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Research paper

Kinematic performance evaluation of high-speed Delta parallel robots based on motion/force transmission indices

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ABSTRACT

Motion and force transmission indices are a common measure for the kinematic performance analysis and optimization of parallel manipulators. However, a separate consideration of the constraint characteristics is inevitable for the analyses of limited-dof parallel manipulators. Such separation may distort the performance evaluation as the design parameters of parallel manipulators are highly coupled. In this context, different formulations for the transmissibility and constrainability of parallel manipulators based on the notion of power coefficients and pressure angles are revisited and applied to the performance evaluation of a non-overconstraint Delta robot, a well-known lower-dof parallel robot. Following the concept of pressure angles, a physically meaningful measure is proposed, which aggregates the transmission and constraint characteristics into a single index. The simple definition does not require the tedious computation of the normalization factor as used for power coefficients. Moreover, the applicability of the different formulations for the performance evaluation and optimization is critically discussed revealing insights into the particularities of the different indices and their interactions as well as proving the validity of the new approach.

1. Introduction

Highly dynamic handling tasks require a high payload-to-weight ratio, a high positioning accuracy as well as excellent stiffness characteristics. Parallel manipulators meet these requirements by their architecture with frame-based actuation and thus low moving masses. The most widely spread manipulators within the niche market of parallel robotics are the 6-dof Gough/Stewart platform [1,2] and the 4-dof Delta robot [3] as commonly used for highly dynamic flight or driving simulation and high-speed pick-and-place applications with light-weight objects, respectively. In recent years, the design of the latter has been modified significantly extending its field of application to handling tasks with up to six dof (e.g., assorting, tooling, or measuring tasks) and/or with heavy-weight objects (e.g., stacking or packing tasks). At the same time, the high degree of industrial automation has led to growing demands for efficient and sustainable robotics systems. While the power consumption of a single system is comparatively low, companies may employ thousands of robots [4]. In addition, economically friendly added value and green manufacturing have become an important selling point of modern industries in recent years. In this context, the reduction of peak power demands is highly important since utility companies and electricity suppliers commonly charge their key accounts based on their peak demands in order to be able to accommodate for which

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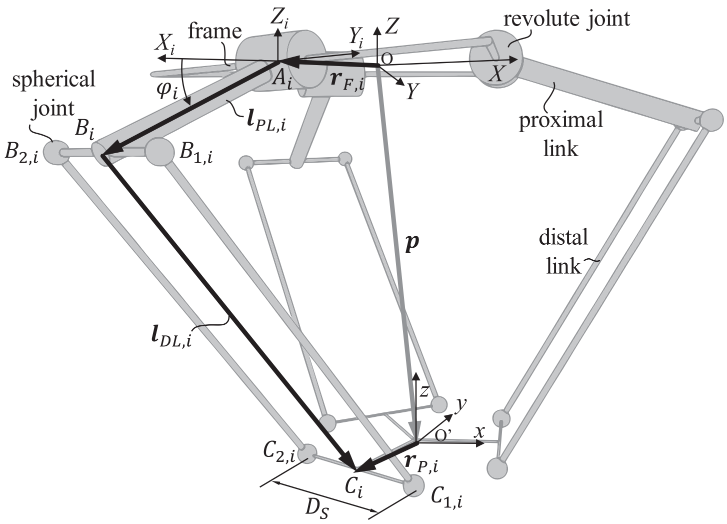

Fig. 1. Geometric relations of the 3-R(2-SS) Delta robot.

[5]. In a previous study [6], it was demonstrated that a purely kinematic design optimization of light-weight high-speed Delta parallel robots may be sufficient to obtain power efficient candidates for industrial application.

The main kinematic concepts for performance optimization are the concepts of condition number, manipulability, and motion/force transmissibility. Both measures the condition number as well as the manipulability are based on the characteristics of the Jacobian. In order to overcome the related problems of inhomogeneity and frame dependency, research has focused on alternative performance measures assessing the quality of motion and force transmission of parallel robots.

Against this background, existing approaches for the derivation of the input/output transmission and constraint characteristics, based on the virtual power coefficient and pressure angles, are reviewed. Taking advantage of the architecture of the Delta robot, in which six links are connected to the platform by spherical joints, a simple definition of the output transmission index is proposed. The proposed index is compared to other definitions for the output transmissibility and critically discussed with respect to its interaction with other measures, such as input transmission and constraint characteristics. Finally, a case study reveals the particularities of the proposed index for design optimization tasks.

2. Delta parallel robot

The Delta robot is one of the best known and most widely spread parallel robots in academia and industry [3]. The architecture is represented by three symmetric kinematic chains of different types (cf. Section. 2.2), whereas industrial variants usually comprise of a rotationally actuated proximal link and a spatial parallelogram with four spherical joints and four links pairwise of the same length. With this design, the connecting rods only need to transmit axial forces allowing for light-weight design. In other variants, the spherical joints are replaced by universal joints in order to suppress the internal mobilities (i.e., the rotation of the rods along their axes of symmetry) that do not contribute to the output motion. Fig. 1 shows the schematic representation of the Delta robot and the related kinematic relations. Hereafter, R, U and S stands for revolute, universal and spherical joints, respectively, while an underlined symbol represents an actuated joint.

2.1. Geometric relations

The translational fully parallel Delta robot is characterized by spatial parallelograms (in which the two parallel connecting rods are denoted as distal link in the following) connecting the actuated proximal link to the moving platform. The platform position is denoted by $\boldsymbol{p}$. The positions of the actuated joints A_i at the frame and the connecting joints C_i at the platform can be expressed by the vectors $\boldsymbol{r}_{F,i}$ and $\boldsymbol{r}_{P,i}$, respectively. The vectors $\boldsymbol{l}_{PL,i}$ and $\boldsymbol{l}_{DL,i}$ point along the proximal and distal links of the i-th kinematic chain with $i = \{1, 2, 3\}$, cf. Fig. 1.

2.2. Mobility analysis

Translational parallel manipulators generally consist of three identical kinematic chains arranged symmetrically around a base. The general architecture of such chain can descriptively be represented by five revolute joints, where groups of two and three joint axes must be parallel [7]. The number of overconstraints of a Delta robot variant is depending on the geometric conditions within and among the chains. Thus, in the following, potential variants are evaluated in respect of their transmission and in particular constraint characteristics.

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