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Research paper

The virtual screw: Concept, design and applications

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ABSTRACT

The research work reported here was motivated by a class of two-limb parallel Schönflies-motion[1] generators, which offer simplicity, isostaticity, and symmetry. The crucial components required to construct a parallel two-limb robot of this class are a cylindrical drive, namely, a cylindrical motion generator, and a load-carrying link playing the role of the moving platform in parallel robots, with four degrees-of-freedom, i.e. 3D translation and rotation about a vertical axis, which operates based on the same cylindrical motion generator. However, the design requirements of such components call upon screw joints with an unusually large pitch, which are not available off-the-shelf; the authors thus propose a cable-driven virtual screw with an arbitrarily large pitch. This concept is elaborated on with regard to its various alternatives, each suitable for different circumstances and applications. Furthermore, the concept of variable-pitch virtual screw is introduced, which enables the designer to adapt the specification of the robot to any given task. In addition, the novel application of the virtual screw in the context of the architecture of Schönflies-motion generators is studied. Finally, the authors report the design and fabrication of two prototypes to conduct a comparison between the screw joint and the virtual screw.

1. Introduction

The growing demand for automation in industry urges the development of a wide variety of manipulators, each with different objectives and goals. Manipulators can fall into two major categories: serial and parallel. Serial manipulators have a larger workspace compared to the parallel architectures because of their serial array of links. However, the actuation of these links requires moving actuators, such as electric motors and translational pneumatic cylinders, which introduce many design constraints due to their moving cables, hoses, and sensors. Moreover, moving actuators increase the deadweight and inertia of the robot. This leads to a greater demand for actuation power, as well as lower speed and lower precision. In order to minimize the moving mass and improve the performance of serial manipulators, some manufacturers mount the actuators on the base platform (BP) and transmit their motion by means of closed kinematic chains [1–3]. Although the driving mechanism eliminates the difficulties brought about by moving actuators, it increases the design complexity and the number of moving parts. This solution, nevertheless, would not be practical when the robot has more than three degrees of freedom (dof). Therefore, using moving actuators, especially for the end-effector, is unavoidable. For instance, selective compliance assembly robot arms (SCARA), namely, serial Schönflies-motion generators (SMG), need to generate rotation about and translation in the direction of the same axis. This can be done by means of either two motors generating

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[1] These motions comprise four degrees of freedom: three translations and one rotation about one axis of fixed direction.

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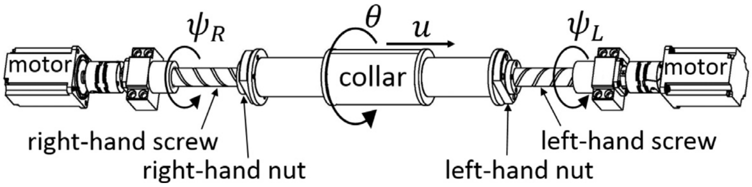

Fig. 1. The C-drive schematic.

each motion individually or using the new product dubbed BNS/NS by THK [4], which is a combination of a screw and prismatic joints (ball-screw and spline rod). However, still using BNS/NS calls upon a moving actuator mounted on the moving platform (MP). In this work, the main design principle is to avoid moving actuators, which leads to placing all the actuators on the BP.

Parallel SMGs benefit from the closure of the loop, which makes it possible to increase the operation speed while keeping the precision, compared to serial pick-and-place robots [5,6]. This enables ABB Robotics' IRB FlexPicker [7] and Adept Technology Inc.'s Quattro s650H [8] to be up to three times faster than their serial counterparts. One should consider that these well-known three- and four-limb architectures, inspired by Clavel's Delta [9], suffer from drawbacks such as a moving telescopic Cardan shaft and limited rotation of the MP due to limb interference, which is the design bottleneck at high-speed operations. To eliminate these drawbacks, Lee and Lee [10,11] proposed four novel two-limb parallel SMG architectures. The Lees' architectures was established based on cylindrical drives, capable of generating the two-dof cylindrical subgroup of the group of rigid-body motions [12]—independent translational and rotational motion, the direction of the former being parallel to the axis of the latter. Harada et al. developed the cylindrical drive, dubbed C-drive, by means of two coaxial right- and left-hand screws [13]. The C-drive transforms the rotation of two stationary motors into cylindrical motion based on the cylindrical differential mechanism. The C-drive has several applications in robotics, such as in full-mobility parallel-kinematics machines (PKMs) [14].

On the other hand, cable-driven mechanisms are appealing due to their high load-carrying capacity, large workspace, high stiffness, and ease of assembly [15,16]. Several cable-driven architectures have been proposed for pick-and-place robots [17–19] targeting high-speed operations, by virtue of the low inertia of cable-driven mechanisms. Usually, the cable is employed to both actuate the MP and impose the required kinematic constraints. Furthermore, cable-based mechanisms can be utilized for motion transformation. For instance, differential cable-driven mechanisms have been introduced to transform the rotation of a motor into the rotational or translational motion of a rigid link with a high mechanical advantage [20,21].

This paper focuses on the development of the virtual screw concept, an alternative to the screw joint (the lead-screw or ball-screw). Since the pitch of screws available off the shelf is limited (much smaller than what is required by the intended applications), the research work reported here aims to introduce a novel mechanism that performs the function of a screw joint. By means of the newly proposed mechanism, that we term the *virtual screw*, the C-drive and the Peppermill, the load-carrying rod of the novel SMG, can be realized to meet highly demanding specifications.

2. Cylindrical differential mechanism

The concept of the differential mechanism, well known in terrestrial vehicles, can be extended to any mechanism whose two outputs are proportional to both the average and the difference of the inputs. Of interest of this paper, the C-drive is a cylindrical differential mechanism that transforms the input motions, namely, the two motor rotations, to a cylindrical motion as the output. Therefore, the generated translation and rotation of the cylindrical subgroup of the Lie group of rigid-body motions [12] are multiples of the difference between the input rotations (relative motion) and the average of the input rotations (synchronized motion). The displacement relations of the C-drive, shown in Fig. 1, is

$$u = \frac{2\pi}{p}(\psi_L - \psi_R), \quad \theta = (\psi_L + \psi_R) \tag{1}$$

where ψ_R and ψ_L are the rotation of the motors coupled to the right- and left-hand screws, respectively, while u and θ are the translation and rotation of the collar. Moreover, p and $-p$ are the pitch of the right- and the left-hand screws, respectively. The Jacobian matrix of the C-drive maps the collar motion variables into the motor rotations, i.e.,

$$\begin{bmatrix} \psi_L \\ \psi_R \end{bmatrix} = \frac{1}{p}\begin{bmatrix} 2\pi & p \\ -2\pi & p \end{bmatrix}\begin{bmatrix} u \\ \theta \end{bmatrix} \tag{2}$$

Four different alternatives for the C-drive are proposed below based on the same principle of motion (the cylindrical differential mechanism) by means of two parallel screws, shown in Fig. 2, each with unique features addressing different needs and applications [22]. Mounting the screws with their axes parallel to each other brings advantages such as a smaller footprint, higher stiffness, and ease of assembling.