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An introduction to utilising the redundancy of a kinematically redundant parallel manipulator to operate a gripper

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ABSTRACT

Although parallel manipulators provide several benefits compared to similar-sized serial manipulators, they typically exhibit a limited rotational workspace. One approach to designing a parallel manipulator with infinite range of tool rotation around one axis is to introduce kinematic redundancy. This is typically achieved by extending a non-redundant mechanism with an additional actuator and a supplemental degree of freedom, while the degrees of freedom of the tool platform remain the same. The main drawback of this approach is the cost of the additional actuator. In this paper, we discuss the possibility of harvesting the motion in the additional degree of freedom to operate a gripper. The benefits of the proposed idea include saving the cost of a gripper actuator and reducing the mass of the manipulated platform. Additionally, the requirement to provide the manipulated platform with compressed air or electric power is removed. Several variants of a kinematically redundant manipulated platform with five degrees of freedom are introduced along with conceptual mechanical designs for transforming the redundant platform motion into the opening and closing of a gripper.

1. Introduction

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

In the original Delta patent [1], Clavel included an actuated kinematic chain to transfer 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. Clavel's design has been successfully employed in the ABB FlexPicker, which is the world's most sold parallel robot [2]. However, 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 [3].

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A different approach to extend the three-degree-of-freedom (3-DOF) Delta robot to a 4-DOF manipulator with 360 degrees tool rotation is to employ gearing on the manipulated platform. Such solutions are employed in a series of papers [3–9]. However, the disadvantage of gearing solutions is that they do not provide infinite rotation of the tool. Infinite tool rotation is a significant advantage, as it allows the tool to always utilise the shortest path between two programmed rotation angles, leading to shorter cycle times for most applications.

The Dual4 manipulator proposed by Company et al. [10] is a rare parallel mechanism utilising only four actuators to provide three tool translations and infinite tool rotation around one axis. The drawback of this concept is that two of the passive linkages manipulating the tool platform are subjected to bending and torsion, which means that they require a stiff and consequently heavy construction. A different approach to provide three tool translations and infinite tool rotation around one axis is presented by Gosselin et al. [11]. The presented mechanism suffers from similar drawbacks as the Dual4 manipulator.

For the majority of proposed parallel robot architectures, 360 degrees tool rotation is prohibited by type two singularities [12], also referred to as parallel singularities. Introducing gearing on the manipulated platform means that these singularities can be avoided while still achieving full rotation [13,14]. A different approach to achieve full rotation is to introduce redundancy, which means that the singularities are eliminated instead of avoided. The main drawback of introducing redundancy is the cost of an additional actuator. There are two types of redundancy. Similar to the description in Lee et al. [15], 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.

Several redundantly actuated parallel robots with the possibility of infinite tool rotation are available in the literature. Kock et al. [16] patented a 4-DOF SCARA-Tau variant with redundant actuators, while Marquet et al. [17] proposed a 3-DOF redundantly actuated planar manipulator, referred to as Archi. The drawback of actuation redundancy is that stress may be introduced in the mechanism if the actuators are operated independently. Hence, any modelling error can wear and potentially break the mechanism. A common approach to overcome the issues of a redundantly actuated mechanism is to employ force control for one actuator. A redundantly actuated manipulator can typically be converted to a kinematically redundant manipulator by introducing an additional DOF in the mechanism. Examples of the use of this approach can be found in Refs. [16, 18–20, 25]. In Ref. [16], the additional DOF was introduced by separating two platform sections by a passive parallelogram while Refs. [18, 19, 25] employed a passive prismatic joint and Ref. [20] utilised a passive revolute joint.

The additional DOF introduced in a kinematically redundant mechanism may be utilised for some additional purpose. Isaksson [18] discussed the possibility of utilising this DOF for a variable transmission ratio for the tool rotation, while Gosselin et al. [20] introduced the idea of employing this DOF to operate a robot gripper. The latter idea is the inspiration for this paper, which aims at extending this concept to spatial manipulators with five DOFs.

The benefits of the proposed architectures include saving the cost of a gripper actuator and reducing the mass of the manipulated platform. Additionally, manipulators with the potential for infinite gripper rotation require a rotary union or slip ring to enable transmission of compressed air or electrical power to the gripper. Otherwise, the infinite rotation cannot be fully utilised. An additional benefit of the proposed architectures is that the requirement of such transmissions is eliminated. Furthermore, some parallel manipulators [19,25] have the potential for infinite rotation of the entire arm system around a central column. For such manipulators, the proposed designs mean that a second rotary union or slip ring, between the central column and the arm system, can be eliminated.

The remainder of this paper is organised as follows. Section 2 introduces several variants of a kinematically redundant manipulated platform. This is followed by a comprehensive singularity analysis of the proposed mechanisms in Section 3. Section 4 introduces conceptual mechanisms that can be used to transform the redundant platform motion into the opening and closing of a gripper, while Section 5 includes a discussion on various methods to actuate the manipulated platform. Finally, Section 6 provides conclusions and ideas for future work.

2. Kinematically redundant manipulated platform

The objective of this paper is to exemplify how the redundancy of a spatial kinematically redundant parallel manipulator can be utilised to operate a gripper. We consider kinematically redundant architectures providing three translational DOFs in addition to infinite rotation around an axis with fixed orientation. Such motion is categorised as Schönflies motion [21]. Consider the general architecture depicted in Fig. 1. In order to achieve infinite rotation of the platform section S_B around the axis V_B, we employ kinematic redundancy. That is, we utilise five actuated kinematic chains, each including a single actuator. A total of n chains are attached to the section S_A, while $5 - n$ chains are attached to the section S_B. A passive 1-DOF kinematic chain K connects S_A and S_B. This chain is either a single passive joint or a more complex construction, such as a parallelogram composed of two RR chains. In order to achieve infinite rotation around V_B, a minimum of two kinematic chains must be attached to S_A.

A mechanism that can generate the described motion may be designed in numerous ways. All possible architectures can be determined using type synthesis techniques [22–24]. However, the objective in this paper is instead to analyse the feasibility of the proposed concept based on practical considerations, such as moving mass, the number of required components and the practicality of the components. Therefore, the scope is immediately limited to a small subset of possible architectures. In order to achieve a lightweight construction, we only consider kinematic chains where the linkages connected to the manipulated platform are only subjected to axial forces, that is, linkages that include a spherical joint on one end and either another spherical joint or a universal joint on the other end. Furthermore, in order to reduce the risk of collisions between the kinematic chains