Configuration Design and Experimental Research of Parallel Mechanism Without Parasitic Motion for Engine Motion Simulation

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This work was supported in part by the National Natural Science Foundation of China under Grant 51775475, in part by the Key Project of the Hebei Natural Science Foundation under Grant E2022203077, and in part by the Key Research and Development Plan of Hebei Province under Grant 202230808010057.

ABSTRACT Aiming at the problem that the existing 2R1T (two rotations and one translation) vehicle engine motion simulation platform mechanism cannot realistically simulate the motion state of the engine due to the parasitic motion. In this paper, the geometric relationship between the restraint force of the branch and the rotation axis of the 2R1T parallel mechanism (PM) is analyzed. A construction criterion of the branch for redundant mechanism without parasitic motion is proposed. From the perspective of mechanism innovation design, a novel 2-RPS/2-UPS/PS PM with large bearing capacity without parasitic motion is designed. This paper solves the problem that the existing 2R1T PM without parasitic motion cannot be applied to the occasion of large load. The kinematics analysis of the mechanism is carried out, and the characteristic of the mechanism without parasitic motion is verified. The workspace of the mechanism is calculated. And the kinematics simulation analysis, stress analysis and prototype experiment of the mechanism are carried out. The correctness of the design index of the motion simulation platform and the characteristic of the mechanism without parasitic motion are proved. It provides a theoretical basis for the application of the mechanism without parasitic motion in large load-bearing occasions.

INDEX TERMS Engine motion simulation platform, parasitic motion, 2R1T parallel mechanism, kinematic analysis, prototype experiment.

I. INTRODUCTION

When the vehicle is driving on different road conditions, the posture and position of the engine changes in real time with the bumps of the vehicle. Its posture and position are mainly divided into three states of pitch, roll and vertical motion. This state will be more obvious when the vehicle is running in a harsh environment. The long-term exposure of the engine to a harsh working environment will increase the probability of engine malfunction. The engine malfunction mainly include lubrication system failure, oil supply system failure and cooling system failure, etc [1]. In order to reduce the possibility of engine malfunction, the engine must be strictly tested before leaving the factory. The traditional engine experiment consumes a lot of financial, human and material resources. It also has the disadvantages of long experiment time and poor effect. Therefore, the indoor testing technology of engine [2] has become a research hotspot.

In order to ensure that the indoor test results of the engine are consistent with the road test results. It is necessary to truly reproduce the actual vehicle road conditions. In the engine performance test, the dynamic test method of rotating along two axes, or the static test of tilting the engine at a certain angle is used. However, the motion of the vehicle body is the coupling of multiple degrees of freedom (DOF). The above test methods are difficult to match with the actual
motion of the vehicle [1], [3]. The 6-DOF PM and 2R1T PM are used to simulate the motion of vehicles. In 1985, the German Daimler-Benz company developed the world’s first motion simulator with 6-DOF [4], [5]. BMW company [6] and Renault company [7] in Europe developed full-scale 6-DOF motion simulators in 2003 and 2004, respectively. In 2003, the university of Iowa developed the largest and most advanced driving simulator NADS-I with 12-DOF at that time [8]. The Stewart structure of the simulator is installed on the horizontal and vertical guide rails. It can realize complex vehicle road interaction in both horizontal and vertical directions. In 2006, the University of Leeds [9] developed a UoLDS driving simulator with 8-DOF. In 2008, the Toyota Higashi Fuji Technical Center developed a driving simulator with a height of 4.5 m and an inner diameter of 7 m. It replaced NADS-I as the largest vehicle motion simulator today [10]. In 2010, Daimler-Benz developed a driving simulator with 7-DOF, a height of about 4.5 m and an inner diameter of about 7.5 m [11]. Dai et al. [12] investigated the motion control of a Stewart parallel robot with uncertain load. Then a novel motion control method is designed with the aim of reducing the effect of the load disturbances. Laffmami et al. [13] proposed a discrete multisegment model in which each segment is a 6-DoF parallel platform. Tong et al. [14] presented a fast and accurate method to maintain the angle of manipulator and effectively resist wave interference. Qiang et al. [15] proposed an improved 3-DOF parallel vehicle motion simulation platform based on the 3-RPS PM. The platform can simulate three DOF of pitch, roll and vertical motion. Song et al. [17] proposed a new 2R1T 3-RSR parallel motion simulator. The mechanism has the characteristics without parasitic motion, and can rotate continuously around any axis of the mid-plane.

Currently, most 6-DOF parallel motion simulators are based on the Stewart platform [18]. It has the disadvantages of small working space, coupling of DOF, complex control, and large footprint. In most cases, the simulation effect of the 3-DOF motion platform and the 6-DOF motion platform is equivalent [19]. The lower-mobility PM has the advantages of simple structure, less driving, low cost and so on. In most practical projects, 3-DOF are enough to meet the application requirements. However, lower-mobility will also cause new problems. The number of branches becomes less, and the bearing capacity decreases. Moreover, 2R1T PM often has parasitic motion in the movement process. It is not conducive to the research of mechanism control and trajectory planning. The above mechanism is used for the engine tilt test. The test bench road spectrum reproduction accuracy is low. And the test result is not accurate. Chen et al. [20] proposed a 3-UPU PM without parasitic motion. There is no parasitic motion when the mechanism rotates. The moving platform of the 3-UPU PM can always rotate continuously around any axis or any point in the symmetry plane. Li et al. [21] revealed the intrinsic relationship between the geometric parameters of the mechanism and the parasitic motion by establishing the kinematics model of the parasitic motion of the 3-PRS PM. Li et al. also pointed out that the [PP]S PM can eliminate the parasitic motion under certain structural conditions. Li et al. [22] obtained a series of 2R1T PMs without parasitic motion by using the displacement group synthesis method. Liu, CARRETERO et al. [23], [24] reduced the influence of the parasitic motion on the complexity of the kinematic model by changing the mechanism structure.

The existing 2R1T PM without parasitic motion can accurately simulate road conditions. The branch chain arrangement conditions of the without parasitic motion mechanism are relatively harsh. The center of the kinematic pair that needs to be close to the moving platform is collinear. It leads to the weak carrying capacity of the mechanism and cannot be used in large-carrying occasions. The PM without parasitic motion proposed by Chen [20] needs to satisfy that the intersection points of the revolute pair axes close to the moving and fixed platform are all located in the middle plane. And such geometric conditions cannot process the prototype.

References [18], [19], and [20] propose configurations of some 2R1T mechanisms without parasitic motion. However, the parasitic motion analysis is only carried out for some mechanism. The obtained mechanism has a very weak bearing capacity and cannot be adapted to the actual working conditions.

Therefore, in order to simulate the actual motion state of the engine and improve the accuracy of road spectrum reproduction. The development of high-precision engine motion simulation platform with large bearing capacity has become an urgent issue to be solved. Based on the working condition of the engine, this paper proposes a large-load 2R1T redundant PM without parasitic motion. Based on the geometric relationship between the branch constraint force and the rotation axis of the mechanism, the spatial distribution of the axis of the 2R1T mechanism without parasitic motion is obtained. A branch construction method of redundant mechanism without parasitic motion is proposed. According to the requirement of adding different DOF of redundant branch, the construction conditions of redundant branch are classified and studied. On the basis of the original non-redundant and mechanism without parasitic motion, a closed-loop unit is constructed. It does not damage the characteristics without parasitic motion of the mechanism, and can significantly improve the bearing capacity of the mechanism. It solves the problem that the bearing capacity of the existing mechanism without parasitic motion is extremely weak and cannot be practically applied. Based on the criterion, a redundant 2-RPS/2-UPS/PS PM without parasitic motion is proposed.
The kinematics analysis and experimental verification of the mechanism are carried out. It is proved that the mechanism can meet the index requirements of high-precision engine road test.

II. DESIGN INDEX AND MECHANISM DESIGN OF ENGINE MOTION SIMULATION PLATFORM

A. TECHNICAL INDEX OF MOTION SIMULATION PLATFORM

According to different types of vehicles, the working road conditions are mainly divided into highways, gravel roads, mountain roads, steep slopes and other environments. In addition, it also includes harsh environments such as sand, ditches, and hills. Vehicle operation under different road conditions is very different, mainly reflected in the ups and downs, bumps, roll and other postures of the vehicle. The vehicle is less undulating when running on the road. It fluctuates greatly and bumps when running on dirt roads and gravel roads. When running on mountain roads and steep slopes, there will be a large pitch and tilt angle.

When the motion state of the vehicle changes, the position and posture of the engine also change in real time. This state of motion has a certain impact on the performance of the engine. During the operation of the vehicle, the engine is always in a complex working environment with different states such as pitch, roll, bump, etc. In order to simulate the real motion state of the vehicle engine, the working state of the engine is divided into three types: pitch, roll and vertical motion. The research goal of this paper is to design a parallel motion simulation platform for engine testing based on parallel mechanism. It can simulate the position and posture changes of the engine under different motion states such as pitch, roll and bump. The single motion state of the engine needs to be simulated, and the composite motion state also needs to be simulated.

The maximum climbing gradient of vehicles is an important index to evaluate the climbing performance of vehicles. At present, the maximum climbing gradient of most vehicles is about 20 degrees. The maximum climbing gradient of some SUV vehicles is about 30 degrees. In order to meet the testing requirements of most vehicle engines, it is determined that the angle range of the parallel motion simulation platform is not less than $\pm 30^\circ$. The specific technical index of the engine test motion simulation platform are shown in Table 1. Based on this technical index, this paper will conduct related research on the motion simulation platform.

B. THE POSITIONAL RELATIONSHIP BETWEEN THE AXIS OF ROTATION AND THE RESTRAINT FORCE OF A MECHANISM WITHOUT PARASITIC MOTION

The relationship between the mechanism’s rotation axis and the moving platform are discussed in this paper. The relationship between the constraint force of branch and the rotation axis are analyzed. The condition that 2R1T mechanism without parasitic motion is studied. Literature [25] points out that when the rotation axis of 2R1T PM is on the moving platform, the mechanism does not have parasitic motion. According to the analysis, there are three kinds of branches for 2R1T PM: (1) 3T2R branch, the branch has a constraint force; (2) 2T2R branch, the branch has one constraint force and one constraint force couple. (3) 1T2R branch, the branch has two constraint forces and one constraint couple. The kinematic pairs connected with the fixed platform can be revolute(R) pairs, universal(U) pairs, spherical(S) pairs and prismatic(P) pairs. When the kinematic pair connected to the fixed platform is a S pair or a U pair, if the restraint force of branch is coplanar with all the R pairs of the branch, the restraint force must pass the center of the U pair and the S pair. If the restraint force of branch is on the fixed platform,
the restraint force will not always intersect with the rotating 
axis of the mechanism. Therefore, the branch restraint force 
is located on the moving platform. The kinematic pair directly 
connected to the moving platform is the U pair or the S pair. 
The kinematic pair connected to the fixed platform can only 
be R pair or P pair.

The kinematic pair connected to the fixed platform is an 
R pair. The three branches intersect with the revolute pair 
connected to the fixed platform. The restraint force of the 
three branches cannot intersect with the rotating axis on the 
moving platform at any time, which does not exist. As shown 
in FIGURE 1.

The revolute pairs connected with the three branches and 
the fixed platform are parallel to each other. There is only 
one restraint force and a restraint couple on the moving 
platform. The moving platform lacks a restraint force. It does 
not satisfy the DOF requirement. As shown in FIGURE 2. 
Therefore, the revolute pair connected to the fixed platform 
can only be one set of parallel, two sets of intersecting. 
As shown in FIGURE 3.

Assume that the R pairs of branch 1 and branch 3 connected 
to the fixed platform are parallel to each other, and perpen-
dicularly intersect with the axis of R pair of branch 2. At this 
time, the restraint force of the three branches is parallel to 
the R pair, acting on the moving platform. The rotation axis 
intersects with the three branch constraints at the same time. 
The rotating axis 1 is the connecting line of the center point 
of the kinematic pair when the three branches are collinear 
with the kinematic pair connected to the moving platform. 
The rotating axis 2 is parallel and coplanar with the constraint 
force directions of the branches 1 and 3. It intersects and 
coplanar with the restraining force directions of the branch 2. 
However, this does not satisfy the theory that the rotation 
axis of the 2R1T PM is all located on the moving platform 
pointed out in the [25]. This paper will correct this statement. 
Reference [25] only proves that one of the rotation axes of 
the moving platform coincides with the y-axis of the moving 
platform. The location of the other axis is not proven. It is 
just inferred that the other rotating axis is also located on the 
moving platform. Through the above analysis, it is proved that 
this statement is wrong.

The spatial distribution conditions of the axis of 2R1T PM 
without parasitic motion are as follows:
(1) When the rotating axis 1 of the mechanism is collinear 
with the center of the kinematic pair connected by three 
branch chains and the moving platform, the connecting 
line R1 of the center point of the kinematic pair.
(2) The rotation axis 2 of the mechanism is the rotation 
axis R2 which passes through the center point of the 
moving platform and is parallel to the X axis of the 
fixed platform.

C. CONSTRUCTION CRITERIA OF REDUNDANT PMS 
WITHOUT PARASITIC MOTION
If the PM without parasitic motion is constructed accord-
ing to FIGURE 3, all the branches of the PM are collinear 
with the kinematic pairs close to the moving platform. The 
bearing capacity on both sides of the R1 axis is weak and 
cannot be used in high-load applications. Therefore, the con-
struction method of redundant mechanism without parasitic 
motion is proposed in this paper. On the basis of the original 
mechanism without parasitic motion, a closed-loop unit is 
constructed. It does not damage the characteristics without 
parasitic motion of the mechanism, but also improves the 
bearing capacity of the mechanism.

The added redundant branch can only have the following 
5 cases:
  1. The 2T3R branch has a restraint force. 2. The 3T2R 
branch has a restraint couple. 3. The 2T2R branch has a 
restraint force and a restraint couple. 4. The 1T2R branch 
has two restraint forces, one restraint couple. 5. 3T3R uncon-
strained branch.

Case 1: When the restraint force is provided by redundant 
branches, the newly added branch and the kinematic pair
TABLE 2. Configurations of 2R1T PM without parasitic motion.

| 2T3R branch | 2T2R branch | redundant branch |
|-------------|-------------|------------------|
| RPS         | RRU         | UPS              |
| PRS         | RPU         | SPS              |
| RRS         | PPU         | RUS              |
| RPPU        | PRU         | PSU              |
| RRPU        |             |                  |
| RRRU        |             |                  |
| RRPU        |             |                  |
| PPRU        |             |                  |
| PPS         |             |                  |
| PRS         |             |                  |

connected to the moving platform must pass through the axis $R_1$. At this time, the restraint force of the mechanism intersects with the rotating axis at all times, but the bearing capacity of the mechanism cannot be improved. $\dagger$, $\ddagger$, and $\S$ do not meet the requirements, as shown in FIGURE 4.

Case 2: When the restraint couples are provided by redundant branches, the restraint couples provided should always be perpendicular to the two axes of rotation. When the platform rotates through a certain angle, the constraint couple $f_4$ cannot always be perpendicular to the axis $R_2$. Therefore $\ddagger$ does not meet the requirements, as shown in FIGURE 5.

Case 3: When the constrained force and constraint couple are not provided by redundant branches, the newly added branches are arranged on both sides of the $R_1$ axis. It does not destroy the characteristics without parasitic motion of the non-redundant mechanism. And it improves the bearing capacity of the mechanism. It meets the requirements, as shown in FIGURE 6.

Therefore, the branch construction criterion of redundant PM without parasitic motion is proposed:

$\dagger$ The non-redundant branch is collinear with the center of the kinematic pair connected with the moving platform;

$\ddagger$ The revolute pairs connected with the fixed platform in the non-redundant branches have one set of parallel and two sets of orthogonal.

$\S$ Only unconstrained branches of 3T3R can be added.

$\ddagger$ The unconstrained branches are arranged on both sides of the $R_1$ axis to form a closed loop and improve the bearing capacity of the mechanism.

According to the above-mentioned construction criteria of redundant PM without parasitic motion, the 2R1T PM without parasitic motion is synthesized.

The configurations that satisfy the criteria are shown in Table 2.

Among them, the revolute pair connected with the fixed platform is the branch perpendicular to the other two branch revolute pairs respectively. The restraint forces can only be provided by this branch, and the restraint couples cannot be provided. Due to this branch provides a restraint couple, the restraint couple cannot always be perpendicular to the axis of rotation of the moving platform. To sum up, there are 14 types of the branch 1 and the branch 3, 4 types of the branch 2, and 7 types of redundant branches. Combining the above branches, 5488 redundant PMs without parasitic motion are obtained.

The 3-RPS PM is a typical 2R1T mechanism, which has rotational DOF around the $x$-axis and $y$-axis and translational DOF along the $z$-axis. When the kinematics of this mechanism is analyzed, it is easy to find that the mechanism has parasitic motion. When the moving platform rotates around the $x$-axis and the $y$-axis, the moving platform often has parasitic motions that translate along the $x$-axis and the $y$-axis. The existence of parasitic motion is not conducive to the control and trajectory planning of the motion simulation platform.

Based on the branch construction criterion of the redundant PM without parasitic motion, the three S pairs of the mechanism are arranged collinearly. The revolute pairs of the branch 1 and the branch 3 are parallel to each other and perpendicular to the connecting line of the S pair. The revolute pair of the branch 2 is parallel to the connecting line of the S pair to obtain a 3-RPS PM without parasitic motion.

The 3-RPS mechanism without parasitic motion is shown in FIGURE 7. $A_1$, $A_2$, $A_3$ are R pairs, $L_1$, $L_2$, $L_3$ are P pairs, $B_1$, $B_2$, $B_3$ are S pairs, the fixed and moving platforms are all isosceles right triangle. The moving platform and the fixed platform are parallel to each other in initial position. $B_1$, $B_2$ and $B_3$ are arranged in line. $A_1$ and $A_3$ are parallel and perpendicular to the connecting line of $A_1A_3$, and $A_2$ is parallel to the connecting line of $A_1A_3$. 

FIGURE 7. Schematic diagram of 3-RPS PM without parasitic motion.

FIGURE 8. The branch coordinate system and mechanism coordinate system of 3-RPS PM without parasitic motion.
As shown in FIGURE 8, the branch coordinate system and the mechanism coordinate system are established. The branch coordinate system $A_1$-$xyz$ is established with $A_1$ as the origin. The fixed coordinate system $O_1$-$XYZ$ is established with the midpoint $O_1$ of $A_1A_3$ as the origin, and the moving coordinate system is established with $B_3$ as the origin $O_3$-$xyz$.

The kinematic screw system of each branch of the mechanism is

$$
\begin{align}
&s_{11} = \begin{pmatrix} 0 & 1 & 0; & 0 & 0 & 0 \end{pmatrix} \\
&s_{12} = \begin{pmatrix} 0 & 0 & 0; & d_2 & 0 & f_2 \end{pmatrix} \\
&s_{13} = \begin{pmatrix} 1 & 0 & 0; & 0 & e_3 & 0 \end{pmatrix} \\
&s_{14} = \begin{pmatrix} 0 & 1 & 0; & -d_4 & 0 & f_4 \end{pmatrix} \\
&s_{15} = \begin{pmatrix} 0 & 0 & 1; & 0 & -e_5 & 0 \end{pmatrix}
\end{align}
$$

(1)

By determining the reciprocal screw of the kinematic screw system of the branch, the constraint screw of the branch can be obtained as

$$
\begin{align}
&s'_{1i} = \begin{pmatrix} 0 & 1 & 0; & -d & 0 & f \end{pmatrix}
\end{align}
$$

(2)

In this paper, the prismatic pair is used as the actuation pair, that is, $s_{12}$ is the input kinematic screw. After rigidizing the actuation pair of the mechanism branch, the reciprocal screw is obtained for $s'_{11}, s'_{13}, s'_{14}, s'_{15}$, and the actuation force screw of the branch is obtained as

$$
\begin{align}
&s''_{1i} = \begin{pmatrix} 0 & b & c; & 0 & 0 & 0 \end{pmatrix}
\end{align}
$$

(3)

The constraint force screw and the actuation force screw of the branch are shown in FIGURE. 8. After stiffens

the actuation pair, all the constraint screw systems can be expressed as

$$
S = (s'_{11} \ s'_{12} \ s'_{13} \ s''_{11} \ s''_{12} \ s''_{13})
$$

(4)

Among them, $s'_{11}$ and $s'_{12}$ are coplanar, $s'_{13}, s''_{11}, s''_{13}$ are located in the $A_1B_1B_3A_3$ plane, and the three planes have a common intersection line $B_1B_3$. According to the linear geometric principle of Grassmann, the maximum linear independent number of three plane harnesses with a common intersection line is 4. Therefore the rank of all constraint screw systems on the moving platform of the mechanism under the initial configuration is 4, that is, $\text{dim}(S)=4$.

For the 3-RPS PM without parasitic motion, when the kinematic pair of three branches is used as the actuation pair, it doesn’t meet the conditions for reasonable input selection condition, so the mechanism cannot perform normal motion at this time.

D. REDUNDANT 2-RPS/2-UPS/PS PM WITHOUT PARASITIC MOTION

In order to enable the mechanism to move normally under the actuation of the P pair, based on the branch construction criterion of the redundant PM without parasitic motion. UPS or SPS unconstrained branches can be added to the mechanism. The actuation force generated by the mechanism can provide the moving platform with a force couple that rotates around the x-axis. Then it drives the moving platform rotate around the x-axis. As shown in FIGURE 9a). A 3-RPS/UPS mechanism is formed by adding a UPS branch on the basis of the 3-RPS mechanism without parasitic motion. As shown in FIGURE 9b). On the basis of the 3-RPS PM without parasitic motion add two UPS branches. At the same time, the R pair of branch 2 of the 3-RPS mechanism without parasitic motion is moved to the center of the fixed platform to form 2-RPS/2-UPS/RPS mechanism.

The bearing capacity of the mechanism and the stability of the force of the moving platform are considered at the same time. The $A_1B_1$ and $A_3B_3$ branches of the 2-RPS/2-UPS/RPS mechanism are symmetrical about the diagonal $B_1B_3$ of the moving platform. And the $A_2B_2$ and $A_4B_4$ branches are
symmetrical about the diagonal of the moving platform \(B_1B_3\). The branch arrangement of the 2-RPS/2-UPS/RPS PM is better than that of the 3-RPS/UPS PM. The R pair in the middle branch of the 2-RPS/2-UPS/RPS mechanism is a passive DOF. The mechanism after removing the R pair in this branch is the 2-RPS/2-UPS/PS mechanism. It is still a 2R1T PM at this moment.

As shown in FIGURE 10, the two RPS branches, two UPS branches and one PS branch are connected to the square fixed platform and the mobile platform, forming a 2-RPS/2-UPS/PS PM. In the initial position, the R pairs of the two RPS branches are parallel to each other and perpendicular to the diagonal \(A_1A_3\) of the fixed platform. The R pairs are located at the \(A_1\) and \(A_3\) positions of the fixed platform, and the S pairs are located at the \(B_1\) and \(B_3\) positions of the moving platform. The U pair axes of the two UPS branches are parallel to each other and. The fixed axis is always perpendicular to the diagonal \(A_2A_4\) of the fixed platform. The U pair is located at the \(A_2\) and \(A_4\) positions of the fixed platform respectively, and the S pair is located at the \(B_2\) and \(B_4\) positions of the moving platform. The PS branch is located at the center of the fixed platform and it is perpendicular to the fixed platform, the S pair is located at the center \(B_0\) of the moving platform. Establishing the coordinate system as shown in the FIGURE 10, take the fixed platform center \(A_0\) as the origin O. Taking the \(A_0A_1\) direction as the positive direction of the X axis, and take the \(A_0A_2\) direction as the positive direction of the Y axis. Establishing a fixed coordinate system O-XYZ. Similarly, take the center of the moving platform \(B_0\) is the origin o, the direction of \(B_0B_1\) is the positive direction of the X axis. And the direction of \(B_0B_2\) is the positive direction of the Y axis, and the moving coordinate system O-XYZ is established. Assume that the diagonal length of the fixed platform is \(2r_1\), and the diagonal length of the moving platform is \(2r_2\), that is, \(OA_1 = r_1, OB_1 = r_2\) (\(i = 1-4\)).

III. KINEMATIC ANALYSIS OF 2-RPS/2-UPS/PS PARALLEL MECHANISM

A. KINEMATIC INVERSE SOLUTION OF MECHANISM

The transformation matrix between the moving coordinate system and the fixed coordinate system is

\[
\begin{pmatrix}
A_x & A_y & A_z \\
B_x & B_y & B_z \\
C_x & C_y & C_z \\
\end{pmatrix}
\]

In this paper, XYZ Euler angles are used to describe the transformation relationship of the position and posture of the moving platform in the fixed coordinate system. The transformation matrix \(A_R^B\) can be expressed as

\[
A_R^B = R(X, \alpha) \cdot R(Y, \beta) \cdot R(Z, \gamma)
\]

In the equation

\[
R(X, \alpha) = \begin{pmatrix}
1 & 0 & 0 \\
0 & \cos \alpha & -\sin \alpha \\
0 & \sin \alpha & \cos \alpha \\
\end{pmatrix}
\]

\[
R(Y, \beta) = \begin{pmatrix}
\cos \beta & 0 & \sin \beta \\
0 & 1 & 0 \\
-\sin \beta & 0 & \cos \beta \\
\end{pmatrix}
\]

\[
R(Z, \gamma) = \begin{pmatrix}
\cos \gamma & -\sin \gamma & 0 \\
\sin \gamma & \cos \gamma & 0 \\
0 & 0 & 1 \\
\end{pmatrix}
\]

The origin of the moving platform coordinate system in the fixed coordinate system is expressed as

\[
A_{p_{B_0}} = \begin{pmatrix}
0 & 0 & z_0 \\
\end{pmatrix}^T
\]

At this time, no matter how the two rotational DOF change, the X and Y coordinates are zero, so there is no parasitic motion in the mechanism.

The representation of each point on the fixed platform in the fixed coordinate system is

\[
A_{p_{A_1}} = \begin{pmatrix}
r_1 & 0 & 0 \\
\end{pmatrix}^T
\]

\[
A_{p_{A_2}} = \begin{pmatrix}
0 & r_1 & 0 \\
\end{pmatrix}^T
\]

\[
A_{p_{A_3}} = \begin{pmatrix}
-r_1 & 0 & 0 \\
\end{pmatrix}^T
\]

\[
A_{p_{A_4}} = \begin{pmatrix}
0 & -r_1 & 0 \\
\end{pmatrix}^T
\]

The representation of each point on the moving platform in the moving coordinate system is

\[
B_{p_{B_1}} = \begin{pmatrix}
r_2 & 0 & 0 \\
\end{pmatrix}^T
\]

\[
B_{p_{B_2}} = \begin{pmatrix}
0 & r_2 & 0 \\
\end{pmatrix}^T
\]

\[
B_{p_{B_3}} = \begin{pmatrix}
0 & -r_2 & 0 \\
\end{pmatrix}^T
\]

\[
B_{p_{B_4}} = \begin{pmatrix}
0 & 0 & 0 \\
\end{pmatrix}^T
\]

The coordinates of each point in the moving coordinate system in the fixed coordinate system are transformed into

\[
A_{p_{B_i}} = A_{R}^B B_{p_{B_i}} + A_{p_{B_0}}
\]

According to the structural characteristics of the 2-RPS/2-UPS/PS PM, there are the following constraints:

\[
A_{B_1} \perp \text{fixed platform}, A_{B_1} \perp A_{B_3} \perp R_3, \text{so we can get:}
\]

\[
A_{B_1} \cdot R_1 = 0 (i = 1, 3)
\]

Among them, the axis vectors of the revolute pairs \(R_1\) and \(R_3\) can be expressed as

\[
R_1 = R_3 = \begin{pmatrix}
0 & 1 & 0 \\
\end{pmatrix}^T
\]

The simultaneous equations (5)-(15) can be obtained

\[
x_m = 0
\]

The coupled relationship between \(\alpha\), \(\beta\), and \(\gamma\) can be obtained from equation (16)

\[
\gamma = -\arctan (\tan \alpha \sin \beta)
\]

According to the above formulas, the length of each actuation branch can be obtained

\[
l_i = \sqrt{|A_{B_1}|^2}
\]
B. SPEED ANALYSIS OF THE MECHANISM

The speed analysis of the PM is to study the mapping relationship between the speed of the moving platform of the mechanism and the speed of the actuation pair of each branch. That is, the derivation process of the Jacobian matrix. The velocity vector $v_{Bi}$ of each spherical pairs center $B_i$ on the moving platform can be expressed as

$$v_{Bi} = v + \omega \times r_{Bi} \quad (19)$$

In the formula
- $v$ — the linear velocity of the center $o$ of the moving platform of the mechanism;
- $\omega$ — the angular velocity of the rotating platform of the mechanism;
- $r_{Bi}$ — the direction vector from the point $o$ to the point $B_i$ on the moving platform.

The linear velocity $v_{li}$ of the branch kinematic pair can be expressed as the projection of the velocity vector $v_{Bi}$ at the point $B_i$ of the moving platform spherical pairs in the direction of the rod length, namely

$$v_{li} = v_{Bi} \cdot k_i \quad (20)$$

In the formula
- $k_i$ represents the unit vector of the moving vice $l_i$,
- $k_i = l_i/|l_i|$.

Equation (28) is substituted into Equation (29) to get

$$v_{li} = (v + \omega \times r_{Bi}) \cdot k_i = k_i \cdot v + (r_{Bi} \times k_i) \cdot \omega \quad (21)$$

The equation (21) is written in matrix form as follows

$$v_{li} = \left[ k_i^T \quad (r_{Bi} \times k_i)^T \right] \begin{bmatrix} v \\ \omega \end{bmatrix} \quad (22)$$

Define $J_i^1$ as follows

$$J_i^1 = \left[ k_i^T \quad (r_{Bi} \times k_i)^T \right] \quad (23)$$

The equation (22) can be written in the following form

$$v_{li} = J_i^1 \begin{bmatrix} v \\ \omega \end{bmatrix} \quad (24)$$

Since the DOF of the 2-RPS/2-UPS/PS PM is 3, only three of the six parameters that describe the pose of the moving platform are independent of each other. Therefore, this paper uses three parameters to describe the position and posture of the moving platform. It is represented by the rotation angle $\alpha$ around the $x$-axis, the rotation angle $\beta$ around the $y$-axis, and the vertical displacement $z_0$.

The relationship between the linear velocity $v$ of the motion platform and $[\dot{\alpha} \quad \dot{\beta} \quad \dot{z}_0]^T$ is

$$v = J^{21} [\dot{\alpha} \quad \dot{\beta} \quad \dot{z}_0]^T \quad (25)$$

In formula (25), the expression of $J^{21}$ is

$$J^{21} = \begin{bmatrix} 0 & 0 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & 1 \end{bmatrix} \quad (26)$$

When XYZ euler angles are used to describe the posture of the moving platform, the rotational motion of the moving platform is described relative to the motion coordinate system. It is necessary to convert the velocity relationship represented by the euler angles into the rectangular coordinate system. The specific conversion expression is as follows

$$\omega = R(X, \alpha) \left[ \begin{array}{c} 1 \\ 0 \\ 0 \end{array} \right] \omega_x + R(Y, \beta) R(Z, \gamma) \left[ \begin{array}{c} 0 \\ 0 \\ 1 \end{array} \right] \omega_z$$

$$+ R(X, \alpha) R(Y, \beta) R(Z, \gamma) \left[ \begin{array}{c} 0 \\ 0 \\ 1 \end{array} \right] \omega_z$$

$$= J^{211} \begin{bmatrix} \omega_x \\ \omega_y \\ \omega_z \end{bmatrix} \quad (27)$$

In formula (27), the expression of $J^{211}$ is:

$$J^{211} = \begin{bmatrix} 1 & 0 & \sin \beta \\ 0 & \cos \alpha & -\sin \alpha \cos \beta \\ 0 & \sin \alpha & \cos \alpha \cos \beta \end{bmatrix} \quad (28)$$

Define $\omega'$ as follows

$$\omega' = \left( \omega_x, \omega_y, \omega_z \right)^T \quad (29)$$

Then the relationship between the angular velocity expressed by Euler angles $\omega'$ and $[\dot{\alpha} \quad \dot{\beta} \quad \dot{z}_0]^T$ is

$$\omega' = J^{222} [\dot{\alpha} \quad \dot{\beta} \quad \dot{z}_0]^T \quad (30)$$

In formula (30), the expression of $J^{222}$ is

$$J^{222} = \begin{bmatrix} 1 & 0 & 0 \\ 0 & 1 & 0 \\ 0 & 0 & 1 \end{bmatrix} \quad (31)$$

Define $J^{22}$ as follows

$$J^{22} = J^{211} \cdot J^{222} \quad (32)$$

According to equations (25), (27) and (30), the following relationship can be obtained

$$\begin{bmatrix} v \\ \omega \end{bmatrix} = J^2 [\dot{\alpha} \quad \dot{\beta} \quad \dot{z}_0]^T \quad (33)$$

In formula (33), the expression of $J^2$ is

$$J^2 = \begin{bmatrix} J^{21} \\ J^{22} \end{bmatrix} \quad (34)$$

Define $J_i$ as follows

$$J_i = J_i^1 \cdot J^2 \quad (35)$$

Therefore, the linear velocity of the revolute pairs of each branch of the mechanism can be expressed as

$$v_{li} = J_i [\dot{\alpha} \quad \dot{\beta} \quad \dot{z}_0]^T \quad (36)$$
It is written in matrix form as:

$$V = J^{-1} \begin{bmatrix} \dot{\alpha} & \dot{\beta} & \dot{z}_0 \end{bmatrix}^T$$

(37)

where $V$—the velocity vector of each branch of the mechanism, its expression is

$$V = \begin{bmatrix} v_{l1} & v_{l2} & v_{l3} & v_{l4} \end{bmatrix}^T;$$

$J^{-1}$—Inverse Jacobian matrix of mechanisms, the expression is: $J^{-1} = \begin{bmatrix} J_1^T & J_2^T & J_3^T & J_4^T \end{bmatrix}^T$.

C. KINEMATICS SIMULATION OF MECHANISMS

The method of comparing the theoretical calculation data and the simulation solution data are used for verification in this paper. The kinematic parameters of the mechanism is set as follows: the radius of the moving platform is 500mm. The radius of the fixed platform is 750mm. And the height between the lower moving platform and the fixed platform in the initial position is 1450mm. In order to calculate the inverse kinematics solution of the PM and the speed of each branch, the rotation equation of the moving platform is set as

$$\alpha = \frac{\pi}{6} \cos \left( \frac{\pi}{3} t \right)$$

(38)

$$\beta = \frac{\pi}{6} \sin \left( \frac{\pi}{3} t \right)$$

(39)

As shown in FIGURE 11a) and FIGURE 11b). The graphs of the kinematic position inverse solution and the velocity theoretical calculation result are drawn, respectively.

As shown in FIGURE 12a) and FIGURE 12b). The kinematic inverse solution and velocity simulation results obtained by Adams software, respectively. And the simulation result curve graph drawn by Matlab software.

The theoretical calculation data obtained by Matlab software is compared with the simulation data obtained by Adams software. As shown in FIGURE 11 and FIGURE 12. The theoretical value of the position inverse solution curve and the velocity inverse solution curve of the PM are completely consistent with the trend and numerical value of the simulation value. The results show that the position inverse solution and the velocity Jacobian are correct.

D. WORKSPACE ANALYSIS

In order to calculate the working space of the 2-RPS/2-UPS/PS PM, it is necessary to limit the structural parameters of the mechanism. After the relevant parameters of the fixed platform and the moving platform of the 2-RPS/2-UPS/PS parallel motion simulation platform are determined. The main factors affecting the working space of the PM are the limitation of the length of the driving link of the mechanism.
The limitation of the movement range of each kinematic pair, and the limitation of interference between each link.

The parameter values of the 2-RPS/2-UPS/PS PM are set as follows: the radius of the moving platform is 500mm. The radius of the fixed platform is 750mm. The length of the drive branch is limited to 1300-2100mm. And the movement range of the S pair and the U pair is $\pm 45^\circ$. According to the above parameters, the working space of the parallel motion simulation platform calculated is shown in FIGURE 13.

The translation range of the parallel motion simulation platform in the Z direction is $\pm 400mm$, and the rotation range around the x-axis and y-axis is 30°. FIGURE 13a) is the three-dimensional view of the parallel motion simulation platform workspace. The shape of the upper and lower parts is similar to a quadrangular pyramid. The shape of the middle part is similar to a cylinder. FIGURE 13b) is a schematic diagram of the projection of the workspace of the PM in the xy plane. It can be seen that the maximum rotation angle of the PM around the x-axis and y-axis directions can reach 30 degrees. It meet the design requirements of parallel motion simulation platform. FIGURE 13c) and FIGURE 13d) are the projection schematic diagrams of the workspace of the PM in the xz plane and yz, respectively. When the position of the center of the moving platform is between 1500-1800mm, the rotation angles of the PM around the x-axis and y-axis directions are both greater than 30 degrees. And when the center of the moving platform is raised or lowered, the rotation angle of the PM gradually becomes smaller.

IV. FINITE ELEMENT SIMULATION OF PARALLEL MOTION SIMULATION PLATFORM PROTOTYPE

In order to verify the rationality of the structure of each component in the parallel motion simulation platform, and to ensure that the strength of each part of the prototype meets the requirements for use. Therefore, it is necessary to perform finite element analysis on the model of the PM before the
prototype is processed. The simplified structure of the parallel motion simulation platform is shown in FIGURE 14.

In this paper, the finite element analysis of the parallel motion simulation platform is carried out. The equivalent stress distribution of the 2-RPS/2-UPS/PS PM and 3-RPS/UPS PM with large bearing capacity under the condition of applying a load of 500kg is obtained. The 3-RPS/UPS PM does not need to meet strict geometric conditions, but there is parasitic motion, and the bearing capacity is very strong. As shown in FIGURE 15 and FIGURE 16.

Both configurations have the same structural parameters, cross-sectional area and boundary conditions. When a 500kg load is added to the moving platform of the model, that is, a force of 5000N is applied to the moving platform of the model. The maximum value of the equivalent stress of the 2-RPS/2-UPS/PS is 7.4MPa. The maximum value of the equivalent stress of the 3-RPS/UPS PM is 8.9MPa. The maximum stress of the 2-RPS/2-UPS/PS PM is much smaller than the maximum stress of the 3-RPS/UPS PM. Therefore, the redundant 2R1T PM without parasitic motion proposed in this paper has a large bearing capacity. At this time, the maximum value of the equivalent stress of the model is less than the yield limit of the material. It meets the requirements of the material. The finite element analysis results show that the equivalent stress distribution of the model meets the index requirements of the prototype design.

V. PROTOTYPE TEST VERIFICATION OF ENGINE MOTION SIMULATION PLATFORM

The electric cylinder with model SV-MM13-2R0E-2-1A4-1000 is selected as the actuation of the mechanism. The parameters of the motor are as follows: the product type of the motor is a servo series product. The rated power of the motor is 2kW. The rated speed of the motor is 2000rpm. The voltage class of the motor is 220V, AC. The encoder type of the motor is photoelectric encoder.

The SV-DA200 series AC servo driver is used to supply power to the electric cylinder. The parameters of the servo driver are as follows: the power class of the servo driver is 2kW. The product series of the servo driver is DA2000. The voltage class of the servo driver is 220V, AC. The servo type of the servo driver is pulse type.

The MPC2860 six-axis motion control card is used as the main controller. The parameters of the motion control card are as follows: the bus type is PCI bus. The single card can control 6-axis servo motor. The control card supports up to 4 cards sharing. And the control function is realized through the upper industrial computer and the motion control card. The industrial computer receives the operation instructions of the external operator through manual control. And it convey the received instruction information to the motion control card. Then the motion control card issues commands to control the servo drive. The motor works under the action of the driver. And then it controls the electric cylinder to realize the motion simulation of the engine. The specific control flow is shown in FIGURE 17.

In this paper, the parallel motion simulation platform is experimented by attitude sensor and laser rangefinder. The attitude sensor is a six-axis Bluetooth attitude sensor with model BWT901BLECL5.0 from Shenzhen Weite. The parameters of the Bluetooth attitude sensor are as follows: the communication mode of the attitude sensor is Bluetooth 5.0. The angle range of the attitude sensor around the x-axis and the z-axis is ±180°. The range of the angle of the attitude sensor around the y-axis is ±90°. The accuracy of the attitude sensor is 0.01°. The sensor is installed in the center of the moving platform, and connected to the host computer software through Bluetooth. The parameters such as pitch and roll angles, acceleration and other parameters of the moving platform can be measured, read and stored in real time. The installation method of the posture sensor is shown in FIGURE 18.

The laser rangefinder is an infrared laser rangefinder model L1s-40 from Shenzhen Motian. The parameters of the laser rangefinder are as follows: The measuring range of the laser rangefinder is 0.05m-40m. The accuracy of the laser rangefinder is ±0.1mm. The voltage of the laser rangefinder is...
5V, DC. It can communicate with the host computer through the RS485 protocol. The parameters such as linear displacement and speed can be measured. The range finder is installed vertically under the moving platform, and a laser reflection sheet is installed on the lower surface of the moving platform. Through the RS485 conversion port and the serial port debugging assistant, the movement data of the moving platform in the z-axis direction is collected. The installation method and communication of the rangefinder are shown in FIGURE 19.

A. KINEMATICS INVERSE SOLUTION EXPERIMENT
The branch values of the inverse solution of the mechanism simulation are input into the software through the data interface module. The moving platform is controlled to perform trajectory motion. The position and posture of the end of the moving platform is measured by the sensor and the rangefinder and fitted to the experimental curve. The simulation curve and the experimental curve are compared, as shown in FIGURE 20 and FIGURE 21. The trends of the two sets of simulation curves and experimental curves are exactly the same. The maximum deviation of the rotation angle around the x-axis is 2.523°. The maximum deviation of the rotation angle around the y-axis is 1.221°. The two sets of curves are within the allowable range of error. The correctness of the inverse solution of the prototype kinematics is verified.

B. DESIGN INDICATOR VERIFICATION
In order to verify whether the platform can meet the index requirements, the angle and displacement experiments are
carried out on the prototype. The angle of the moving platform can be read in real time through the position and posture sensor. And the moving displacement of the moving platform can be measured by the laser rangefinder. As shown in FIGURE 22 and FIGURE 23. The position and posture of the moving platform after rotating ±30 degrees around the x-axis. As shown in FIGURE 24 and FIGURE 25. The position and posture of the moving platform after rotating ±30 degrees around the x-axis. FIGURE 26 shows the posture of the moving platform after moving 400mm. The position and posture of the moving platform after rotating 30 degrees around the two axes at the same time, as shown in FIGURE 27. It can be seen from FIGUREs 22 to 27 that the rotation angle and displacement of the moving platform are consistent with the calculation results of the workspace. It can meet the design index requirements of the engine motion simulation platform.

C. PLATFORM REPEATED MOTION EXPERIMENT AND WITHOUT PARASITIC MOTION VERIFICATION

In this paper, the repeated motion experiment of the platform is carried out. And the moving platform is rotated 30 degrees around the x-axis and around the y-axis; it moves 400mm along the z-axis. The compound trajectory motion is performed with the rotation equation angle of 30 degrees. The ten experiments are performed for each pose and actual measurements are obtained. When the trajectory motion starts, it needs to perform a jog that rotates 30 degrees around the x-axis to enter the initial point of the trajectory, and returns to this point when the trajectory motion ends. Therefore, it is only necessary to measure the x-axis degree of the point at the end of the trajectory motion. The obtained experimental data are shown in Table 3 and Table 4. The maximum rotation angle around the x-axis is 31.876 degrees. The minimum rotation angle around the x-axis is 29.072 degrees. The maximum rotation angle around the y-axis is 31.417 degrees. The minimum rotation angle around the y-axis is 28.667 degrees. The maximum displacement along the z-axis is 402mm. The minimum displacement along the z-axis is 398mm. The maximum rotation angle of the compound motion trajectory is 32.682 degrees. The minimum rotation angle of the compound motion trajectory is 28.077 degrees. The maximum displacement along the x-axis is 2mm. The minimum displacement along the x-axis is 0mm. The maximum displacement along the y-axis is 2mm. The minimum displacement along the y-axis is 0mm.

The difference is compared with the given position and posture values, and the difference histogram is drawn.

| Table 4. Experimental verification data of PM without parasitic motion. |
|---------------------------------------------------------------|
| Frequency | x-axis angle(°) | y-axis angle(°) | z-axis displacement(mm) | y-axis displacement(mm) |
| Theoretical value | 30 | 30 | 400 | 30 |
| 1 | 31.521 | 28.872 | 400 | 32.682 |
| 2 | 30.552 | 29.024 | 401 | 28.077 |
| 3 | 31.107 | 31.234 | 402 | 28.414 |
| 4 | 29.072 | 29.451 | 398 | 31.985 |
| 5 | 28.836 | 30.656 | 401 | 30.687 |
| 6 | 30.623 | 30.231 | 400 | 28.135 |
| 7 | 31.544 | 28.667 | 400 | 31.856 |
| 8 | 29.288 | 31.012 | 399 | 32.076 |
| 9 | 31.876 | 31.417 | 399 | 30.487 |
| 10 | 30.791 | 30.386 | 401 | 31.856 |

FIGURE 26. Rotate 30 degrees around the x-axis and y-axis at the same time.

FIGURE 27. Change of the height position of the moving platform.

TABLE 3. Experimental verification data of repetitive motion of PM.
as shown in FIGURE 28 a)-d). The repeated motion error of the moving platform rotating 30 degrees around the x-axis is between 1.164° and 1.876°. The maximum deviation is 1.876°. The minimum deviation is 0.520°. The repetitive motion deviation of the compound trajectory motion rotating 30 degrees is between 1.923° ~ 2.682°. The maximum deviation is 2.682mm. The minimum deviation is 0.483mm.

As shown in Table 4. The maximum deviation of the rotation angle around the z-axis is 0.30°. And the maximum deviation of x, y axis displacement is 2mm, 2mm. Therefore, through this experiment, it can be verified that the repeated motion deviation of the moving platform is low. The mechanism has no parasitic motion and can meet the performance requirements. The correctness of the construction criterion of redundant PM without parasitic motion proposed in this paper is verified.

VI. CONCLUSION
(1) The working environment of different vehicles is analyzed, the design index of the engine motion simulation platform is proposed. Based on the theory of space geometry, the relationship between the constraint force of branch and the rotation axis are studied. The branch construction criterion for redundant mechanisms without parasitic motion is proposed. And a series of redundant PMs without parasitic motion are synthesized. An optimal redundant 2-RPS/2-UPS/PS PM without parasitic motion is designed.

(2) The kinematics inverse solution and velocity of the mechanism are solved. And the kinematics verification is carried out by kinematics simulation software. Furthermore, the working space of the mechanism is solved. And the position and posture of the mechanism at the limit angle position of the performance test are given. Under the condition of the same size parameters, the stress comparison of the PM without parasitic motion with large bearing capacity proposed in this paper and the 3-RPS/UPS PM with the same large bearing capacity is carried out. The large carrying capacity of 2-RPS/2-UPS/PS PM is verified.

(3) Using attitude sensors and laser rangefinders, and operating the human-computer interface to conduct experiments on the platform. The correctness of the mechanism kinematics inverse solution and workspace design indexes is verified. The repeated motion experiment and the characteristic without parasitic motion verification experiment are carried out. The results show that the platform can run smoothly. The correctness of the characteristic of the platform without parasitic motion is verified.

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