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A homogeneous payload specific performance index for robot manipulators based on the kinetic energy

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ABSTRACT

Performance indices are extensively used in the optimization of robot structures. However, in the case of manipulators with mixed translational and rotational DOFs, traditional indices are not readily applicable due to the non-homogeneity of the Jacobian matrix. In this paper, special cases of generalized inertia ellipsoid, GIE, [1] and rms velocity norm [2] are used to define a payload specific performance index based on the transferred kinetic energy to the payload. The proposed kinetic energy index, KEI, is dimensionally homogeneous and is independent from the units. Moreover, this index is scale invariant and simultaneously considers both of the translational and rotational motions. A unit KEI indicates that a uniform kinetic energy is transferred to the payload for all the feasible joint velocities. For better representations, kinetic energy ellipsoids are drawn using a new vector form definition of the kinetic energy. A two-link manipulator and a 3-RRR robot are considered as case studies for evaluation of the proposed index. The kinetic energy ellipsoids and contours of KEI value are plotted over the entire workspace of the two robots. For a given payload with specified dynamic characteristics, KEI can be used to design an optimal structure of the manipulator such that a uniform kinetic energy is transferred to the payload.

1. Introduction

An important step in designing a manipulator is to optimize its geometrical and structural parameters. In order to evaluate the performance of the robots, multiple indices have been introduced such as the condition number, manipulability, dexterity, structural length, accuracy, stiffness, etc [3–5].

The dexterity index measures the maneuverability of the manipulators in positioning and orienting their end-effector, EE. This index is extensively used in the design and optimization of different manipulators. A small dexterity value indicates that the robot is in a singular configuration. In this configuration the robot does not have the ability to deal with external forces in certain directions and its maneuverability is decreased [6]. To ensure that the robot is not in a singular configuration, the condition number of its Jacobian matrix is examined in different configurations. The Jacobian matrix maps the robot velocities between joint space and Cartesian space. If the rank of the Jacobian matrix is reduced in a certain position, that configuration is said to be singular.

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Nowadays, researchers apply multiple performance indices to determine certain structures and configurations where the robot is in good manipulability conditions. The most popular indices are based on the manipulability concept [7] and dexterity criteria [8], proposed to enhance the maneuverability of manipulators. In many studies, the condition number of the Jacobian matrix is used as a kinematic accuracy index [9–11]. Using the condition number of the Jacobian matrix, the error amplification factor is investigated between the joint space and Cartesian space of the robots. In [12,13] the concepts of the manipulability and dexterity are interpreted based on the manipulability ellipsoids which depend on the manipulator Jacobian. When the manipulability ellipsoid is close to a sphere, the robot is in a good maneuverability condition.

Most of the available indices suffer from the non-homogeneity issue, occurring when the manipulators have mixed translational and rotational degrees of freedom, DOF. This issue causes the indices to provide inaccurate and unreliable performance measures. Specifically, measuring the condition number of a non-homogeneous Jacobian matrix is physically meaningless [14].

Researchers have proposed different methods for resolving the non-homogeneity issue of the Jacobian matrix. Instead of considering the translational and rotational velocities of the EE, Gosselin [15] used a Jacobian matrix between the joint velocities and the linear velocities of two specific points on the EE. Pond and Carretero [16] extended the Gosselin idea and presented a dimensionally homogeneous Jacobian matrix between the joint velocities and the linear velocities of three points on the moving platform. However, this method may result in different Jacobian matrices because of some arbitrariness in selection of the points on the EE. Some references propose to use a characteristic length of the robot as a scaling factor to homogenize the Jacobian matrix [17–20]. The arrays of the Jacobian matrix with length dimension are divided by the chosen characteristic length. Various methods are proposed for defining a suitable characteristic length, each of which may result in a different scaling factor and consequently a different value for the performance indices. Another method for homogenizing the Jacobian matrix is to separate the translational and rotational motions of the EE [21–23]. Using this method, two homogeneous Jacobian matrices are obtained for translational and rotational motions of the EE, each of which should be studied separately. Clearly, one aspect of the robot motions, translational or rotational, is ignored in this method. Moreover, separate optimization of the translational and rotational parts does not guarantee a well-conditioned overall Jacobian matrix.

The concept of generalized inertia ellipsoid, GIE, represents the dynamic isotropy of a manipulator. When GIE becomes a sphere, the manipulator is in a dynamic isotropy configuration and the nonlinear dynamic forces are reduced [1]. GIE is defined based on the kinetic energy of the whole manipulator. Therefore, this concept can be used to define a homogenous performance index which considers the translational and rotational movements simultaneously. In this paper, a special case of GIE concept and rms velocity norm [2] are used to define a payload specific kinetic energy index, KEI, for performance evaluation of manipulators. Instead of considering the kinetic energy of the whole manipulator, the proposed index merely measures the transferred kinetic energy to the payload. This index is particularly useful in some applications, e.g. motion simulators, where the robot should be design to move a given payload or when the mass and inertia of the robot components are negligible comparing to the payload. In fact, for a given payload with specified dynamic characteristics, KEI may be applied to find an optimized structure of manipulator in which a uniform kinetic energy is transferred to the payload for all the feasible joint velocities.

Besides its clear physical interpretation, the proposed kinetic energy index, resolves the non-homogeneity issue and considers both the translational and rotational motions of the manipulator, simultaneously. In this paper, the behavior of the new index is studied for the cases of a serial manipulator and a parallel robot. The kinetic energy ellipsoids are plotted over the entire workspace of the robots as well as the contours of their KEI value. The kinetic energy ellipsoids are defined based on a new vector form definition of the kinetic energy of the payload.

The rest of this paper is organized as follows. In Section 2 the new vector form of the kinetic energy is defined for a general manipulator. Section 3 introduces the KEI index and defines the concept of the kinetic energy ellipsoids. The proposed index is evaluated through implementation on a two link serial manipulator and a 3-$\underline{R}$RR parallel robot as the two case studies in Section 4. This section also compares the behavior of the KEI with some well-known performance indices for the two selected robots. Finally, Section 5 concludes the paper.

2. Kinetic energy of the payload

This paper seeks to define a payload specific performance index which is dimensionally homogeneous and considers both of the translational and rotational motions of robots. The rms velocity norm proposed by Lin et al. [2] provides a very good tool for this purpose. The rms norm is given by,

$$\left\| {}^{\mathcal{B}}\mathbf{t}_P \right\|_{rms} = \left({}^{\mathcal{B}}\mathbf{t}_P^T \mathbb{R}\mathbb{M}\mathbb{R}^T \, {}^{\mathcal{B}}\mathbf{t}_P \right)^{1/2} \tag{1}$$

where, $\{\mathcal{B}\}$ is the base coordinate system and ${}^{\mathcal{B}}\mathrm{t}_P = [{}^{\mathcal{B}}\mathrm{V}_P^{\mathrm{T}},\ {}^{\mathcal{B}}\Omega_P^{\mathrm{T}}]^{\mathrm{T}}$ is the vector of the generalized velocity of the payload or, in other words, the twist vector of the payload. Moreover,

$$\mathbb{R} = diag\left({}^{\mathcal{B}}_{\mathcal{P}}\mathcal{R}, {}^{\mathcal{B}}_{\mathcal{P}}\mathcal{R}\right), \quad \mathbb{M} = \int \nu\left({}^{\mathcal{P}}\mathbf{r}\right) \begin{pmatrix} \mathbf{I} & {}^{\mathcal{P}}\hat{\mathbf{r}}^T \\ {}^{\mathcal{P}}\hat{\mathbf{r}} & -{}^{\mathcal{P}}\hat{\mathbf{r}}^2 \end{pmatrix} d\mathbf{r} \tag{2}$$