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Design of parallel hybrid-loop manipulators with kinematotropic property and deployability

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ABSTRACT

General applications of spatial overconstrained linkages are limited by their special output motions without pure rotations or translations. To promote more widespread industrial applications and to develop the potential capabilities of such linkages, this paper presents novel parallel hybrid-loop manipulators and a novel design method based on the constrained motion properties of related spatial overconstrained linkages and general parallel mechanisms. The conventional topological connecting relationships between subchains and platforms are categorized into ten basic forms, among which a novel parallel hybrid-loop form of topological arrangement is presented for the design of parallel hybrid-loop manipulators. In the presented examples of structural design, the Bennett linkage, the threefold-symmetric Bricard linkage and two linkages that will be derived, i.e., the twofold-symmetric 8-bar and the threefold-symmetric 12-bar spatial single-loop linkages are adopted as the basis for the synthesis of the structures of parallel hybrid-loop manipulators with kinematotropic property and deployability based on variable constraint analysis and the structural properties of these linkages. Other similar parallel hybrid-loop manipulators can also be developed based on the presented design method. Possible applications of parallel hybrid-loop manipulators are also highlighted.

1. Introduction

General spatial overconstrained linkages have been in existence for many years. These linkages possess some special structural configurations and geometric properties in their closed joints and links. The most prevalent structural configurations are the Bennett linkage [1] and the Bricard linkages [2], whose many special properties and applications have been studied by different scholars. Baker [3] delineated the axodes motion of the Bennett linkage and established the relationships between the ruled surface and the corresponding centrode of the linkage's planar form. Perez and McCarthy [4] examined the Bennett linkage and its associated cylindroid and an efficient technique for solving the synthesis equations of kinematic chains was presented. For 6-bar linkages, a thorough analysis of all six Bricard linkages was done by Baker through appropriate sets of independent closure equations [5]. A novel method for generating 6-bar linkages was developed based on the Bennett linkage by Baker [6], while Jin and Yang [7] presented a complete closed form analytical method to verify the overconstraints of the trihedral Bricard linkage.

Based on the special geometrical motion properties of overconstrained linkages, many related applications have focused on the design of deployable structures. Chen and You [8] presented a method for building large mobile assemblies using the Bennett linkage. They have also shown that a number of 6-bar linkages can be assembled to form large-scale deployable structures [9]. They have further demonstrated that the century-old invention can play an important role in the construction of deployable structures. A systematic study of the kinematics of closed-loop structures for deployable applications was presented by Gan and Pellegrino [10]. Baker [11] presented a deployable network for the applications of the Bennett linkage, while Luo et al. [12]

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replaced each link of the threefold-symmetric Bricard linkage with a tetrahedron to realize deployable applications of overconstrained linkages in architecture.

In addition to deployable applications of overconstrained linkages, another possible application was analyzed by Chai and Chen [13] based on one of the six distinct Bricard linkages. The line-symmetric octahedral case can be used for reconfigurable structure design. However, as far as the industrial applications of overconstrained linkages are concerned, there are only a few available designs. Racila and Dahan [14,15] presented a type of one degree of freedom (DOF) translator based on the threefold-symmetric Bricard linkage. They have shown that three non-successive revolute joints can be constrained to remain in a horizontal plane, so that a translatory movement for the plane, defined by the other three revolute joints, can be obtained. This constituted a possible industrial application of overconstrained linkages, but the design was limited by the threefold-symmetric Bricard linkage. To overcome this limitation and to facilitate more widespread industrial applications, this paper will focus on a new structural design approach based on general forms of spatial overconstrained linkages. Potential new capabilities of spatial overconstrained linkages will be developed starting from existing theoretical research and applications. It is anticipated that general spatial overconstrained linkages can be applicable in many general industrial manipulators.

In the structural design of general industrial manipulators, the independent output rotations or translations are considered as different displacement subgroups [16,17], which is a necessary requirement for general applications. However, the special output motions (without pure rotations or translations) of spatial overconstrained linkages are not associated with any unique displacement subgroup. To overcome the motion limits of spatial overconstrained linkages and to facilitate their industrial applications, additional motion constraints and actuations need to be provided by subchains of parallel mechanisms and incorporated into the conventional spatial overconstrained linkages. In the structural design of parallel mechanisms, the conventional design theory consists of displacement group theory [16–20], screw theory [21–25], and other theories [26,27]. Numerous parallel mechanisms have been developed in different forms with different constrained output motions. This paper will adopt displacement group theory to realize the design of external parallel subchains to provide motion constraints and actuations for spatial overconstrained linkages.

Among the different forms of linkage mechanisms, the conventional parallel forms that connect subchains and platforms can be replaced by serial–parallel hybrid forms or other multi-loop forms for different applications. The resulting hybrid structures can, as a consequence of this, be categorized into two types: (1) two or more parallel mechanisms are connected serially [28–34], and (2) two parallel mechanisms are operated in the form of collaborative motions [35,36]. However, most contributions to date were only concerned with hybrid forms of serially connected parallel mechanisms, namely two adjacent parallel mechanisms are connected by a platform. All of these hybrid topological arrangement forms were designed and analyzed as spanning tree forms [28–34]. Actually, some non-spanning tree forms do exist among multi-loop structures of serial–parallel hybrid mechanisms. Based on the developed non-spanning tree forms [37–40], a novel parallel hybrid-loop form of topological arrangement will be proposed in this paper that will lead to new structural designs that are a combination of spatial overconstrained linkages and parallel mechanisms.

Among the practical motion function applications of general linkage mechanisms, more and more requirements are focusing on the provision of multiple motion states for different output functions. In other words, the output motions of a linkage mechanism can be transformed between different states of DOFs, while their topological structure remains unchanged. This kind of property, referred to as kinematotropic property, was presented by Wohlhart in some kinematotropic linkage mechanisms [41]. Galletti and Fanghella [42] proposed an approach for the design of kinematotropic mechanisms based on four basic kinematotropic chains. The chains can be modified to obtain different kinematotropic mechanisms. Kong et al. [43] presented a method for the type synthesis of parallel mechanisms with multiple motion states. 3-DOF parallel mechanisms with both spherical and translational states were developed. Other related kinematotropic designs have also been developed for general linkage mechanisms [44–55].

In conventional multi-functional/reconfigurable mechanisms, the multiple output motion states are changed by the variable connections of additional links and actuators that provide the constraints [56–58]. In these mechanisms, the strength of the variable constraints depends on the corresponding power of the actuators. The strength of the variable constraints that is provided by the kinematotropic property is, in turn, determined by the connecting constraining rigid links in different output motion states. Thus, the kinematotropic property can provide more stable constraints to maintain the output motion states. As a consequence, better functions and performance can be achieved in practical kinematotropic applications.

As far as the variable constraints of spatial overconstrained linkages are concerned, the features of kinematic bifurcations are discussed in detail by Chen and You [59]. Bifurcations exist during the deployable applications of overconstrained linkages. They identified a feasible area for the design parameters in which bifurcations can be completely removed [60,61]. Unlike previous works, in the current paper bifurcations of spatial overconstrained linkages will be used to realize multiple output functions of new structures in the multiple motion states. Thus, by considering the variable geometric constraint relations and structural properties of spatial overconstrained linkages, the corresponding kinematotropic property will be considered in the new structural design.

Most available research to date primarily focuses on the design of conventional spatial overconstrained linkages or parallel mechanisms independently with simple constraints and unchangeable output functions. In reality, however, multiple/additional constraints are required for multiple functions and stable motions of linkage mechanisms. In multi-loop linkage mechanisms, additional connecting subchains can provide additional constraints to guarantee more stable constraint states in their continuous motions. However, general multi-loop linkage mechanisms were only developed in planar forms or simple spatial parallel forms, while general deployable multi-loop linkages were only developed as single-DOF mechanisms for construction applications [9].