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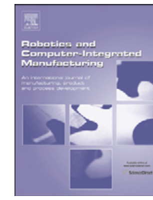

Velocity anisotropy of an industrial robot

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A R T I C L E I N F O

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A B S T R A C T

Industrial robots are part of production systems and it is important to place them into the system according to their properties and behaviour. The information, obtained from the technical sheets of robots, about workspace (its dimensions and shape) is insufficient for designing the production system. The information about mobility is missing. To represent the behaviour of the robot in the workspace, velocity anisotropy of the robot is introduced and defined as the length of the shortest velocity ellipsoid axes, which can be constructed for any position of robot in its tool centre point. The position of a tool centre point is equivalent to the point in the workspace. A graphical representation of the 3D workspace with included velocity anisotropy is then performed and an example for a design of a robotised welding production system is given. In this example the benefits of the graphical representation of the workspace with included velocity anisotropy are presented and discussed.

1. Introduction

When we design robotised production systems, we recognise some difficulties, which result from the data sheets of industrial robots. Technical manuals offer insufficient information about the robot's workspace. The given data are restricted to two layouts, which give us just rough information about the dimension and the shape of the workspace. From this data we cannot comprehend the manipulability and the real velocity levels of the tool centre point (TCP) of the robot in an arbitrary point in the workspace. So it can happen that some difficulties appear after designing of the robotised production system within the first testing run. In the testing phase we can recognise some, for the robot, inaccessible points on the work piece or there are some parts on the produced work piece where the robot cannot perform the prescribed technological requirements.

The robot workspace analysis has different goals. The visualization on the basis of workspace computation based on geometric sweep of spatial elements, representing partial workspaces is presented in [1]. Each workspace is generated by iteratively rotating or translating workspace (i+1) with respect to joint axes i between the joint limits. This approach achieves workspace representation since it can; in most cases generate the analytical representation of all boundary surfaces. The capabilities for a two-arm DLR humanoid robot are investigated in the article of Zacharias [2]. The aims are to define places in the workspace which are easily reached with the robot's hands, and reposition of robot's torso to enable optimal manipulation. In this article the internal structure of the workspace is visualized and manipulability measures and reachability index are introduced for a discrete set of points in the workspace. The article by Ottaviano [3] deals with the workspace topologies. A level-set reconstruction is used to analyse workspace topology by using algebraic expressions. The two-parameter set of curves is used to characterize the workspace cross-section and it gives an interesting insight of the internal structure of the workspace boundary obtained as an envelope of generating circles. An interesting approach is given by Lenarcic and Bajd [19]. In their work they define the robot's workspace as the reachable space when moving all robots' axes within their limits. A subset of the reachable workspace is introduced as the dexterity workspace. This subset is a set of points in which the robot can perform all possible orientations of the wrist. The analysis of the workspace singularities for three-axes positioning manipulator is given in the work of Angeles [32]. The author shows that the workspace boundary can be calculated with a system of linear homogeneous equations. The workspace boundary of general N-revolute manipulators is given in the article of Ceccarelli [4]. The workspace boundary is obtained from the envelope of a torus family, which is traced by the parallel circles cut in the boundary of a revolving hyper ring. The formulation is a function of dimensional parameters in manipulator chain and especially of the last revolute joint angle. An article which is close to the presented work is given by Gotlih [5]. The aim of the work is giving the designers of production cells a tool for proper placement of robots into the cell. This is done according to the shape of the task space and the prescribed threshold smallest singular value of the robot's Jacobian matrix in each discrete point of the task space. The procedure is developed for a 2D SCARA

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robot mechanism with two degrees of freedom and a rectangular 2D task space.

In the presented articles the work is focused on the analytical formulation of the boundary of the workspace and just the works of Zacharias [2] and Gotlih [5] give the possibility to analyse velocity relations inside the workspace. The aim of the present paper is to give the planning process of robotised production cells a useful tool for correct decision where to put the robot in the cell with respect to technologically conditioned tasks. The developed tool enables 3D representation of the velocity anisotropy of the industrial robot in the workspace. The velocity anisotropy is defined as the normalized length of the shortest velocity ellipsoid axes, which can be constructed for any position of robot in its TCP.

The presented paper is structured as follows: The theory of manipulability and different approaches to this matter are discussed in Section 2. In Section 3 the decision for choosing the shortest velocity ellipsoid axes as the velocity anisotropy measure is explained. The workspace of a typical welding robot according to the velocity anisotropy is developed in Section 4. In this section the 3D graphic representation of the velocity anisotropy for the welding robot is given and also the calculation of the Jacobian matrix and the manipulability for the robot is presented. An application for a designed and produced welding robotised production system with the welding robot is given in the discussion in Section 5. It is shown what can happen when the velocity anisotropy of the workspace is not taken into consideration while designing the production system. At the end of Section 5 the benefits of the presented approach are emphasised.

2. Measure of manipulability

The TCP trajectories of industrial robots can be divided into two main groups: the trajectories for simple manipulation (PTP programming—just the time for passing the trajectory or the minimal power consumption is important) and the technologically conditioned trajectories (CP programming – there are additional constraints – the exact tracking of the prescribed trajectory with additional velocity and/or force constraints is important).

This work deals with technologically conditioned trajectories, where besides correct tracking also the velocity profile on it is important.

To overcame the difficulties which result from the description of the position and the orientation of the TCP [6–9] and because the transmission of kinematic and kinetic quantities from the actuators to the TCP depends in general on the first three "positional" degrees of freedom, the wrist degrees of freedom which are responsible for the orientation of the TCP are not taken into consideration. The parameter for determining the velocity anisotropy in each point in the robot's workspace depends on the momentary robot's position in the space.

The transmission of motions, from each actuator to the TCP, will not guarantee equal velocities of the TCP in all points in the space.

Each point in the workspace $\{\vec{x} \in U\}$, Fig. 1, represents one position of the robot mechanism $\vec{x} \equiv TCP$. The transmission of the motion and the force from each actuator to the TCP is dependent on the actual position of the mechanism [10–13].

In literature several approaches for calculating the manipulability or the dexterity of robot mechanisms are presented. Most of them are developed from the well-known Jacobian matrix of the robot's kinematical structure. We analyse some measures to find the best of them that represent the velocity anisotropy.

2.1. The manipulability index

Yoshikava [14] was one of the first scientists who investigated the problem of manipulability of robot mechanisms and other authors continued his work [15–19]. The definition of manipulability index was given in Eqs. (1) and (2).

$$w = \sqrt{\det(J(\vec{q})J^T(\vec{q}))} \quad (1)$$

where $\vec{q}$ is the position of the mechanism in the configuration space and $J(\vec{q})$ is the Jacobian matrix of the mechanism. It represents the linear transformation of velocities from the configuration space coordinates $\vec{q}$ to the task space coordinates (robot's workspace) $\vec{x}$ Eq. (1) is used when $m \neq n$, where n denotes the number degrees of freedom of the robot and m is the number of needed parameters for exact determination of the position and the orientation of the TCP. When $m=n$, Eq. (1) transforms into

$$w = \left|\det J(\vec{q})\right| \quad (2)$$

Serial manipulators with five or six degrees of freedom are mostly used industrial robots. The position part of the structure of such robot is given in Fig. 2.

The configuration space coordinates are $\vec{q} = \{q_1, q_2, q_3\}^T$ and the task space coordinates of the TCP are $\vec{x} = \{x, y, z\}^T$. For the structure in Fig. 2 the Jacobian matrix is

$$J(\vec{q}) = \begin{bmatrix} -s_1(l_2s_2+l_3s_{23}) & c_1(l_2c_2+l_3c_{23}) & c_1l_3c_{23} \\ c_1(l_2s_2+l_3s_{23}) & s_1(l_2c_2+l_3c_{23}) & s_1l_3c_{23} \\ 0 & -(l_2s_2+l_3s_{23}) & -l_3s_{23} \end{bmatrix} \quad (3)$$

and the manipulability index

$$w = l_2l_3\left|(l_2s_2+l_3s_{23})s_3\right| \quad (4)$$

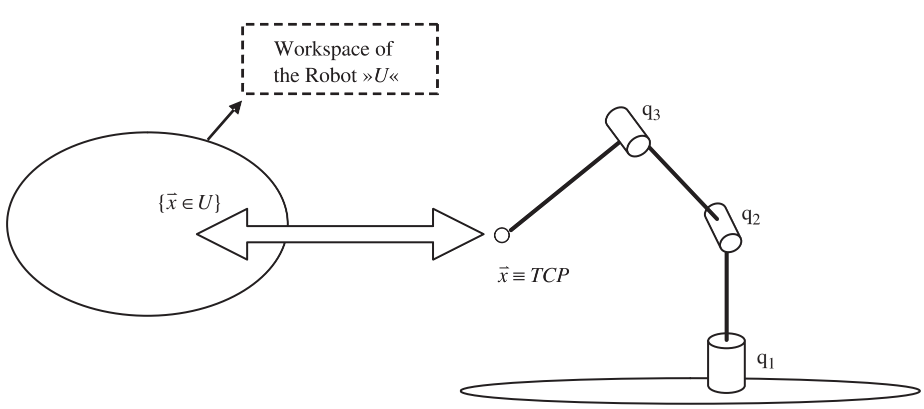

Fig. 1. The position of the robot and a point in the workspace.