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ORIGINAL ARTICLE

Simulation of obstacles' effect on industrial robots' working space using genetic algorithm

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Abstract The study of robot workspace is an interesting problem since its applications are directly related to industry. However, it involves several mathematical complications; Thus, many of the arising questions are left without a definite answer. With the motivation of industrial demand, the need for finding better answers than the existing ones lasts. The workspace (WS) determination of a robot with general structural parameters is a complex problem, which cannot be solved in an explicit way. Closed form solutions are only available in some particular cases. Otherwise, computational algorithms and numerical techniques are used. The task becomes even much more complicated by the presence of obstacles in the robot accessible region. Obstacle presence does not only exclude points from the original WS but it affects the whole robot workspace's shape and size to the extent that it sometimes divides the working space in two or more separate regions that cannot be linked by the same robot. Much research work in the literature is directed toward path planning in the presence of obstacles without having to determine the robot WS. However, a real situation in industry occurs when the knowledge of the WS is of importance in facility layout. This paper presents an approach for the estimation of a generic open-chain robot in the presence of obstacles with any desired number of prismatic and/or revolute joints of any order. Joints' axes may have any orientation relative to each other. The robot can be placed in free space or in a work cell consisting of a set of Computer Numerically Controlled (CNC) machines and some obstacles.

1. Introduction

The study of robot's global geometrical performance has been an area of ongoing interest in the last decade due to its industrial importance. The knowledge of robot WS can provide useful information for facility planning and layout. The boundary contours of the WS of a robot of general structure are difficult to be described in a closed form solution, which is only available in some particular cases. Examples of such cases are the research of Tsai and Soni (1981, 1983); Gupta and Roth (1982); Williams and Reinholtz (1988) and Salerno et al. (1995). Otherwise,

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numerical techniques and computational algorithms are used such as the work of Liegeois et al. (1986); Kumar and Patel, 1986; Riley and Torfason (1994); Wang and Hsieh (1998) and Megahed and S.M. (2001). Other researchers resorted to experimental design for workspace estimation as in the work of Chen et al. (2007). One of the major factors that affect the geometry and size of the robot WS is the presence of obstacles in its accessible region. (Wenger, 1989) studied the influence of obstacles represented by different constituents of a work cell on the robot WS. His work aimed to characterize the free WS of a robot and the changes that occur in the presence of obstacles. However, the methodology used by Wenger was based on an exhaustive search, in which the computational effort increases with the increase in the number of actuated axes. Trials of such methodology show that exhaustive search is not suited for robots with more than three joints. A lot of up to date research is oriented toward planning of robot motions in the presence of stationary and moving obstacles in its accessible region (Marchis et al., 1994; Kavraki, 1995; Curto and B., 1997; Huang and Lawrence, 1999; Kyatkin and Chirikjian, 1999; Abdel-Malik and Yang, 2005). Some of this work uses visual tracking for robot control and path planning such as the work of Tsai (Tsai and Song, 2009) while others use PLC coding and model generation for collision detection within a workcell (Flordal et al., 2007).

Estimation of the full WS of a robot of a general structure in the presence of obstacles is an under-explored topic, which needs more study and investigation. This paper presents a technique for approximate estimation of the WS of a simple chain robot of general structure having any number of joints in the presence of obstacles in its accessible region. These joints may be of revolute (R) and/or prismatic (P) type. Robot type may be represented by a series of letters R and/or P starting from its base.

2. Workspace mathematical modeling

Determining robots' working space is directly linked to their geometry and the types and orientation of connecting joints of its links. The mathematical analysis presented here is for an open chain robot structure, which is conveniently done using Denavit–Hartenberg (D–H) representation (Denavit and Hartenberg, 1955). The next section briefly explains the D–H representation and its implementation in WS estimation.

2.1. Denavit–Hartenberg representation

Denavit and Hartenberg (1955) is used to establish the relationship between consecutive links of a robot. The robot Tool Center Point (TCP) coordinate system is subsequently represented in terms of the robot base coordinate system. Fig. 1 shows the D–H parameters relating the robot moving links and joints numbered from 1 to n starting from the base. Using these D–H parameters, the resulting HTM between the two successive coordinate systems R_i & R_{i+1} is given by:

$$\begin{bmatrix} X_i \\ Y_i \\ Z_i \\ 1 \end{bmatrix} = [T_{i,i+1}]_{4\times4} \begin{bmatrix} X_{i+1} \\ Y_{i+1} \\ Z_{i+1} \\ 1 \end{bmatrix} \;\&\; [T_{i,i+1}]_{4\times4} \begin{bmatrix} c_i & -c_{\alpha i}s_i & s_{\alpha i}s_i & a_i c_i \\ s_i & c_{\alpha i}c_i & -s_{\alpha i}c_i & a_i c_i \\ 0 & s_{\alpha i} & c_{\alpha i} & r_i \\ 0 & 0 & 0 & 1 \end{bmatrix} \quad (1)$$

$$[T_{i,i+1}]_{4\times4} = \left[\begin{array}{c|c} R_{i,i+1}(q_i) & P_{i,i+1}(q_i) \\ \hline 0 & 1 \end{array} \right] \quad (2)$$

where $c_i = \mathrm{Cos}(\theta_i)$, $s_i = \mathrm{Sin}(\theta_i)$, $c_{\alpha i} = \mathrm{Cos}(\alpha_i)$ and $s_{\alpha i} = \mathrm{Sin}(\alpha_i)$. q_i is the generalized coordinates of the ith joint given by: $q_i = \sigma'_i\theta_i + \sigma_i r_i$where $\sigma_i = 0$ for revolute joints and $\sigma_i = 1$ for prismatic joints, and $\sigma' = 1-\sigma_i$.

The Homogeneous Transformation Matrix between the Tool Center Point R_{n+1} with respect to the robot base R_0 (0_0, X_0, y_0, z_0) is given by:

$$T_{0,n+1} \times T_{1,2} \times T_{2,3} \times T_{3,4} \ldots\ldots\ldots T_{n,n+1} \quad (3)$$

with $[\,x_0\; y_0\; z_0\; 1]^t = T_{0,n+1}\,[\,x_{n+1}\; y_{n+1}\; z_{n+1}\; 1]^t$

The 4×4 Homogenous Transformation Matrices (HTM) are used to evaluate the position and orientation of the robot links relative to the robot's base.

The final position and orientation of the Tool Center Point (TCP) also known as the robot end effector (x, y, z) can be expressed as a function of all the robot generalized coordinates (q_1, q_2, …., q_n).

2.2. Workspace points generation

Approximate determination of robot WS is based upon discretization of the volume about the robot, which is expected to contain the WS defined as search volume. The search volume (SV) is divided into a finite number of points located on imaginary grid lines that partition the SV into a number of divisions along each of the robot base axes directions x_0, y_0, and z_0.

Determining which points in the discretized SV belong to the WS starts by setting all the joints to their minimum range (Initial Position). Then, the closest point on the grid to the TCP location is marked as a surface point on the WS (WSP). By incrementally moving the last joint through its range of motion the initial point sweeps a set of new points. These new points are added to the WS. For each of these points, the closest point on the grid is added to the existing WS (Fig. 2). The existing WS points are swept through the range of motion of the preceding joint to form a new WS. The process is repeated until sweeping through the first joint (attached to the ground) range is completed. It should be noted that only the surface points of the existing WS (WSP) are used for the sweeping since they enclose the extreme reaches of the WS.

Sweeping of a WSP is done by first computing the HTM of the joint axes that does the sweeping (active joint) according to Eq. (3). Next, the position of the WSP with respect to the active joint axes is computed by:

$$\begin{bmatrix} X_{sp,a} \\ Y_{sp,a} \\ Z_{sp,a} \\ 1 \end{bmatrix} = [T_{0,a}]^{-1} \begin{bmatrix} X_{sp} \\ Y_{sp} \\ Z_{sp} \\ 1 \end{bmatrix} \quad (4)$$

Where: $X_{sp,a}$, $Y_{sp,a}$, $Z_{sp,a}$ are the coordinates of the WSP with respect to the active joint axes, X_{sp}, Y_{sp}, Z_{sp} are the coordinates of the WSP with respect to the robot base axes respectively and $[T_{0,a}]$ is the HTM of the active joint axes at its initial position.