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CUBEs: Decoupled, Compact, and Monolithic Spatial Translational Compliant Parallel Manipulators

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Abstract: This paper deals with the conceptual design of decoupled, compact, and monolithic XYZ compliant parallel manipulators (CPMs): CUBEs. Position spaces of compliant P (P: prismatic) joints are first discussed, which are represented by circles about the translational directions. A design method of monolithic XYZ CPMs is then proposed in terms of both the kinematic substitution method and the position spaces. Three types of monolithic XYZ CPMs are finally designed using the proposed method with the help of three classes of kinematical decoupled 3-DOF (degree of freedom) translational parallel mechanisms (TPMs). These monolithic XYZ CPMs include a 3-PPP XYZ CPM composed of identical parallelogram modules (a previously reported design), a novel 3-PPPR (R: revolute) XYZ CPM composed of identical compliant four-beam modules, and a novel 3-PPPP R XYZ CPM. The latter two monolithic designs also have extended lives. It is shown that the proposed design method can be used to design other decoupled and compact XYZ CPMs by using the concept of position spaces, and the resulting XYZ CPM is the most compact one when the fixed ends of the three actuated compliant P joints thereof overlap.

Keywords: Compliant Parallel Mechanisms; Position Spaces; Decoupling; Compactness; Monolithic Fabrication; Extended Life

1 Introduction

Spatial translational compliant parallel manipulators (CPMs), i.e. XYZ CPMs, have extensive applications as atomic force microscopes (AFMs), nano-positioning stages, bio-cell injectors, adjusting mountings, and precision optical alignment devices, etc [1-4]. They transmit motion/loads by deformation of their compliant links (namely jointless), and belong to a class of parallel-type mechanisms, which results in many potential merits such as zero backlashes, no friction, no need for lubrication, reduced wear, high precision, etc [5].

How to design a decoupled, compact, and monolithic XYZ CPM is always desired but challenging when taking actuator isolation into account. A commonly-used method is to employ kinematic substitution method to design the XYZ CPMs with actuator isolation based on the type synthesis of 3-DOF (degrees of freedom) translational parallel mechanisms (TPMs) [6]. A number of designs of decoupled 3-legged XYZ CPMs have been reported in [7-12] using the kinematic substitution method where each of the three kinematic legs, which are coupled in parallel, is individually a serial-parallel hybrid arrangement. But none of them has shown the possibility for monolithic fabrication. Also, these designs have their own limitations such as small motion range (due to the use of lumped-compliance joints), bulky and complex configuration (due to the serial-parallel hybrid arrangement), and/or large lost motion and parasitic rotation (due to the poor out-of-plane stiffness of the passive kinematic sub-chain in each leg).

For a planar CPM such as the XY CPM, it is always easy to fabricate towards a monolithic configuration using existing well-developed planar manufacturing technologies such as wire EDM (electrical discharging machining), water jet, and laser cutting (or MEMS lithography/DRIE for miniaturized version). However, these manufacturing technologies usually fail to satisfy the needs of fabricating most XYZ CPMs monolithically, and therefore assembly has to be passively applied as shown in [7-12]. The assembly leads to some issues such as assembly error, increased number of parts, reduced stiffness (by about 30% by bolted joints), and increased cost [7]. Over recent years, 3-D printing technology has been developed rapidly. Various base/substrate materials, such as engineering plastics, ceramics and metal, can be employed for a variety of applications. But the emerging 3-D printing technology may lead to limited or undesired performance characteristics of material due to no traditional heat treatment applied and the inherent layer-by-layer fabrication. Ref. [13] recently proposed a new XYZ parallel kinematic flexure mechanism with geometrically decoupled three-axis motion using identical flexure plates, which has a more compact and simpler construction and can be fabricated monolithically through the cutting in three orthogonal directions. This design is obtained based on the constraint based design method combining with the brainstorming method for creating the compactness.

Therefore, in compliant mechanisms, the design problem becomes a) how to identify appropriate compliant joints/building blocks, and (b) how to appropriately arrange those compliant joints/building blocks to make a compact and even monolithic configuration. For the former one, one can resort to the library of compliant modules [14] or design new types of compliant modules. For the latter one, there is no a systematic method/guideline in the prior art apart from the brainstorming method.

Building on the above advances, it is essential to conceive a guideline for compact and monolithic design and propose novel decoupled, compact, and monolithic XYZ CPMs: CUBEs. This paper is organized as follows. Section 2 revisits three classes of 3-DOF TPMs. In Section 3, position spaces of three types of compliant P joints are first discussed, and three types of XYZ CPMs are then proposed based on both the kinematic substitution method and the position spaces. Further discussions for three monolithic XYZ CPMs (CUBEs) are provided in Section 4 with conclusions followed in Section 5.
2 Decoupled 3-DOF TPMs

The works on 3-DOF TPMs [6, 15-17] are capable of providing a basis to construct the XYZ CPMs. Based on these works, we can obtain three classes of kinematically decoupled 3-DOF TPMs (Fig. 1) as follows:

1. 3-PPP TPMs;
2. 3-PPPR TPMS: equivalent to 3-PRRR, 3-P PRR, and 3-PRC TPMS in some cases;
3. 3-P PRR TPMS: equivalent to 3-PRPR, 3-PCR, 3-CRU, 3-PUU and 3-PPR TPMs in some cases.

In the above, P, P, R, C, U and P denote actuated prismatic, prismatic, cylindrical, revolute, universal joints and spatial four-bar parallelogram with four spherical joints, respectively.

Note that the 3-PPP TPM and 3-PPPR TPM are both the over-constrained designs, but the 3-PPPRP TPM is the exactly-constrained design. The P joint directly connected to base is the actuated joint, and the PP/PR/PRR sub-chain connected to the motion stage is the passive kinematic sub-chains. Note that all the R joints in the 3-PPPR TPM and 3-PPRRP TPM are inactive [6] due to the inherent constraint of the XYZ TPMS, and the three motion planes associated with the three passive PP kinematic sub-chains in three legs are orthogonal to produce the kinematic decoupling. Each actuated P joint is arranged to be perpendicular to the passive PP motion plane in each leg so that the configuration of the resulting 3-DOF TPMs can be used to construct the following approximately kinematically decoupled XYZ CPMs. In the 3-PPPR TPMS and 3-PPRRP TPMS, the order for the passive joints in each leg can vary as long as the constraint characteristics of the 3-DOF TPMS have no changes. Also, several P and/or R joints in each leg can form other multi-DOF joint(s) such as C and U joint(s).

Note that kinematostatic decoupling means that one primary output translational displacement is only influenced by the actuation force along the same direction. There is no absolute kinematostatic decoupling in compliant mechanisms due to loading nature, but one can minimize the cross-axis coupling in compliant mechanisms. Kinematostatic coupling may lead to complicated motion control, which is the sufficient condition of kinematic decoupling.

Once the appropriate rigid-body decoupled 3-DOF TPMs are identified, the next step is to replace the traditional kinematic joints/sub-chains with the compliant counterparts based on appropriate arrangements of compliant building blocks towards “compact” configuration and “monolithic” fabrication.

3 Design of Decoupled, Compact, and Monolithic XYZ CPMs

3.1 Position spaces of compliant P joints

As mentioned in [18], a compliant P joint has a translational DOF in the motion direction, and therefore can rotate at any angle about its motion direction, which forms the position space of the compliant P joint. The position spaces for three types of compliant P joints are shown in Fig. 2. The compliant P joint is simplified to a “black straight line” whose one end point is fixed and another end point has a translation, TP, represented by a “blue straight line”. The position space of the compliant P joint is a “red circle” about its translation, TP.

The compliant P joint I (Fig. 2a) consists of two identical leaf beams in parallel, i.e. a parallelogram module. The compliant P joint II (Fig. 2b) is composed of a four-beam module and a two-beam module in parallel. The compliant P joint III (Fig. 2c) is composed of two identical four-beam modules in parallel. Here, the compliant four-beam module, composed of four identical wire beams in parallel, produces three planar motions, while the compliant two-beam module offers three planar motions plus an extra out-of-plane rotation.

Figure 1 Three classes of kinematically decoupled 3-DOF TPMs
blocks connected with the motion stages can be determined at this stage.

**Step 2:** Rotating each compliant P joint (except the passive compliant P joint/building block directly connected with the motion stage) about its motion direction within the position space to achieve the most compact configuration. It is concluded that when the fixed ends of three actuated compliant P joints, denoted by black black straight lines, are connected at the same point, the resulting configuration is the most compact one.

**Step 3:** Taking further measures to achieve monolithic fabrication such as swapping the sub-building blocks within the compliant P joint or adding redundant building blocks/over-constraints.

In the following, we use $P_j$ (black straight line in figures) to denote the compliant P joint along the $i$-axis in the leg $j$ with its translational motion $T_{ij}$ (blue straight line). Here, $i=x, y,$ or $z$; and $j=1, 2,$ or $3$. $P_{x1}$, $P_{y2}$, and $P_{z3}$ represent three actuated compliant P joints.

### 3.2.2 3-PPP XYZ CPM

Based on the 3-PPP TPM (Fig. 1a) and Step 1 in Section 3.2.1, a 3-PPP XYZ CPM with a random representation of position spaces of compliant P joints is obtained in Fig. 3 by replacing each traditional P joint in Fig. 1a with the compliant P joint I in Fig. 2a. Figure 3 can represent any a 3-PPP XYZ CPM composed of the identical parallelogram modules.

![Figure 3 3-PPP XYZ CPM with a random representation of position spaces of compliant P joints not directly connected to the motion stage](image)

**Figure 3** 3-PPP XYZ CPM with a random representation of position spaces of compliant P joints not directly connected to the motion stage

Based on Step 2 in Section 3.2.1, we can further obtain the compact design [13] in Fig. 4 where three black straight lines denoting three actuated compliant P joints are connected at the same point, and $T_{x1}$, $T_{y2}$, and $T_{z3}$ (blue straight lines) are perpendicular to $P_{x1}$, $P_{y2}$, and $P_{z3}$ (black straight lines), respectively.

It can be observed that three actuations on the three actuated compliant P joints of the compact design (Fig. 4) are skewed and cannot intersect at the center of the XYZ motion stage. It can also be found that when $T_{x1}$, $T_{y2}$, and
T_{x3} (blue straight lines) coincide with P_{x1}, P_{y2}, and P_{z3} (black straight lines), respectively, three actuation forces can intersect at the center of the motion stage. Detailed position arrangements of compliant P joints in the 3-PPP XYX CPM using CAD models are shown in Fig. A1.

According to the constraint characteristics in Fig. 5, a varied 3-PPP XYZ CPM can be produced as shown in Fig. 6 [19] by removing one leaf beam in each parallelogram module in Fig. 5. Moreover, another two varied 3-PPP XYZ CPMs can be proposed as shown in Fig. 7. This is achieved by using a double parallelogram module (two parallelogram modules in an embedded serial arrangement) or a compound parallelogram module (two parallelogram modules in a mirror-symmetry parallel arrangement) to replace each parallelogram module in Fig. 5.

Based on Step 3 in Section 3.2.1, we can generate the monolithic 3-PPP design (CUBE) [13] in Fig. 5 by adding extra three parallelogram modules. A monolithic polycarbonate prototype with a dimension of 35 mm × 35 mm × 35 mm, has been fabricated (Fig. 5b) through the cutting in three orthogonal directions by the CNC milling machining.

Figure 4 3-PPP XYZ CPM with a specific representation of position spaces of compliant P joints not directly connected to the motion stage: most compact configuration [13]

Figure 5 3-PPP XYZ CPM: monolithic configuration [13]

Figure 6 3-PPP XYZ CPM variation I: monolithic configuration [19]

Figure 7 3-PPP XYZ CPM variation II: monolithic configuration
It should be emphasized that based on the monolithic 3-PPP XYZ CPMs in Figs. 5 and 6 one can obtain other well-behaving monolithic 3-PPP XYZ CPMs with reduced cross-axis coupling effect. For example, each parallelogram module in Fig. 5 can be replaced by another well-behaving compliant P joint (such as the novel flexure parallelogram module composed of four identical monolithic cross-spring flexural pivots using parasitic motion compensation [20]), or each single leaf beam in Fig. 6 can be replaced by a compliant RR joint (such as half of the above novel flexure parallelogram module [20]).

3.2.3 3-PPPR XYZ CPM
Based on the 3-PPPR TPM (Fig. 1b) and Steps 1 and 2 in Section 3.2.1, a compact 3-PPPR XYZ CPM composed of identical compliant four-beam modules is presented in Fig. 8. This is done by replacing each traditional actuated P joint in Fig. 1b with the compliant P joint III in Fig. 2c, and replacing each passive PPR sub-chain in each leg in Fig. 1b with the compliant four-beam module for planar motion.

Based on Step 3 in Section 3.2.1, one can further produce the monolithic 3-PPPR design (CUBE) as shown in Fig. 9 by adding three redundant compliant four-beam modules. Note that the added three redundant compliant four-beam modules are inactive in the monolithic design (i.e. fixed). A monolithic prototype, made of aluminum alloy, with a dimension of 35 mm × 35 mm × 35 mm has been fabricated (Fig. 9b) using the CNC milling machining.

3.2.4 3-PPPRR XYZ CPM
Similarly, based on the 3-PPPRR TPM (Fig. 1c) and Steps 1 and 2 in Section 3.2.1, a compact 3-PPPRR XYZ CPM is obtained as shown in Fig. 10 by replacing each traditional actuated P joint in Fig. 1c with the compliant P joint II in Fig. 2b, and replacing each passive PPRR sub-chain in each leg in Fig. 1c with the compliant two-beam module.

Based on Step 3 in Section 3.2.1, the monolithic 3-PPPRR design (CUBE) (Fig. 11) can be obtained by adding three redundant compliant four-beam modules. It should be noted that it may be needed to swap the compliant four-beam module and compliant two-beam module in the actuated compliant P joint for facilitating monolithic manufacturing.
Three redundant building blocks can be used to design diverse \( \text{XYZ} \) compliant parallel manipulators (CPMs) through the IRC of compact multi-motion stages (herein, \( P \) is the compliant parallel manipulator). The decoupled, compact, and monolithic \( \text{XYZ} \) compliant \( P \)-joint indirectly connected to the new \( \text{XYZ} \) CPMs has been shown in this paper. The extended life of \( \text{XYZ} \) CPMs using wire-beam based modules have been obtained, which can also offer the extended lives. These novel \( \text{XYZ} \) CPMs may promote nano-tube based manufacturing. It is expected that the position space based approach may be extended to design other types of compact multi-axis CPMs.

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**References**

Appendix: Position arrangements of compliant P joints

Figure A1 Position arrangements of compliant P joints in the 3-PPP XYZ CPM using CAD models