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December 4, 2020

The 4th INTERNATIONAL WORKSHOP ON FUNDAMENTAL ISSUES, APPLICATIONS AND FUTURE RESEARCH DIRECTIONS FOR PARALLEL MECHANISMS / MANIPULATORS / MACHINES, BELFAST, UK, 25-26 JUNE 2020

# A Novel Method for the Constructing Design of Parallel Mechanisms with RPS Kinematic Chains

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**Abstract.** Structure and configuration of kinematic chain is the key problems of parallel mechanisms for type synthesis. This paper will take RPS kinematic chains as an example, the relationship between axes of revolve pairs (R) and moving direction of prismatic pairs (P) (such as vertical, intersect, parallel and collinear), and the distribution forms were studied, which causes the change of motion characteristic of moving platform. The spatial location relation of constraining forces vectors and the motion state of moving platform were analyzed, Then, some motion characteristics for the different types of parallel mechanisms with RPS kinematic chain were studied, respectively. The relationship between axes of pairs and configuration of kinematic chains relative to the fixed platform are changed, but the number, type, order of pairs without change, so some novel parallel mechanisms are designed. It will provide new ideas for constructing design of parallel mechanisms.

**Keywords.** Parallel mechanisms, kinematic chains, constructing design, type synthesis

## 1. Introduction

Relative to the conventional serial mechanisms, parallel mechanisms are spacial closed-loop mechanisms which composed of more than one kinematic chain. It possesses the advantages of high stiffness, high precision, low movement inertia, small cumulative error, etc. So it can be widely used in virtual axle machine tool, flight simulator and medical equipment fields [1-3]. Many scholars and research institutions pay close attention to the research reviewed of parallel mechanisms. However, there are still some problems need to be solved, such as the mutual coupling between kinematic chains, it caused direct kinematics, Jacobian matrix, dynamics models, locomotion control arithmetic of parallel mechanism are hardly established or solved. For all this, urgently need one kind of design method for parallel mechanism to solve above problems, which are able to meet the requirements of application and simple operation.

Type synthesis of parallel mechanism is one of the effective means for parallel mechanism design.

The process of type synthesis of parallel mechanism is to determine the types and numbers of kinematic chains which connected between fixed platform and moving platform, and the configuration of kinematic chains relative to fixed platform. Then, the various types of parallel mechanisms were constructed, which can meet the anticipate requirements. The designers for the early parallel mechanisms were typically relying on personal experiences or instincts. They lack of systematic design methods of parallel mechanisms. At present, the routine type synthesis methods of parallel mechanisms are as follows: (a) displacement group or differential geometry methods [4], (b) screw theory methods [5], (c) single opened chains methods [6], (d) GF set methods [7]. Moreover, the configurations of kinematic chains of parallel mechanisms mainly in the following three conditions:

(1)The number, type, arrange order and relation between the axes of pairs are equal for the kinematic chain, but the installation ways of kinematic chains relative to fixed platform are different. Chen [8] presented 3-CRC parallel mechanisms with three different motion states, in which by changing the installation ways of kinematic chains relative to fixed platform. Han [9] presented a 4-Dof movement of moving platform by added a same RUC kinematic chain to the 3-Dof of 3-RUC parallel mechanism. Jin [10] presented a three translational parallel mechanism by changing the installation ways of kinematic chains for ordinary 3-RRR planar mechanism. The axes of revolve pairs of mechanism are parallel to each other, and they are perpendicular to the fixed platform.

(2)The number, type, arrange order are equal for the kinematic chain, but the relation between the axes of pairs of kinematic chain are different. Gosselin [11-13] presented a three rotation spherical parallel mechanism (Agile eye) by changing the relation between the axes of pairs of kinematic chain, in which all axes of revolute pairs for the mechanism intersect at a point in space. Huang and Guo [14-15] also presented several types of parallel mechanisms by changing the relation between the axes of pairs of kinematic chain.

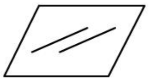
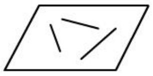
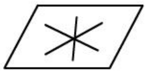
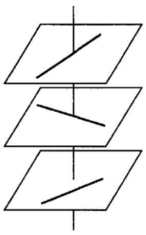
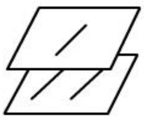
(3)The number, type, arrange order, relation between the axes of kinematic pairs, and the installations of kinematic chains relative to fixed platform are different. Shi [16] presented a three translational parallel mechanism by the different numbers or types of pairs of kinematic chains. Huang [17] presented several types of parallel mechanism by changing the numbers and types of pairs of kinematic chain.

Now, scholars and research institutions pay more attention to the relationship between the kinematic chains and outputs of moving platform. However, their often neglect several new type of parallel mechanisms were constructed by the different kinds of transform for the same kinematic chains. This paper take the RPS kinematic chains as an example, the spatial relationships for the three constraining force vectors and it works on object to produce corresponding motion output are studied. Then, three types of RPS kinematic chains are analyzed. ((1) the axes lines of revolute pair is perpendicular to the moving direction of prismatic pair. (2) the axes lines of revolute pair and the moving direction of prismatic pair intersect at a point. (3) the axes lines of revolute pair is parallel/collinear to the moving direction of prismatic pair). Finally, the motions characteristic of several types of parallel mechanisms are analyzed, which based on the different installation ways for the kinematic chains relative to fixed platform.

## 2. The relationships for the three constraining force vectors

The spatial relationships for the three constraining force vectors, which includes parallel and coplanar, coplanar (intersect each other), coplanar (intersect in one point), intersect at a point in space, different planes each other, spatial parallel, as show in Table 1.

**Table 1.** Maximum linear independent numbers of line vectors under different geometrical conditions[1]

| **geometric characteristics** | **graph** | **Maximum linear independence** |
|---|---|---|
| parallel and coplanar |  | 2 |
| coplanar(intersect each other) |  | 3 |
| coplanar(intersect at a point) |  | 2 |
| intersect at a point in space |  | 3 |
| different planes each other |  | 3 |
| spatial parallel |  | 3 |

(1)The three constraining force vectors are parallel and coplanar, and then they are linearly independent. One translational motion and one rotational motion of moving platform were restricted. The directions of motion of moving platform are perpendicular to the plane which consists of those constraining force vectors.
(2)The three constraining force vectors are coplanar and intersect each other. Two translational motions and one rotational motion of moving platform were restricted. The directions of motion of moving platform are perpendicular to the plane which consists of those constraining force vectors, and the axes of rotational motion of moving platform in this plane.

(3)The three constraining force vectors are coplanar and intersect at a point, and then they are linear independent. Two translational motions of moving platform were restricted. The mechanism with one translational motion and three rotational motions, and the directions of translational motion of moving platform are parallel to the plane normal vector which consists of those constraining force vectors. The three axes of rotation of moving platform through an intersection point.
(4)The three constraining force vectors intersect at a point in space. Three translational motions of moving platform were restricted, the mechanism with three rotational motions, and then the three axes of rotation of moving platform through this space point.
(5)The three constraining force vectors are in different planes, respectively. They are not public intersect point. (a)The three constraining force vectors in three parallel planes, they are not common vertical line. Two translational motions and one rotational motion of moving platform were restricted, and the axes of rotation of moving platform through those planes. (b) The three constraining force vectors in three parallel planes, and they have a common vertical line. Two translational motions and one rotational motion of moving platform were restricted, and the axes of rotation of moving platform are coplanar. (c) The three constraining force vectors in three perpendicular planes each other, then three translational motion of moving platform were restricted.
(6)The three constraining force vectors are spatial parallel each other, they are not in same plane. One translational motion and two rotational motions of moving platform were restricted, and then the direction of constraining force vectors is perpendicular to the direction of translational motions of moving platform.

## 3. The RPS kinematic chains

Most of kinematic chains of parallel mechanisms are composed of revolve pair(R), prismatic pair (P) and ball pair (S). Such as RPS kinematic chains, SPS kinematic chains, RRR kinematic chains, RRS kinematic chains. Among them, the RPS kinematic chains can be classified in to three types: (1) the axis of revolute pair is perpendicular to the moving direction of prismatic pair. (2) the axis of revolute pair and the moving direction of prismatic pair intersect at a point. (3). the axis of revolute pair is parallel/collinear to the moving direction of prismatic pair. Besides, the installation ways of kinematic chains relative to fixed platform are different, it leads to the motion characteristic of moving platform with novel performance.

### *3.1. The first type of RPS kinematic chain*

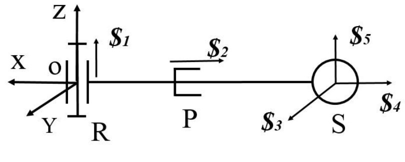



**Figure 1.** First type of RPS kinematic chain

For this type of RPS kinematic chain, the axis of revolute pair is perpendicular to the moving direction of prismatic pair, as shown in Fig 1. The center point of revolve pair(R) of kinematic chain is selected as the origin of the coordinate system, its X axis is collinear to the axis of revolute pair, its Z axis is perpendicular to the fixed platform, its Y-axis is determined by right-hand rule. Set coordinates of the center of prismatic pair (P) is （$x_1$， $y_1$， $z_1$） , and coordinates of the center of ball pair (S) is ($x_2$， $y_2$， $z_2$), the kinematic screws of this kinematic chain, as shown in formula (1).

$$\begin{cases} \$_1 = (0 \quad 0 \quad 1;0 \quad 0 \quad 0) \\ \$_2 = (0 \quad 0 \quad 0;1 \quad 0 \quad 0) \\ \$_3 = (1 \quad 0 \quad 0;0 \quad 0 \quad 0) \\ \$_4 = (0 \quad 1 \quad 0;0 \quad 0 \quad x_2) \\ \$_5 = (0 \quad 0 \quad 1;0 \quad x_2 \quad 0) \end{cases} \tag{1}$$

The constraint screws were obtained by $\$_i \circ \$_r = 0$

$$\$_{1r} = (0 \quad 0 \quad 1;0 \quad -x_2 \quad 0) \tag{2}$$

According to constraint screws of kinematic chain, this kinematic chain exerts a constraining force on the moving platform, it passes through the center of ball pair, and it is parallel to the axis lines of revolute pair. Such as the 3-RPS parallel pyramid mechanism, the axis of revolve pair of RPS kinematic chains are perpendicular to each other, as shown in Fig 2(a). Because of this three constraining forces are perpendicular to each other, so the moving platform can only take three independent rotation movements in the initial position. The axes of rotation movement of moving platform in the same direction with the direction of motion of prismatic pairs, but those axes changes with the posture of the moving platform.

The axes of revolve pairs for three RPS kinematic chains are coplanar and intersect each other, as shown in Fig 2(b). When the moving platform in initial position, the three constraining forces have no common point, so the moving platform takes two rotation movements and one translational movement. The two axes of rotation movement of moving platform in the plane which by itself. When the moving platform in general position, the three constraining forces in different planes, respectively. The moving platform takes two rotation movements and one translational movement. Then the axes of rotation movement are determined by those three constraining forces, which may in or out the plane of moving platform. The other case is that one of three RPS kinematic chains upside down at the fixed platform, as shown in Fig 2(c). The directions of axes of revolve pairs in accord with two constraining forces, respectively. The remaining one constraining force parallel to the axes of revolve pairs, and it pass through the center of ball pair. The moving platform takes two rotation movements and one translational movement. One of the axes of rotation movement of moving platform is parallel to axes of revolve pairs of fixed platform, another axis of rotation movement of moving platform pass through the projective point and projective line. The projective point which is intersection point of axes of revolve pairs map in the fixed platform. The projective line which is axes of revolve pairs map in the moving platform. The axes of revolve pairs for three RPS kinematic chains are coplanar and intersect in a point, as shown in Fig 2(d). When the size of moving platform is equal to size of fixed platform, the three constraining forces are coplanar and intersect in one point, and they are not linearly independent. The moving platform can take three independent rotation movements and one translational movement in the initial position. When the size of moving platform is not equal to size of fixed platform, the three constraining forces are intersect at a point in space, so the moving platform can take three independent rotation movements, and the axes of rotation movements of moving platform pass through this intersection point, respectively.

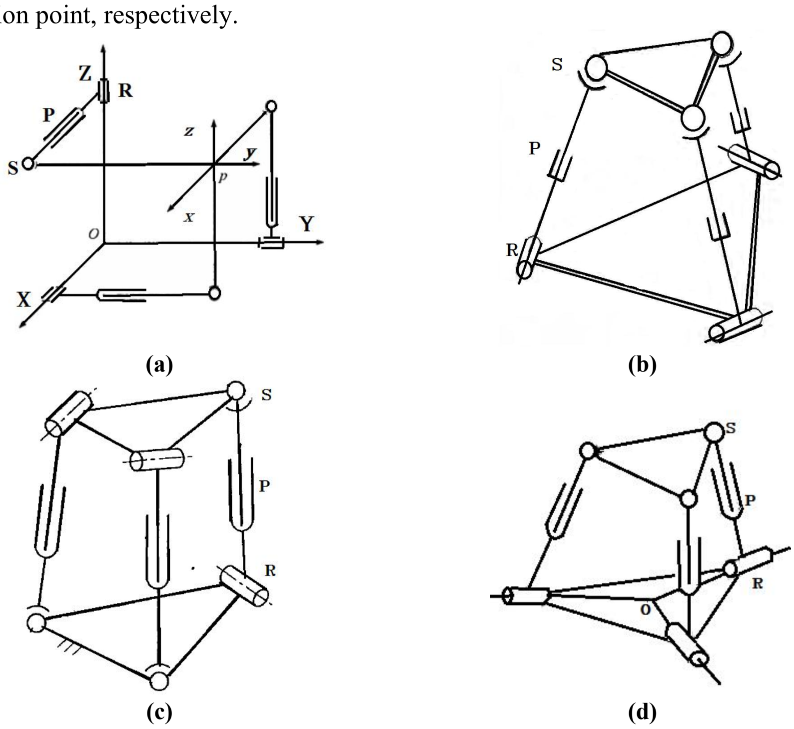


**Figure 2.** Four types of 3-RPS parallel mechanisms

### *3.2. The second type of RPS kinematic chain*

The axis of revolute pair of RPS kinematic chain intersects with the moving direction of prismatic pair, as shown in Fig 3. The center point of revolve pair(R) of kinematic chain is selected as the origin of the coordinate system, its Z axis is collinear to the axis of revolute pair, its X axis is perpendicular to the axis of revolute pair, its Y-axis is determined by right-hand rule. Set the coordinates of center of ball pair (P) is （$x_1$, $y_1$, $z_1$）, the kinematic screws of this kinematic chain as shown in formula (3).

$$\begin{cases} \$_1 = (0\ 0\ 1;0\ 0\ 0) \\ \$_2 = \left(0\ 0\ 0; \dfrac{\sin(\alpha_1)}{\tan(\theta_1)}\ \dfrac{\cos(\alpha_1)}{\tan(\theta_1)}\ 1\right) \\ \$_3 = (1\ 0\ 0;0\ z_1\ \text{-}y_1) \\ \$_4 = (0\ 1\ 0;\text{-}z_1\ 0\ x_1) \\ \$_5 = (0\ 0\ 1;y_1\ \text{-}x_1\ 0) \end{cases} \tag{3}$$

The constraint screw is obtained by $\$_i \circ \$_r = 0$

$$\$_{1r} = \begin{bmatrix} l_1 & m_1 & n_1 ; -y_1 & x_1 & 0 \end{bmatrix} \quad (4)$$

$$l_1 = \left[ \frac{x_1}{\sqrt{x_1^2 + y_1^2 + (z_1 - R)^2}} \right], \ m_1 = \left[ \frac{y_1}{\sqrt{x_1^2 + y_1^2 + (z_1 - R)^2}} \right]$$

$$n_1 = \left[ \frac{z_1 - R}{\sqrt{x_1^2 + y_1^2 + (z_1 - R)^2}} \right]$$

$\$_{1r}$ represents a force vector that connects the spherical hinge and the center of arc rod, $\theta_1$ is the moving direction of the arc prismatic pair, the coordinates of the centre point of the spherical hinge is $P_1=(x_1, y_1, z_1)$, $\alpha_1$ is the driving angle of the kinematic chain 1. Wang [18-23] presented three types of 3-RPS parallel mechanisms with arc prismatic pairs, as shown in Fig 4.

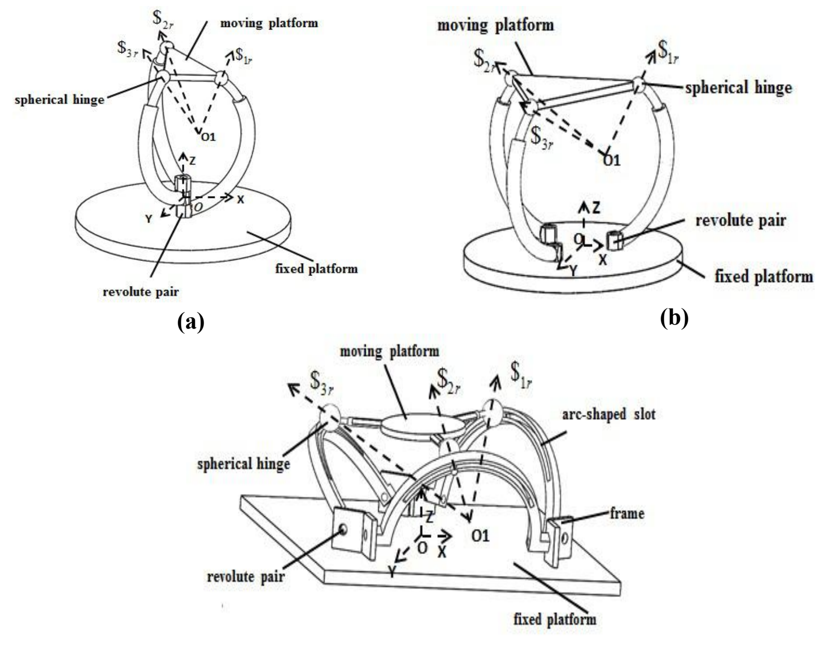



**Figure 4.** Three types of 3-RPS parallel mechanisms

For the first type of parallel mechanism, three axes of revolute pairs of RPS kinematic chains are collinear, and they are perpendicular to the fixed platform. Thus, each kinematic chain applies a force vector on the moving platform. They are intersected at one point that passing through each center of arc rod and the center of spherical joints, and this three force vectors are linearly independent of each other. There are no public constraints and virtual constraints in this parallel mechanism. Therefore, this mechanism is not instantaneous mechanism [24-25]. The moving platform rotates around the Z-axis with respect to the other two directions is decoupled, as shown Fig 4(a). For the second type of parallel mechanism, three axes of revolute pairs of RPS kinematic chains are parallel, respectively. Each kinematic chain applies a force vector on the moving platform, and the three force vectors are intersected at one point in space, which passes through center of arc rods and the center of spherical joints, they are linear independent, respectively. Therefore, three translational movements of the moving platform are restrained, and the moving platform can take three independent rotation movements which rotations round a point in space, as shown in Fig 4(b). For the third type of parallel mechanism, three axes of revolute pairs of RPS kinematic chains are intersect with each other and coplanar, and they are parallel to the fixed platform. Each kinematic chain applies a force vector on the moving platform, and they are intersected at one point that passing through center of arc rod and the center of spherical joints, respectively. Those force vectors are linearly independent, respectively. The moving platform can take three independent rotation movements which rotations round a point in space, as shown in Fig 4(c). Therefore, those three types of parallel mechanism are belonging to the 3-US parallel mechanism.

*3.3. The third type of RPS kinematic chain*

The axes of revolute pairs of RPS kinematic chain and the moving direction of prismatic pair are collinear, as shown in Fig 5. The center point of revolve pair(R) of kinematic chain is selected as the origin of the coordinate system, its Z axis is collinear to the axis of revolute pair, its X axis is perpendicular to the axis of revolute pair, its Y-axis is determined by right-hand rule. Set coordinates of center of prismatic pair (P) is $(x_1, y_1, z_1)$ , and coordinates of center of ball pair (S) is $(x_2, y_2, z_2)$, the kinematic screws of this kinematic chain shown in formula (5).

$$\begin{cases} \$_1 = (1 \quad 0 \quad 0; 0 \quad 0 \quad 0) \\ \$_2 = (0 \quad 0 \quad 0; 1 \quad 0 \quad 0) \\ \$_3 = (1 \quad 0 \quad 0; 0 \quad 0 \quad 0) \\ \$_4 = (0 \quad 1 \quad 0; 0 \quad 0 \quad x_2) \\ \$_5 = (0 \quad 0 \quad 1; 0 \quad x_2 \quad 0) \end{cases} \tag{5}$$

The constraint screw is obtained by $\$_i \circ \$_r = 0$

$$\$_{1r} = (0 \quad 0 \quad 1; 0 \quad -x_2 \quad 0), \$_{2r} = (0 \quad 1 \quad 0; 0 \quad 0 \quad -x_2) \tag{6}$$

According to constraint screws of kinematic chains, this kinematic chain exerts two constraining forces on the moving platform, they pass through the center of ball pair, and it is perpendicular to the axis of revolute pair, respectively. As shown in Fig 6(a). The axes of revolve pairs for three RPS kinematic chains are parallel to each other, and they are perpendicular to the fixed platform, so the moving platform can only take one independent translational movement. The direction of movement of moving platform is consistent with the direction of movement of prismatic pair. When the axes of revolve pairs for two RPS kinematic chains are parallel to each other, and they are perpendicular to the fixed platform. Besides, the axis of prismatic pair for remaining one RPS kinematic is intersect to plane which composed of the previous two RPS kinematic chains, as shown in Fig 6(b). The moving platform can only take one independent translational movement. The direction of movement of moving platform is consistent with the direction of movement of prismatic pair, but the range of motion is decided by the angle between the axis of revolve pair of remaining RPS kinematic and fixed platform. The axes of revolve pairs for three RPS kinematic chains are intersected at a fixed space point, as shown in Fig 6(c). The motions of moving platform were limited, it can't move under any state.

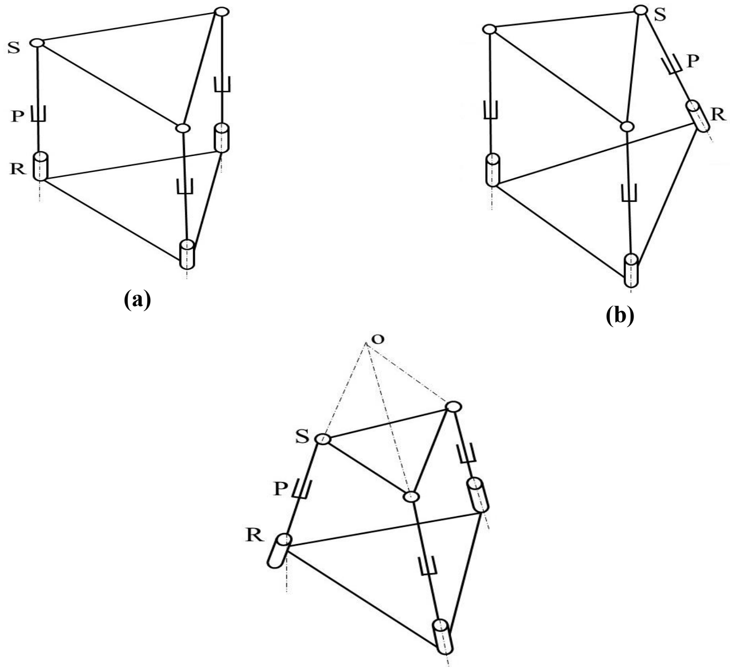



**Figure 6.** Three types of 3-RPS parallel mechanisms

## 4. Conclusion

In this paper, the spatial relationship between constraining forces is proposed, it affects the movement characteristics of moving platform. Take the RPS kinematic chains as a example, the relationship between axes of revolute pairs and moving direction of prismatic pairs, which include the vertical, intersect, parallel and collinear, and the distribution forms of kinematic chains relative to the fixed platform were studied, so several types of parallel mechanisms were proposed.

Then, the fundamental issue for type synthesis of parallel mechanisms is how to design the various types of parallel mechanisms based on simple kinematic chains. In the traditional method, the motion characteristic of parallel mechanisms was determined, and then the kinematic chains were structured, various types of parallel mechanisms were designed by mathematical theory. At last, the degrees of freedom of mechanism were checked. Those parallel mechanisms have either complicated structure of kinematic chains or redundancy kinematic chains. However, many novel parallel mechanisms were designed by kinematic chains, which compose of the same structure of kinematic chains. (The number, type, order and relation between the axes of pairs are the same). Moreover, the relation between the axes lines of pairs of kinematic chain and the order of pairs of kinematic chain are changed, it can also design the various types of parallel mechanisms. It will provide a new idea for type synthesis of parallel mechanisms.

**Acknowledgements**

The authors would like to thank all reviewers for their valuable comments. This study has been financed partially by the Shenzhen Science and Technology Development Fund (JCYJ20170818163505850), National Key R&D Program of China (2018YFC2001400/04, 2019YFB1311400/01), the National Natural Science Foundation of China (61761166007, 71532014), Shandong Key R&D Program (2019JZZY011112), the Innovation Talent Fund of Guangdong Tezhi Plan (2019TQ05Z735), and Shenzhen Public Technology Service Platform Improvement Project of Biomedical Electronics.

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