Kinematics and Dynamics Simulation of a Stewart Platform

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Fengchao Liang*, Shuang Tan, Xiaolin Zhao, Jiankai Fan, Zhe Lin, Zhicheng Shi and Xiaojun Kang

Beijing Institute of Space Mechanics & Electricity, Beijing 100094, China
Email: fc.liang@qq.com

Abstract. Position and orientation adjustment of the secondary mirror is one of the effective ways to improve the image quality of space camera. In order to optimize the structural design of a 6-DOF Stewart platform for secondary mirror, simulation method of kinematics and dynamics of parallel manipulator based on virtual prototyping technology was studied. Firstly, the ADAMS parametric model and inverse mathematical model are built. Secondly, theory analysis of inverse kinematics of Stewart platform was performed, and the analytical results of inverse kinematics were obtained by mathematical modeling. Thirdly, simulation of inverse kinematics run in ADAMS after the virtual prototype of parallel manipulator was established. The simulation results in ADAMS and analysis results are consistent, which proved the correctness of the virtual prototype model. Lastly, the kinematics and inverse dynamics simulation were realized by driving each strut using result of inverse kinematics. The analysis method of kinematics and dynamics of parallel manipulator provided a theoretical basis for optimizing design of a Stewart platform.
Keywords. Stewart platform, kinematics, dynamics, secondary mirror.

1. Introduction

In space camera, the relative pose between the primary and the secondary mirror has an obvious effect on high-quality imaging. However, the space camera is affected by launch impact, vibration, temperature change, stress release and other factors, which may cause the error of the relative position and orientation, leading to poor imaging quality [1]. There are mainly two 6-DOF pose tuning mechanism, series and parallel mechanism. Stewart parallel mechanism has many merits, such as high stability, high stiffness, and high precision [2]. For instance, 6-DOF Stewart platform is used in many telescope systems, such as VST, JWST and ESA [3-5].

Stewart platform includes moving, static platforms and six driving struts. The platforms and the driving struts are linked by ball or Hook hinges. These six struts can be retracted independently and freely. Through the coordinated control of the six driving struts, the moving platform can realize the 6-DOF movement of X, Y, Z and U, V W, so as to realize the change of position and orientation [6-10]. However, a Stewart platform is a MIMO system, which is easy to generate singular configuration and poor flexibility. For avoiding or reducing the influence of the above shortcomings, the optimum structural design has to be carried out, which requires the simulation research of a Stewart platform.

2. Theoretical Basis

Kinematic analysis is to solve the position, velocity and acceleration's relationships with time. There are two kinds of kinematic analysis, one is called forward kinematics, and the other one is called inverse kinematics. The first one is solving the pose of the moving platform based on position of struts, and the second one is solving the displacement of the struts base on the pose of the moving platform.

As shown in figure 1, A Stewart platform includes upper platform, lower platform and six parallel struts. Hook hinges A_i and B_i (i=1, 2,..., 6) link the struts and platforms together. The pose of the upper (moving) platform can be controlled by commanding the input variable, the displacement of the retractable struts, move precisely and co-ordinately. That is to say, the position and orientation of the platform is determined by the expansion and contraction quantity of the six supporting struts.

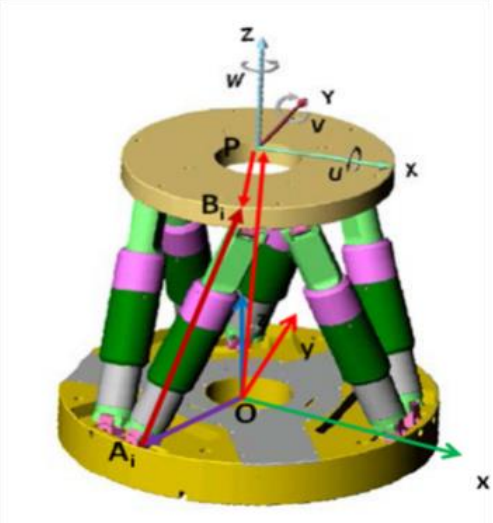

Figure 1. A typical coordinate system of a Stewart parallel mechanism.

To establish mathematical model, two coordinate systems, *O-xyz* and *P-XYZ*, are created. One is at the centre point of the static platform, and the other is at the centre point of the moving platform. The coordinate vector of the upper hinge points are $\boldsymbol{B_i}$, and the coordinate vector of the lower hinge points are $\boldsymbol{A_i}$. After the coordinate system is determined, the position and orientation of the moving platform is represented by the generalized coordinate vector $\boldsymbol{q}$, where $\boldsymbol{q}$ = [X, Y, Z, U, V, W]^{T}. In this paper, the rotation around the X → Y → Z coordinate axis is selected, as shown in figure 2 [11-15]. After three times rotation, the rotation matrix can be derived as shown in equation (1). And equation (2) gives the length of each driving struts, where $\boldsymbol{L_i}$ is the driving struts' vector$\overrightarrow{\boldsymbol{A_i B_i}}$ shown in figure 1, and l_i is the strut length.

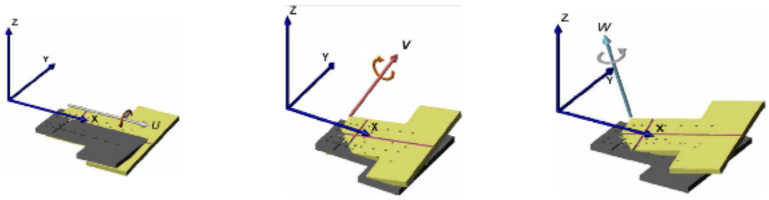

Figure 2. X-Y-Z Euler angle rotation.

$$ {}_B^A\mathbf{R} = \mathbf{R}(X,U)\cdot\mathbf{R}(Y,V)\cdot\mathbf{R}(Z,W) = $$

$$ \begin{bmatrix} \cos(V)\cdot\cos(W) & -\sin(V)\cdot\sin(W) & \sin(V) \\ \sin(U)\cdot\sin(V)\cdot\cos(W)+\cos(U)\cdot\sin(W) & -\sin(U)\cdot\sin(V)\cdot\sin(W)+\cos(U)\cdot\cos(W) & -\cos(V)\cdot\sin(U) \\ -\cos(U)\cdot\sin(V)\cdot\cos(W)+\sin(U)\cdot\sin(W) & \cos(U)\cdot\sin(V)\cdot\sin(W)+\sin(U)\cdot\cos(W) & \cos(U)\cdot\cos(V) \end{bmatrix} \quad (1) $$

$$ l_{\mathrm{i}} = |\mathbf{L}_{\mathrm{i}}| = \sqrt{\mathbf{L}_{\mathrm{i}}^{\mathrm{T}}\cdot\mathbf{L}_{\mathrm{i}}} \quad (2) $$

3. Parametric Modeling

The principle of establishing virtual prototype model is the same as that of establishing physical prototype model, and the model should be simplified as much as possible. In the initial simulation analysis and modeling, there is no need to excessively pursue the consistency between the details of the component geometry and the reality. From the principle of the program, as long as the mass, center of mass and moment of inertia of the virtual prototype model are the same as the actual components, the simulation results are equivalent to the physical prototype.

ADAMS software is a virtual prototype software integrating modeling, solution and visualization technology [16-19]. Usually, when modeling with ADAMS, the built-in geometry module is used. After the parameters of the geometry are determined, the geometry is also determined. When the size of the geometry changes or the influence of the parameters on the whole system needs to be analyzed, the parameters need to be modified manually, which greatly increases the workload. In order to avoid repeated work, ADAMS provides parametric modeling function. The model in the analysis process of this paper is established under ADAMS/view. The whole Stewart platform system is simplified into static platform, dynamic platform, 6 supporting struts, 12 Hooke hinges. The upper hinges B_i, lower hinges A_i and platform radius are set as variables. The parametric modeling parameter table and model are shown in figure 3.

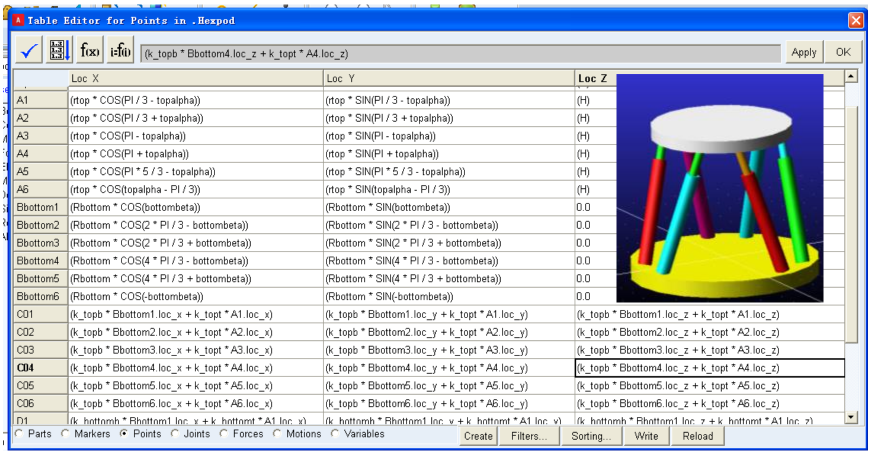

Figure 3. Parameter table and virtual prototype of the Stewart platform.

4. Kinematics Simulation

When the moving platform moves, its speed and acceleration are strictly dependent on the speed and acceleration of each strut, but the relationship between the length of the driving strut and the pose of the moving platform is nonlinear. From the perspective of servo control, the motion space of the moving platform is virtual axis space, and the driving space is real axis space. Therefore, in motion control, the given position, orientation and speed information of the moving platform must be transformed into the control command of each strut length, so as to drive the moving platform to realize the desired motion.

The displacement, speed and acceleration of each support strut are calculated through the inverse kinematics solution in the general design of the Stewart platform, so that the designed Stewart platform can meet the required motion capacity. The movement of the moving platform within the range of motion is to make the center of the moving platform reach any position within the range of motion through changing the struts length. In order to realize the 6-DOF motion in ADAMS, the general point motion excitation is applied at the center of the moving platform, so as to simulate the general motion in the actual work. The general point motion drive dialog box is shown in figure 4. Add the drive to the center point of the moving platform, i.e. marker_79. The center point of the static platform is selected as the reference point, marker_80, which ensures that the reference system of the given motion index is the static coordinate system. The driving types of degrees of freedom include displacement, velocity, acceleration and driving function.

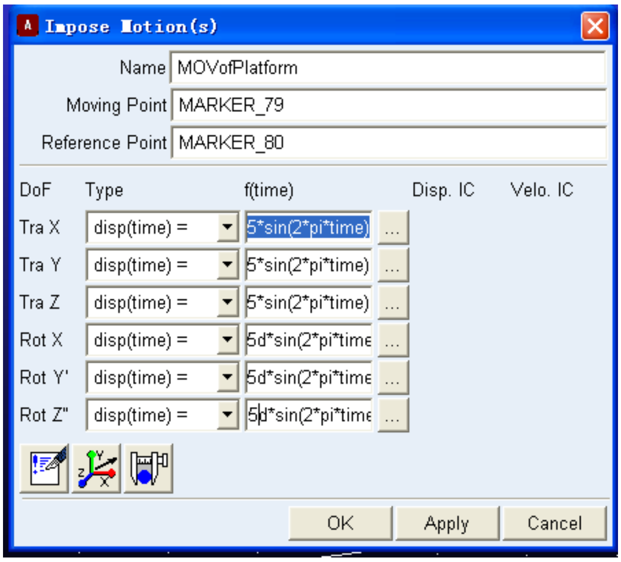

Figure 4. A general point motion drive at the center point of the moving platform.

In order not to lose generality, the sinusoidal displacement/rotation angle driving function is loaded simultaneously in the 6-DOF direction at the center point of the moving platform. After post-processing, the length change curve of six supporting struts can be obtained, which is the inverse kinematics solution. The planned trajectory function of the loading driving instant platform is shown in figure 4. The displacement function in X, Y and Z directions is set to 5 * sin (2 * pi * time), which is a sinusoidal driving signal with an amplitude of 5 mm and a frequency of 1 Hz. The driving function in the rotation direction of U, V and W is 5d * sin (2 * pi * time), which is an angular drive with an amplitude of 5 degrees and an angular frequency of 360 degrees / s.

Set the simulation duration as 1 s and the number of simulation steps as 100 steps, so that the length of each support strut in a cycle can be obtained. The simulation results are shown in figure 5. In order to obtain the change of each support strut, first measure the length of each support strut at each time, and then subtract the initial value from the length value to obtain the expansion and contraction of each support strut. For verifying the correctness of the theoretical model and ADAMS model, the real-time length of each strut is calculated by MATLAB. The error between the two models is maintained at the order of 10^{-5} mm, which shows that the expansion and contraction of the two models are the same at the same time, and the theoretical model and ADAMS virtual prototype model are correct.

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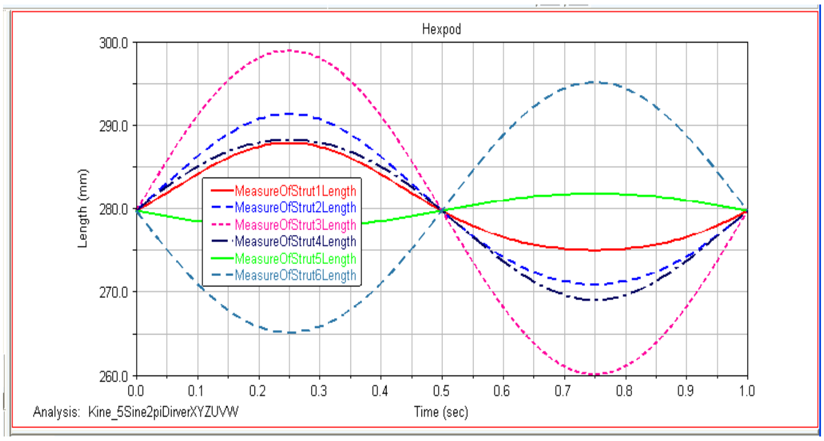

Figure 5. The simulation results of driving struts length in a cycle.

5. Dynamics Simulation

For a given driving force or torque of each joint connecting strut, what will happen to the posture and how the dynamic process of its motion depends not only on its geometric structure, but also on the inertia of each joint connecting strut. For a Stewart platform, when the moving platform realizes a certain movement under a certain load, the driving force of each strut will also change. In the whole movement process, whether the driving force of each strut changes smoothly and whether the force meets the requirements is of great significance for the design of mechanism, the selection of servo actuator and actual control.

The dynamic research of a Stewart platform includes dynamic modeling, force analysis, inertial force calculation, dynamic balance and dynamic response. It plays a very important role in the design and control of 6-DOF Stewart platform and is the basis for determining the main structural parameters of a Stewart platform. Due to the complexity of a Stewart platform, its dynamic model is usually a complex system with multi degrees of freedom, multi variables, high nonlinearity and multi parameter coupling. When using ADAMS to simulate the dynamics of a Stewart platform, ADAMS will automatically establish the Lagrange motion equation of the system according to the mechanical system model. For each rigid body, six Lagrange equations with multipliers in generalized coordinates and corresponding constraint equations are listed and solved automatically without user programming. When doing dynamic analysis, we need to know the output of each strut in any position and orientation. The output of the strut can be obtained by doing the forward kinematics solution. Using the simulation results of inverse kinematics of ADAMS model, the spline function corresponding to strut 1~6 can be obtained: SPLINE_1~SPLINE_6. In this way, the elongation of each strut corresponding to each simulation time is known. Then remove the point-to-point driving of the moving platform of ADAMS model, and add the translation driving motion at the moving joint of each strut MOTION_1 ~MOTION_6, so as to ensure that the extension of each support strut at each simulation time point is consistent with the inverse solution. In order to verify that the moving platform does move sinusoidally in the X, Y, Z, U, V and W directions, the displacement curve of the moving platform need to be measured. At the same time, the force of each drive can be measured to obtain the output of each strut when the moving platform moves. Finally, the simulation time is set to 1.0 s and the number of simulation steps is 100. It can be seen that the positive solution curve of the position and orientation is consistent with the six-dimensional drive loaded on the moving platform during the inverse solution.

Use the add force option in ADAMS to add a constant force fixed on the center of mass of the moving platform. Assuming that the load force is 500N along the negative direction of the Z axis, it can be measured that when the motion laws are 5 * sin (2 * pi * time), the force output of the six supporting struts is as shown in figure 6 that the maximum value reaches 129.9 N. After determining the maximum output of each strut, the load capacity of the Stewart platform can be determined, and the driving and actuating elements of each actuating strut can be selected accordingly.

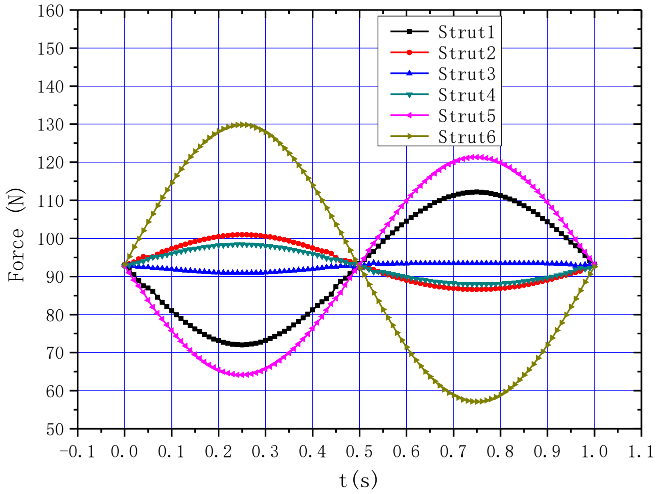

Figure 6. The force output of the six driving struts when load is 500 N.

6. Conclusion

Kinematics and dynamics simulation analysis of a Stewart platform is the basis of optimum structural design, servo component selection and control algorithm. The kinematics and dynamics analysis of a Stewart platform mostly adopts the analytical method, but its mathematical modeling is difficult, the flexibility is poor, the workspace of the moving platform is complex, and the spatial motion is difficult to visualize. In this paper, ADAMS is used to analyze the motion and dynamic performance of a Stewart platform. Compared with the analytical method of theoretical modeling, this method has the advantages of flexible parametric modeling, no complicated theoretical formula derivation and calculation, motion simulation visualization and so on. It provides a new method for the research of a Stewart platform.

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