Mechanism and Machine Theory 122 (2018) 361–370

Contents lists available at ScienceDirect

Mechanism and Machine Theory

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

Research paper

The translating Π-joint: Design and applications

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ARTICLE INFO

Article history:
Received 1 November 2017
Revised 28 December 2017
Accepted 11 January 2018

Keywords:
Π-Joint
Cylindrical drive
Schönflies-motion
Kinematic chain
Parallel architecture
Motion subgroups
Kinematic bond

ABSTRACT

It is first recalled that a Π-joint is a parallelogram four-bar linkage whose coupler link undergoes pure translation w.r.t. its fixed link; moreover, all the points of the coupler link describe circles with identical radii, the length of the other two links. Innovative and sophisticated joints have a crucial role in simplifying the architecture of manipulators for specific tasks, like fast pick-and-place operations. A novel joint is introduced in this paper, dubbed the translating Π-joint, the series array of a prismatic and a Π-joint, the plane of latter being normal to the direction of the former. A realization of the translating Π-joint is the RHRRHR kinematic chain, R and H standing for revolute and screw joint, respectively. Furthermore, four implementations are disclosed here, each with unique features. In addition, the applications of this joint are studied, including two novel architectures for Schönflies-motion generators. The authors report the detailed design and fabrication of two prototypes based on the above-mentioned implementations. The experimental results are used to conduct a comparison between two designs, which reveal their advantages and drawbacks.

1. Introduction

The impressive growth of robotics knowledge in the past decade brought about many novel architectures to the field of robotic manipulators. Within the rich variety of the latter, there is a great emphasis on parallel manipulators, termed Parallel-Kinematics Machines (PKM), due to their many advantages, such as stiffness, precision of operation, and high load-carrying capacity. Extensive and intensive research has been conducted on the analysis, synthesis and optimization of parallel architectures [1,2]. However, there is high demand for innovative drives, capable of delivering more sophisticated motions than a pure rotation or a pure translation. Harada et al. designed and developed a novel actuator with two degrees of freedom (dof), dubbed the C-drive (cylindrical drive), based on a cylindrical differential mechanism [3]. The C-drive is capable of generating the cylindrical subgroup of rigid-body motions [4]. The motivation behind this work lies in the need for new drives to simplify the robot architecture, while meeting the severe design specifications imposed by fast pick-and-place operations. The C-drive can be used in pick-and-place manipulators or in six-dof flight simulators [5], which are designed to perform a variety of maneuvers.

The concept of Π-joint was introduced in 1991 by Wohlhart [6], and later termed Π-joint by Hervé and Sparacino [7]. The Π-joint can be regarded as a higher kinematic pair of two links, with each point on one link tracing identical circular trajectories on the other link. This joint is nothing but a parallelogram mechanism, i.e., a four-bar linkage with its opposite links of the same length. Such a mechanism, as a higher kinematic pair, has its two opposite links coupled by a Π-joint.

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https://doi.org/10.1016/j.mechmachtheory.2018.01.011
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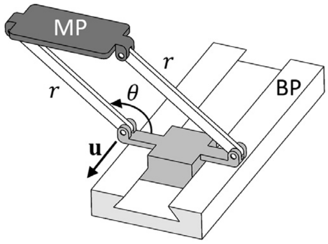

Fig. 1. The translating Π-joint.

Wohlhart [8] and Dietmaier [9] proposed and analyzed the applications of Π-joints in mechanical systems. In the context of PKM, several famous architectures have been proposed, using the Π-joint as a key element of the design. The well-known Delta [10], a parallel robot capable of generating three-dof translational motions, features one Π-joint in each of its three limbs. Each limb carries one RR dyad[1], coupling the base plate (BP) to its Π-joint, which is coupled to the moving plate (MP) via one additional R-joint. Moreover, many proposed parallel architectures [11–13] for the generation of Schönflies motions, translation in three independent directions and rotation about one axis of fixed orientation (usually vertical) [4], benefit from the Π-joints implemented in the array of links, including the Orthoglide-type mechanisms [14]. Adept Technology Inc.'s Quattro s650H [15] and ABB Robotics' IRB FlexPicker [16] are the best known Schönflies-motion generators (SMG); they use the Π-joint. Some combinations of Π-joints, namely RΠ-, Π^2-, and Π^3-joints, are also known [17].

The focus of this paper is on the implementation of a new drive, dubbed the translating Π-joint, capable of producing two-dof motion. The Π-joint is conveyed by a prismatic joint that translates in a direction normal to the Π-joint plane. The initial need for such a drive appeared while conducting the design and fabrication of an innovative SMG [18], dubbed the Peppermill Carrier (PMC), based on a concept proposed by Lee and Lee [19].

2. Kinematics background

A linkage is a mechanical system composed of rigid *links*, coupled by *kinematic pairs*. Based on its definition, a *lower kinematic pair* (LKP) is obtained when two links share a common surface [20]. A *higher kinematic pair* (HKP) is the result of a coupling along a common line or a common point. In the theory of kinematic chains six LKPs are known, namely: *revolute* R; *prismatic* P; *screw* H; *cylindrical* C; *planar* E; and *spherical* S. It is noteworthy that the Π-joint is not a LKP, because in the parallelogram mechanism the coupled links do not share one common surface. Let the Π-joint $\Pi_{\mathbf{e}}$ be defined by means of its plane of motion via the unit vector **e** normal to the plane, and the radius of the circular motion.

In the theory of kinematic chains, moreover, the concept of kinematic *bond* was introduced by Hervé [21]. The term refers to a generalization of the concept of motion subgroup, Hervé having identified 12 such subgroups, six of them generated by corresponding LKP, the others by combinations thereof. The kinematic bond produced by the coupling of links $i, i+1, \ldots, n$ of a lower pair kinematic chain, is represented as $\mathcal{L}(i, n)$. The bond describes the set of relative displacements that link n is capable of undergoing w.r.t. link i.

Two operations are defined within the displacement subgroups, namely, the intersection ($\cap$) and the product ($\bullet$). For example, the Schönflies subgroup can be generated as the product of the planar and the prismatic subgroups: $\mathcal{X}(\mathbf{e}) = \mathcal{F}(\mathbf{u}, \mathbf{v}) \bullet \mathcal{P}(\mathbf{e})$ where $\mathbf{e} = \mathbf{u} \times \mathbf{v}$, under the assumption that **u** and **v** are mutually orthogonal unit vectors, defining the plane of motion of the subgroup $\mathcal{F}(\mathbf{u}, \mathbf{v})$. Studies have been conducted on the construction of serial [22] and parallel [23,24] manipulators, by means of the operations of the displacement subgroups.

3. Translating Π-Joint and its realization

As shown in Fig. 1, the simple realization of the translating Π-Joint, TΠ for brevity, in terms of basic kinematic pairs consists of a Π-Joint mounted on a BP via a prismatic joint whose direction **u** is normal to the plane of the former. Therefore, the bond generated by the TΠ-joint is the product of the sets of motion of these two joints. It is noteworthy that this bond is not a motion subgroup. The TΠ-joint generates the set of relative motions between two rigid bodies, namely, the BP and the MP, which allows any point of the MP to generate a cylindrical surface of a given radius r and axis parallel to vector **u**.

In order to drive a joint, an actuator is needed. The most common actuators are rotary and translational. In addition, the rotary actuator is preferred by designers over its translational counterpart [25]. Therefore, this paper focuses on the implementation of a drive for the TΠ-joint by means of rotary actuators. An important design criterion is to avoid moving actuators. This leads to the necessity of keeping the motors stationary on the BP to reduce the inertial load on the actuation system. Moreover, the implementation of moving actuators calls upon overcoming some difficulties such as moving power

[1] R stands for revolute joint.