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Research paper

A class of novel 2T2R and 3T2R parallel mechanisms with large decoupled output rotational angles

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ABSTRACT

This article focuses on the synthesis and analysis of a class of novel 2T2R (T denotes Translation and R denotes Rotation) and 3T2R parallel mechanisms (PMs) with large decoupled output rotational angles. Two articulated moving platforms (AMPs) composed by revolute joints are proposed. A common parallelogram and an evolution parallelogram which are used to orient the rotation axes of the AMPs are designed and analyzed. By means of Lie group theory, the limbs connected in the AMPs are enumerated and two types of 2T2R PMs are synthesized. Then, based on the proposed 2T2R PMs, a family of 3T2R PMs are obtained through adding a translational degree of freedom (DOF). The fact that the orthogonal arrangement of the revolute joints in the AMPs eliminates the interference between the two rotations guarantees the high rotational performance of the manipulators. Finally, the inverse kinematics of the example PM is conducted and the workspace is obtained to illustrate the high rotational capability.

1. Introduction

PMs with lower-mobility have the advantages of simple architecture, lower cost of manufacturing compared with its 6-DOF counterpart. Meanwhile, it is suitable for many tasks requiring less than 6-DOF. Therefore, synthesis and analysis about lower-mobility PMs have drawn extensive interests. Many lower-mobility PMs are proposed and applied to productions, such as the famous Delta robot [1], the PMs for ankle rehabilitation [2,3], the asymmetrical 2T3R PM for surgical operation [4], and parallel manipulators applied in bionics of spinal column [5]. However, the traditional parallel mechanisms suffer from problems of small workspace, limited rotational angles. To overcome the drawbacks of the traditional PMs, researchers focus on the design and analysis of the generalized PMs, which are not limited to the definition that the rigid moving platform is connected with the base with multiple independent kinematic chains. Scholars make a breakthrough from two aspects. One is to design spatial mechanisms with coupling chains [6–8], which have higher rigidity and greater load-carrying capacity. The other is to construct PMs with non-rigid moving platform to obtain larger workspace and perform specific objective [9–11].

There are two types of PMs with non-rigid moving platforms. One is the PM with configurable platform, which was studied by Yi [12] first and generalized by Gosselin [13] in 2005. A distinct characteristic for the PM with configurable platform is that a closed-loop chain is used as the end-effector, which can be used to grasp irregular and large objects. The other kind is the PMs with articulated moving platform. Typically the articulated moving platform (AMP) can be seen as an

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open-loop parallel combination of rigid bodies and joints. Since an APM has some relatively independent DOF, it can greatly reduce the interference between the platform and limbs, as a result, achieve larger workspace, especially the orientation-workspace.

The H4 mechanisms series [14–17] is the typical example of using the AMP. Since different components in the articulated platform have relative rotations which are amplified by the gear system or other amplifying mechanisms, the H4 series possess large rotational angles. With the similar principle, Sun [18,19] designed an AMP using the helix pairs and synthesized a class of 3R1T PMs. Wang and Fang [20,21] synthesized four types of AMPs using revolute joints only, based on which obtained a family of 2T2R, 3T2R, 3T3R PMs with high rotational capability. The reason why the PMs with AMPs possess relatively large rotational angles is that these PMs obtained the property of partially-decoupled through adding coaxial kinematic pairs in the platform. Based on the idea of partially-decoupled, Liu [22] designed a class of two to six DOFs PMs in which the three DOFs possess the advantage of high rotational capability. Using the parallelograms to realize the kinematic decoupling, Salgado [23,24] presented two types of 4-DOF PM which can generate the Schönflies motion. Based on the theory of linear transformations and the evolutionary morphology, Gugo [25] proposed a family of kinematic-decoupled and fully-isotropic PMs, whose rotations are generated by the relative motion of two groups of limbs.

Synthesis approaches of PMs include the enumeration approach based on the general Chebyshev–Grübler–kutzbach mobility formula [26], the constraint approach based on the reciprocal screw theory [27,28], the synthesis method based on the Lie group theory [29,30]. The reciprocal screw theory is effective for the synthesis of the symmetrical and isotropic PMs, such as the symmetrical lower-mobility PMs presented by Huang [31] and the 4&5-DOF PMs with identical limb structures proposed by Fang [32]. The Lie group theory is more intuitive to characterize the limbs structure, as a result, is a convenient method to synthesize the asymmetrical and non-isotropic PMs. For example, Refaat and Hervé [33] Proposed four families of 3-DOF translational-rotational PMs which are asymmetric by Lie group theory. Fan [34] obtained a large number of 2T2R, 1T2R and 2R PMs based on the integration of configuration evolution and Lie group theory.

This paper devotes to synthesize and analyze a class of parallel mechanisms with large orientation-workspace. Two kinds of AMPs constructed by revolute joints only are designed, which guarantee the proposed PMs to be partially decoupled. The common parallelogram is used and an evolution is created to orient the rotation axes of the AMPs. By means of Lie group theory, the basic limb structure to prompt a rotation is deduced and the non-identical limb structures connected with the AMPs are obtained. Using the proposed limbs, two types of 2T2R and a type of 3T2R PMs are presented. The PMs presented in this paper are constructed only by lower pairs with single DOF to reduce the interference and guarantee the high rotational performance. The proposed PMs possess large workspace and high rotational capability, which are proved by the inverse kinematics and the workspace analysis.

The structure of this article is as follows. Section 2 introduces the concept of the Lie group theory and proposes two kinds of AMPs as well as a common and an evolution parallelogram. The motion property of the parallelograms is analyzed in this part. Two types of 2T2R PMs are synthesized and their limb structures are listed by means of Lie group theory in the Section 3. Then based on the proposed 2T2R PMs, a class of 3T2R PMs is obtained in Section 4 through adding a translational degree of freedom. Section 5 conducts the inverse kinematics of the example PMs and depicts the constant-orientation workspace and the orientation-workspace to analyze the performance of the proposed PMs. Finally, conclusion is presented in Section 6.

2. Design of two novel AMPs and two parallelograms

2.1. Basic conceptions about lie group theory

The set of 6-dimensional rigid motion can be endowed with the algebraic structure of a group, represented by $\{D\}$ as Lie group. Further any motion of a rigid body can be described by a subset of $\{D\}$, which may be either a group, called a displacement subgroup (DSG) or a displacement submanifold (DSM). According to Hervé [35], $\{T\}$ denotes the set of 3-DOF translation, $\{T_2(\boldsymbol{u})\}$ denotes 2-DOF planar translation whose plane is perpendicular to $\boldsymbol{u}$, $\{T(\boldsymbol{u})\}$ represents linear translations parallel to $\boldsymbol{u}$, and $\{R(N,\boldsymbol{u})\}$ is the representation of one-dimensional rotational subgroup, in which $(N, \boldsymbol{u})$ represents the axis determined by the unit vector $\boldsymbol{u}$ and point N. In other words, $\{T(\boldsymbol{u})\}$ and $\{R(N,\boldsymbol{u})\}$ are associated with the lower pairs of prismatic pairs P and revolute pairs R. The displacement set of a limb is the product of DSGs of all pairs in this limb. The product of groups is closed [36,37]. Assume that the rigid bodies constructed a limb in a parallel mechanism are 1, 2, 3, … , j-1, j in turn and the DSGs or DSMs (DSGs/DSMs) of corresponding pairs are $\{D_1\}$,$\{D_2\}$,$\{D_3\}$,…, $\{D_{j+1}\}$, the DSG/DSM of the end of the limb is the product of all the DSGs/DSMs, i.e.

$$\{L_i\} = \{D_1\}\{D_2\}\{D_3\}\cdots\{D_{j+1}\} \tag{1}$$

where $\{L_i\}$ is the DSG/DSM of the end of the limb. The intersection of two subgroups is always a subgroup. The DSG/DSM of the moving platform of a parallel mechanism is the intersection of the DSGs/DSMs of all limbs, i.e.

$$\{M\} = \bigcap_{i=1}^{n} \{L_i\} \tag{2}$$

where $\{M\}$ denotes the DSG/DSM of the moving platform.