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-PPPRR 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 brain-storming 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 brain-storming 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.

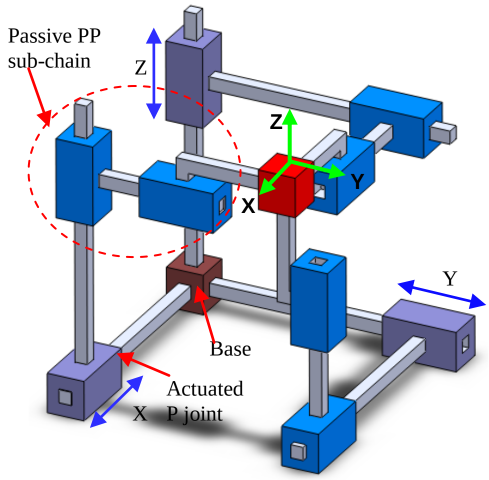
2 Decoupled 3-DOF TPMs

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:

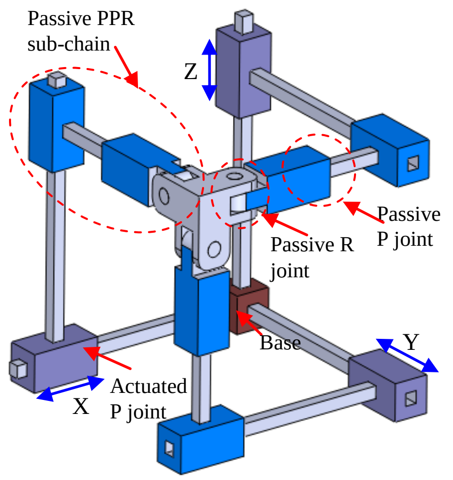
(1) 3-PPP TPMs;

(2) 3-PPPR TPMs: equivalent to 3-PRRR, 3-PPRR, and 3-PRC TPMs in some cases;

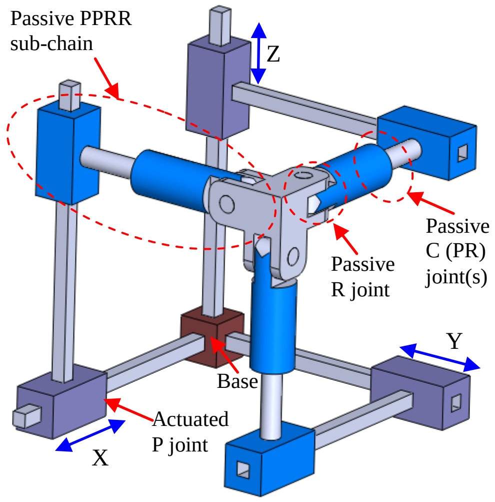
(3) 3-PPPRR TPMs: equivalent to 3-PRPPR, 3-PPCR, 3-CRU, 3-PUU and 3-PP^{s} TPMs in some cases.



(a) 3-PPP TPM



(b) 3-PPPR TPM



(c) 3-PPPRR TPM

Figure 1 Three classes of kinematically decoupled 3-DOF TPMs

In the above, P, P, R, C, U and P^{s} 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-PPPRR TPM is the exactly-constrained design. The P joint directly connected to base is the actuated joint, and the PP/PPR/PPRR 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-PPPRR 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 kinematostatically decoupled XYZ CPMs. In the 3-PPPR TPMs and 3-PPPRR 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.

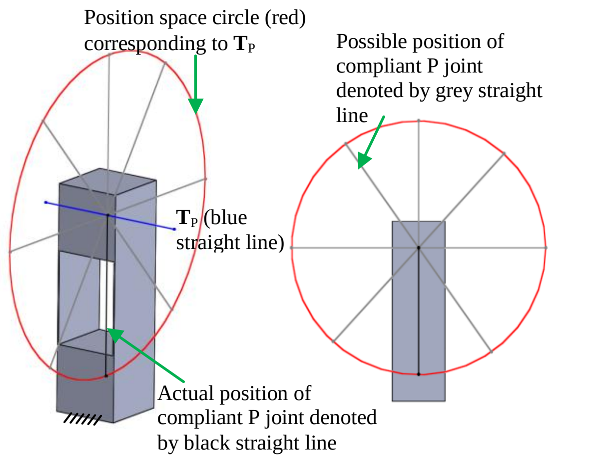
Once the appropriate rigid-body decoupled 3-DOF TPMs are identified, the next step is to replace the traditional kinematic joints/sub-chains with the compliant counterparts based on appropriate arrangements of compliant building blocks towards "compact" configuration and "monolithic" fabrication.

3 Design of Decoupled, Compact, and Monolithic XYZ CPMs

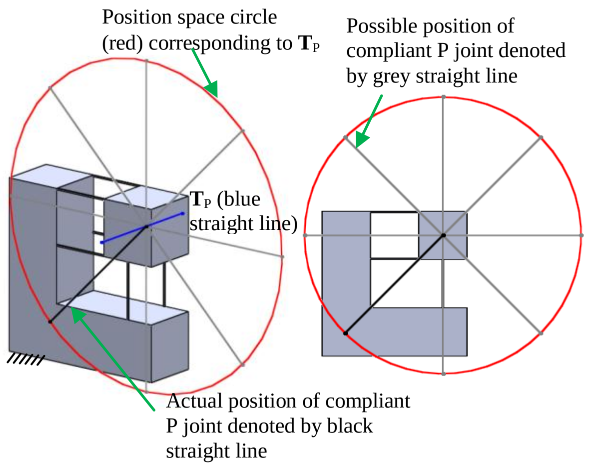
3.1 Position spaces of compliant P joints

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, $\mathbf{T}_{P}$, represented by a "blue straight line". The position space of the compliant P joint is a "red circle" about its translation, $\mathbf{T}_{P}$.

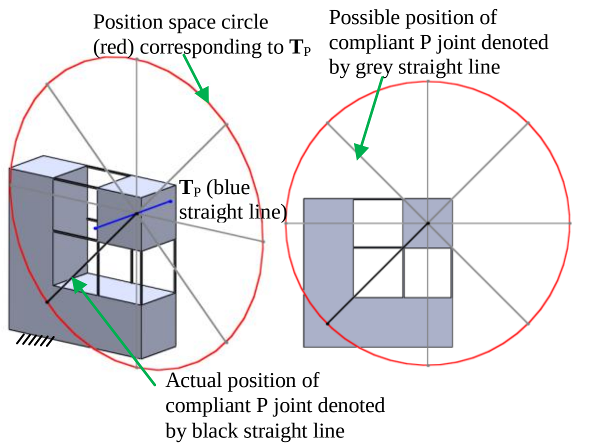
The compliant P joint I (Fig. 2a) consists of two identical leaf beams in parallel, i.e. a parallelogram module. The compliant P joint II (Fig. 2b) is composed of a four-beam module and a two-beam module in parallel. The compliant P joint III (Fig. 2c) is composed of two identical four-beam modules in 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*.



(a) Compliant P joint I composed of two leaf beams in parallel (parallelogram module)



(b) Compliant P joint II composed of a four-beam module and a two-beam module in parallel



(c) Compliant P joint III composed of two identical four-beam modules in parallel

Figure 2 Position spaces of three compliant P joints

3.2 Design of three types of XYZ CPMs

3.2.1 Design method of monolithic XYZ CPMs (CUBEs)

Monolithic XYZ CPMs (CUBEs) can be obtained based on the procedure below:

Step 1: Replacing the traditional kinematic joints/sub-chains in the rigid-body 3-DOF TPMs (Fig. 1) with their compliant counterparts. Note that after the substitution, the positions of compliant P joints/building 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 three 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_{ij} (black straight line in figures) to denote the compliant P joint along the *i*-axis in the leg *j* with its translational motion $\mathbf{T}_{ij}$ (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.

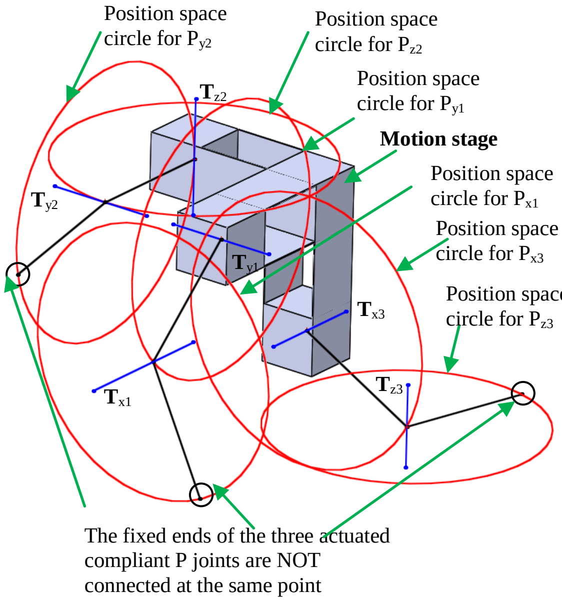


Figure 3 3-PPP XYZ CPM with a random representation of position spaces of compliant P joints not directly connected to the motion stage

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_{z3} (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 XYZ CPM using CAD models are shown in Fig. A1.

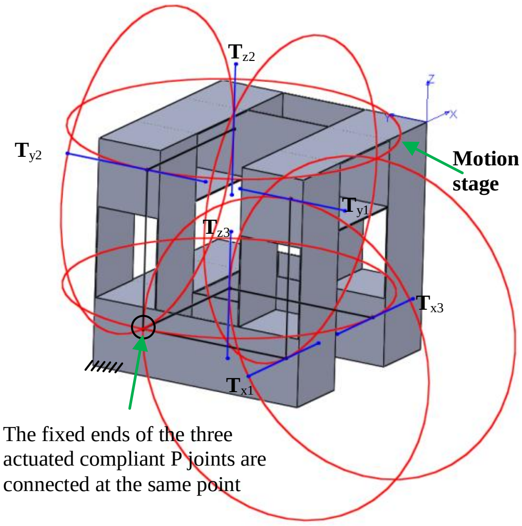
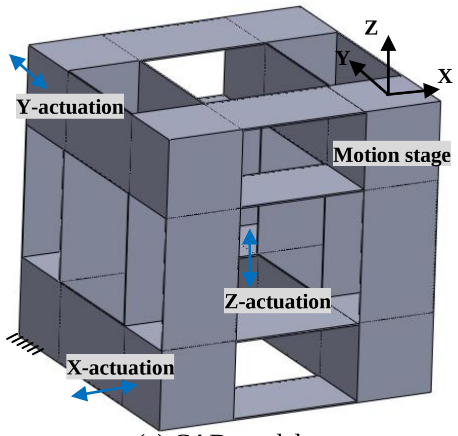
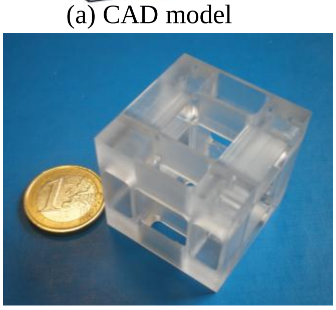


Figure 4 3-PPP XYZ CPM with a specific representation of position spaces of compliant P joints not directly connected to the motion stage: most compact configuration [13]

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.



(a) CAD model



(b) Prototype

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

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.

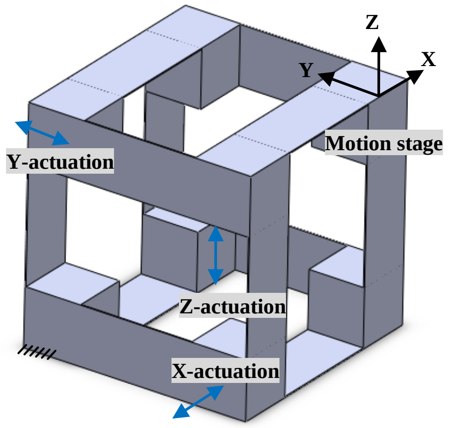
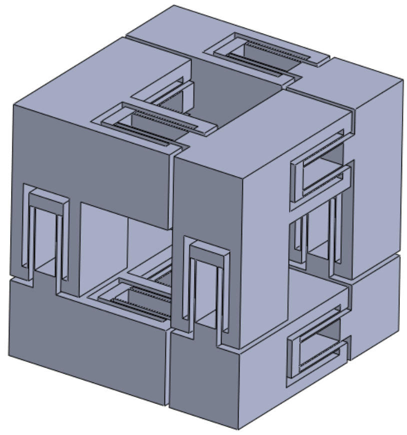
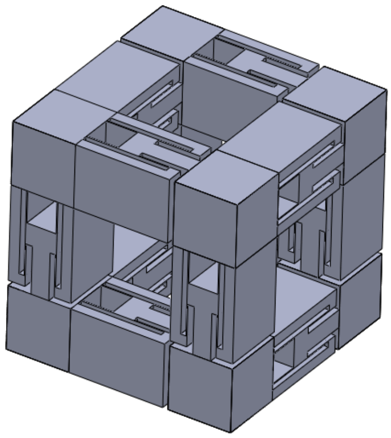


Figure 6 3-PPP XYZ CPM variation I: monolithic configuration [19]



(a) Using double parallelogram module



(b) Using compoud parallelogram module

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 join 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.

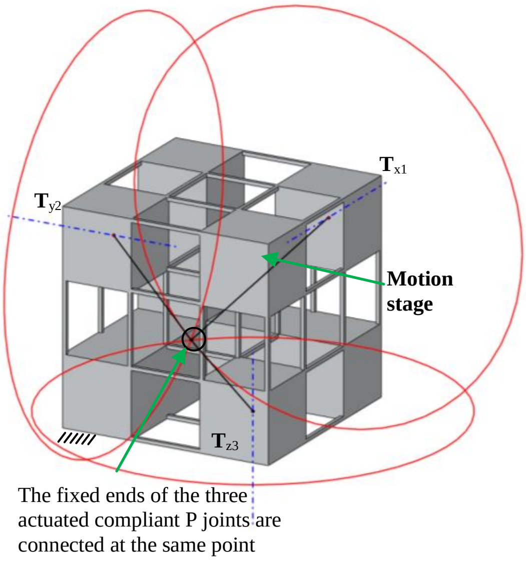
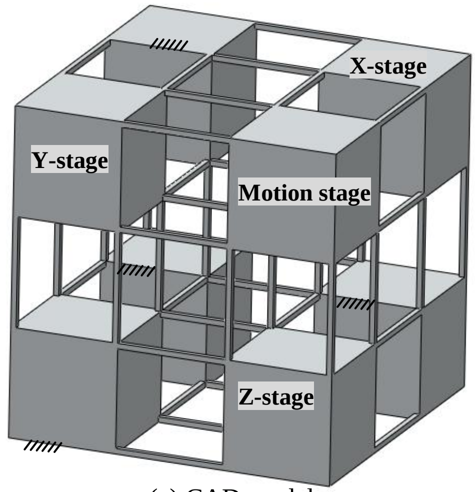


Figure 8 3-PPPR XYZ CPM with a specific representation of position spaces of the actuated compliant P joints: the most compact configuration

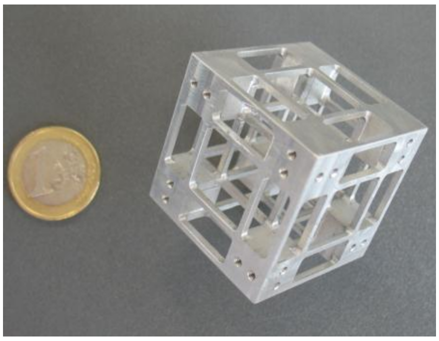
3.2.4 3-PPPRR XYZ CPM

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 join 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.



(a) CAD model



(b) Prototype

Figure 9 3-PPPR XYZ CPM: monolithic configuration

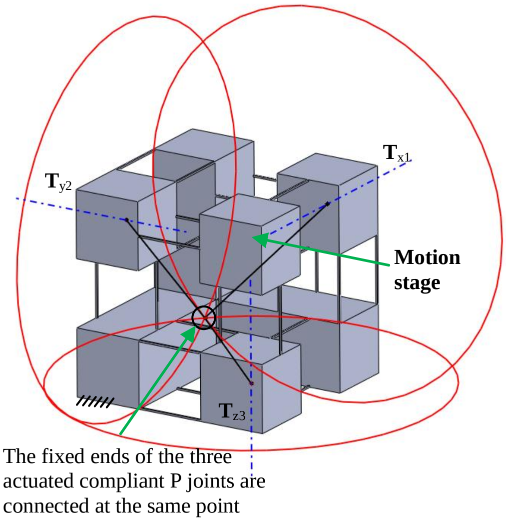


Figure 10 3-PPPRR XYZ CPM with a specific representation of position spaces of actuated compliant P joints: the most compact configuration

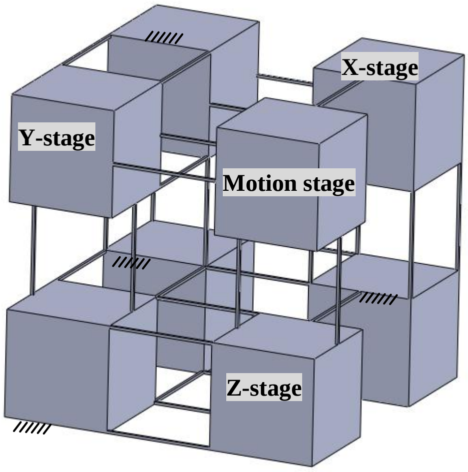


Figure 11 3-PPPRR XYZ CPM: monolithic configuration

4 Discussions

Comparing all of the above monolithic designs (CUBEs), the monolithic 3-PPP design (Fig. 5, 6, or 7), composed of leaf beams, can cause complicated modeling and relatively large primary stiffness. Moreover, the three actuations in the monolithic 3-PPP design are skewed, which can result in negative effects such as the relatively big lost motion and parasitic rotation [13] due to the poor out-of-plane stiffness of the intermediate passive compliant P joint.

A major drawback of the monolithic design is that the failure (yield/fraction) of certain compliant beam can cause the whole system's permanent strike due to the fact that the failed beam is difficult to replace. However, the present monolithic decoupled 3-PPPR/3PPPRR XYZ CPM (Fig. 9 or 11) in this paper has an extended life [21] with three redundant building blocks (compliant four-beam modules). The three redundant building blocks can swap the functions with the three passive mobile PPR building blocks to extend the system's life. In our monolithic design (Fig. 9 or 11), each of three passive building blocks connected to the XYZ motion stage undergoes two translations, and is prone to fail compared to others to produce only one translation. If any one of the three passive building blocks fails, the base frame originally connecting the four fixed cubic stages can be moved to connect with the four originally mobile cubic stages in their initially undeformed configuration. Such a way, the originally fixed cubic stage in the diagonal direction associated with the original XYZ motion stage becomes the new XYZ motion stage, and then the life of the XYZ CPM is retrieved.

It should be noted that when the originally fixed four stages in the monolithic 3-PPPRR XYZ CPM (Fig. 11) become the new mobile stages for extending life, the new X- Y- or Z-stage in each leg is a PR joint (herein, P is the actuated joint) indirectly connected to the new XYZ-stage through a passive PPR joint.

5 Conclusions

The decoupled, compact, and monolithic XYZ compliant parallel manipulators (CPMs), CUBEs, have been presented in this paper. A new method to design diverse decoupled XYZ CPMs has been elaborated by combining the kinematic substitution method and the position space concept of compliant P joints. It has been shown that when the fixed ends of the three actuated compliant P joints overlap at the same point, the resulting XYZ CPM has the most compact configuration.

Two novel types of monolithic XYZ CPMs using wire-beam based modules have been obtained, which can also offer the extended lives. These novel 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.

Acknowledgements

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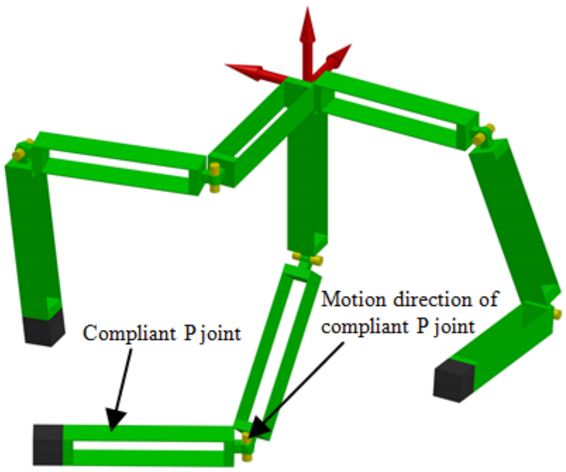
References

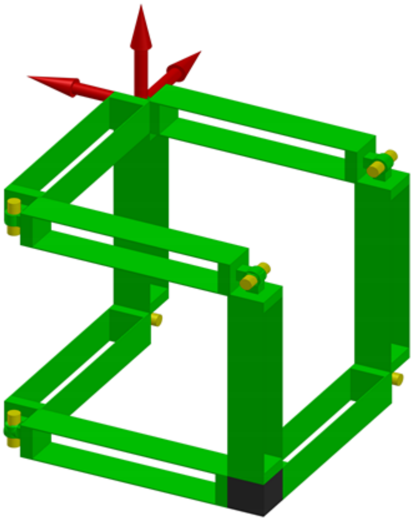
1. Schitter, G., Thurner, P.J, and Hansma, P.K., 2008, "Design and Input-Shaping Control of a Novel Scanner for High-Speed Atomic Force Microscopy", *Mechatronics*, 18:282-288.
2. Werner, C., Rosielle, P.C.J.N., and Steinbuch, M., 2010, "Design of a Long Stroke Translation Stage for AFM", *International Journal Machine Tools and Manufacture*, 50(2):183-190.
3. Shinno, H., and Yoshioka, H., 2010, "A Newly Developed Three-Dimensional Profile Scanner with Nanometer Spatial Resolution", *CIRP Annals – Manufacturing Technology*, 59(1):525–528.
4. Martock Design Limited, 1987, *Adjustable Mountings*, United States Patent, No.:4635887.
5. Howell, L.L., 2001, *Compliant Mechanisms*, Wiley, New York.
6. Kong, X., and Gosselin, C.M., 2007, *Type Synthesis of Parallel Mechanisms*, Springer, Berlin.
7. Hao, G., and Kong, X., 2012, "Design and Modelling of a Large-Range Modular XYZ Compliant Parallel Manipulators Using Identical Spatial Modules", *Journal of Mechanisms and Robotics*, 4: 021009.
8. Li, Y., Xu, Q., 2011, "A Totally Decoupled Piezo-Driven XYZ Flexure Parallel Micropositioning Stage for Micro/Nanomanipulation", *IEEE Transactions on Automation Science and Engineering*, 8(2):265–279.
9. Pham, H.-H., Yeh, H. C., and Chen, I.-M., 2006, "Micromanipulation System Design Based on Selective Actuation Mechanisms", *The International Journal of Robotics Research*, 25(2):171–185.
10. Hao, G., and Kong, X., 2009, "A 3-DOF Translational Compliant Parallel Manipulator Based on Flexure Motion", P*roceedings of the ASME 2009 International Design Engineering Technical Conferences & Computers and Information in Engineering Conference (IDETC/CIE 2009)*, August 30 – September 2, 2009, San Diego, California, USA. DETC2009-86075
11. Yue, Y., Gao, F., Zhao, X., and Ge, Q., 2010, "Relationship among Input-Force, Payload, Stiffness and Displacement of a 3-DOF Perpendicular Parallel Micro-Manipulator", *Mechanism and Machine Theory*, 45(5):756–771.
12. Tang, X., Chen, I.-M., and Li, Q., 2006, "Design and Nonlinear Modeling of a Large-Displacement XYZ Flexure Parallel Mechanism with Decoupled Kinematics Structure", *Review of Scientific Instruments*, 77:115101.

13. Awtar, S., Ustick, J., and Sen, S., 2012, "An XYZ Parallel Kinematic Flexure Mechanism with Geometrically Decoupled Degrees of Freedom", *ASME Journal of Mechanisms and Robotics*, 5(1):015001
14. Howell, L.L., Maglegy, S.P., and Olsen B.M., 2013, *Handbook of Compliant Mechanisms*, Wiley, New York.
15. Kong, X., and Gosselin, C.M, 2002, "Type Synthesis of Linear Translational Parallel Manipulators", *Advances in Robot Kinematics – Theory and Applications*, Lenarcic J. and Thomas F. (Eds.), Kluwer Academic Publishers, pp. 411–420.
16. Gogu, G., 2004, "Structural Synthesis of Fully-Isotropic Translational Parallel Robots via Theory of Linear Transformations", *European Journal of Mechanics A/Solids*, 23(6):1021–1039.61.
17. Carricato, M., Parenti-Castelli, V., 2002, "Singularity Free Fully-Isotropic Translational Parallel Mechanisms", *The International Journal of Robotics Research*, 21(2):167–174.
18. Li, H., Hao, G., and Kavanagh, K., 2014, "Synthesis of Decoupled Spatial Translational Compliant Parallel Mechanisms via Freedom and Actuation Method (FAM)", *Proceedings of the ASME 2014 Biennial Conference on Engineering Systems Design and Analysis (ESDA 2014)*, June 25–27, 2014, Copenhagen, Denmark. ESDA 2014-20196
19. Awtar, S., 2004, "*Analysis and Synthesis of Planar Kinematic XY Mechanisms*", Sc.D. thesis, Massachusetts Institute of Technology, Cambridge, MA, United States.
20. Hao, G., Meng, Q., and Li, Y., 2013, "Design of Large-range XY Compliant Parallel Manipulators Based on Parasitic Motion Compensation", *Proceedings of the ASME 2013 International Design Engineering Technical Conferences & Computers and Information in Engineering Conference*, August 4–7, 2013, Portland, Oregon, USA. DETC2013–12206.
21. Hao, G., 2013, "Towards the Design of Monolithic Decoupled XYZ Compliant Parallel Mechanisms for Multifunction Applications", *Mechanical Sciences*, 4:291-302.

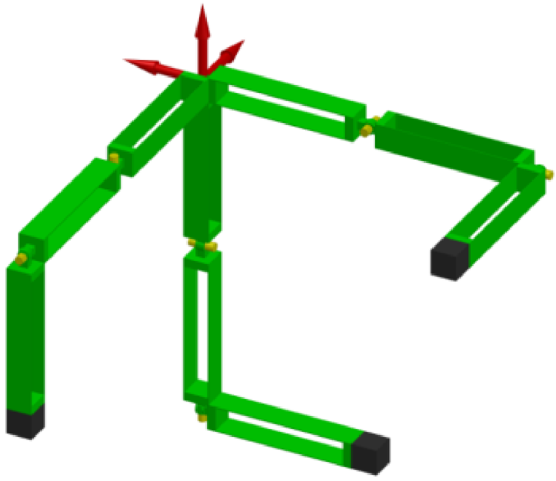
Appendix: Position arrangements of compliant P joints



(a) Any arrangement



(b) The most compact arrangement



(c) The arrangement with three actuation forces intersecting at the center of the motion stage

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