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Conceptual Designs of Multi-DOF Compliant Parallel Manipulators Composed of Wire-Beam Based Compliant Mechanisms

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Abstract
This paper proposes conceptual designs of multi-DOF (degree(s) of freedom) compliant parallel manipulators (CPMs) including 3-DOF translational CPMs and 6-DOF CPMs using a building block based PRBM (pseudo-rigid-body-model) approach. The proposed multi-DOF CPMs are composed of wire-beam based compliant mechanisms (WBBCMs) as distributed-compliance compliant building blocks (CBBs). Firstly, a comprehensive literature review for the design approaches of compliant mechanisms is conducted, and a building block based PRBM is then presented, which replaces the traditional kinematic sub-chain with an appropriate multi-DOF CBB. In order to obtain the decoupled 3-DOF translational CPMs (XYZ CPMs), two classes of kinematically decoupled 3-PPPR (P: prismatic joint, R: revolute joint) TPMs (translational parallel mechanisms) and 3-PPPRR TPMs are identified based on the type synthesis of rigid-body parallel mechanisms, and WBBCMs as the associated CBBs are further designed. Via replacing the traditional actuated P joint and the traditional passive PPR/PPRR sub-chain in each leg of the 3-DOF TPM with the counterpart CBBs (i.e. WBBCMs), a number of decoupled XYZ CPMs are obtained by appropriate arrangements. In order to obtain the decoupled 6-DOF CPMs, an orthogonally-arranged decoupled 6-PSS (S: spherical joint) parallel mechanism is first identified, and then two example 6-DOF CPMs are proposed by the building block based PRBM method. It is shown that, among these designs, two types of monolithic XYZ CPM designs with extended life have been presented.

Keywords: Conceptual designs; Compliant mechanisms; Parallel mechanisms; Wire-beam based mechanisms; Compliant building blocks; Multi-DOF manipulators

1. Introduction

Compliant mechanisms (aka flexure mechanisms) transmit motion/loads (at least one of them) by deformation of their compliant members [1] with positive stiffness usually or even zero stiffness [2] and negative stiffness [3]. They aim to utilize the material compliance/flexibility instead of only analysing/suppressing the negative flexibility effect like those initial works in the area of kinematics of mechanisms with elasticity [4]. This revolutionary change leads to many potential merits such as reduced part count (up to monolithic configuration), zero backlashes, no need for lubrication, reduced wear, increased reliability, high precision and compact configuration in comparison with the rigid-body counterparts [1]. Compliant mechanisms can be used in a variety of applications including micro and macro scales, especially where high-precision motion is required, such as high-precision positioning stages [5-7], biomedical devices [8], metrology instruments [9], MEMS sensors [10, 11], amplifiers [12-14], relays [15] and actuators [16, 17], grippers [18-20], friction force microscopes [21], atomic force microscopes [22], adaptive mechanisms [23], human assistance systems, and design for no assembly [24].

This paper focuses on the design of multi-DOF (degree(s) of freedom) compliant parallel manipulators (CPMs) for the high-precision positioning stage applications [5-7] such as bio-cell injectors, adjusting mountings, and precision optical alignment devices. While typical dynamic ranges (the ratio of the motion range to the minimum motion resolution) of 10^5 are easily achievable in flexure/compliant stages, large specific range (the ratio of the motion range to the system size/footprint) is still the most desirable but challenging issue in high-precision (such as nanopositioning) compliant mechanisms with the specific range of 3×10^{-3} for a typical design [7]. Large range of motion is generally affected by the following factors: a) system size (beam length), b) beam thickness, c) material selection (high yield strength/Young's Modulus ratio), d) linear actuator, and e) conceptual-level design. Improving the last factor is the most effective way to raise the motion range by using the distributed compliance for the given material and actuators. This is because enlarging the length of beams can make the configuration bulky and reducing the thickness of beams may result in the decrease of stiffness significantly and other issues such as manufacturability.

Recently, wire-beam based compliant mechanisms (WBBCMs), composed of one or more wire beams with symmetrical cross sections, have drawn plenty of attentions. For example, a number of synthesis works for WBBCMs have been reported in [25-31], spatial 3-DOF translational compliant parallel manipulators only composed of identical WBBCMs have been proposed in [32, 33], and nonlinear analysis/modelling has been carried out for WBBCMs in [34, 35]. In comparison with the leaf-beam based distributed-compliance compliant mechanisms, the WBBCMs benefit from the following potential merits:

(a) A single wire beam is the simplest distributed-compliance compliant module that has the large motion range in the DOF directions but with very high stiffness along the wire axial direction, a DOC (degree of constraint) direction [25]. This will result in the high stiffness of resulting WBBCMs in the directions along the wire-beam axis.

(b) The 3D modelling of the wire beam is easier and better developed compared with the 3D modelling of the conventional lumped-compliance hinge/pivot and distributed-compliance leaf/blade/sheet [34-36].

(c) WBBCMs cannot result in very large primary stiffness. This enables the use of the electromagnetic actuator for large-range motion since a larger primary stiffness will require a bulkier electromagnetic actuator to produce a higher peak force and therefore a quadratic larger heat creation [32].

(d) WBBCMs may promote the fabrication using the carbon nanotubes (CNTs). This may lead to novel CNT-based compliant mechanisms used in the emerging nano-electro-mechanical-systems (NEMS) [37-39].

Based on the above advances, it is therefore that the objective of this paper is to: a) conceive a good design approach; and then b) propose new WBBCMs and large-range multi-DOF CPMs, composed of WBBCMs, including 3-DOF translational CPMs and 6-DOF CPMs. This paper is organised as follows. Section 2 implements a literature review for the design approaches of compliant mechanisms, and proposes a building block based PRBM method. In Sections 3 and 4, a number of multi-DOF CPMs composed of WBBCMs are generated using the proposed design method. Further discussions on the design criteria are detailed in Section 5. Conclusions are finally drawn.

2. Design Approaches of Compliant Mechanisms

2.1 Review of emerging design approaches

There are several emerging approaches to design compliant mechanisms: a) the pseudo-rigid-body-model (PRBM) approach [41-46], b) the continuum structure optimization (CSO) approach [47-50], and c) the other innovative design approaches such as the constraint-based design (CBD) approach [6, 25, 51-53], the screw theory based (STB) approach [26-28, 54], the freedom and constraint topology (FACT) approach [29-31], and the building-block synthesis (BBS) approach [55, 56]. Compliant mechanisms obtained using different design approaches can be classified into three categories: lumped-compliance mechanisms such as that in Li' work [43], distributed-compliance mechanisms such as that in Awtar's work [6], and hybrid-compliance mechanisms such as that in Polit's work [45].

The PRBM approach is a kinematic substitution method based on the type synthesis of rigid-body mechanisms. It can be further broken down into a *direct substitution based PRBM approach* [41] and a *building block based PRBM approach* [32]. The former directly replaces the traditional kinematic joint with a suitable compliant joint with lumped or distributed compliance, and the latter replaces the traditional kinematic sub-chain with an appropriate multi-DOF compliant building block (CBB) with lumped or distributed compliance. Note that although the PRBM method is a lumped-parameter model, it does not mean that the resulting compliant mechanism is of lumped compliance. The performance of compliant mechanisms generated by the PRBM approach largely depends on the selected compliant joints/CBBs and their arrangements. If lumped compliance is adopted in the PRBM approach, a limited motion range is produced, but if distributed compliance is used, a relatively large motion range can be generated.

The CSO approach is to re-consider the design problem as an optimal material distribution problem so that the resulting continuum structure can fulfil the motion requirements of a mechanism [50]. The CSO approach based design involves three aspects: (a) topology, i.e. the connectivity of material, (b) size, i.e. the cross-sectional area of each segment, and (c) geometry, i.e. the orientations of the connecting segments and locations of the junctions [8]. However, the CSO approach generates mechanisms with the point flexure, and the resulting compliant mechanisms involve many parameters, which are also highly sensitive to manufacture error.

The CBD approach uses the fundamental prerequisite that the motion of a rigid-body is determined by the position and orientation of the constraints, which is well-suited for the conceptual design of compliant mechanisms [25, 26, 51]. This approach has obtained good outcomes in designing precision instruments [6, 52].

Different from the CBD approach, the STB approach uses the mathematical expressions, *screw theory*, to represent the CBD approach and synthesize the constraints under given motion requirement based on *reciprocity principle*, while the FACT employs the geometric figures to visualize the CBD approach. Both the STB approach and FACT approach can also be used to synthesize the mechanisms capable of producing screw motion (also helical motion) that cannot be synthesized using the CBD approach.

The BBS approach is the method of capturing kinematic behaviour using compliance ellipsoids, the mathematical model of which facilitates the characterization of the building blocks, transformation of problem specifications, decomposition into sub-problems, and the ability to search for alternate solutions [55]. This approach is also intuitive and provides key insight into how individual building blocks contribute to the overall function [55]. However, this approach is currently focusing on dealing with low order, planar, and linear problems.

In summary, the PRBM approach is the popular and easiest method that is well suitable for spatial CPM design with actuator isolation consideration. However, the other approaches mentioned above are mainly dedicated to designing the distributed-compliance modules/joints without considering the actuator isolation [54]. Here, actuator isolation means the minimal transverse motion of the actuator since the high-precision linear actuators (such as PZT and Voice Coil) and the input linear displacement sensors (such as optical linear encoder) cannot tolerate the transverse motion/load. In order to ensure maximal actuator isolation, the actuated compliant P joint is always designed to guide the linear actuator.

Note that one can also obtain compliant mechanisms with good performance characteristics such as eliminated parasitic motion, enlarged motion range and compact configuration by *symmetrical*, *serial* and *stacked* arrangements, respectively [57]. Moreover, stiffness center overlapping can also be used to minimise the parasitic rotations instead of the symmetrical design to reduce the system dimension/leg number [57].

As an example, we demonstrate how to use the CBD approach [25] to identify the DOF of a spatial compliant mechanism composed of multiple wire beams following the procedure below.

(a) Identify the independent ideal constraints, and draw a DOC line going through the central axis of each ideal constraint. Here, a wire beam is defined as an ideal constraint.

In the case of the spatial three-beam module shown in Fig. 1, which has been proposed before [25], each wire beam is an ideal constraint that allows five DOF other than the axial motion. Therefore there are three independent constraints in this module, i.e. three independent parallel DOC lines.

(b) Calculate the number of the DOF using the equation:

$$N_F=6-N_C$$

where, the number "6" is the total DOF number of a free rigid body in spatial motion, N_F is the number of DOF, and N_C is the number of DOC. In the case of Fig. 1, there are three DOF lines, which will be determined in the next step.

(c) Determine the orientation and position of each DOF line by making each DOF line intersect all DOC lines and produce independent motion.

In Fig. 1, each DOF line is parallel to all DOC lines to make each DOF line intersect three DOC lines at the infinity, and therefore one DOF line can go through the symmetrical centre of the spatial compliant mechanism, and the other two DOF lines are at the infinity where one DOF line is within the XZ-plane, and another DOF line is within the XY-plane.

(d) Determine the DOF of the spatial three-beam module by rotating the motion stage about each DOF line.

In the case of Fig. 1, the DOF line passing through the symmetrical centre of the spatial three-beam module produces a purely rotational motion, and the two DOF lines at the infinity produce two independent translational motions.

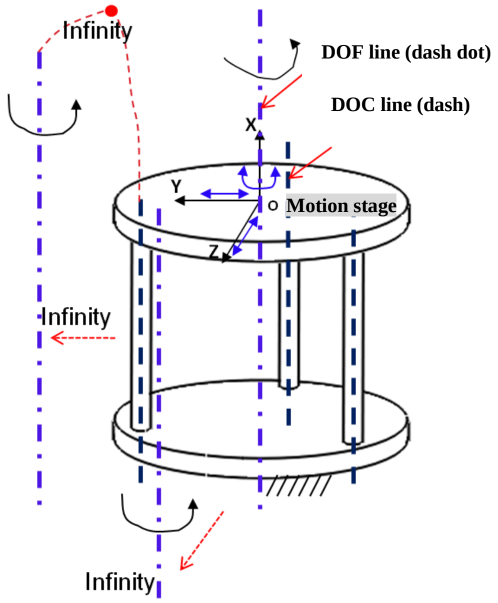


Fig. 1 A WBBCM composed of three independent wire beams: spatial three-beam module

In addition, a blade/sheet/leaf flexure module can also be replaced equivalently with three ideal constraints [25]. Therefore, we can conclude that a blade/sheet/leaf is able to achieve two rotational displacements and one translational displacement using the CBD approach.

2.2 Building block based PRBM method

This section proposes a building block based PRBM method to design large-range multi-DOF CPMs, which is detailed in Fig. 2. This method is a straightforward way to design complex compliant manipulators considering actuator isolation for the engineers. The multi-DOF CPMs composed of WBBCMs as distributed-compliance CBBs will be obtained in the next two sections using the building block based PRBM method.

The following two points should be emphasized for the building block based PRBM approach.

a) Same as the direct substitution based PRBM approach, the building block based PRBM method is also the kinematic substitution method. It needs to appropriately arrange the CBBs for making the system configuration more compact and easier to fabricate, and requires the knowledge of the rigid-body mechanisms as the prerequisite. Although the other methods such as FACT and STB do not need any prerequisite in the rigid-body mechanisms to generate compliant mechanisms, but as mentioned earlier they are mainly dedicated to the relatively simple design without considering the actuator isolation. Unlike the direct substitution based PRBM approach in which the traditional kinematic joint is directly replaced with a suitable compliant joint, the presented approach replaces the traditional kinematic sub-chain with an appropriate multi-DOF CBB. Therefore, this building block based PRBM approach may produce more and better CPMs for large-range applications and is very efficient in designing multi-DOF CPMs.
b) When the CBB acts as the kinematic sub-chain, a purely parallel mechanism is always desired for making the configuration compact and reducing the number of the stages/mass (i.e., without secondary/intermediate stage). However, the CBB has to be a hybrid (parallel and serial) mechanism due to the characteristic improvement need or

the design limitation instead of the purely parallel mechanism. Here, the hybrid mechanism can involve either non-controllable secondary stage for improving the performance characteristics (in the case of the two parallel modules with same function/DOF arranged in series) or controllable intermediate stage for no purely parallel mechanism available (in the case of two parallel modules with different function/DOF arranged in series). The former case can make the mechanism more compact than the latter case.

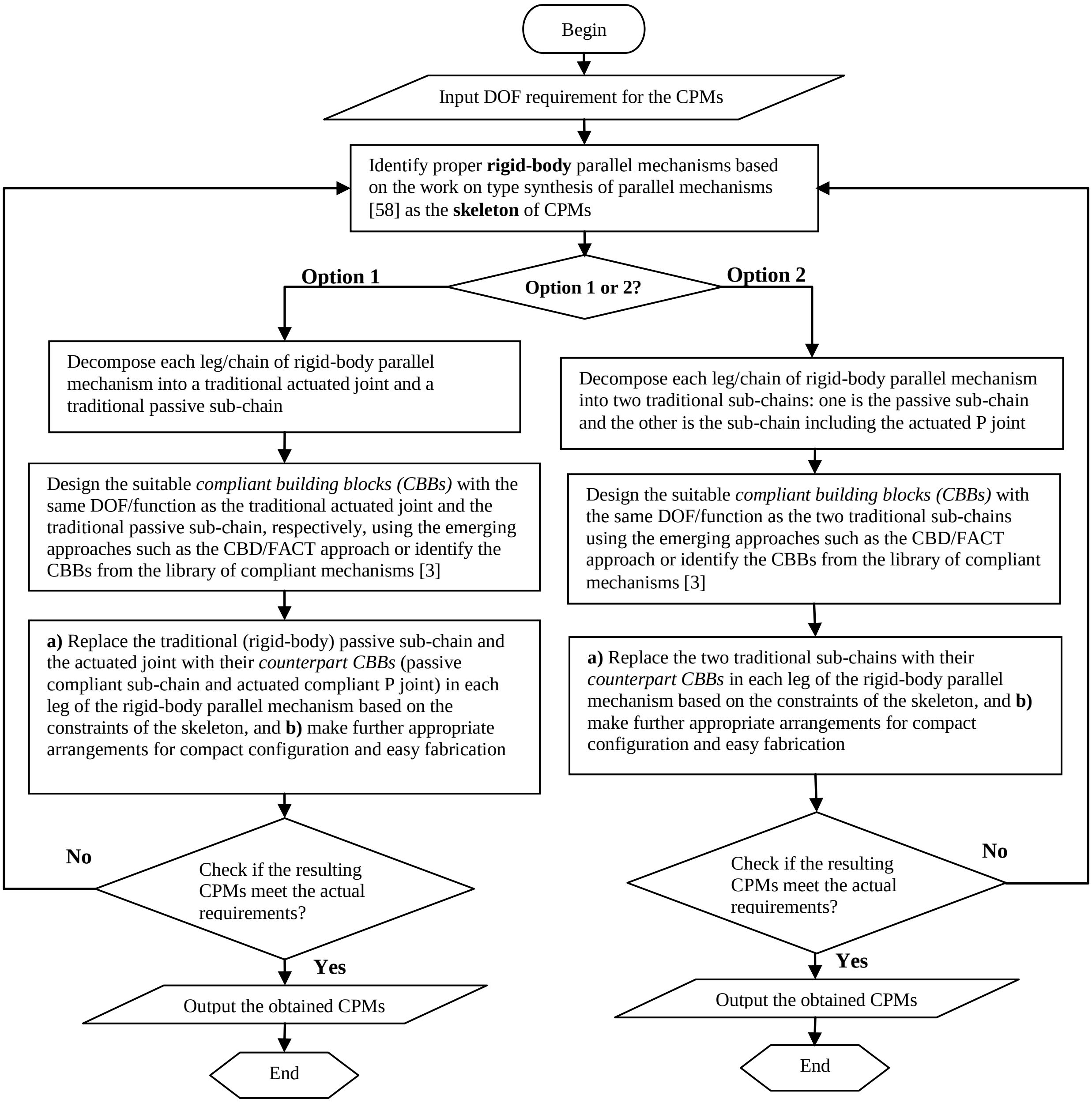


Fig. 2 Flow chart for the building block based PRBM method

3. Decoupled 3-DOF Translational CPMs

The works on 3-DOF rigid-body translational parallel mechanisms (TPMs) [59-61] provide a basis to construct the XYZ CPMs. Based on these works, we can obtain three classes of typical kinematically decoupled 3-DOF TPMs (Fig. 3) as follows:

(1) 3-$\underline{P}$PP TPMs;

(2) 3-$\underline{P}$PPR TPMs (equivalent to 3-$\underline{P}$RRR, 3-$\underline{P}$PRR, and 3-$\underline{P}$RC TPMs in some cases);

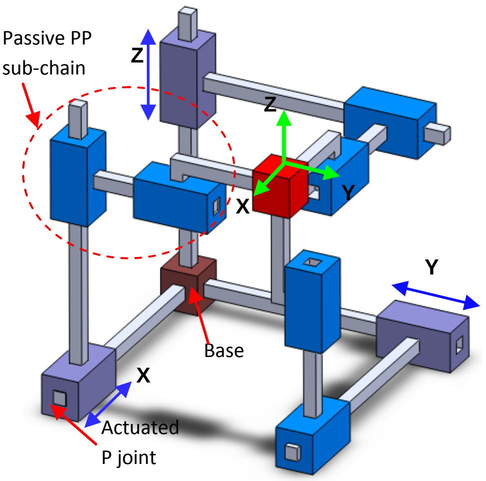
(3) 3-$\underline{P}$PPRR TPMs (equivalent to 3-$\underline{P}$RPPR, 3-$\underline{P}$PCR, 3-$\underline{P}$UU and 3-$\underline{P}P^s$ TPMs [46] in some cases).

In the above, $\underline{P}$, 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.

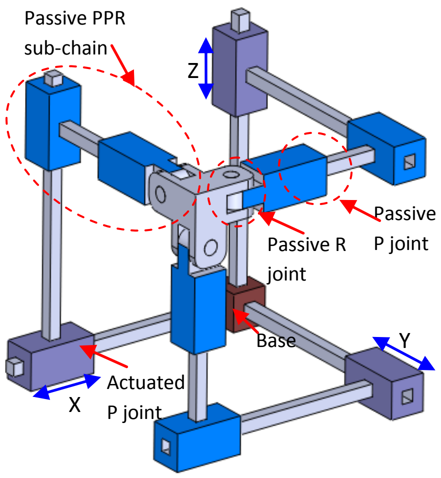
Note that the 3-$\underline{P}$PP TPM and 3-$\underline{P}$PPR TPM are both the over-constrained design, but the 3-$\underline{P}$PPRR TPM is the exactly-constrained design. The P joint directly connected to base is the actuated joint, and the PP/PPR/PPRR sub-chain connected to the motion stage is the passive one. Note that all the R joints in the 3-$\underline{P}$PPR TPM and 3-$\underline{P}$PPRR TPM are inactive [58] due to the inherent constraints 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 kinematostatically decoupled XYZ CPMs.

Once the appropriate rigid-body TPMs are identified, the next step is to decompose each leg for each class of 3-DOF TPM as indicated in Fig. 3. It is noted that the 3-$\underline{P}$PP TPM won't be adopted in this paper since there is no a compact WBBCM as the passive CBB capable of producing only two independent translations [25, 54] to replace the traditional passive PP kinematic sub-chain.

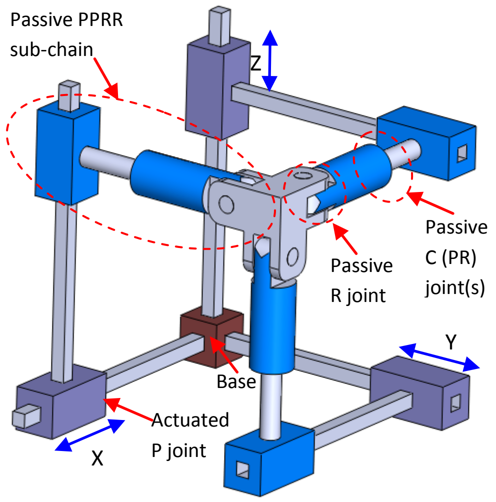
The suitable WBBCMs with orthogonal constraint arrangements as the CBBs for the 3-$\underline{P}$PPR and 3-$\underline{P}$PPRR TPMs can be designed based on CBD approach (as detailed in Section 2.1), which are shown in Table 1. In addition, equivalent representations of the two WBBCMs in Table 1 are illustrated in Table 2. The orthogonal constraint arrangements for the WBBCMs are preferred in this paper due to their good manufacturability.



(a) 3-$\underline{P}$PP TPM



(b) 3-$\underline{P}$PPR TPM



(c) 3-$\underline{P}$PPRR (3-$\underline{P}$PCR) TPM

Fig. 3 Three classes of kinematically decoupled 3-DOF TPMs

Table1 WBBCMs with orthogonal constraint arrangements

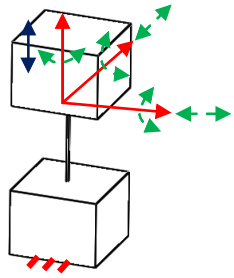
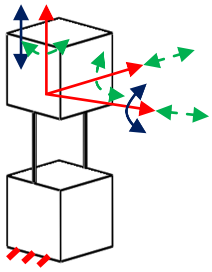
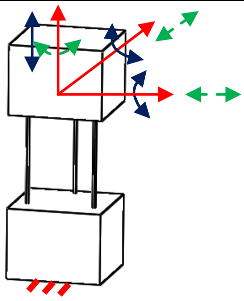
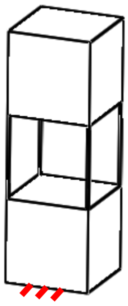
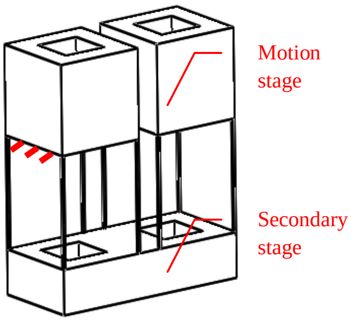
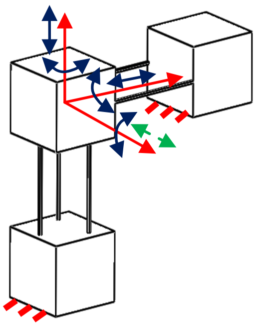
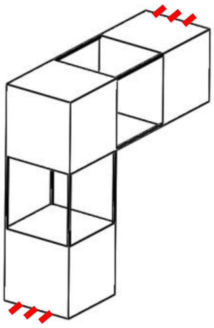
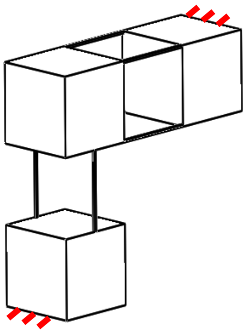
WBBCMs (exactly-constrained design)	**WBBCMs (under/over-constrained design considering better manufacturing and/or performance)**	**DOC** (blue double-arrow solid line)	**DOF** (green double-arrow dash line)	**Comments**
 (WBBCM1)	**N/A**	**1**	**5**	*1-SS (or 2P3R/PPRRR) CBB [35], which acts as the passive kinematic sub-chain.*
 (WBBCM2)	**N/A**	**2**	**4**	*2-SS (or 2P2R/PPRR) CBB, which acts as the passive kinematic sub-chain.*
 (WBBCM3)	 (WBBCM3-1)  (WBBCM3-2)	**3**	**3**	*3-SS (or 2P1R/PPR) CBB, which acts as the passive kinematic sub-chain.* WBBCM3-1 is a purely parallel WBBCM with one redundant wire-beam constraint. WBBCM3-2 is a hybrid (parallel and serial) WBBCM with the secondary stage non-controllable but reduced parasitic translations.
 (WBBCM4)	 (WBBCM4-1)  (WBBCM4-2)	**5**	**1**	*1P CBB, which acts as the actuated P joint.* WBBCM4-1 is a purely parallel WBBCM, composed of two identical WBBCM3-1s, with three redundant wire-beam constraints. WBBCM4-2 is a purely parallel WBBCM, composed of WBBCM3-1 and WBBCM2, with one redundant wire-beam constraint.

Table 1 WBBCMs with orthogonal constraint arrangements **(**continued)

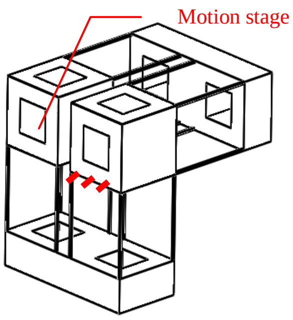
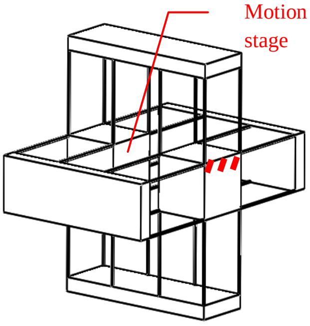
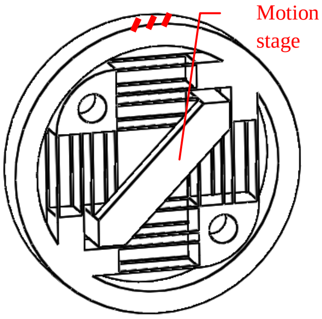
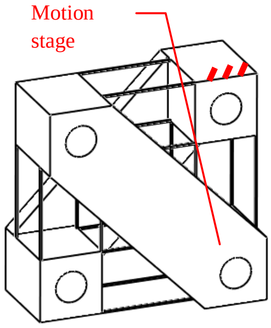
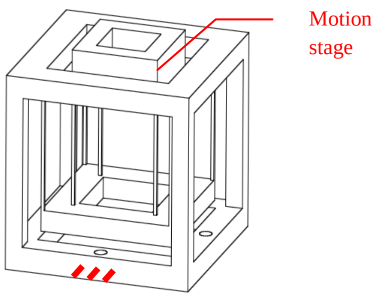
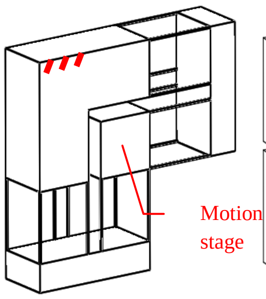
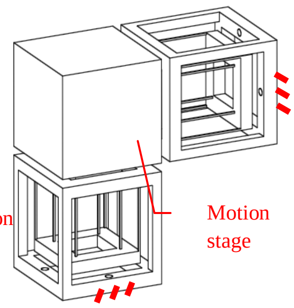
WBBCMs (exactly-constrained design)	**WBBCMs (under/over-constrained design considering better manufacturing and/or performance)**	**DOC**	**DOF**	**Comments**
WBBCM4	 (WBBCM4-3)  (WBBCM4-4)  (WBBCM4-5)  (WBBCM4-6)	**5**	**1**	*1P CBB, which acts as the actuated P joint.* WBBCM4-3 is a hybrid WBBCM with two non-controllable secondary stages but *reduced parasitic translation*. WBBCM4-4 is a fully symmetrical and hybrid WBBCM with four non-controllable secondary stages but *reduced parasitic translation and rotation*. WBBCM4-5 is a symmetrical and hybrid WBBCM with two non-controllable secondary stages but *reduced parasitic translation and rotation*. WBBCM4-6 is a symmetrical and purely parallel WBBCM with *reduced parasitic translation and rotation*.

Table 2 Other equivalent representations

Equivalent representation of WBBCM3-2	Equivalent representations of WBBCM4-3
 WBBCM3-2-1	 WBBCM4-3-1  WBBCM4-3-2

3.1 Design of 3-PPPR XYZ CPMs

Once the decomposition of each leg in the rigid-body 3-DOF TPM and the design of WBBCMs are completed, one can employ the building block based PRBM method option 1 (Fig. 2) to design the XYZ CPMs in a conceptual way.

Using the 3-PPPR TPM in Fig. 3b, a decoupled XYZ CPM (Fig. 4) composed of identical WBBCM3-1s is obtained [33] by replacing the traditional actuated P joint and the traditional passive PPR sub-chain in each leg with a WBBCM4-1 and a WBBCM3-1 (Table 1), respectively, and making appropriate arrangements.

In order to avoid the negative effects such as assembly error, increased number of parts, reduced stiffness (by about 30% by bolted joints) and increased cost, the monolithic fabrication is always desired. Therefore, an improved design of the decoupled XYZ CPMs (Fig. 5) is adopted in terms of the proposed decoupled XYZ CPM (Fig. 4), which can be fabricated monolithically from a cubic material by three orthogonal directions' cutting [33]. The improved design is composed of eight rigid cubic stages organically connected by twelve identical WBBCM3-1s to form a monolithic and compact cubic configuration (extra three WBBCM3-1s are added compared with Fig. 4d). When any four adjacent rigid stages are fixed in the non-deformed configuration (and therefore three WBBCM3-1s are inactive), the other four rigid stages act as the mobiles stages (X-, Y-, Z-, and XYZ-stages), displaced by the deformation of the nine WBBCM3-1s, to achieve the function of XYZ CPMs. The detailed linear analytical modelling and optimization results can be found in [33].

A major drawback of the monolithic design is that the failure (yield/fraction) of certain compliant wire beam(s) can cause the whole system's permanent strike due to the fact that the failed wire beam is difficult to replace. However, the present monolithic decoupled XYZ CPM in this paper is a redundant design with extended life [33] through three redundant building blocks (inactive WBBCM3-1s), and therefore the three redundant building blocks can swap the functions with the three passive mobile building blocks to extend the system life. In our design (Fig. 5), each of three passive WBBCM3-1s connected to the XYZ-stage undergoes two translations, and is prone to fail compared to others that produce only one translation. If any one of the three passive WBBCM3-1s 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-stage becomes the new XYZ-stage and the originally fixed cubic stages become the new X-, Y-, and Z-stages, and then the life of the XYZ CPM is retrieved.

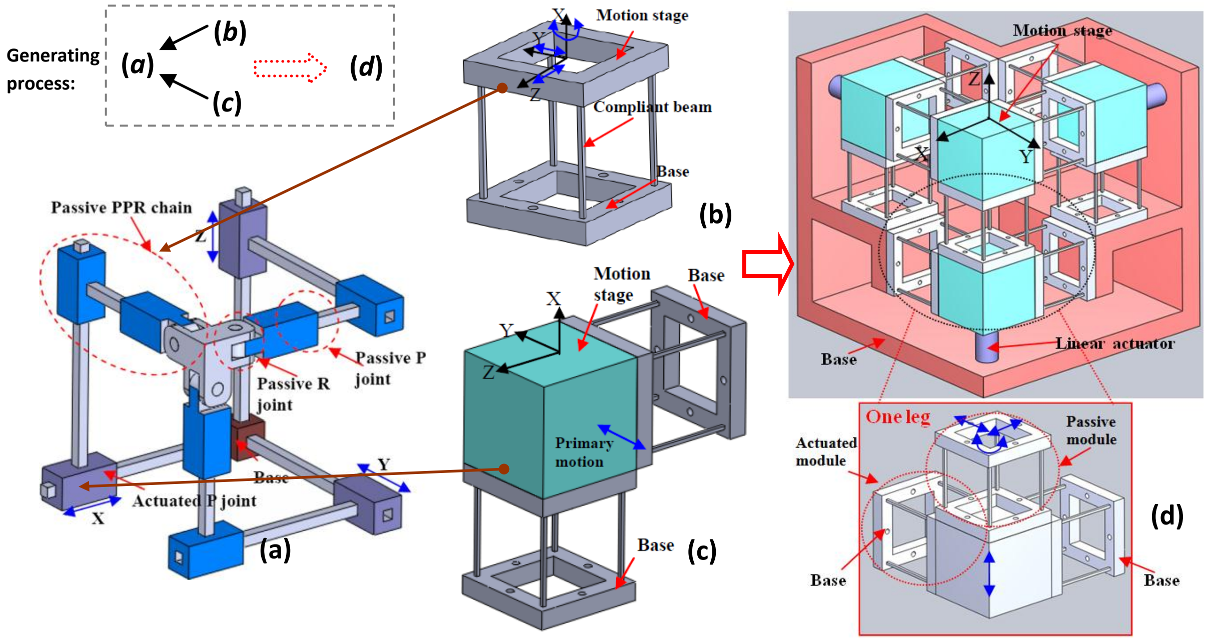


Fig. 4 The generating process of a decoupled 3-PPPR XYZ CPM: (a) A kinematically decoupled 3-PPPR TPM; (b) WBBCM3-1; (c) WBBCM4-1 composed two identical WBBCM3-1 in parallel; (d) A decoupled XYZ CPM composed of identical WBBCM3-1s

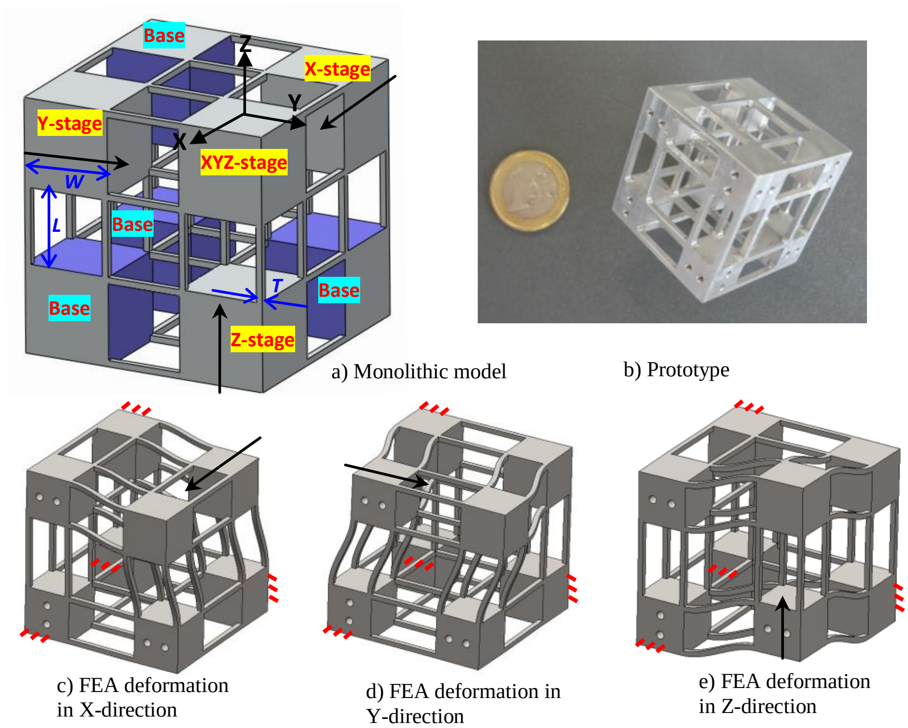


Fig. 5 A monolithic decoupled 3-PPPR XYZ CPM with extended life composed of 12 identical WBBCM3-1s

The other diverse decoupled 3-PPPR XYZ CPMs (Fig. 6) can also be obtained using the design approach proposed in Section 2 as detailed below.

The design in Fig. 6a is obtained by replacing the traditional actuated P joint with the WBBCM4-3 and replacing the traditional passive PPR sub-chain with the WBBCM3-1 in order to reduce the negative parasitic translation of the actuated compliant P joint for good actuator isolation.

The design in Fig. 6b is obtained by replacing the traditional actuated P joint with the WBBCM4-4 and replacing the traditional passive PPR sub-chain with the WBBCM3-1 in order to reduce the negative parasitic translation and parasitic rotation of the actuated compliant P joint for good actuator isolation.

The design in Fig. 6c is obtained by replacing the traditional actuated P joint with the WBBCM4-3 and replacing the traditional passive PPR sub-chain with the WBBCM3-2 in order to reduce the negative parasitic translation of the actuated compliant P joint and reduce the cross-axis coupling.

The design in Fig. 6d is obtained by first replacing the traditional actuated P joint with the WBBCM4-3 and replacing the traditional passive PPR sub-chain with the WBBCM3-2 (in order to reduce the negative parasitic translation of the actuated compliant P joint and reduce the cross-axis coupling), and then adding extra three WBBCM3-2s to achieve redundant design with extended life. Note that the three actuation direction are skew in Fig. 6d.

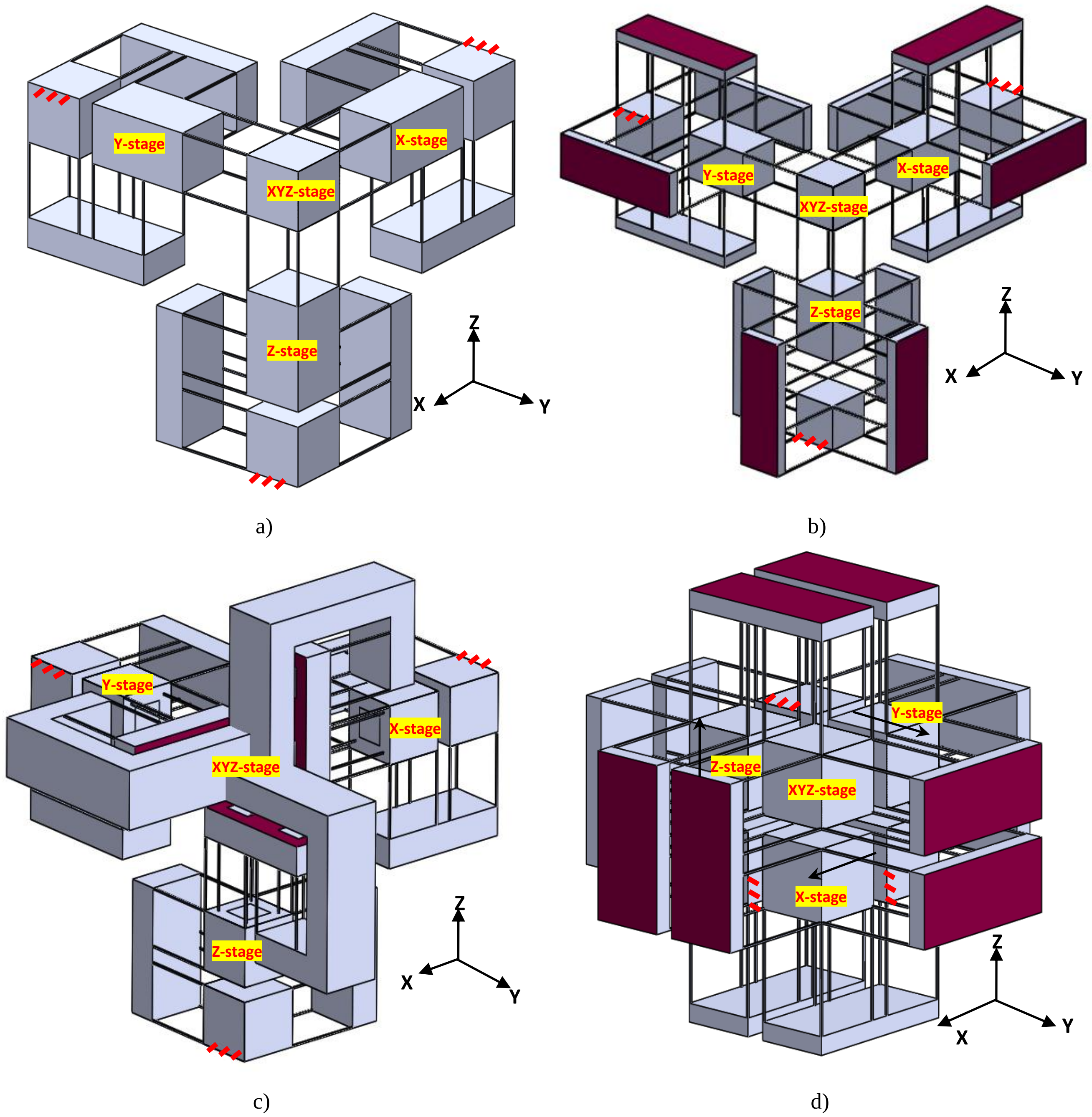


Fig. 6 Other 3-PPPR XYZ CPMs

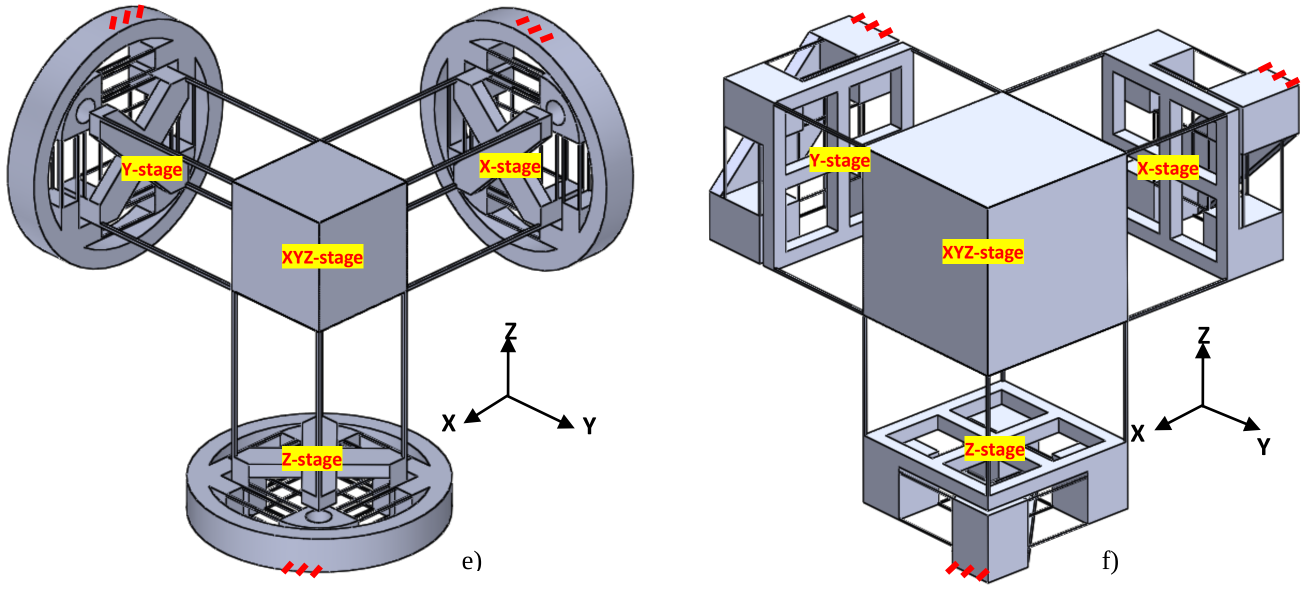


Fig. 6 Other 3-PPPR XYZ CPMs (continued)

The design in Fig. 6e is obtained by replacing the traditional actuated P joint with the WBBCM4-5 and replacing the traditional passive PPR sub-chain with the WBBCM3-1 in order to reduce the negative parasitic translation and parasitic rotation of the actuated compliant P joint for good actuator isolation.

The design in Fig. 6f is obtained by replacing the traditional actuated P joint with the WBBCM4-6 and replacing the traditional passive PPR sub-chain with the WBBCM3-1 in order to reduce the negative parasitic translation and parasitic rotation of the actuated compliant P joint for good actuator isolation. Note that the actuated compliant P joint has the load-stiffening effect.

3.2 Design of 3-PPPRR XYZ CPMs

Using the 3-DOF TPM in Fig. 3c, a 3-PPPRR XYZ CPM (Fig. 7a) can be presented through replacing the traditional actuated P joint and the traditional passive PPRR chain in each leg with a WBBCM4-2 and a WBBCM2 (Table 1), respectively, and making appropriate arrangement for facilitating manufacture. Here, the three geometrical planes formed by the three passive WBBCM2s are orthogonal.

Similar to the monolithic 3-PPPR XYZ CPM (Fig. 5), the monolithic 3-PPPRR XYZ CPM (Fig. 7b) with extended life can be produced via adding extra three WBBCM3-1s. The other various 3-PPPRR XYZ CPMs (Fig. 8) can also be generated as follows. It should be noted that when the originally fixed four stages in the monolithic 3-PPPRR XYZ CPM (Fig. 7b) 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. This can be well explained by the design approach option 2 in Fig. 2.

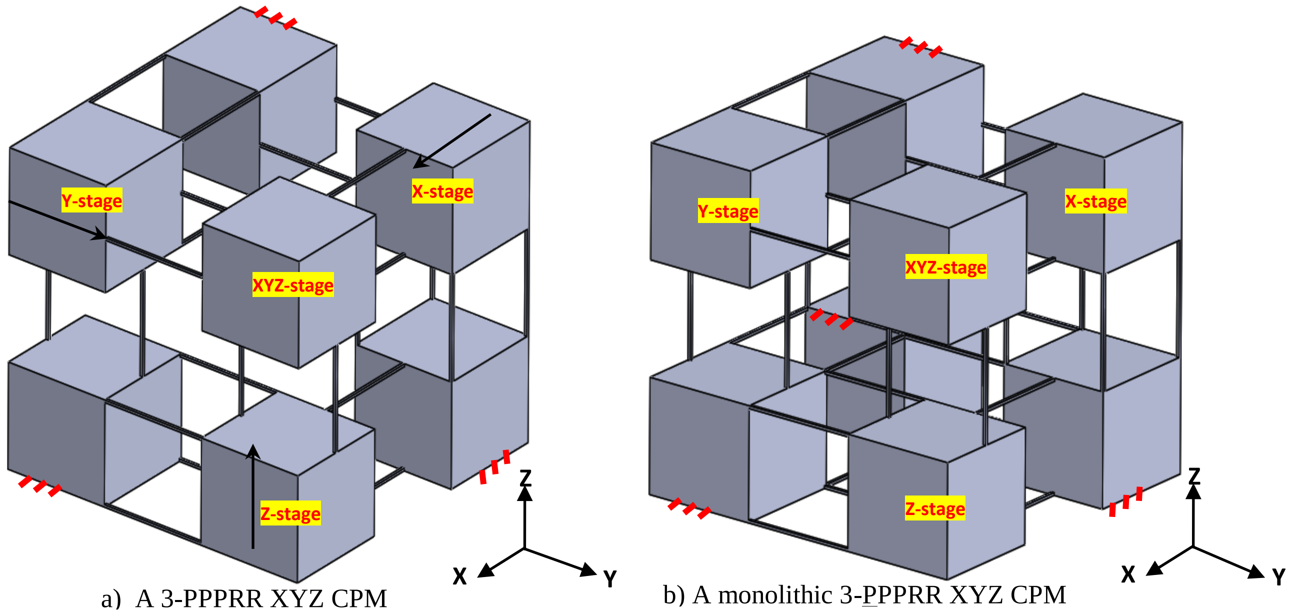


Fig. 7 3-PPPRR XYZ CPMs

The design in Fig. 8a is proposed through replacing the traditional actuated P joint with the WBBCM4-3 and replacing the traditional passive PPRR sub-chain with the WBBCM2 in order to reduce the parasitic translation of the actuated compliant P joint for good actuator isolation. The design in Fig. 8b is obtained via replacing the traditional actuated P joint with the WBBCM4-4 and replacing the traditional passive PPRR sub-chain with the WBBCM2 in order to reduce the parasitic translation and parasitic rotation of the actuated compliant P joint for good actuator isolation. The design in Fig. 8c is proposed by replacing the traditional actuated P joint with the WBBCM4-5 and replacing the traditional passive PPRR sub-chain with the WBBCM2 in order to reduce the negative parasitic translation of the actuated compliant P joint and reduce the cross-axis coupling effect. The design in Fig. 8d is presented by replacing the traditional actuated P joint with the WBBCM4-6 and replacing the traditional passive PPRR sub-chain with the WBBCM2 in order to reduce the parasitic translation and parasitic rotation of the actuated compliant P joint for good actuator isolation. Note that in Figs. 8c and 8d the passive WBBCM2s are made a special arrangement (i.e. the three geometrical planes formed by the three passive WBBCM2s are not orthogonal) via understanding constraint devices such as *spheres in vees* [25]. Moreover, the actuated compliant P joint in Fig. 8d has the negative load-stiffening effect.

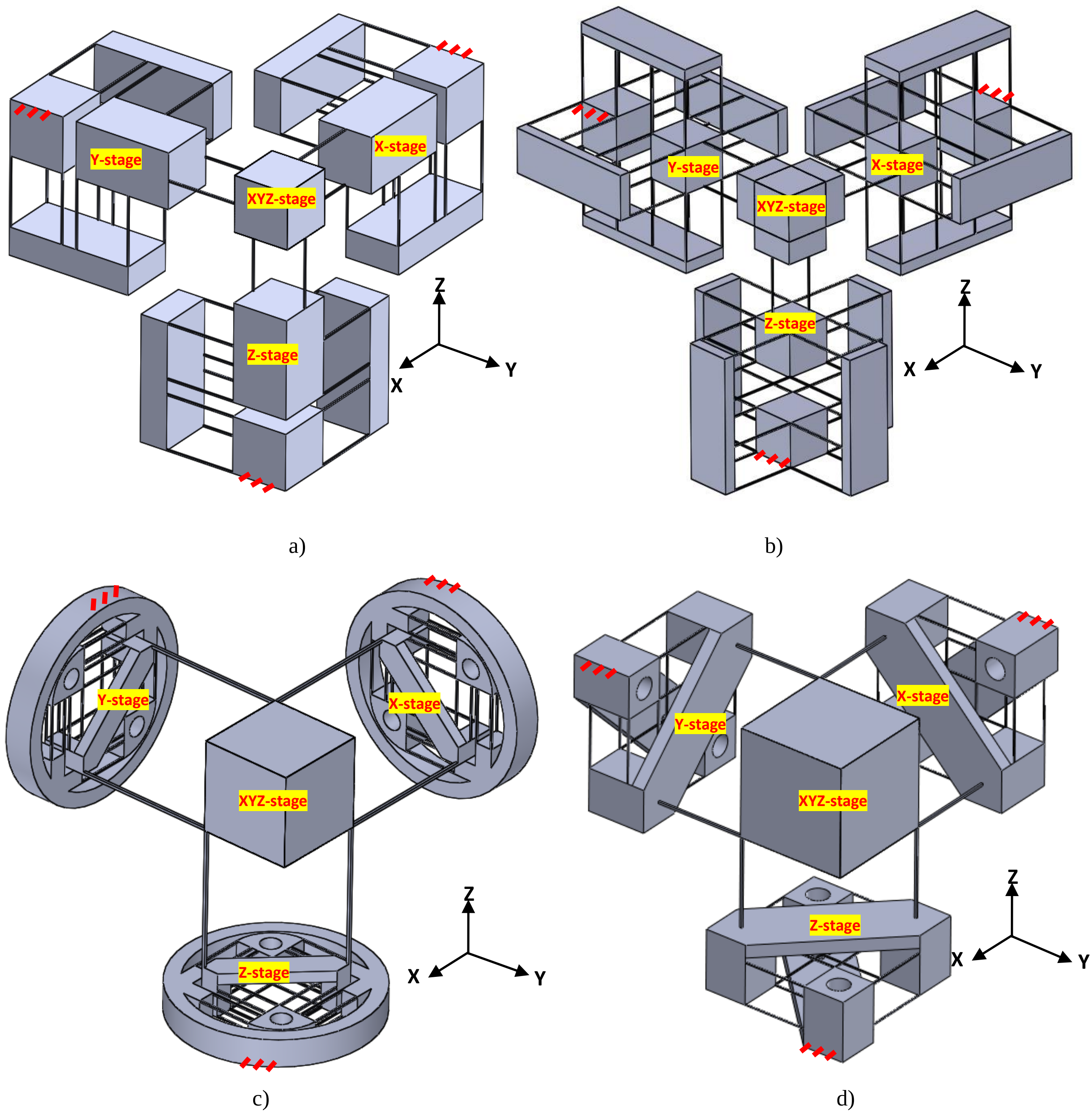


Fig. 8 Other 3-PPPRR XYZ CPMs

3.3 Qualitative characteristic comparisons

In summary, the qualitative characterisitc comparisons for the XYZ CPMs are detailed in Table 3 to consider several key performance characteristics.

Table 3 Qualitative performance characteristic comparisons

	Monolithic manufacture	**Good actuator isolation (due to reduced parasitic translation of the actuated P joint) [6]**	**Good actuator isolation (due to reduced parasitic rotation of the actuated P joint) [6]**	**Minimal cross-axis coupling [6]**	**Redundant life**	**No under-constrained mass for good dynamics**	**Good thermal stability (without over-constraint in the passive sub-chain)**	**Composed of the same type of WBBCMs for easy modelling and analysis etc**
Fig. 5	Yes				Yes	Yes		Yes
Fig. 6a		Yes						Yes
Fig. 6b		Yes	Yes					Yes
Fig. 6c		Yes		Yes				Yes
Fig. 6d		Yes		Yes	Yes			Yes
Fig. 6e		Yes	Yes					Yes
Fig. 6f		Yes	Yes			Yes		Yes
Fig. 7b	Yes				Yes	Yes	Yes	
Fig. 8a		Yes					Yes	
Fig. 8b		Yes	Yes				Yes	
Fig. 8c		Yes	Yes				Yes	
Fig. 8d		Yes	Yes			Yes	Yes	

It should be noted that the stiffness center overlapping approach [57, 62] can be further used to reduce the parasitic rotations of the XYZ motion stage instead of the use of the fully symmetrical design for the passive WBBCMs. It deserves mentioning again that the above XYZ CPMs should be chosen based on the actual application requirements.

4. Decoupled 6-DOF CPMs

Based on the orthogonally-arranged decoupled rigid-body 6-PSS parallel mechanism [58, 63] (Fig. 9), a decoupled 6-DOF CPM is therefore obtained in Fig. 10 via replacing the traditional actuated P joint and the traditional passive SS (or PPRRR) sub-chain with the WBBCM4-1 and the WBBCM1, respectively, in each leg and making compact arrangment for the two actuated compliant P joints. Compared to the design in Fig. 8d, the only difference is that the two actuated P joints are not rigidly connected together to act as two independent P joints. Here, the translation along the X/Y/Z-axis is controlled by actuating two actuated P joints along the X/Y/Z-direction for the same motion inputs, and the rotation about the X/Y/Z-axis is controlled by actuation two actuated P joints along the X/Y/Z-direction for the same motion inputs in magnitude but with opposite directions.

Another type of 6-DOF CPM can be obtained (Fig . 11b) through the use of a WBBCM with non-orthogonal constraint arrangment as the 1-SS CBB using remote rotational center (Fig. 11a) to replace the traditional passive SS sub-chain. Here, the 1-SS CBB using remote rotational center is a hybrid (parallel and serial) mechanism with a controllable intermediate stage/mass.

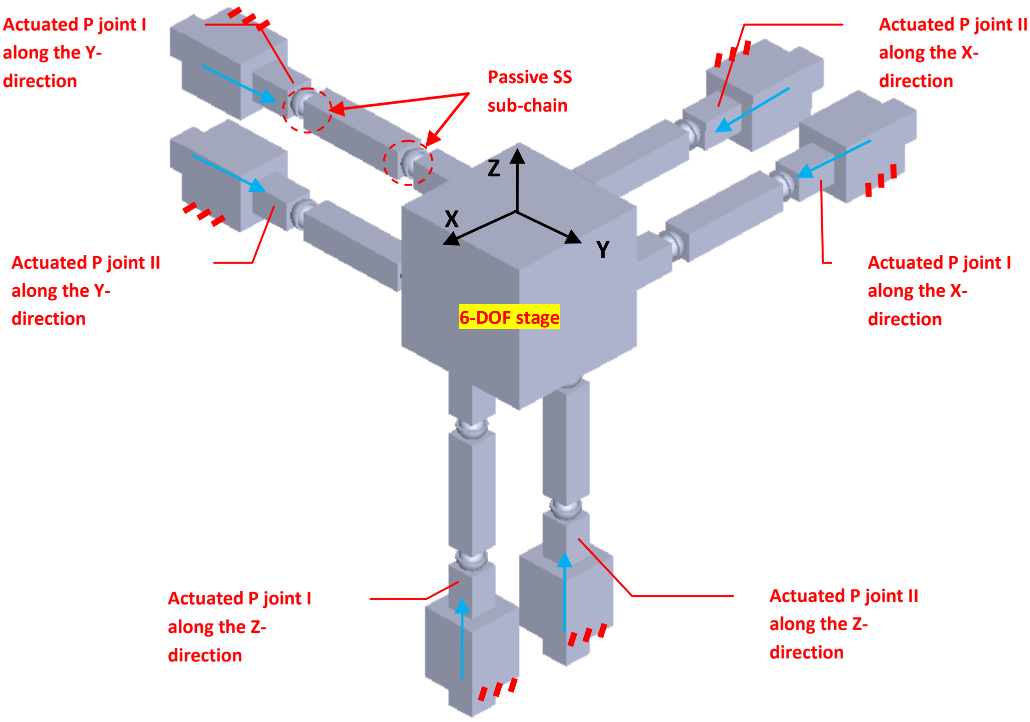


Fig. 9 A 6-PSS parallel mechanism

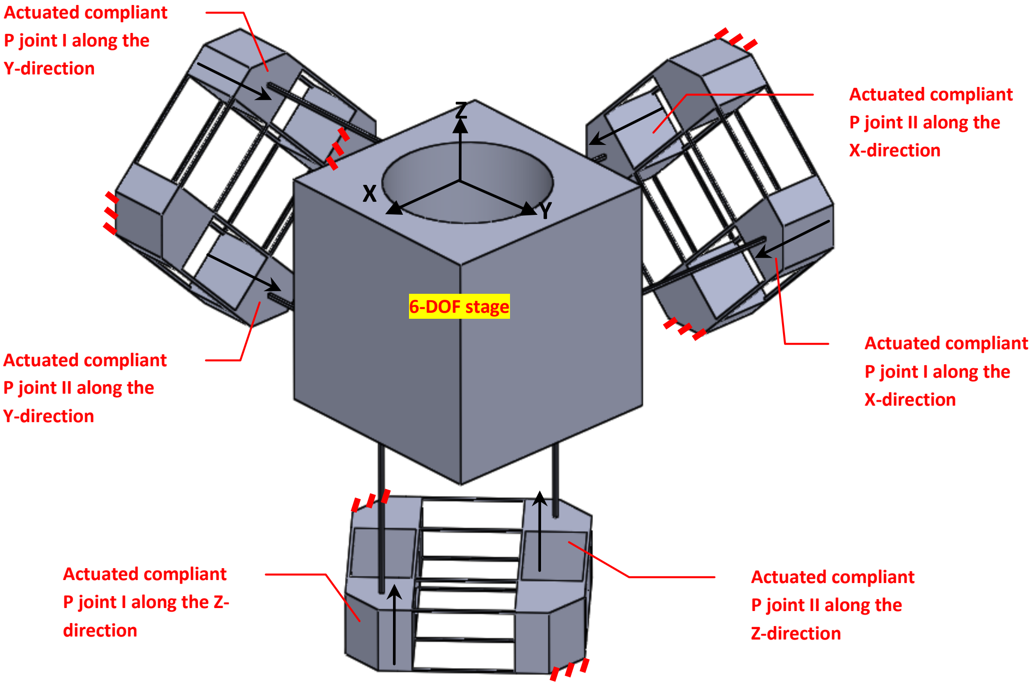
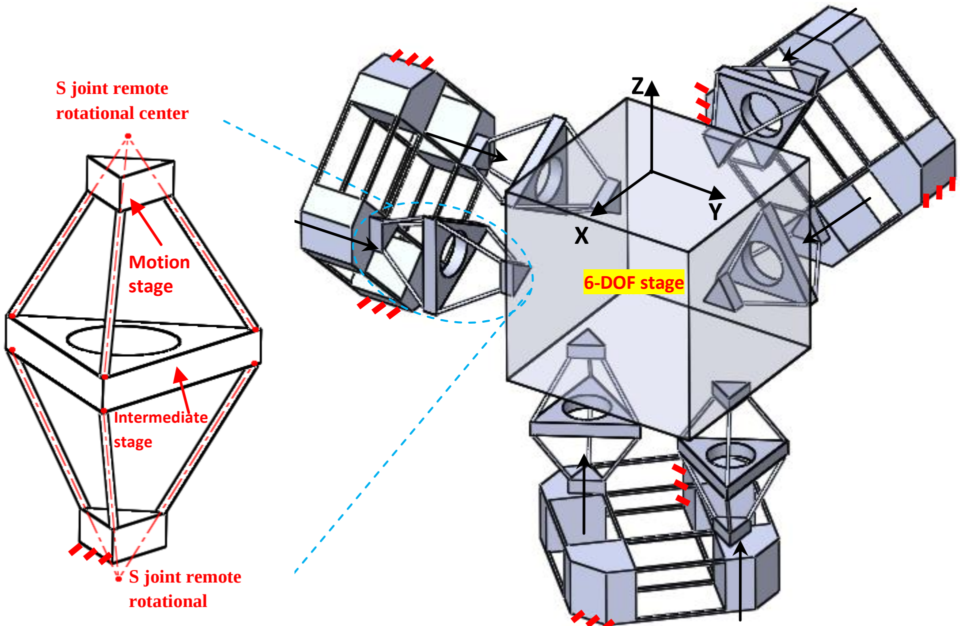


Fig. 10 A 6-DOF CPM



a) A 1-SS CBB using remote rotational center with non-orthogonal constraint arrangement

b) A 6-DOF CPM

Fig. 11 Another type of 6-DOF CPM

In order to improve the performance characteristics of the 6-DOF CPM such as the maximal actuator isolation, better actuated compliant P joints with reduced parasitic motions as illustrated in Tables 1 and 2 can be adopted to obtain other types of 6-DOF CPMs.

5. Discussions

In addition to the performance characteristics listed in Table 3, the following design criteria should be considered to obtain a high-performance CPM.

1) Material and actuator selections

AL6061-T6 and AL7075-T6 are recommended for precision instruments due to the material's low internal stresses, good strength and phase stability [5]. AL6061-T6, with Young's Modules of 69 Gpa, Yield stress of 276 Mpa and

Poisson's ratio of 0.33, is commonly selected owing to its lower cost, but AL7075-T6 is adopted for larger motion range due to its high ratio of Yield stress to Young's Modules.

It is noted that the millimetre-level motion range requires a large-range linear actuator, which cannot be a PZT actuator. Although amplifiers as actuated compliant P joints can be combined with the PZT actuator to enlarge the motion range [9], adversely, they lead to relatively low off-axis stiffness and augment the minimum incremental motion of the actuators. Thus, one needs to choose the linear Voice Coil actuator [64] for millimetre-level actuation range. This linear actuator has merits such as large-range nanopositioning (the large range of motion and high nanometric resolution), linear model, and force-control along with hysteresis-free, frictionless and cog-free motion. Due to the nature that heat dissipates from the coil in the actuator, thus the magnet along with the back iron is usually connected to the input stage of the CPM to improve the thermal stability [65].

2) Monolithic fabrication

The well-known CNC multi-axis milling machining is extensively used to fabricate precise parts in industry. However, there are three main issues for the compliant mechanism manufacture. One is that the thickness of the in-depth features must be not larger than the driller length. The second is that the in-plane small thickness of the features is limited by the nature of the contact machining producing loading to the thin features, which has to be verified by repeated experiments by an experienced technician. The third is that the gap size between two adjacent features is largely constrained by the diameter of the driller. In addition, the milling machining is also time-consuming for fabricating a deep feature due to the nature of the machining.

However, the presented monolithic XYZ CPMs (Fig. 5 and Fig 7b) can be directly fabricated using wire electrical discharge machining (wire EDM). Dimensional tolerances better than 12 microns in plane are easily achievable due to the non-contact machining, parallelism and perpendicularity of the machined feature can be tightly controlled [5]. Also, with wire EDM, the in-depth feature thickness of the plate being machined is not a concern. But the EDM process requires a fairly significant amount of set-up works and is generally expensive.

In addition, one can employ the lithography/DRIE for an MEMS version with same masks on three surfaces of the cubic material.

3) Good dynamics

From the dynamic equation, it is clear that one may reduce the mass or increase the stiffness to raise the modal frequencies for improving the dynamic performance of the proposed mutli-DOF CPMs.

If there are under-constrained secondary stages involved in multi-DOF CPMs (e.g. Fig. 6d), which can undergo free vibration along the unconstrained directions. Therfore, the resulting CPMs can behave well under quasi-statical/low speed motion mode, in which the secondary stages do not vibrate uncontrollably. However, if one intends to run the CPMs in an appreciable speed, a tradeoff has to be made between good characteristics such as good actuator isolation and the uncontrollable vibration mentioned above. The mounting strategy for the Voice Coil actuator mentioned earlier will add also large mass of the magnet and back iron to the CPM and result in the low natural frequency issue limiting the bandwidth of the motion system [65].

In order to improve the dynamic performance, we can therefore further increase the wire beam number (elasticity average) in the actuated compliant P joints to raise the natural frequency with better actuator isolation performance but without affecting the maximal motion range and causing worse lost motion [33, 57]. In addition to the above measures, one may also improve the dynamic performance by using a high-order controller to achieve a high bandwidth greater than the first natural frequency [64].

It is apparent that the increase of geometrical size of the assumed rigid parts (including primary motion stage and the non-controllable secondary stage) can improve the system's static performacne but worsen the dynamic performance due to the increase of mobile mass. Therefore, the optimization considering a balance between dynamic performance and the geometrical parameters of the assumed rigid parts should be implemented.

6. Conclusions

In this paper, a number of multi-DOF CPMs including XYZ CPMs and 6-DOF CPMs have been presented using the WBBCMs based on the building block based PRBM method. The proposed design approach is a straightforward method to design the multi-axis compliant manipulators by replaceing the traditional kinematic sub-chain with an appropriate multi-DOF CBB.

Several novel 1-DOF compliant P joints such as WBBCM4-5 and WBBCM4-6 have been designed for different application requirements, which may be good candidates for integrating with the Voice Coil actuators. Two types of 3-PPPR and 3-PPPRR XYZ CPMs have also been conceived for monolithic manufacture through three-direction orthogonal cutting, which also show good characteristic of extended life.

It is noted that the qualitative characteristic comparisons among the XYZ CPMs have been given in this paper, however, the detailed quantitative characteristic analysis and comparison should be further carried out via analytical modelling, FEA, and/or experiment testing. The proposed XYZ CPMs can be transferred to XY CPMs with enhanced out-of-plane stiffness via fixing the actuated compliant P joint in the Z-direction.

It can be envisaged that the proposed WBBCMs and multi-DOF CPMs will complement the library of compliant mechanisms, and the building block based PRBM method will assist the other emerging design approaches to extend the design ranges of compliant mechanisms.

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