Tổng Hợp Cơ Cấu Động Học Song Song Dẫn Động Tùy Chọn

Design of Selective-Actuation Flexure Parallel Mechanisms

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Tóm tắt

Cơ cấu động học song song (PKM) có độ cứng vững cao và có tính dẫn động tùy chọn (SA) có thể tạo những chuyển động riêng rẽ theo các bậc tự do mà không có các chuyển động phụ và được điều chỉnh và sử dụng dễ dàng. Do đó SA PKM có cả những ứng dụng vi mô lẫn vĩ mô như là: định vị ăng-ten hay ra-đa, tay máy dung trong giải phẫu, kết nối các đầu cáp quang, gia công các linh kiện bán dẫn, tay máy dùng trong sinh học, ... Việc tổng hợp các SA PKM bao gồm tổng hợp dạng cơ cấu song song có số bậc tự do theo yêu cầu và điều chỉnh vị trí tương đối các khâu để đạt tính chất dẫn động tùy chọn. Viêc tổng hợp trên dựa trên việc tạo nên ma trận Jacobi có dạng đường chéo. Việc tổng hợp được minh họa bởi việc thiết kế cơ cấu song song dẫn động tùy chọn có sáu bậc tự do và dựa trên cơ cấu đàn hồi.

ABSTRACT

Flexure parallel mechanism (FPM) possessing selective actuation (SA) feature can be used as a micro-positioner. The design of SA FPMs consists of type synthesis of parallel mechanisms possessing the required number of degree of freedom (DOF), geometric arrangement of the structure to obtain the SA and conversion of the kinematic mechanism into the flexure mechanism. This paper focuses on the SA synthesis and the conversion into flexure mechanism. The diagonal form Jacobian matrix of the mechanism is the guideline for synthesizing a SA mechanism. The synthesis method is illustrated by the design of a SA 6-DOF FPM.

Index Terms – Selective-actuation, parallel mechanism, flexure.

1. INTRODUCTION

Thanks to characteristics such as high stiffness, clean room compatibility, no error accumulation and no backlash, FPM is employed as the micro-positioners. Recently, several FPM-based precision positioners are developed (Chang et al. [1], Ryu et al. [2], Koseki et al. [3], Yi et al. [4], Shim et al. [5], Gao et al. [6], Hudgens et al. [7], Canfield et al. [8], Oiwa et al. [9], Chung et al [10], Culpepper et al [11, 12], Dagalakis et al [13] and Glöss [14]). Beside those, there are studies about the determination of the error existing in the flexure mechanisms and the improvement of the accuracy of the flexure mechanisms (Niaritsiry et al [15, 16]).

Here, the concept of SA is proposed for FPM design. An FPM with SA characteristics is one that each actuator will effect only one-axis direction movement, i.e., the motion axes are decoupled. Moreover, the actuators can be reconfigured on the system to obtain the desired axes of motion without affecting the work of other existing actuators. In this way, SA rejects fully or eliminates partially the dependence of the end-effector motion on different axes of the actuators, and therefore, aids the decoupling of motion control. As the cost of precision actuators is relatively high compared to other subcomponents in a precision positioner, it is possible to configure the SA FPM to have appropriate number of actuators to perform the task for cost effectiveness. Hence, SA becomes an important design approach for miniaturized micro-positioners.

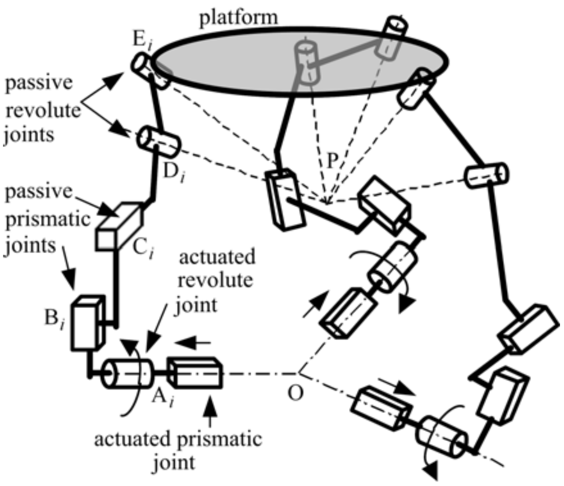


Fig. 1 Six-DOF parallel kinematic mechanism.

The constraint systems defined using screw theory allows us to define the geometric conditions of the limbs and, then, to construct the classes of parallel mechanisms in the synthesis of parallel mechanisms. FPM has small motion that can be considered as instantaneous motion. Hence, the design of FPM can employ screw theory describing the instantaneous kinematics of the mechanism. Type synthesis of parallel mechanisms using screw theory has been well studied in recent years by Fang and Tsai [17], Huang and Li [18], Frisoli et al. [19], Kong and Gosselin [20 - 22]. Recently, by combining a spherical and a translational mechanism into a single mechanism, Jin et al. proposed a three-identical-limb 6-DOF parallel mechanism actuated by three 2-DOF actuators [23, 24] (Fig. 1). This paper focuses only on the SA synthesis and the conversion from the SA parallel mechanism into the SA FPM. Screw theory can be used to establish FPM Jacobian matrices carrying information of the geometrical configuration of the mechanism [25]. The information is then employed to synthesize the SA FPM that requires a special form of the Jacobians.

2. SCREW THEORY-BASED SYNTHESIS OF SA PARALLEL MECHANISM

The relationship between the end-effector motion of the parallel mechanism and the motions of acutated joints can be expressed using the instantaneous kinematics:

$$\boldsymbol{dX} = \boldsymbol{J}(\boldsymbol{q})\boldsymbol{dq}\ ,$$

where

$\boldsymbol{dX} = (d\theta_x, d\theta_y, d\theta_z, dx, dy, dz)^{\mathrm{T}}$ is the vector of the infinitesimal end-effector motion,

$\boldsymbol{dq} = (dq_1, dq_2, dq_3, dq_4, dq_5, dq_6)^{\mathrm{T}}$ is the vector of infinitesimal joints variables,

$\boldsymbol{J}(\boldsymbol{q})$ is the Jacobian matrix.

A mechanism is considered as an SA mechanism when the infinitesimal end-effector motion along every DOF is driven by only one specified actuator. The influence between the set of joint variables $\{dq_1, dq_2, \ldots, dq_6\}$ on the set of the infinitesimal DOF motions of the end-effector $\{d\theta_x, d\theta_y, d\theta_z, dx, dy, dz\}$ is desired to be an one-to-one mapping, i.e., Jacobian matrix $\boldsymbol{J}(\boldsymbol{q})$ has diagonal form.

Definition: Selective-actuation mechanism.

A mechanism possessing a diagonal-form Jacobian matrix is a selective-actuation mechanism.

We consider a parallel mechanism including m limbs, and each limb, without loss of generality, is an open-loop chain connecting the platform to the fixed base by l one-DOF joints (revolute/prismatic joint) and actuated joints in one limb appear in the first g joints (Fig. 2). The total number of DOF of the mechanism is thus $(m \cdot g)$. We denote $\boldsymbol{S}_{\mathrm{P}}$ and $\dot{\boldsymbol{q}}$ as the instantaneous twist of the platform and the rate of joint variables respectively:

$$\boldsymbol{S}_{\mathrm{P}} = (\dot{\theta}_x, \dot{\theta}_y, \dot{\theta}_z, \dot{x}, \dot{y}, \dot{z})^T\ ,$$

$$\dot{\boldsymbol{q}} = (\dot{q}_{11}, \dot{q}_{21}, \cdots, \dot{q}_{g1}, \dot{q}_{12}, \dot{q}_{22}, \cdots, \dot{q}_{g2}, \cdots \dot{q}_{1m}, \dot{q}_{2m}, \cdots, \dot{q}_{gm})^{\mathrm{T}},$$

where

$\dot{\theta}_x, \dot{\theta}_y, \dot{\theta}_z, \dot{x}, \dot{y}$ and $\dot{z}$ are the rotation and displacement rates of the end-effector.

$\dot{q}_{ji}$ is the intensity of the unit screw $\boldsymbol{S}_{ji}$ associated with the actuated joint j of limb i.

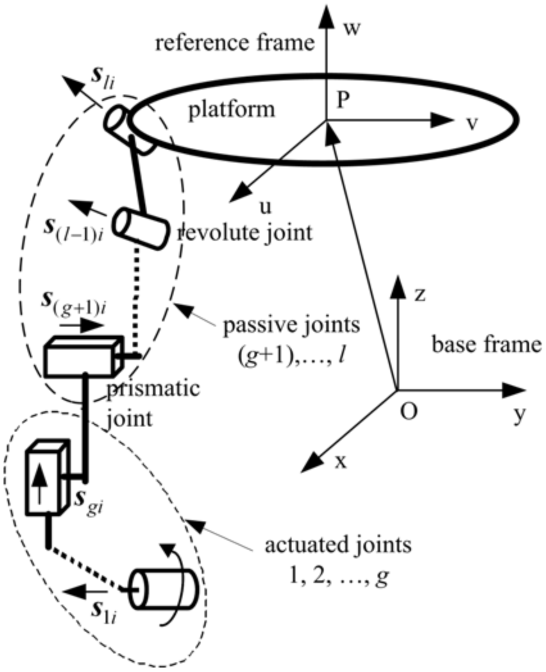


Fig. 2 Limb i of a parallel mechanism.

Following [25], the relationship between the instantaneous twist (displacement and rotation rate of the end-effector) and the actuated joint variables can be expressed as follows.

$$\boldsymbol{J}_x \boldsymbol{S}_{\mathrm{P}} = \boldsymbol{J}_q \dot{\boldsymbol{q}}\,, \tag{1}$$

where $\boldsymbol{J}_x$ and $\boldsymbol{J}_q$ are the direct and inverse Jacobian matrices respectively.

The direct Jacobian matrix has the form:

$$\boldsymbol{J}_x = (\boldsymbol{J}_{x1}, \boldsymbol{J}_{x2}, \cdots \boldsymbol{J}_{xm})^{\mathrm{T}}\,, \tag{2}$$

where

$\boldsymbol{J}_{xi} = [\boldsymbol{S}^{\mathrm{T}}_{r1i}, \boldsymbol{S}^{\mathrm{T}}_{r2i}, \cdots, \boldsymbol{S}^{\mathrm{T}}_{rgi}]^{\mathrm{T}}$ is the matrix assembled from the unit screws $\boldsymbol{S}_{rji}$, (j = 1, 2,…, g and i = 1, 2,…, m) that are reciprocal to all passive-joint screws in the limb i.

The inverse Jacobian matrix has the form:

$$\boldsymbol{J}_q = diag(\boldsymbol{J}_{q1}, \boldsymbol{J}_{q2}, \cdots, \boldsymbol{J}_{qm})\,, \tag{3}$$

where

$$\boldsymbol{J}_{qi} = \begin{bmatrix} \boldsymbol{S}_{r1i} \otimes \boldsymbol{S}_{1i} & \boldsymbol{S}_{r1i} \otimes \boldsymbol{S}_{2i} & \cdots & \boldsymbol{S}_{r1i} \otimes \boldsymbol{S}_{gi} \\ \boldsymbol{S}_{r2i} \otimes \boldsymbol{S}_{1i} & \boldsymbol{S}_{r2i} \otimes \boldsymbol{S}_{2i} & \cdots & \boldsymbol{S}_{r2i} \otimes \boldsymbol{S}_{gi} \\ \vdots & \vdots & \vdots & \vdots \\ \boldsymbol{S}_{rgi} \otimes \boldsymbol{S}_{1i} & \boldsymbol{S}_{rgi} \otimes \boldsymbol{S}_{2i} & \cdots & \boldsymbol{S}_{rgi} \otimes \boldsymbol{S}_{gi} \end{bmatrix}.$$

Assume that the mechanism is working in a singularity-free workspace, the direct Jacobian $\boldsymbol{J}_x$ is invertible. Equation (1) expressing the relationship of actuated joint variables and the DOF of the end-effector can be rewritten as:

$$\boldsymbol{S}_{\mathrm{P}} = \boldsymbol{J}_x^{-1} \boldsymbol{J}_q \dot{\boldsymbol{q}}\,. \tag{4}$$

Lemma 1: *The product $\boldsymbol{J}_x^{-1}\boldsymbol{J}_q$ of a selective-actuation parallel mechanism is in diagonal form.*

In case that only one actuated joint appears in each limb (g = 1), from Eq. (3), we can see that the inverse Jacobian $\boldsymbol{J}_q$ is always in diagonal form. Therefore, the above condition can be simplified as follows.

Lemma 2: *For a parallel mechanism with only one actuated joint in each limb, the condition of selective actuation requires only that the direct Jacobian matrix $\boldsymbol{J}_x$ is in diagonal form.*

Lemmas 1 and 2 are then employed as a guideline to arrange the geometrical structure of the parallel mechanism resulted from type synthesis to achieve the SA condition.

3. SYNTHESIS EXAMPLES

The synthesis of a SA parallel mechanisms based on the 6-DOF dexterous parallel mechanism obtained respectively in [23, 24] is presented in this section.

The 6-DOF parallel mechanism with three identical limbs (Fig. 1) proposed by Jin et al. [23, 24] is synthesized to obtain the SA characteristic. Each limb is an open-loop chain with two actuated joints: one prismatic joint and one revolute joint. The mechanism possesses some structure characteristics: all axes of the passive revolute joints intersect at one point in space, the axis of the actuated prismatic joint is perpendicular to the axes of corresponding passive prismatic joints, and the axes of three actuated revolute joints intersect at one point. This mechanism decouples the 3-DOF rotation and translation but not completely separate the all 6 DOFs.

We define an instantaneous reference frame, (uvw), with its origin locates at the intersecting point P of the axes of six passive revolute joints and u-, v-, w-axes parallel to the x-, y-, z- axes of the base frame, (xyz), located at origin O that is the intersecting point of the axes of three actuated revolute joints (Fig. 3). The joint screws of limb i with respect to this instantaneous reference frame are determined as follows.

$$\boldsymbol{S}_{1i} = \begin{pmatrix} \boldsymbol{s}_{1i} \\ \overrightarrow{\mathrm{OA}_i} \times \boldsymbol{s}_{1i} \end{pmatrix}, \quad \boldsymbol{S}_{2i} = \begin{pmatrix} \boldsymbol{0} \\ \boldsymbol{s}_{2i} \end{pmatrix}, \quad \boldsymbol{S}_{3i} = \begin{pmatrix} \boldsymbol{0} \\ \boldsymbol{s}_{3i} \end{pmatrix},$$

$$\boldsymbol{S}_{4i} = \begin{pmatrix} \boldsymbol{0} \\ \boldsymbol{s}_{4i} \end{pmatrix}, \boldsymbol{S}_{5i} = \begin{pmatrix} \boldsymbol{s}_{5i} \\ \overrightarrow{\mathrm{OD}_i} \times \boldsymbol{s}_{5i} \end{pmatrix}, \ \boldsymbol{S}_{6i} = \begin{pmatrix} \boldsymbol{s}_{6i} \\ \overrightarrow{\mathrm{OE}_i} \times \boldsymbol{s}_{6i} \end{pmatrix}, \tag{5}$$

where $\boldsymbol{0}$ is a 3×1 zero vector and $\boldsymbol{s}_{ji}$ is the unit vector along the axis of prismatic joint j when j = 2, 3, 4 or along the axis of revolute joint j when j = 1, 5, 6 of limb i.

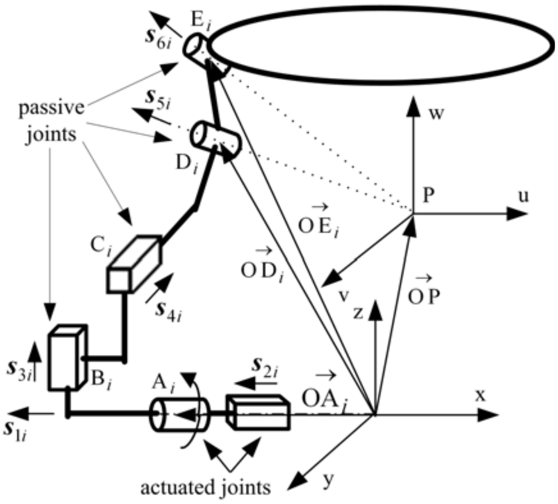


Fig. 3. RPPPRR limb.

Since the unit vector $\boldsymbol{s}_{1i}$ is perpendicular to the unit vectors $\boldsymbol{s}_{3i}$ and the unit vectors $\boldsymbol{s}_{4i}$, and $\boldsymbol{s}_{5i}$ and $\boldsymbol{s}_{6i}$ intersects at point P, two screws $\boldsymbol{S}_{r1i}$ and $\boldsymbol{S}_{r2i}$ that are reciprocal to all screws except for $\boldsymbol{S}_{1i}$ and $\boldsymbol{S}_{2i}$ respectively are defined as

$$\boldsymbol{S}_{r1i} = \begin{pmatrix} \boldsymbol{0} \\ \boldsymbol{s}_{5i} \times \boldsymbol{s}_{6i} \end{pmatrix}, \ \boldsymbol{S}_{r2i} = \begin{pmatrix} \boldsymbol{s}_{1i} \\ \overrightarrow{\mathrm{OP}} \times \boldsymbol{s}_{1i} \end{pmatrix}. \tag{6}$$

Applying above screws and reciprocal screws to Eq. (2) and note that

$\boldsymbol{S}_{r1i} \otimes \boldsymbol{S}_{2i} = \boldsymbol{0} \cdot \boldsymbol{s}_{2i} + (\boldsymbol{s}_{5i} \times \boldsymbol{s}_{6i}) \cdot \boldsymbol{0} = 0$ and

$\boldsymbol{S}_{r2i} \otimes \boldsymbol{S}_{1i} = \boldsymbol{s}_{1i} \cdot (\overrightarrow{\mathrm{OA}_i} \times \boldsymbol{s}_{1i}) + (\overrightarrow{\mathrm{OP}} \times \boldsymbol{s}_{1i}) \cdot \boldsymbol{s}_{1i} = 0$,

we have the inverse Jacobian matrix

$$\boldsymbol{J}_q = diag[\boldsymbol{s}_{11}(\boldsymbol{s}_{51} \times \boldsymbol{s}_{61}), \boldsymbol{s}_{12}(\boldsymbol{s}_{52} \times \boldsymbol{s}_{62}), \boldsymbol{s}_{13}(\boldsymbol{s}_{53} \times \boldsymbol{s}_{63}), 1, 1, 1]. \tag{7}$$

Applying above screws and reciprocal screws to Eq. (3) we have the direct Jacobian matrix

$$\boldsymbol{J}_x = \begin{bmatrix} (\boldsymbol{s}_{51} \times \boldsymbol{s}_{61})^{\mathrm{T}} & \boldsymbol{0}^{\mathrm{T}} \\ (\boldsymbol{s}_{52} \times \boldsymbol{s}_{62})^{\mathrm{T}} & \boldsymbol{0}^{\mathrm{T}} \\ (\boldsymbol{s}_{53} \times \boldsymbol{s}_{63})^{\mathrm{T}} & \boldsymbol{0}^{\mathrm{T}} \\ (\overrightarrow{\mathrm{OP}} \times \boldsymbol{s}_{11})^{\mathrm{T}} & \boldsymbol{s}_{11}^{\mathrm{T}} \\ (\overrightarrow{\mathrm{OP}} \times \boldsymbol{s}_{12})^{\mathrm{T}} & \boldsymbol{s}_{12}^{\mathrm{T}} \\ (\overrightarrow{\mathrm{OP}} \times \boldsymbol{s}_{13})^{\mathrm{T}} & \boldsymbol{s}_{13}^{\mathrm{T}} \end{bmatrix}. \tag{8}$$

Equation (7) shows that the inverse Jacobian matrix is in diagonal form. Therefore, the SA condition can be simplified as the direct Jacobian matrix is in diagonal form, i.e.,

$$\begin{bmatrix} (\boldsymbol{s}_{51} \times \boldsymbol{s}_{61})^{\mathrm{T}} \\ (\boldsymbol{s}_{52} \times \boldsymbol{s}_{62})^{\mathrm{T}} \\ (\boldsymbol{s}_{53} \times \boldsymbol{s}_{63})^{\mathrm{T}} \end{bmatrix} = \begin{bmatrix} \times & 0 & 0 \\ 0 & \times & 0 \\ 0 & 0 & \times \end{bmatrix}. \tag{9}$$

$$\begin{bmatrix} \boldsymbol{s}_{11}^{\mathrm{T}} \\ \boldsymbol{s}_{12}^{\mathrm{T}} \\ \boldsymbol{s}_{13}^{\mathrm{T}} \end{bmatrix} = \begin{bmatrix} \times & 0 & 0 \\ 0 & \times & 0 \\ 0 & 0 & \times \end{bmatrix}. \tag{10}$$

$$\begin{bmatrix} (\overrightarrow{\mathrm{OP}} \times \boldsymbol{s}_{11})^{\mathrm{T}} \\ (\overrightarrow{\mathrm{OP}} \times \boldsymbol{s}_{12})^{\mathrm{T}} \\ (\overrightarrow{\mathrm{OP}} \times \boldsymbol{s}_{13})^{\mathrm{T}} \end{bmatrix} = \begin{bmatrix} 0 & 0 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & 0 \end{bmatrix}. \tag{11}$$

Note that $\boldsymbol{s}_{ji}$ is a unit vector, hence, Eqs. (9) and (10) can be respectively changed to:

$$(\boldsymbol{s}_{51} \times \boldsymbol{s}_{61}) = (1 \quad 0 \quad 0)^{\mathrm{T}};$$
$$(\boldsymbol{s}_{52} \times \boldsymbol{s}_{62}) = (0 \quad 1 \quad 0)^{\mathrm{T}};$$
$$(\boldsymbol{s}_{53} \times \boldsymbol{s}_{63}) = (0 \quad 0 \quad 1)^{\mathrm{T}}. \tag{12}$$

$$\boldsymbol{s}_{11} = (1 \quad 0 \quad 0)^{\mathrm{T}};\ \boldsymbol{s}_{12} = (0 \quad 1 \quad 0)^{\mathrm{T}};\ \boldsymbol{s}_{13} = (0 \quad 0 \quad 1)^{\mathrm{T}} \quad (13)$$

Equation (11) is satisfied when $\overrightarrow{\mathrm{OP}} \perp \boldsymbol{s}_{1i}$ $(i = 1,2,3)$ or $\overrightarrow{\mathrm{OP}} = 0$. Equation (16) shows that unit vectors $\boldsymbol{s}_{11}, \boldsymbol{s}_{12}$ and $\boldsymbol{s}_{13}$ are mutually perpendicular, hence the first case is impossible. Therefore, Eq. (11) is satisfied if and only if

$$\overrightarrow{\mathrm{OP}} = 0 . \quad (14)$$

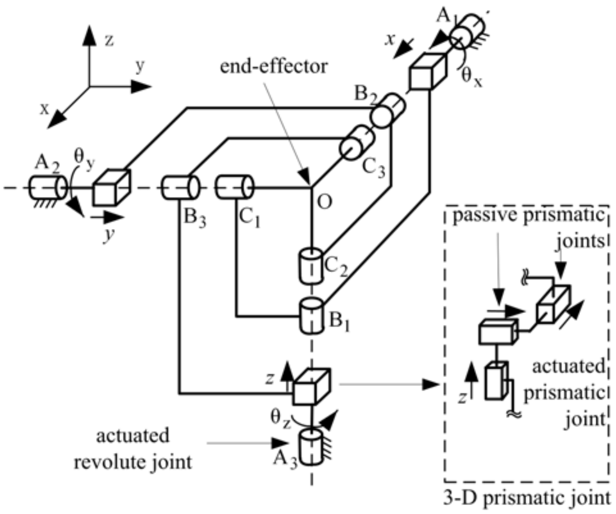


Fig. 4 Selective-actuation 6-DOF parallel mechanism.

The conditions of Eq. (12), Eq. (13) and Eq. (14) can be explained based on the geometrical arrangement of the mechanism respectively as follows.

(1) The axes of passive revolute joints of each limb are perpendicular together and create a plane. That plane is perpendicular to other planes created in similarly manner by axes of passive revolute joints of the remaining limbs.

(2) The axes of actuated prismatic joints (or actuated revolute joints) of the three limbs are perpendicular to each other.

(3) Points O and P coincide with each other. This condition guarantees decoupling of the translational motions.

Together with the conditions proposed by Jin et al. [23, 24], the above three conditions allow the 6-DOF dexterous parallel mechanism to provide six fully decoupled motion axes. The configuration of the SA 6-DOF parallel mechanism is illustrated in Fig. 4. The synthesized SA mechanisms possess diagonal Jacobians with unity diagonal elements. This guarantees the uniformity of the resolution of the mechanisms along different directions.

4. CONVERSION OF SYNTHESIZED SA PARALLEL MECHANISMS INTO SA FPM

The conceptual design of an SA 6-DOF FPM is proposed based on the kinematic mechanism presented in Fig. 4. The RPPPRR limb of the mechanism is realized as a flexure limb including three flexure hinges, one linear spring and one 2-D flexure prismatic joint (Fig. 5). Two passive prismatic joints in Fig. 4 are combined into one 2-D flexure prismatic joint. To avoid error of the end-effector motion due to

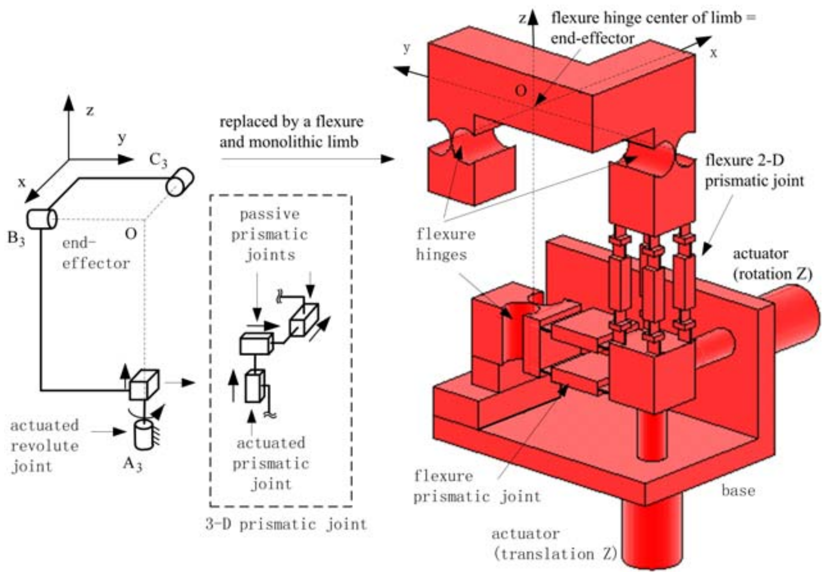


Fig. 5 RPPPRR Flexure limb

deformation along non-working directions of these passive prismatic joints, we use the 2-D linear spring built from four columns with two pairs of orthogonal corner-filleted hinges as a 2-D flexure prismatic joint. One flexure hinge and one flexure spring is serially connected and actuated by two linear actuators to perform two actuated joints. The complete limb is designed as a monolithic structure and satisfies the manufacturability required by the cutting tools such as EDM or water jet machine. The monolithic structure of the limb avoids assembly error and allows three revolute joints to be intersectional and orthogonal at a center (called center of three flexure hinges) as stated by the SA condition.

Three limbs are connected to a hollow-cube platform. The center of the cube is the end-effector. The position of connection interfaces is strictly arranged using positioning pins so that the flexure-hinge centers (Fig. 5) of three limbs coincide at the end-effector. The assembly scheme of the entire mechanism is shown in Fig. 6. Figure 7 illustrates the fully assembled SA 6-DOF FPM.

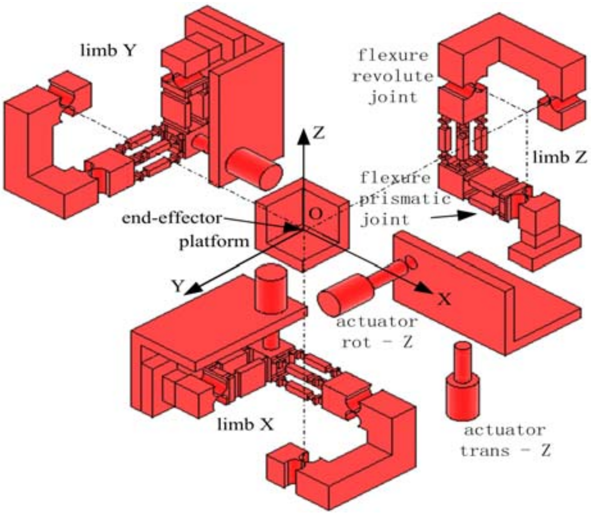
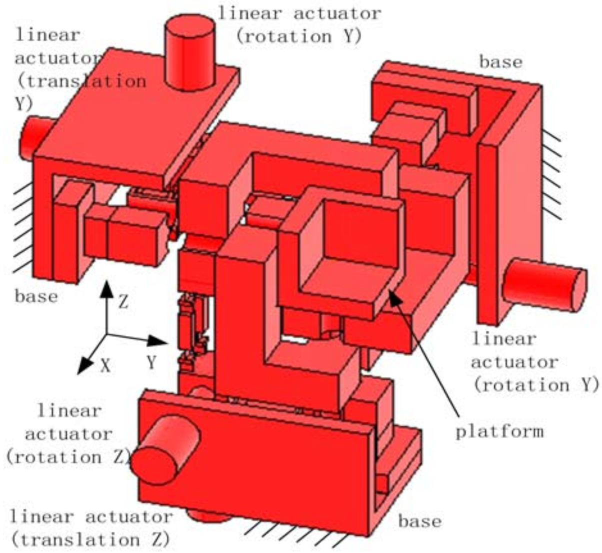


Fig. 6 Assembly scheme of SA 6-DOF FPM.

Fig. 7 Assembled SA 6-DOF FPM.



5. CONCLUSION

The conceptual design of an SA 6-DOF FPM with three identical limbs is proposed based on the selective-actuation synthesis and the flexurization of the rigid-body mechanism. The condition of SA is stated as the diagonal matrix form of Jacobian matrix of the mechanism. Based on the Jacobian matrix formulated using screw theory, the links and joints of the mechanism matching the requirement of DOF resulted from recent type synthesis is geometrically arranged to satisfy the SA condition. The links and joints of the SA parallel mechanisms are then realized as the flexure groups in order to obtain the desired SA FPMs.

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