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On the feasibility of utilising gearing to extend the rotational workspace of a class of parallel robots

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ABSTRACT

Parallel manipulators provide several benefits compared to serial manipulators of similar size. These advantages typically include higher speed and acceleration, improved position accuracy and increased stiffness. However, parallel manipulators also suffer from several disadvantages. These drawbacks commonly include a small ratio of the positional workspace relative to the manipulator footprint and a limited rotational capability of the manipulated platform. A few parallel manipulators featuring a large ratio of the positional workspace relative to the footprint have been proposed. This paper investigates the feasibility of employing gearing to extend the range of the end-effector rotation of such mechanisms. The objective is to achieve parallel manipulators where both the positional and rotational workspace are comparable to that of serial manipulators.

1. Introduction

Parallel manipulators offer several benefits over serial manipulators of similar size. These benefits typically include higher load capacity, increased speed and acceleration, higher stiffness and improved position accuracy. However, parallel mechanisms commonly suffer from several drawbacks, including a small positional workspace in relation to the manipulator footprint and a limited range of rotation of the end-effector (EEF).

A traditional approach to extend the range of EEF rotation for a parallel manipulator is to include redundancy. Redundancy is explained here in terms of mobility, similar to the description used by Lee et al. [1]. If the mobility of a manipulator is greater than the mobility of its EEF, the mechanism is called a kinematically redundant manipulator, while a mechanism with a mobility that is lower than the number of actuators is called a redundantly actuated manipulator.

Fig. 1 exemplifies how the two types of redundancy can be used to extend the rotational workspace of a parallel manipulator. The illustrated mechanisms were proposed by Kock et al. [2]. Each mechanism features a crank-shaped tool platform and can manipulate three positional degrees of freedom (DOF) and one rotational DOF of the EEF. The manipulators include four or five actuated arms rotating around a central base column. Each actuated arm is connected to the manipulated platform by one or two SU linkages, composed of a fixed-length link with a universal joint on the platform end and a spherical joint on the other end. Three axes (A, B, Z) are marked in all drawings. All actuated arms rotate around axis Z. Rotation of the EEF is created by moving axis A in a circle around axis B.

The mechanism in Fig. 1(a) features both a large range of 3-DOF positioning and a sizeable range of yaw rotation (rotation around axis B). A different variant may be achieved by instead attaching five linkages to the lower section of the crank-shaped platform and one to the upper section. The inverse kinematics for both these variants is straightforward. The platform position and yaw angle are expressed by $\dot{\mathbf{x}} = [x, y, z, \phi]^T$ while the actuated arm angles are given by $\dot{\mathbf{q}} = [q_1, q_2, q_3, q_4]^T$. Analytical expressions for $\dot{\mathbf{q}}$ were derived according to the description in [3]. Structural parameters were chosen to achieve manipulators with similar proportions as in Fig. 1(a). The inverse kinematics solutions were verified by solving the length equations of the SU linkages numerically. Analytical expressions for the Jacobians $\mathbf{J}_x$ and $\mathbf{J}_q$ (where $\mathbf{J}_x\dot{\mathbf{x}} = \mathbf{J}_q\dot{\mathbf{q}}$) were derived by differentiating the length equations for the SU linkages using MATLAB's Symbolic Math Toolbox. The Jacobian calculations were verified by a numerical differentiation of the actuated arm angles $\dot{\mathbf{q}}$. The latter calculation provides an expression for $\mathbf{J}$, where $\dot{\mathbf{q}} = \mathbf{J}\dot{\mathbf{x}}$, and it was verified that $\mathbf{J} = \mathbf{J}_q^{-1}\mathbf{J}_x$.

Both the manipulator in Fig. 1(a) and the variant with five linkages connected to the lower end of the crank-shaped platform exhibit two type 2 singularities [4] during 360° yaw rotation. For the latter variant, the singular configurations are geometrically intuitive and occur when the horizontal projection of the crank-shaped platform is collinear with the horizontal projection of the single linkage attached to the upper section of the crankshaft. For

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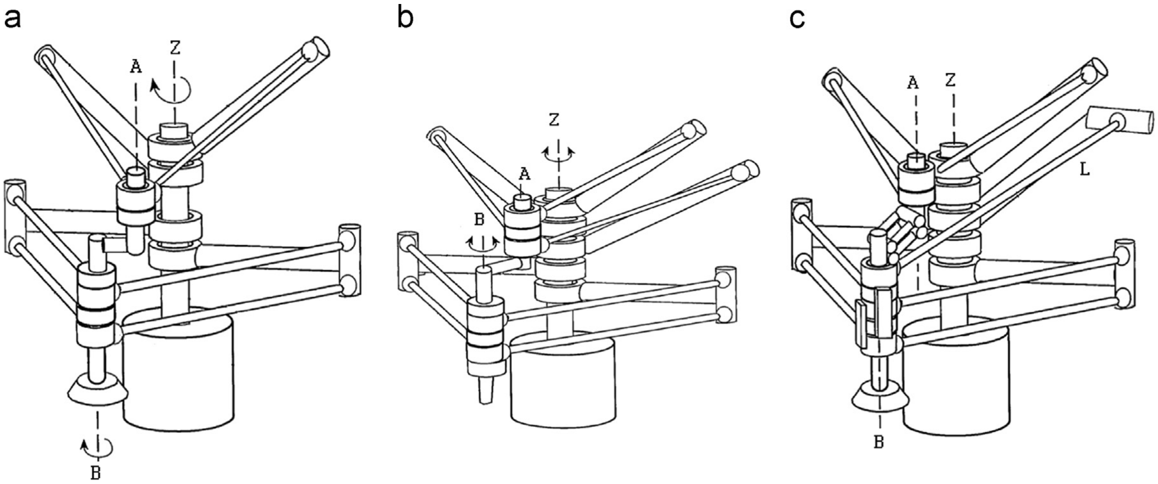

Fig. 1. Parallel manipulators featuring four actuated DOF of the manipulated platform. The manipulator (a) exhibits limited platform rotation while the manipulators (b) and (c) have the possibility for infinite platform rotation. (a) No redundancy. (b) Actuation redundancy. (c) Kinematically redundant. Figures courtesy of [2].

the manipulator in Fig. 1(a), the singular configurations are less self-evident. A singular value decomposition of **J** in the singular configurations of both manipulator variants reveals that the variant with five collinear platform joints exhibits zero stiffness for pure rotation while the direction with zero stiffness for the manipulator in Fig. 1(a) is a combination of a rotation and a vertical motion. The ratio between vertical motion and rotation varies in different platform positions and between manipulators with different dimensions.

The type 2 singularities limit the achievable range of yaw rotation. Industrial usage, such as pick-and-place applications, typically require 360° yaw rotation of the manipulated platform. By including a fifth kinematic chain in the mechanism, as shown in Fig. 1(b), the singularities encountered during platform rotation are eliminated, enabling infinite rotation of the platform. The additional kinematic chain is of the same type as the two uppermost chains in Fig. 1(a). The mobility of this redundantly actuated manipulator remains four. The patent [2] mentions the possibility of instead connecting the additional kinematic chain to the lower section of the crank-shaped platform. The drawback of the redundantly actuated mechanism in Fig. 1(b) is that stress will be introduced in the mechanism if the actuators are operated independently. One strategy for controlling manipulators of this type is to employ force control for one of the actuators.

By introducing an internal DOF in the crank-shaped platform, as shown in Fig. 1(c), seven SU linkages are required to fully constrain the platform when the actuators are locked. When the three lowest actuated arms are locked, the five linkages connected to the lower section of the platform together constrain all DOF of the EEF, except rotation around axis B. Because the parallelogram introduces an additional DOF, two SU linkages are required to fully constrain the upper section of the crank-shaped platform and hence the EEF rotation. The resulting mechanism allows infinite rotation of the EEF. As the mobility of the mechanism is now five while the DOF of the EEF remain four, it is classified as a kinematically redundant manipulator. For such a manipulator, the inverse kinematics exhibit infinite solutions and rules must be introduced to select which solution to use.

The manipulators in Fig. 1(b) and (c) feature infinite rotation of the EEF around axis B. Such manipulators can minimise cycle times by always choosing the shortest path between two EEF angles. However, utilising an additional actuated kinematic chain adds significantly to the cost of the manipulator. This paper investigates the possibility of achieving 360° yaw rotation of the manipulated platform without requiring redundant actuators. By instead employing a gearing solution, the cost of the mechanism can be reduced.

Combining gearing with parallel robots has been proposed previously; one example is a series of papers [5–11] describing how the Delta robot [12,13] can be extended to four DOF without employing the central $\underline{R}$UPUR kinematic chain suggested by Clavel [12]. One mechanism derived in these papers has been patented [14] and is now manufactured by Adept under the product name Quatro. The core idea in papers [5–11] is to introduce one or two internal DOF in the manipulated platform combined with an additional actuated kinematic chain. This chain is either identical to the other three kinematic chains of the original Delta manipulator or differs only by the removal of one linkage in the parallelogram connecting the actuated arm to the platform. The relative motion of the platform sections is transformed to the required rotation by various gear arrangements.

The original paper [5] describes the H4 robot, for which the manipulated platform of the Delta mechanism is modified to an H-shape comprising three sections separated by rotational joints at both ends of the crossbar of the H. The mechanism includes an additional actuated kinematic chain of the same type as the other three chains of the Delta mechanism. Two kinematic chains are attached to each of the two vertical segments of the H-shape. The relative motion of the positions of the two rotational joints is transferred to an EEF rotation using a gear arrangement. As the two rotational joints introduce two DOF in the manipulated platform, and the additional kinematic chain imposes two constraints on this platform when its actuator is locked, the platform is not over-constrained.

Two variants of the H4 mechanism were introduced by Krut et al. [6]. Both variants were named I4 manipulators. The first variant employs three platform sections connected by prismatic joints. Two parallelograms are attached to each of two sections and the relative translation of these platform sections is transferred to an EEF rotation via a rack-and-pinion drive. In the second variant, only one prismatic joint is employed. As only one internal DOF is added to the platform, an over-constrained platform is avoided by using a single linkage in the fourth kinematic chain instead of a parallelogram. Another I4 variant, where the manipulated platform comprises three sections separated by one prismatic joint and one rotating joint, was later proposed by Krut et al. [7].

Further studies [8–11] of the H4 and I4 manipulators revealed that the main disadvantage of the I4 was the short service life of the prismatic joints in the manipulated platform while the main