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ORIGINAL ARTICLE

Dual-well potential field function for articulated manipulator trajectory planning

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Abstract A new attractive potential field function is proposed in this paper for manipulator trajectory planning. Existing attractive potential field constructs a global minimum through which maneuvering objects move down the gradient of the potential field toward this global minimum. The proposed method constructs a potential field with two minima. The purpose of these two minima is to create a dual attraction between links rather than affecting each link by the preceding one through kinematic constraints.

1. Introduction

An Industrial manipulator is a complex nonlinear mechanical system. Large number of degrees of freedom and interaction between manipulator links impose some sort of complexity in constructing direct and inverse dynamic model. A key issue in designing an industrial robot is to simulate the mutual effect of the motion of one link on other links. Essentially, the preceding link motion will change the position of the first joint in the subsequent link. That creates a hierarchy of link (i) over link ($i + 1$). However, what if link ($i + 1$) approaches an obstacle? For this circumstance, link ($i + 1$) should dominate and link (i) has to react accordingly.

Potential field methods provide a simple and elegant solution to many motion planning problems. It works as if a Ferro-material material is placed in a magnetic field, or an electric charge in an electric field. Objects will be attracted to some places in the field while being repelled away from others.

The attraction well is located in such a way it is required to be reached by the maneuvering objects. Both object positions and orientations are considered whenever extended objects are considered. If the maneuvering objects are considered as particles, as considered in majority related papers, positions are only considered in defining the potential field function.

Repulsion zones are defined to protect maneuvering objects from collision with other objects in the workspace. Not only is collision avoidance the role of the repulsive potential, but it also helps in decreasing maneuvering objects kinetic energy when approaching obstacles to smooth their motion, and consequently to reduce the collision avoidance cost.

Variety of applications have emerged for the potential field method during the last quarter century in the fields of robotic manipulators [1], dynamic obstacles [2], and moving goal points through defining a potential function that is velocity dependent [3], and defined over both the Cartesian space and the configuration space [4]. However, limitations of this approach arise when the superposition of the repulsive potential and attractive potential creates local minima. In addition, motion oscillation in the presence of obstacles or in narrow passages and the problem of trapping between two close

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obstacles also arise [5]. The potential field can then defined as vector functions in [6,7], which produces a smooth and bounded control and can provide better performance compared to scalar fields. Sliding mode theory (SMC) can be used with the potential field function to perform fast maneuvers [8].

The rest of this paper is organized as follows. Section 2 discusses attractive potential field function, Section 3 discusses articulated manipulator maneuver strategy, Section 4 presents dual-well potential function, Section 5 presents the numerical results, and finally conclusion of the paper results is presented in Section 6.

2. Attractive potential field function

Scalar potential functions are defined to have only one global minimum, to where the maneuvering object is attracted. It moves down-hill through the negative gradient of the potential function until reaching the required goal configuration, at the global minimum. For a point-like object, the potential field can be defined in the form of a parabolic function as follows [9]:

$$V_{att} = \frac{A}{2}(\mathbf{r}-\mathbf{r}_g)\cdot(\mathbf{r}-\mathbf{r}_g) + C(\bar{\mathbf{q}}\cdot\bar{\mathbf{q}}) \tag{1}$$

where

A and C are control gains.

$\mathbf{r}$ and $\mathbf{r}_g$ are the position and goal position of a reference point on the link; for link i, the reference point is joint i.

$\bar{\mathbf{q}}$ is the vector of the error (unit) quaternion $[q_1\ q_2\ q_3]^T$. The fourth quaternion parameter will reach its goal value, $q_4 = 1$, as the first three terms reach zero,

$$q_4 = \sqrt{1-q_1^2-q_2^2-q_3^2} \tag{2}$$

Minimizing the Euclidian distance between some reference point on the link and its goal position will bring this link to its desired position, whereas attitude is controlled through minimizing the error quaternion. Error quaternion is the difference between the quaternion parameters of the link at any time instant and the goal quaternion parameters. For both quantities, their values should be null at goal configuration. Following Eq. (2), the error quaternion is $[0\quad 0\quad 0\quad 1]^T$ at goal configuration. Error quaternion is determined as [10] follows:

$$\begin{bmatrix} q_1 \\ q_2 \\ q_3 \\ q_4 \end{bmatrix} = \begin{bmatrix} q_{4g} & -q_{3g} & q_{2g} & q_{1g} \\ q_{3g} & q_{4g} & -q_{1g} & q_{2g} \\ -q_{2g} & q_{1g} & q_{4g} & q_{3g} \\ -q_{1g} & -q_{2g} & -q_{3g} & q_{4g} \end{bmatrix} \begin{bmatrix} q_{1c} \\ q_{2c} \\ q_{3c} \\ q_{4c} \end{bmatrix} \tag{3}$$

where $\mathbf{q}_g$ and $\mathbf{q}_c$ are the goal and current quaternion respectively.

Using the potential function as defined in Eq. (1), the potential forces any maneuvering object to keep moving to minimize the Euclidian distance between its position and the goal position, meanwhile reducing the error quaternion vector so it reaches the required orientation.

3. Articulated manipulator maneuver strategy

An articulated industrial robot is composed of several rigid links, such that its first joint is attached to a fixed frame of reference. Consider a robot in 3R configuration as shown in Fig. 1.

Since the manipulator links are physically attached, the first point in link (i + 1) has to follow last point in link (i). Each link is then described kinematically as a rigid body motion in $\Re^3$ through the position of a reference point; the first point in each link, and the rotation about this point. This idea is adopted through introducing the position of the attractive well of link (i + 1) at the end of link (i) [11] as follows:

$$\mathbf{r}_{i+1,g} = \begin{bmatrix} 1-2q_2^2-2q_3^2 & 2(q_1q_2-q_3q_4) & 2(q_1q_3+q_2q_4) & 0 \\ 2(q_1q_2+q_3q_4) & 1-2q_1^2-2q_3^2 & 2(q_2q_3-q_1q_4) & 0 \\ 2(q_1q_3-q_2q_4) & 2(q_2q_3+q_1q_4) & 1-2q_2^2-2q_1^2 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix}_i \times \begin{bmatrix} 0 \\ 0 \\ L_i \\ 1 \end{bmatrix} + \mathbf{r}_i \tag{4}$$

In many cases, the subsequent links suffer zones of high potential due to the existence of obstacles. Consequently, according to the maneuver strategy presented in [11] only rotational maneuvers are then used for obstacle avoidance. A combination of rotational and translational maneuvers is preferable from the point of view of reducing time and cost [12].

Considering the case of prismatic joint with its joint parameter in the z direction, the attractive well of link (i + 1) is then related to the motion of link (i) as follows:

$$\mathbf{r}_{i+1,g} = \begin{bmatrix} 1-2q_2^2-2q_3^2 & 2(q_1q_2-q_3q_4) & 2(q_1q_3+q_2q_4) & 0 \\ 2(q_1q_2+q_3q_4) & 1-2q_1^2-2q_3^2 & 2(q_2q_3-q_1q_4) & 0 \\ 2(q_1q_3-q_2q_4) & 2(q_2q_3+q_1q_4) & 1-2q_2^2-2q_1^2 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix}_i \times \begin{bmatrix} 0 \\ 0 \\ L_i+d_{i+1} \\ 1 \end{bmatrix} + \mathbf{r}_i \tag{5}$$

where d_{i+1} is the joint parameter.

4. Dual-well potential function

The original method adopted in [11] with one moving potential well located at the end of the link i will force the first point of link i + 1 to follow the last point in link i whether this motion is suitable or not for link i + 1.

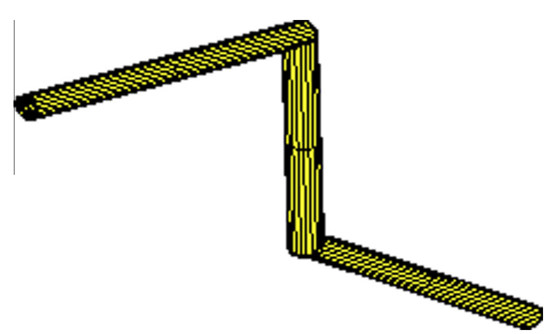

Figure 1 Manipulator Architecture.