Path Planning for Multi-Joint Manipulator Based on the Decomposition of Configuration Space

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***Abstract*—The problem of collision-free path planning for six joints manipulator used for nuclear reactor repairing was considered, a new approach based on the decomposition of configuration space was presented in this paper. Since the collision with the environment occurs mainly on the three joints near the proximal joints of manipulator, the six dimensional configuration space was decomposed into two three low dimensional subspaces. Respectively, the discrete configurations were generated in each subspace for the local path searching, then a collision table was set up for the on-line path planning. In order to reduce the size of collision table and avoid the redundant collision checking, in the process of sampling configuration, we check the collision status of these points and avoid the collided configuration points to be generated in the collision table. In order to further improve the reasonability distribution of sampled points, we used the distance information with the obstacle to guide the generation of configurations. The simulation results showed that the approach not only reduced the length of searing path, but also improved the efficient of on-line planning.**

Keywords-manipulator; path planning; configuration space ;collision check; collision table

I. INTRODUCTION

Collision-free path planning is the hot topic for multi-joint manipulator accomplishing automatically task. The high dimensional space of manipulator makes that the path planning problem become more difficult. Many researchers present some planning strategies, such as the potential field method[1-2],the cell decomposition[3-4],the probabilistic roadmap method (PRM)[5-7] and the rapidly exploring random trees(RRT)[8-10].

Since the simplicity and realization of the potential-field approach, it is widely used for robots. But the main disadvantage is that the presence of local minimum. The idea behind cell decomposition methods is to partition the whole configuration space into some cells. The algorithm complexity will greatly increase in high dimensional space. So some efficiently strategies based on sampling technique are addressed, such as the PRM and RRT. Karvraki presented the PRM that consists two phases: a learning phase and a query phase. And several improved algorithms are addressed in [6] and [7].

In this paper, consider that the six joints manipulator always moves inside the quarter wall ball in a bending posture and high dimension searching space. We decompose the whole configuration space into two three dimensional subspaces. Respectively, we carry out the path planning in each subspace. This method consists two phases: an off-line learning phase and an on-line query phase. In the first phase, the discrete configurations are sampled in each low dimensional subspace. And the collision table is built for the on-line query phase. In order to reduce the size of collision table and avoid the redundant collision- checking, in the process of sampling configurations, we check the collision status of these points and avoid the collided configuration points to be generated in the collision table. At the same time, we use the distance information with the obstacle to guide the generation of configurations in order to improve the reasonability distribution of the sampled points. In the on-line phase, the paths can be found using the collision table. At last, we carry out the simulation with the introduced method.

II. The MODEL OF MULTI-MANIPULATOR USED FOR NUCLEAR REACTOR REPARING

This manipulator consists of six articulated joints, as shown in figure1.And the center of those joints are the points of B、C、 D、 E、 F and G. And the length of joints are represented by L_{Gf} 、L_{FE} 、L_{ED} 、L_{DC} 、L_{CB} L_{BA} .

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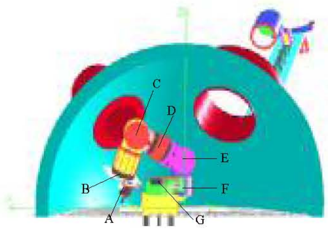

Figure1.The sketch of manipulator

In the process of collision checking, we need to facilitate the manipulator's structure. We regard each joint as cylinder. And we only check the top and button points of each joint .It can be seen in [11]and [12].

III. THE APPROACH OF CONFIGURATION SPACE DECOMPOSITION

The basic principle of this method is that the high dimensional configuration space is decomposed into two low dimensional space. It consists two phases: an off-line learning phase and an on-line query phase.

A. The off-line Learning Phase

In this phase, we decompose the six joints into two chains. Considered the collision joints of manipulator occurs mainly on the F、E、C points. So the whole angle vector $\boldsymbol{\theta}$ is decomposed as follows

$$\boldsymbol{\theta} = \boldsymbol{\varphi} \oplus \boldsymbol{\psi}$$

Where $\boldsymbol{\theta} = [\theta_G \quad \theta_F \quad \theta_E \quad \theta_D \quad \theta_C \quad \theta_B]^T$, $\boldsymbol{\varphi}$ = $[\theta_G \quad \theta_F \quad \theta_E]^T$, $\boldsymbol{\psi}$ = $[\theta_D \quad \theta_C \quad \theta_B]^T$ .Then we discretize $\boldsymbol{\varphi}$ and $\boldsymbol{\psi}$ into a finite number values.

$$\boldsymbol{\varphi} = \{\boldsymbol{\varphi}_i \mid i = 1,2,\cdots,N_1\}, \boldsymbol{\psi} = \{\boldsymbol{\psi}_j \mid j = 1,2,\cdots,N_2\}$$

So the angle vector $\boldsymbol{\theta}$ can be represented as follows:

$$\boldsymbol{\theta} = \{\boldsymbol{\theta}_{ij} \mid \boldsymbol{\theta}_{ij} = (\boldsymbol{\varphi}_i, \boldsymbol{\psi}_j), \; i = 1,\cdots,N_1, j = \cdots, N_2\}$$

Since the dense distributions of angle vector can lead to more collision checking , but the sparse distributions will lead to failure of searching. So the configuration should be generated rationality with some Heuristic methods. Firstly, we define some conceptions.

1 *The distance function*

We define the function $d(\boldsymbol{\theta}_1, \boldsymbol{\theta}_2)$ as a measure of the workspace region swept by the manipulator between $\boldsymbol{\theta}_1$ and $\boldsymbol{\theta}_2$ .Since the maximum workspace distance between $\boldsymbol{\theta}_1$ and $\boldsymbol{\theta}_2$ often occurs on the ends two points of each joint. So $d(\boldsymbol{\theta}_1, \boldsymbol{\theta}_2)$ can be defined as follows:

$$d(\boldsymbol{\theta}_1, \boldsymbol{\theta}_2) = \max\{\| J_i(\boldsymbol{\theta}_1) - J_i(\boldsymbol{\theta}_2) \|_2, \mathrm{i} \in \{1,\cdots,6\}\}$$

Similarly, we define $d(\boldsymbol{\psi}_1, \boldsymbol{\psi}_2)$、 $d(\boldsymbol{\varphi}_1, \boldsymbol{\varphi}_2)$ as follows.

$$d(\boldsymbol{\psi}_1, \boldsymbol{\psi}_2) = \max_{i=1,\cdots,N_1} \{d((\boldsymbol{\varphi}_i, \boldsymbol{\psi}_1), (\boldsymbol{\varphi}_i, \boldsymbol{\psi}_2))\}$$
$$= \max_{i=1,\cdots,N_1} \{\max_{m=4,5,6} \| J_m(\boldsymbol{\varphi}_i, \boldsymbol{\psi}_1) - J_m(\boldsymbol{\varphi}_i, \boldsymbol{\psi}_2) \|_2\}$$

$$d(\boldsymbol{\varphi}_1, \boldsymbol{\varphi}_2) = \max_{j=1,\cdots,N_2} \{d((\boldsymbol{\varphi}_i, \boldsymbol{\psi}_j), (\boldsymbol{\varphi}_2, \boldsymbol{\psi}_j))\}$$
$$= \max_{j=1,\cdots,N_2} \{\max_{m=1,\cdots,6} \| J_m(\boldsymbol{\varphi}_1, \boldsymbol{\psi}_j) - J_m(\boldsymbol{\varphi}_2, \boldsymbol{\psi}_j) \|_2\}$$

Where N1and N2 is the points account in $\boldsymbol{\psi}$ and $\boldsymbol{\varphi}$

2 *The path planner resolution*

Considered any arbitrary vector $\boldsymbol{\theta}_{arb}$, if there exists a defined vector $\boldsymbol{\theta}_{ij}$ satisfied $d(\boldsymbol{\theta}_{arb}, \boldsymbol{\theta}_{ij}) \le D_{res}$,then the path planning resolution is $1/D_{res}$. Since the angle vector in $\boldsymbol{\varphi}$ mainly determined the collision state, so we generate configurations in $\boldsymbol{\varphi}$ with the small step incremental method, that is

$$\boldsymbol{\varphi}_i = (\theta_{Gi}, \theta_{Fi}, \theta_{Ei}), \; \theta_{ki} = \theta_{k,\min} + i * \frac{(\theta_{k,\max} - \theta_{k,\min})}{N_i}$$

Where k=G、F、E. And the collision of F 、E、C joints will cause other joints collided. So the obtained configurations should be checked for collision, if it is collision–free, it is retained otherwise it is discarded. Also generated, we carry out the following distance detection:

$$d(\boldsymbol{\varphi}_i, \boldsymbol{\varphi}_j) \ge \alpha D_{res} , \; j = 1,2,\cdots,i-1 , \; 0 < \alpha < 1$$

Where $\{\boldsymbol{\varphi}_j\}$ is the generated configuration set. If the above inequality is satisfied, the new sampled configuration will be retained, otherwise it will be discarded. And in order to further improve the reasonability distribution of sampled points, we change the sampled step use the distance with obstacles.

Let $\Delta\boldsymbol{\theta}_{\boldsymbol{\varphi}}(n+1)$ denotes the incremental of $\boldsymbol{\varphi}$

in the n+1th sampled process, $d_\varphi(n-1)$ 、 $d_\varphi(n)$ are the minimums. If the inequality $d_\varphi(n-1) \le d_\varphi(n)$ is satisfied, it means that the manipulator is moving away the obstacles. Then we should increase the step.

$$\Delta\boldsymbol{\theta}_\varphi(n+1) = \Delta\boldsymbol{\theta}_\varphi(n) + \boldsymbol{\lambda}_\varphi \operatorname{sgn}(d_\varphi(n) - d_\varphi(n-1))$$

$$\boldsymbol{\theta}_\varphi(n+1) = \boldsymbol{\theta}_\varphi(n) + \Delta\boldsymbol{\theta}_\varphi(n+1)$$

Where $\boldsymbol{\lambda}_\varphi = \begin{bmatrix}\lambda_G & \lambda_F & \lambda_E\end{bmatrix}^T$ is the regulatory factor,

$$\Delta\boldsymbol{\theta}_\varphi(n+1) = \begin{bmatrix}\Delta\theta_G(n+1) & \Delta\theta_F(n+1) & \Delta\theta_E(n+1)\end{bmatrix}^T$$

3 *The adjacent node*

If the distance between $\boldsymbol{\varphi}_1$ and $\boldsymbol{\varphi}_2$ satisfied $d(\boldsymbol{\varphi}_1, \boldsymbol{\varphi}_2) \le D_{res}$, then $\boldsymbol{\varphi}_1$ and $\boldsymbol{\varphi}_2$ are adjacent. In order to avoid large neighbors generated, we limit the size of the adjacent set $\boldsymbol{\Theta}_i$ .So $\boldsymbol{\Theta}_i$ is defined as follows:

$$\boldsymbol{\Theta}_i = \{\boldsymbol{\varphi}_i^{\ a} \in \boldsymbol{\varphi} \mid d(\boldsymbol{\varphi}_i, \boldsymbol{\varphi}_i^{\ a}) \le D_{res} \cap d(\boldsymbol{\varphi}_i, \boldsymbol{\varphi}_i^{\ a}) \ge \alpha D_{res}\}$$

Since the combination $\boldsymbol{\psi}_j$ with different configuration in $\boldsymbol{\varphi}$ will obtain different collision results. So we use the rand sampling technique to generate the configurations.

$$\boldsymbol{\psi}_j = (\theta_{Dj}, \theta_{Cj}, \theta_{B'j}), k = D, C, B$$
$$\theta_{kj} = \theta_{k,\min} + rand(1)(\theta_{k,\max} - \theta_{k,\min})$$

Similar, the adjacent node set ψ_j can be defined:

$$\boldsymbol{\Psi}_j = \{\boldsymbol{\psi}_j^{\ a} \in \boldsymbol{\psi} \mid d(\boldsymbol{\psi}_j, \boldsymbol{\psi}_j^{\ a}) \le D_{res} \cap d(\boldsymbol{\psi}_j, \boldsymbol{\psi}_j^{\ a}) \ge \alpha D_{res}\}$$

4 *The collision table*

The collision checking results of $\boldsymbol{\theta}_{ij} = (\boldsymbol{\varphi}_i, \boldsymbol{\psi}_j)$ are stored in a two dimensional collision table. The element in table can only be taken 0 or 1, 0 represents the collision-free status.

B. The on-line Query Phase

Firstly, the given start and goal configurations $\boldsymbol{\theta}_s$ 、 $\boldsymbol{\theta}_g$ can be decomposed as the forms of $\boldsymbol{\theta}_s = (\boldsymbol{\varphi}_s, \boldsymbol{\psi}_s)$, $\boldsymbol{\theta}_g = (\boldsymbol{\varphi}_g, \boldsymbol{\psi}_g)$ .We try to connect $\boldsymbol{\theta}_s$ 、 $\boldsymbol{\theta}_g$ to the defined configurations $\tilde{\boldsymbol{\theta}}_s = (\tilde{\boldsymbol{\varphi}}_i, \tilde{\boldsymbol{\psi}}_j)$ 、 $\tilde{\boldsymbol{\theta}}_g = (\tilde{\boldsymbol{\varphi}}_k, \tilde{\boldsymbol{\psi}}_l)$.

Then, we search of adjacent configuration sequence. Find two sequences of adjacent configurations that connect $\tilde{\boldsymbol{\varphi}}_i$ and $\tilde{\boldsymbol{\varphi}}_k$ 、 $\tilde{\boldsymbol{\psi}}_j$ and $\tilde{\boldsymbol{\psi}}_l$ .In this paper we make full use of the collision information from the established table. Denote $N_{1i}^{\ a}$ as account of the word 1 of the $\tilde{\boldsymbol{\varphi}}_i^{\ a}$ ($\tilde{\boldsymbol{\varphi}}_i^{\ a} \in \boldsymbol{\Theta}_i$) colum in the collision table. Then we establish the following goal function.

$$J_1 = \| \tilde{\boldsymbol{\varphi}}_i^{\ a} - \boldsymbol{\varphi}_k \| + w_1 N_{1i}^{\ a}$$

Where w_1 is the weighted factor, so the problem of choosing the adjacent configurations is translated into the problem of solving the minimum values of J_1 ,that is.

$$\tilde{\boldsymbol{\varphi}}_i^{\ a} = \{\tilde{\boldsymbol{\varphi}}_i^{\ a} \in \boldsymbol{\Theta}_i \mid J_1 = \min\}$$

Similar,we decide the adjacent sequence $(\tilde{\boldsymbol{\psi}}_j, \boldsymbol{\psi}_{j+1}, \cdots, \tilde{\boldsymbol{\psi}}_l)$ with the above method

$$\tilde{\boldsymbol{\psi}}_i^{\ a} = \{\tilde{\boldsymbol{\psi}}_i^{\ a} \in \boldsymbol{\Psi}_j \mid J_2 = \min\}$$

Where $J_2 = \| \tilde{\boldsymbol{\psi}}_j^{\ a} - \boldsymbol{\psi}_l \| + w_2 N_{2i}^{\ a}$, $N_{1i}^{\ a}$ is account of 1 of the $\tilde{\boldsymbol{\psi}}_j^{\ a}$ ($\tilde{\boldsymbol{\psi}}_j^{\ a} \in \boldsymbol{\Psi}_j$) row, w_2 is the weight.

So we obtain two adjacent sequences that connected the $\tilde{\boldsymbol{\varphi}}_i$ 、 $\tilde{\boldsymbol{\varphi}}_k$ and $\tilde{\boldsymbol{\psi}}_j$ 、 $\tilde{\boldsymbol{\psi}}_l$ .Last we should build the The collision subtable

According to the two adjacent sequences $(\tilde{\boldsymbol{\varphi}}_i, \boldsymbol{\varphi}_{i+1}, \cdots, \tilde{\boldsymbol{\varphi}}_k)$ 、 $(\tilde{\boldsymbol{\psi}}_j, \boldsymbol{\psi}_{j+1}, \cdots, \tilde{\boldsymbol{\psi}}_l)$,we select the rows and the columns from the collision table and consist a subtable. The vertical edge represents the collision-free path between $\boldsymbol{\psi}_j$ and $\boldsymbol{\psi}_{j+1}$.The horizontal edge represents the path between $\boldsymbol{\varphi}_i$ and $\boldsymbol{\varphi}_{i+1}$.So these adjacent sequences consist a connected graph, and the Dijkstra algorithm used for the searching of graph.

IV. SIMULATION RESULTS OF THE ROBOT MANIPULATOR

Since the main task of this manipulator is that carry the blocked pipe in the XOY plane. The end-effector should be perpendicular with this plane. So we define the initial configurations θ_s and goal one θ_g are set as follows:

$$\theta_s = \begin{bmatrix} 0^o & 100^o & 170^o & 35^o & 50^o & 280^o \end{bmatrix}^T$$

$$\theta_g = \begin{bmatrix} 120^o & 130^o & 180^o & 40^o & 40^o & 10^o \end{bmatrix}^T$$

In order to generate the collision table, we sample 175 configurations in subspace of $\boldsymbol{\varphi}$ .Since the 175 configurations are all collision-free. So we only check the last joint point A state when build the collision table. And we sample 500 configurations in subspace of $\boldsymbol{\psi}$. The searched path is given in figure[2],the contour of each joint movement is given in figure [3]and the curve of each angle vector can be seen in figure[4].

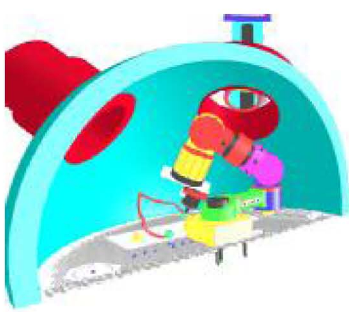

Figure 2 The searched path

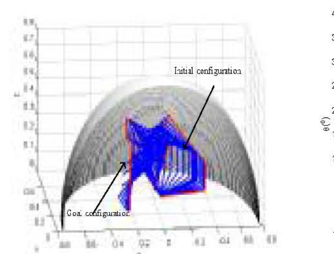

Figure 3 Contour curves of joint motion

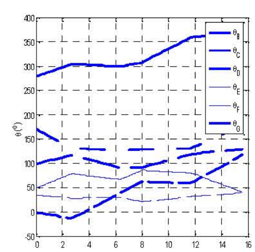

Figure 4 The curves of joint angle

V. CONCLUSION

This paper presents a new path planning method based on the decomposition of configuration space. The path planning problem in high dimensional space is transformed into the problem in two low dimensional subspaces. Respectively, the sub-path is found in each subspace, then the sub-paths are combined into the whole path through the collision table generated in off-line.The collision checking in low dimensional subspace avoids the collided configuration points to be generated and not only reduce the size of collision table but also reduce the on-line planning time.

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