Mechanism and Machine Theory 112 (2017) 172–191

Contents lists available at ScienceDirect

Mechanism and Machine Theory

journal homepage: www.elsevier.com/locate/mechmachtheory

Research paper

Singularity analysis of a class of kinematically redundant parallel Schönflies motion generators

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ARTICLE INFO

Article history:
Received 30 July 2016
Revised 24 January 2017
Accepted 24 January 2017

Keywords:
Parallel kinematics
Singularity analysis
Screw theory
Schönflies motion
Kinematic redundancy

ABSTRACT

This paper provides an analysis of the singularities of a class of kinematically redundant parallel manipulators. The studied mechanisms are capable of spatial translations in addition to rotation around an axis with constant orientation. Such motion is classified as Schönflies motion and is of high importance for industrial applications. The studied mechanisms include a manipulated platform composed of two platform sections, which are connected by a passive joint. The mechanisms include five actuated kinematic chains of a specific type, where three kinematic chains are connected to one platform section and two to the other section. Several novel mechanisms in this class are introduced and the singularities of all introduced variants are analyzed utilizing screw theory. In particular, all configurations leading to a redundant passive motion (RPM) singularity are determined. In such configurations, at least one of the passive joints in the mechanism may have a non-zero velocity while the velocity of the tool and all actuated joints are zero. For the studied mechanisms, such configurations correspond to the system of wrenches acting on the platform section including the tool has full rank while the wrench system acting on the other platform section is rank deficient.

1. Introduction

This paper provides a singularity analysis of the members of a class of parallel kinematic manipulators providing three translational degrees of freedom (DOFs) in addition to infinite rotation around an axis with fixed orientation. Such motion is categorised as Schönflies motion [1].

It is well known that Schönflies motion generators based on a parallel kinematic architecture have the potential for several benefits compared to similar-sized serial manipulators. Such advantages include higher speed and acceleration, larger payload capacity, improved position accuracy, and higher stiffness. However, typical applications for industrial robots, such as assembly tasks and pick-and-place tasks, require the employed manipulator to provide 360° rotation of the tool around one axis, while only a few of all parallel manipulators exhibit this functionality.

One approach to design a Schönflies motion generator providing 360° tool rotation is to include a multiplying gear on the manipulated platform [2–7]. One drawback of this approach is that mechanisms of this type do not provide infinite rotation

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http://dx.doi.org/10.1016/j.mechmachtheory.2017.01.012
0094-114X/

of the tool. Infinite tool rotation is a significant advantage, as it allows the tool to always utilize the shortest path between two programmed rotation angles, which reduces the cycle times for most applications.

A few non-redundant parallel kinematics Schönflies motion generators providing infinite tool rotation have been proposed [8–10]. All of these mechanisms are hybrid parallel manipulators, as none of them are composed of four independent actuated chains connecting the fixed base and a rigid manipulated platform.

The Delta mechanism [8] employs three kinematic chains to manipulate the spatial position of a platform while keeping its orientation constant. A fourth actuated kinematic chain transfers rotation from a motor on the fixed base to rotation relative to the manipulated platform. This chain is composed of an actuated revolute joint in series with a passive universal joint, a passive prismatic joint and a second passive universal joint. The chain is connected to the manipulated platform by a passive revolute joint. Constructing a lightweight kinematic chain including a prismatic joint that is subjected to torsional stress is a challenge, and such transmissions typically suffer from a short service life [6]. Furthermore, as the chain actuating rotation is long, it raises the issues of torsional stiffness and deflection, in addition to undesirable dynamic effects generated when this long chain undergoes high-speed rotations around the axes of its first universal joint [10].

The main drawback of the Dual 4 manipulator proposed by Company et al. [9] and the mechanism introduced by Gosselin et al. [10] is that at least one of the kinematic chains actuating the tool platform is subjected to bending and torsion. The disadvantage of such chains is a low stiffness-to-mass ratio.

As all non-redundant Schönflies motion generators suffer from distinct drawbacks, considering actuator redundancy is motivated, even though such manipulators have the inherent disadvantage of the cost of an additional actuator. Similar to the description in Lee et al. [11], we refer to a manipulator with a mobility that is lower than its number of actuators as a redundantly actuated manipulator, while a manipulator with a mobility greater than the mobility of its tool platform is referred to as a kinematically redundant manipulator[1]. As exemplified by Kock et al. [12], manipulators of both types can be used to eliminate the singularities limiting the rotational workspace, thereby enabling infinite tool rotation.

The drawback of actuation redundancy is that stress may be introduced in the mechanism if the actuators are operated independently. Hence, any modeling error can wear and potentially break the mechanism. Such issues may be avoided by controlling these manipulators using advanced control algorithms, where the coordination of the actuators play a central role [13].

The issues of a redundantly actuated mechanism may be avoided by introducing additional DOFs in the mechanism, leading to a kinematically redundant manipulator. In [14], Isaksson et al. introduced lightweight mechanisms for Schönflies motion, where the additional DOF was used to actuate a gripper. This paper analyses mechanisms utilizing the same lightweight actuated chains as in [14], however, investigates more general designs for the manipulated platform. Due to the stated shortcomings of non-redundant Schönflies motion generators, lightweight kinematically redundant mechanisms can be an industrially viable alternative for such motion, in spite of the cost of an additional actuator.

Singularities are one of the most important issues affecting the performance of parallel mechanisms and determining their locations is essential for the development of a usable mechanism. The classification and determination of the singular configurations of parallel mechanisms has been the subject of many research initiatives over the past decades. A variety of mathematical tools have been employed in order to identify and characterise singular configurations, such as Jacobian based methods [15,16], Grassmann geometry [17], differential geometry [18], instability analysis of structures [19], screw theory [20] and Grassmann–Cayley algebra [21–23]. Recently, a detailed and systematic singularity analysis of parallel mechanisms was presented in [24], which includes all types of possible degeneracies, including constraint singularities [25]. Interestingly, singular configurations may provide a transition point to operation modes with different DOFs. The operation modes of Schönflies motion generators have been analyzed by Coste and Demdah [26] and Nurahmi et al. [27].

This paper provides a singularity analysis of a class of kinematically redundant parallel Schöenflies motion generators. The analysis is based on screw theory and all possible cases of singularities are considered. Since the topology of the mechanisms studied in this paper departs slightly from the topology of conventional parallel mechanisms[2], the potential singularities of these mechanisms include redundant passive motion (RPM) singularities [16]. The presented analysis has been adapted in order to incorporate the analysis of such singularities.

The remainder of this paper is organised as follows. Section 2 introduces the studied architectures. The methodology utilized for the singularity analysis is described in Section 3. In Section 4, the described methodology is applied to mechanism variants employing a passive revolute joint between the platform sections, while Section 5 provides the corresponding analysis for manipulators employing a passive prismatic joint. Section 6 employs the knowledge of the singular configurations to provide design suggestions for mechanisms of the proposed type. Section 7 provides conclusions and ideas for future work, while Section 8 provides a nomenclature.

[1] This definition permits certain mechanisms to be both redundantly actuated and kinematically redundant. This seems reasonable as such mechanisms would exhibit the characteristics of both redundantly actuated mechanisms and kinematically redundant mechanisms; however, other definitions of kinematic redundancy add the condition that the mobility must equal the number of actuators, in which case the two groups of redundant mechanisms are disjoint.

[2] The legs are not all connected to a common platform but rather to two platforms which are connected by a passive joint, similarly to the architectures presented in [10,28,29]