planning in narrow space is an important research field, where the autonomous robot has to plan its own motions quickly considering all the aspects of its motion. The advanced motion planning problem is described as follows: given an initial configuration and a final configuration of the robot, the robot has to find a path connecting both configurations that avoids collisions with obstacles and in the same time the trajectory has excellent dynamic and kinematic features. Assumptions are that the geometry and the position of obstacles are known in advance and that obstacles are stationary.

There are several algorithms can realize the obstacle avoidance task. GA is a good choice which is adept at multi-objective optimization. Fares J. Abu-Dakka ([1] 2014, [2] 2013, [13] 2016) divides the space into small cubic grids and optimizes the moving time between adjacent configurations with GA. The output of this method is a second order continuous trajectory which has linear acceleration. And in their previous research (Fares J. Abu-Dakka [3]), GA is also used to optimize a cubic spline trajectory to limit its velocity, acceleration, jerk and dynamic features such as power and energy. Biswas et al.[5] studied an optimization problem for a 3-Degrees-Of-Freedom (DOF) spatial manipulator to minimize the energy required by the actuators to perform the desired task. Salgado and Mallea [19] also minimized the energy consumed in the active actuators by planning the best trajectory followed by the manipulator. They did not change the physical dimensions of the manipulator while performing their work. Berntorp K[4] derived an Euler-Lagrange model of the robot dynamics including the energy effect of the obstacles. And by writing it on special form a convex reformulation of the path-tracking problem can be utilized to optimize the moving time. The planning process proposed by Chen C T [6] is composed of searching for a motion ensuring the accomplishment of the assigned task, minimizing the traverse time, and expended energy subject to various constraints. Guo J C [7] proposed a multi-objective method to optimize the trajectory of a three link plane manipulator. But it is too time-consuming to use. When the freedom of the manipulator is more than three or the manipulator is a space structure, the method will be invalid. Haddad M[8] established a cost function to estimate and optimize the trajectory of a mobile robot with a manipulator fixed on. Meligy R E [9] established a time series and use the maximum velocity and acceleration to minimize the moving time of the manipulator. Perumala S [10] used a sphere as the bounding box of the obstacles and plan the jerk limited trace of the end effector of the manipulator in Cartesian space. Parsa S [11] established a polynomial function which is used to smooth the trajectory, avoid the obstacles and joint singularities. Ramabalan S [12] optimized the trajectory with the dynamic function of the manipulator and compared and analyzed two multi-objective evolutionary algorithms. Saravanan R [14-17] proposed a evolutionary trajectory planning method to optimize 6 objective functions, 88 variables, and 21 constraints. Warnakulasooriya S used Particle Swarm Optimization Algorithms to get an ideal time optimal trajectory.

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II. SYSTEM STRUCTURE

The method as mentioned above achieves some effects. But there are three outstanding issues: One is they ignore the collision detection method especially when the manipulator is placed in a narrow space. Another is the efficiency of the algorithm which will decline rapidly when the parameters to be optimized increases. The third one is the dynamic feature of the trajectory which is very important for the manipulator working in high speed or with heavy load. Most of current methods use cubic splines which are not that complex but only second-order differentiable. That means the jerks of the joints are step signals which will affect the performance of the manipulator in some high level cases.

In order to elaborate the method proposed in this paper, we take a manipulator that works with other instruments in a closed box shown in Fig.1 as an example. The manipulator is a 6-dof mechanism composed with an arc slide and five rotate joints. The kinematic model is shown in Fig.2 and the DH parameter is listed in Tab.1.

Fig.1 Structure of the system

It is hard to control a manipulator as the one shown in Fig.1 works in a narrow space that crowded with brittle glasses and delicate instruments. The manipulator is too easy to make an interference with the obstacles to achieve the aim point from the initial point safely. So, how to plan a trajectory that avoids the obstacles with excellent dynamic property and in the same time obtain the optimized geometry magnitude and time magnitude of the trajectory is the aim of this paper.

Fig.2 Kinematic model of the manipulator

| Tab.1 DH parameter of the manipulator |
|-----------------------------|----------------|----------------|
| Axis | \( a_{i-1} \) | \( \alpha_{i-1} \) | \( d_i \) | \( \theta_i \) |
| 1   | 0              | 0              | 0    | 0    |
| 2   | \(-L_0\)       | 0              | \(L_1\) | 0    |

3 0 -90° 0 0
4 \(L_2\) 0 0 0
5 0 90° \(L_3\) 0
6 0 -90° 0 0
End 0 90° \(L_4\) 0

The remainder of this paper is organized as follows. We start by discussing a new collision detection calculation method in Section 2. A rapid multi-objective obstacle avoidance optimization algorithm is explained in Section 3. In Section 4, we discuss application examples and simulation results. And conclusion is in Section 5.

III. RAPID MULTI-OBJECTIVE OPTIMIZATION METHOD

We define the trajectory with high order splines in joint space firstly. That’s because the spline trajectory in joint space is beneficial to the velocity, acceleration and even jerk property of a joint. And then we extract the unknown parameters, estimate them, and change the parameters to generate a trajectory that avoids the obstacles and in the same time minimize the time and distance manipulator moves.

A. Definitive Spline Planning Strategy

Trajectory planning in joint space is conducive to promoting the dynamic property of the manipulator such as speed and acceleration. The RMOM method assume that there is a middle point corresponding to a state vector in the joint space of the manipulator that connect the start joint state and the end joint state with two sets of high order splines. The middle point state vector moves and distorts to conduct the trajectory to avoid the obstacles. When the circumstance is too complex to avoid all the obstacles, we could constantly set another middle point to connect previous middle point and the end joint state until the trajectory avoids all the obstacles. The sketch map of RMOM method is shown in Fig.6.

Fig.6 Sketch map of continuous obstacle avoidance principle

It assumes that there are \(n\) middle points. For the \(jth\) joint at the \(ith\) middle point, the mathematic description of the previous trajectory can be written as,

\[
\theta_{j,i,j+1}(t) = a_{j,0} + a_{j,1}t + a_{j,2}t^2 + a_{j,3}t^3 + a_{j,4}t^4 \quad (0 \leq i \leq n)
\]

(1)

Where \(a_{j,0}, a_{j,1}, \ldots, a_{j,4}\) are constants that given as:
where \( a_{j,0} = \theta_{j,i} \) \hspace{1cm} (2)
\[ a_{j,1} = \dot{\theta}_{j,i} \] \hspace{1cm} (3)
\[ a_{j,2} = \ddot{\theta}_{j,i} / 2 \] \hspace{1cm} (4)
\[ a_{j,3} = (4\ddot{\theta}_{j,i} - \dot{\theta}_{j,i+1}T_i - 4\dot{\theta}_{j,i} - 3\ddot{\theta}_{j,i}T_i - \dot{\theta}_{j,i}T_i^2) / T_i^3 \] \hspace{1cm} (5)
\[ a_{j,4} = (\dot{\theta}_{j,i+1} - 3\dot{\theta}_{j,i}T_i + 3\dot{\theta}_{j,i}T_i^2 + 2\ddot{\theta}_{j,i}T_i + \dot{\theta}_{j,i}T_i^2 / 2) / T_i^4 \] \hspace{1cm} (6)

\( T_i \) is the execution time in the \( j \)th section spline trajectory from point \( i \) to point \( i+1 \). Where \( \theta_{j,i} \), \( \dot{\theta}_{j,i} \), \( \ddot{\theta}_{j,i} \) are known quantities of the start joint state or previous middle vector state. \( \theta_{j,i+1} \), \( \dot{\theta}_{j,i+1} \) are unknown quantities of the middle joint state. \( \ddot{\theta}_{j,i+1} \) can be obtained as:

\[ \ddot{\theta}_{j,i+1} = 2a_{j,2} + 6a_{j,3}T_i + 12a_{j,4}T_i^2 \] \hspace{1cm} (7)

For the \( j \)th joint at the \( i \)th middle point, the mathematic description of the back trajectory can be written as,

\[ \theta_{j,i+1}(t) = b_{j,0} + b_{j,i}t + b_{j,i+1}t^2 + b_{j,i+2}t^3 + b_{j,i+3}t^4 + b_{j,i+4}t^5 \]
\hspace{1cm} (0 \leq i \leq n) \hspace{1cm} (8)

Where \( b_{j,0}, \ldots, b_{j,4} \) are constants that given as:

\[ b_{j,0} = \theta_{j,i} \] \hspace{1cm} (9)
\[ b_{j,1} = \dot{\theta}_{j,i} \] \hspace{1cm} (10)
\[ b_{j,2} = \ddot{\theta}_{j,i} / 2 \] \hspace{1cm} (11)
\[ b_{j,3} = (20\ddot{\theta}_{j,i} - 20\dot{\theta}_{j,i} - (8\ddot{\theta}_{j,i+1} + 12\dot{\theta}_{j,i})T_i - (3\dddot{\theta}_{j,i} - \ddot{\theta}_{j,i+1})T_i^2) / 2T_i^3 \] \hspace{1cm} (12)
\[ b_{j,4} = (30\dot{\theta}_{j,i} - 30\dot{\theta}_{j,i+1} + (14\dddot{\theta}_{j,i} + 16\dot{\theta}_{j,i})T_i + (3\dddot{\theta}_{j,i} - 2\dddot{\theta}_{j,i+1})T_i^2) / 2T_i^4 \] \hspace{1cm} (13)
\[ b_{j,5} = (12\dddot{\theta}_{j,i} - 12\dot{\theta}_{j,i} - (6\dddot{\theta}_{j,i+1} + 6\dot{\theta}_{j,i})T_i - (\dddot{\theta}_{j,i} - \dddot{\theta}_{j,i+1})T_i^2) / 2T_i^4 \] \hspace{1cm} (14)

Where \( \theta_{j,i+1}, \dot{\theta}_{j,i+1} \) are unknown quantities. So if the trajectory has \( n \) middle points, \( m \) joints, and \( p \) degree of freedoms, the number of unknown quantities are:

\[ \text{Num} = 2m + (m - p) + (n + 1) \] \hspace{1cm} (15)

Taking a 6-dof manipulator for example, \( m = 6 \), \( n = 1 \), \( p = 6 \), the parameters to be determined is \([q_1, q_2, q_3, q_4, q_5, q_6, \dot{q}_1, \dot{q}_2, \dot{q}_3, \dot{q}_4, \dot{q}_5, \dot{q}_6, v_1, v_2, v_3] \). Where \( q_1, q_2, q_3, q_4, q_5, q_6 \) are the joint angles, \( \dot{q}_1, \dot{q}_2, \dot{q}_3, \dot{q}_4, \dot{q}_5, \dot{q}_6 \) are the joint velocities, and \( t_1, t_2 \) are the moving time of previous and back segment of trajectories.

\[ \dot{q} = J^{-1}(q)V \] \hspace{1cm} (17)
\[ V_{\nu} = s \cdot [v_x, v_y, v_z] \] \hspace{1cm} (18)

In which, \( \dot{q} = [\dot{q}_1, \dot{q}_2, \dot{q}_3, \dot{q}_4, \dot{q}_5, \dot{q}_6] \), \( J^{-1}(q) \) is the Jacobin matrix at the joint angles of \( q_1, q_2, q_3, q_4, q_5, q_6 \). And \( V_{\nu} \) is the speed vector of the end effector. \( s \) is the speed value of the

B. Parameter Estimation

The GA method proposed by QI[20] and Fares J. Abu-Dakka [13] is excellent but time consuming. But experiment and simulation testified that when the number of the unknown quantities is large and when the manipulator moves in 3D space, it is very hard to get a feasible solution to search in the total solution space randomly. We used an excellent supercomputer to search the feasible solution of the fourteen quantities in section 3.1, which is so called the initial population of the GA method. But we only got 8 feasible solutions in an entire time about 11 hours. Tested by experiment, it can not be used in a 6-dof manipulator for the time complexity increases exponentially. In face, there are inner relations between the parameters which we can use to promote the calculation speed. In this section, we discuss the relationship between the parameters and establish the method to optimize the parameters quickly. The sketch map of the end path in Cartesian coordinate system is shown in Fig.7.

![Fig.7 Sketch map of the End Path in Cartesian Coordinate](image)

When estimating the joint velocity parameters \( \dot{q}_1, \dot{q}_2, \dot{q}_3, \dot{q}_4, \dot{q}_5, \dot{q}_6 \), we abandon the direct estimation which choose one random value between its minimal and maximum limit values. For this method has to estimate six parameters without considering their relationship which would cause low successful rate to get the optimal parameters. When the joint angles \( q_1, q_2, q_3, q_4, q_5, q_6 \) are estimated, the end position of the manipulator could be calculated by the kinematics.

\[
\begin{pmatrix}
P_x \\
P_y \\
P_z \\
0 \\
0 \\
1
\end{pmatrix} =
J^T(q_1)J^T(q_2)J^T(q_3)J^T(q_4)J^T(q_5)J^T(q_6)
\begin{pmatrix}
P_x \\
P_y \\
P_z \\
0 \\
0 \\
1
\end{pmatrix}
\] \hspace{1cm} (16)

\( P_x, P_y, P_z \) are the position of end effector in Cartesian coordinate. When the end effector moves in different direction with different speed, the joint velocities \( \dot{q}_1, \dot{q}_2, \dot{q}_3, \dot{q}_4, \dot{q}_5, \dot{q}_6 \) would have a set of corresponding values. According to Jacobin matrix which is the relationship between the velocity of the end effector and the joints, the six parameters could be estimate as,

\[ \dot{q} = J^{-1}(q)V_{\nu} \] \hspace{1cm} (17)
\[ V_{\nu} = s \cdot [v_x, v_y, v_z] \] \hspace{1cm} (18)

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speed vector and \([v_x, v_y, v_z]\) is the unit vector of the direction. For \(v_x^2 + v_y^2 + v_z^2 = 1\), \(v_x\) could be known when three parameters \(s, v_x, v_y\) is determined. Hence the estimation of the six parameters could be substituted by the three parameters with two other limit conditions,

\[
V_x \in (V_{\min}, V_{\max})
\]

\[
\dot{q}_i \in (\dot{q}_{i,\min}, \dot{q}_{i,\max})
\]

The initial value of \(s\) could be \(3 \times |V_x| / 4\). Even though the other parameter \(t_1, t_2\) could not be calculated accurately, the possible value could be estimated as initial values to be optimized. \(t_1\) and \(t_2\) could be estimated as,

\[
t_1 = \max\left[\frac{1}{2}(q_{i,\init} - q_{i}) / \dot{q}_{i}\right]
\]

\[
t_2 = \max\left[\frac{1}{2}(q_{i,\end} - q_{i}) / \dot{q}_{i}\right]
\]

So far, the fourteen parameters listed at the end of section 3.1 to be optimized can be listed as \([q_1, q_2, q_3, q_4, q_5, q_6, v_x, v_y, v_z]\), the other parameters \([\dot{q}_1, \dot{q}_2, \dot{q}_3, \dot{q}_4, \dot{q}_5, \dot{q}_6, t_1, t_2]\) could be got indirectly.

C. Multi-objective Optimization Method

C.1 Optimization Process

For getting the optimized solution, a multi-objective optimization method is proposed to get the optimal solution.

The flow chart of RMOM is shown in Fig.8. Firstly, we generate \(n\) groups random solution of \([q_1, q_2, q_3, q_4, q_5, q_6, v_x, v_y, v_z]\), and get \([\dot{q}_1, \dot{q}_2, \dot{q}_3, \dot{q}_4, \dot{q}_5, \dot{q}_6, t_1, t_2]\) indirectly by (17)–(22). The larger the integer parameter \(n\) is, the more possible the random solutions include the best solution. But if the group number is larger, the optimize process would consume more time. So we can choose the number of parameter \(n\) according the optimized accurate, the operational capability of the CPU and endure level of the operational stuff. However, for the joint rotation range of most manipulator is smaller than or equal to 360 degrees and the RMOM is a local optimization method, we recommend the parameter \(n\) is 200.

We establish an equation that accesses the trajectory shown as (23). In which, \(f_{ob}\) is the collision state of the trajectory. \(f_{o}\) characterizes the torque exceeding state. \(f_0\) is the trajectory length of the manipulator end. \(f_s\) is the summation of the joints moves. \(f_i\) is the time that manipulator moves. It is the sum of \(t_1\) and \(t_2\) as shown in (24). \(f_o\) is the total evaluation value of a trajectory. \(\eta_1, \eta_2, \eta_3, \eta_4, \eta_5, \eta_6\) are the weights of corresponding parameters. They could set according to the actual needs. Which aspect we care about more, which weight we would set larger.

\[
f_G = f_{ob} / (\eta_1 f_{t_0} + \eta_2 f_{t_1} + \eta_3 f_1 + \eta_4 f_i)
\]

\[
f_i = t_1 + t_2
\]

C.2 Trajectory length of the Manipulator End

The interrupt period \(T\) of the manipulator is a fixed value defined by the robot system. For a set of trajectory composed by a forward segment and a latter segment, the moving time are \(t_1 / T\) and \(t_2 / T\) separately. For the \(i\)th interrupt period, substitute the time constant into equation (1) and (8) to get the six joint angle values. According to the DH parameters and kinematics, the position and posture can be expressed as,

\[
\hat{T}_n = \hat{T}(q_1) \hat{T}(q_2) \hat{T}(q_3) \hat{T}(q_4) \hat{T}(q_5) \hat{T}(q_6)
\]

\[
= \begin{bmatrix}
    r_{11} & r_{12} & r_{13} & p_x \\
    r_{21} & r_{22} & r_{23} & p_y \\
    r_{31} & r_{32} & r_{33} & p_z \\
    0 & 0 & 0 & 1 
\end{bmatrix}
\]

In which, \(p_x, p_y, p_z\) is the end position of the manipulator in Cartesian space. The trajectory length of the manipulator end,

\[
f_i = \sum_{i=0}^{b_i + b_{i+1}} \left[(p_x - p_{x_{i-1}})^2 + (p_y - p_{y_{i-1}})^2 + (p_z - p_{z_{i-1}})^2\right]
\]

C.3 Torque exceeding limit

According to the dynamics of the manipulator, \(M(\theta)\) is the inertial matrix, \(B(\theta)\) is the Coriolis force matrix, \(C(\theta)\) is the centrifugal force, \(G(\theta)\) is the force of gravity. So the torque of the joints can be computed by equation (25) in every interrupt period. \(\dot{\theta}\) can be computed by equation (7) and the second order derivative of equation (1) and (8). \(\ddot{\theta}\) can be computed by the first order derivative of equation (1) and (8).

\[
\tau = M(\theta) \ddot{\theta} + B(\theta)[\dot{\theta}] + C(\theta)[\dot{\theta}] + G(\theta)
\]

We use \(\tau_{ij}\) to illustrate the torque of the \(j\)th joint in the \(i\)th interrupt period. \(\hat{\tau}_{ij}\) is the maximum limit value of the joint \(j\).

\[
f_{\text{ob}} = \sum_{i=0}^{b_i + b_{i+1}} \sum_{j=1}^{6} \left|\tau_{ij} - \hat{\tau}_{ij}\right| \text{ (if } \tau_{ij} > \hat{\tau}_{ij})
\]
C.4 Angles Changing in Joint Space

The joint changing angles $f_q$ is the summation of the six joints changing in every interrupt period.

$$f_q = \sum_{i=0}^{j_1} \sum_{j=0}^{j_2} |q_{i,j} - q_{i-1,j}|$$

(29)

In which, $q_{i,j}$ is the angle of the $j$th joint in the $i$th interrupt period.

C.5 Interference Judgment

The method of interference judgment is described in section 2. When the manipulator collides with the environment, the interference judgment parameter $f_{ob}$ is 0. Otherwise it is 1.

IV. Experiment

To test the effectiveness of the method proposed in this paper, we design two typical working conditions. In this two working conditions, the manipulator is expected to start from different initial states and moves to the same ending states avoiding the obstacles in its environment. We inspect the trajectory in three aspects: obstacle avoidance capability, trajectory dynamic property and consuming time.

A. Trajectory Generation Experiment

Using the method proposed in this paper, we get the optimized trajectories as shown in Fig.9 and Fig.10. The changing states of position, speed and acceleration of the two experiments are shown in Fig.11-16. From the results, we can find that the manipulator moves with high order continuous dynamic features and in the same time avoid collision with surrounding obstacles. An Intel i7 2.2GHz Processor that we use can do the calculation cycle up to 50 times in 6 seconds to optimize 200 sets of random solutions and get the optimized result.

As shown in Fig.9 and Fig.10, the manipulator works in an inclosed cabinet in which there is a set of scientific instrument living a relative narrow space for the manipulator to move in. For experiment 1, the manipulator starts from [1.4344, -96, -36, 138, 24, 78]. For experiment 2, the manipulator starts from [97.4344, 48, -42, 126, 18, 48]. In these two experiments, the aims of the manipulator are all [127.4344, -66, -27, 150, 27, 36].

B. Trajectory Optimization Experiment

Taking the experiment 1 for example, the optimization process of the manipulator trajectory is shown in Fig.11 and Fig.12. In the process of the 50 times optimization, every random solution corresponds to an evaluation value. The Lines drawn in Fig.13 are the average numbers of the 200 evaluation values. In Fig.13(a), we can see the reciprocal number of the total evaluation value decreases quickly. It denotes that the denominator of equation (23) decreased by the method proposed in this paper.

Real experiments were taken in a glove box with scientific instruments in it, as shown in Fig.14. The experiment proves the algorithm proposed in this paper is useful and applicable.
obstacles. But with several optimization cycles, the solution will be better. So we can set the optimization cycle time according our need and endurance to wait a better trajectory.

VI. CONCLUSION AND FUTURE WORK

Every random solution, which has a nonzero total evaluation value, is a feasible solution that could conducts the manipulator moving with high order dynamic features and avoiding the

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