Equivalence Analysis of Mass-matching of Simulated Space Manipulator Based on Certain Quality

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Abstract. Space manipulator is a high level of integrated space of mechanical and electrical systems in mechanical, electrical, thermal and control fields. Before the experiments, it’s necessary to use a simulated manipulator to verify the reliability of a zero-gravity test system. To assure the consistency between a simulated manipulator and a space manipulator, the mass and barycenter of a simulated manipulator need to be matched. In this paper, an equivalent method based on constant mass is proposed, which can quickly adjust the position of the center of mass of the simulated Space Manipulator joint and achieve the desired objective. Firstly, the fan-shaped and notched counterweights are designed to meet the adjustment requirements of radial and axial barycenter. Then, the joint barycenter models of different types of counterweights are established, and a barycenter equivalence optimization scheme based on constant mass is proposed. Through the design scheme of this paper, the quality and center of mass meet the requirements, and the experimental verification of the simulation manipulator is realized.

1. Introduction
Under the zero-gravity environment of outer space, the manipulator suffers from alternating of high and low temperature, high radiation and other severe working conditions. Therefore, it is necessary to carry out a large amount of analysis and experiments on the ground in advance to ensure the safety and reliability of its in-orbit work. The ground zero-gravity environment simulation experiment system largely is created by the mechanical devices, which places the robot in the zero-gravity environment similar to the outer space. The zero-gravity simulation system can be divided into three types according to the working principle (1,2). Falling motion is made under the gravitational acceleration to form a weightless environment, such as drop tower method (3), uniform circular motion is made under the earth’s gravitational force, such as microgravity experiments on the space shuttle (4). Gravity is counteracted with an equilibrium force, such as suspension method and air flotation method (5). With their advantages and disadvantages, the experimental systems should be selected reasonably according to the actual situation.

After the preliminary design of the ground experiment system, the zero-gravity simulation experiment system should be verified and perfected through experiments. If the developed space manipulator is directly used in the experiment, it may result in high cost and risk. Therefore, it is necessary to develop a set of simulated robot to replace the space manipulator for various functional experiments and improve the zero-gravity simulation experimental system. Then the sound zero gravity system is used to carry out experiments on the space manipulator. Because of the redundant
design such as double motor and double reducer of the actuated joint of space manipulator, only single
motor and single transmission are used in the actuated joint of simulation manipulator. In addition, in
the design of simulation manipulator, the torque sensor is added, so the internal structure and quality
are very different from the real one. In order to ensure the motion performance of the simulated
manipulator consistent with that of space manipulator, it is necessary to design the equivalent
parameters including mass, center of mass and others.

The theory of rotor dynamic balance on mass equivalence has been developed maturely. According
to the principle, dynamic balance methods can be divided into the following categories[6][7], modal
balance method, influence coefficient method and mixed balance method. Wang Liping and Guan
Liwen of Tsinghua University added mass s at different locations to counterbalance heavy gantry
hybrid machine tools, and compared the advantages and disadvantages of several schemes[8]. Hou
Yuemin and Ji Linhong of Tsinghua University used dynamic programming to balance small satellites
at two counterweight planes[9]. In this paper, the counterweight of space manipulator actuated joint is
similar to that described in these literature. The difficulty lies in that the mounting position of the
counterweight is strictly limited due to the requirement of joint construction. The position of the
counterweight should be adjusted according to the actual requirements. More importantly, under the
condition that the center of mass is consistent with the predetermined position, the joint mass should
exactly conform to the target value. So the difficulty lies in ensuring the equivalence of the center of
mass under constant mass condition.

2. Structure of the simulated manipulator

The computer model of the simulated manipulator is shown in figure 1. The physical model of the
simulated manipulator is shown in figure 2. Based on the original space manipulator structure, the
manipulator is designed with 7 joints of identical structure, 2 end effector, 2 manipulator rods and 1
central controller. The 7 joints are shoulder rotary joint, shoulder yaw joint, shoulder pitch joint, elbow
joint, wrist pitch joint, wrist yaw joint and wrist rotary joint, which are symmetrical and
interchangeable. During operation, one end of the manipulator is fixed on the bracket and the other
end is installed with end effector, which can be used to grasp the target object and realize the motion
with 6 degree of freedom of the end.

Figure 1. Structure of the simulated manipulator

Figure 2. Mock-up manipulator

The original space manipulator has the redundancy design such as double motor and double
transmission for the actuated joints in order to ensure the reliability of in-orbit practice. For the
experiment of simulated manipulator is only conducted on the ground, the joints are designed with
single motor and reducer. Based on the requirements of experiment, the joints are also installed with
the torque sensing device, the component that original space manipulator doesn’t have. As a result, the
internal structure and mass the joint changes greatly. The central controller, end effector and other
components of the simulated manipulator only copy the shape of the prototype without corresponding
functions, making great differences in the parameters such as the mass center of mass.

The mass comparison between components of the original space manipulator and the simulated
manipulator are shown in Table 1. The mass difference of actuated joint is the largest and there are a
lot of joints. In order to ensure that the mass and center of mass of the simulated manipulator are exactly the same as that of the space manipulator, it is necessary to match the mass and center of mass of the joints of the manipulator first.

### Table 1. Mass of each component of the manipulator

| Joint          | Mass/kg | End effector | Central control | Manipulator rod |
|----------------|---------|--------------|-----------------|-----------------|
| Space manipulator | 67.5    | 87.2         | 37.7            | 22.5            |
| Simulated manipulator | 59.2    | 83.5         | 30.7            | 22.5            |

3. **Mass-modeling of the joint**

The joints of the simulated manipulator are shown in figure 3 and is shown in figure 4, which is composed of a box, a servo-driven module and a counterweight module. The box is made of aluminum alloy, with 10mm of wall thickness. The servo-driven module is composed of a motor, a reducer box, a torque sensor and their corresponding connecting parts and a base. In order to ensure the mass and easy adjustment of joints, the counterweight module is designed to be composed of three parts: threaded connecting rod, fan-shaped counterweight and the counterweight with a notch. The center of mass can be adjusted in axial and radial direction. The fixed shaft and the output shaft of the joint are perpendicular to each other, and the motor shaft coincides with the fixed shaft. The origin of the coordinate system ACS0 coincides with the intersection of the fixed axis and the output axis, the Y-axis overlaps with the fixed axis, and the Z-axis overlaps with the output axis.

The total mass of simulated manipulator joint is required to be constant, that is, under the condition that the same weight of the joint after counterbalance and the space manipulator, the center of mass of simulated manipulator is adjusted to be the same as the space manipulator. According to the degree of adjustment of the parts mass, the parts can be divided into three categories: A, B and C. Among them, the quality of Class-A parts cannot be adjusted completely due to the limitation of structure requirements and processing difficulty, including box, bearing assembly and end cap; Class-B parts can be slightly adjusted including torque sensor, reduction box, motor and rear flange, and as the counterweight system, Class-C parts is fully adjustable including balancing weight.

\[
\sum_{i=1}^{\text{OA}_i} \cdot m_i + \sum_{i=1}^{\text{OB}_i} \cdot n_i + \sum_{i=1}^{\text{OC}_i} \cdot m_p = \text{OC}_i \cdot M_i
\]

4. **Analysis of mass-matching of joints**

4.1. **Counterweight Design**

The joint after counterweight should meet the requirement that the position deviation of center of mass is less than 5mm and the mass deviation is less than 1%. In order to ensure the experimental effect, the target mass after the joint counterweight is a constant value, and the total mass of the counterweight should be reduced or increased according to the quality of class B parts. According to the joint design, the center of mass of the distribution is set as follows: \(x, y \in [-165, 165], z \in [-249, 165]\)

According to Formula 1, the center of mass of the counterweight can be calculated as:
Since the length in the Z direction is beyond the joint size, mass matching cannot be completed, so weight reduction is needed for the B part. According to formula 1, after subtracting 1.5kg from the large flange at the output end, 0.5kg from the torque sensor seat and 0.5kg from the fixed seat of the reduction box, the desired position of the center of mass of the counterweight can be obtained:

\[ \overline{OC}_p(5.18, 65.51, -221.90) \]  

### 4.2. Research on design and modeling of counterweight

According to the requirements, 8 threaded connecting rods are arranged on the circumference of one end of the actuated joint, and numbered as 1, 2...8 counterclockwise. Through calculation, the counterweight is installed on the corresponding connecting rod, the mass and center of mass of the joint can be adjusted to make it consistent with the original joint. The balancing weight is designed in two forms: the first is the fan-shaped balancing weight with large mass, which is fixed on two connecting rods at the same time. It mainly adjusts the axial position of the center of mass of the driving joint, and roughly adjusts the radial position. The second is a circular counterweight with a notch, which is fixed on a connecting rod, with various specifications such as 1kg, 0.5kg, etc., mainly for precise adjustment of the position of the center of mass. The mass characteristics of the two counterweight and their influence on the center of mass of the actuated joint are discussed.

#### 4.2.1. Modeling of sector counterweight

The size parameters of the counterweight are shown in Figure 5, where the adjustable values are R1, R2, vertex angle2α and thickness.

With a large mass, the fan-shaped counterweight is installed on two or more threaded connecting rods to make rough adjustment to the position of the center of mass. The relationship between the center of mass yw1 of the counterweight and the major diameter R1, the minor diameter R2 and the vertex angle2α can be calculated according to Formula 4.

\[ y_{w1} = \frac{\int ydm}{m} = \int (\int (r \cos \theta) dr \cdot rd\theta) = \frac{2}{3} \frac{R_1^3 - R_2^3}{R_1^3 - R_2^3} \sin \alpha \]  

Considering the size constraint of joint structure, the range of large diameter and small diameter of the counterweight has certain requirements, R1 ∈ [130mm, 170mm] and R2 ∈ [50mm, 120mm]. When the vertex angle2α is 180°, 210° and 240°, respectively, the center of mass yw1 of the counterweight changes with major diameter R1 and minor diameter R2, as shown in figure 6.

![Figure 5. Parameters of the fan-shaped counterweight](image)

![Figure 6. Effects of barycenter of the counterweight caused by fan-shaped counterweight](image)

#### 4.2.2. Modeling of circular counterweight with a notch

The counterweight is the cut-off part of the circle. During the counterweight, it is installed on a threaded connecting rod. The mounting angle of the counterweight can be adjusted, as shown is shown in figure 7, to slightly adjust the position of the radial center of mass.
The counterweight has a variety of specifications such as 1kg, 0.5kg, 0.3kg, etc. An example of its installation on the No.1 connecting rod is as follows and analyzed. The 1 kg of the counterweight is temporarily taken. After the installation of the counterweight, the position of the joint center of mass is calculated by Formula 5.

\[
x_c = \frac{(M_2 \times X_2 + m(r \sin 22.5^\circ + y_{n1} \sin \theta))}{(M_2 + m)}
\]
\[
y_c = \frac{(M_2 \times Y_2 + m(r \cos 22.5^\circ + y_{n1} \cos \theta))}{(M_2 + m)}
\]

(5)

Since there is a big difference between the mass of the counter weight and the mass of the joint, changing the mounting angle has little influence on the position adjustment of the center of mass, which is only 0.5mm.

Let \(a_1, a_2, ..., a_8\) be the weights of the notch of counterweight on the eight connecting rods, \(\Theta_1, \Theta_2, ..., \Theta_8\) be the angles of counterweights with notches, which meets formula 6.

\[
(m_1 \cdot y_1 + (a_1 \cdot a_8)) / M_p \rightarrow Y_p = M_2 + m_1 + a_1 + \cdots + a_8 \rightarrow M_4
\]

(6)

In order to simplify the calculation, a circular counterweight is introduced with specifications of 1 kg, 0.5 kg, 0.3 kg, etc. For the counterweight, the center of mass is adjusted to the approximate position with the circular counterweight, and then the corresponding circular counterweight is replaced with one with a notch. Finally, the installation angle is adjusted. Before counterweight, the mass of the joint is \(M_2\), and the mass of counterweight is \(m_2\). The position of the center of mass in the x direction satisfies formula 7.

\[
\frac{x \times M_2 + 125 m_2 \sin 22.5^\circ}{M_2 + m_2} = \frac{x}{1 + \frac{m_2}{M_2}} + \frac{125 \sin 22.5^\circ}{M_2 + 1}
\]

\[
\approx x + \frac{125 \sin 22.5^\circ}{M_2}
\]

(7)

The influence curve of the total joint mass \(M\) on the offset of the weight to the center of mass \(\Delta x\) is shown in Figure 8.
4.3. Calculation of counterweight position

In the middle of counterbalance, the radial error is considered before adjusting the axial position of the counterweight. According to formula 4, the shape of the fan-shaped counterweight is determined to roughly adjust the position of the center of mass of the joint. Then the size and position of the circular counterweight is selected according to Table 2, the circular counterweight is replaced with a counterweight with a notch of the same mass to adjust the mounting angle of the counterweight and slightly adjust the position of the joint center of mass. The projection distance \( l \) between the center of mass of the required weight and the origin of coordinates of ACS0 plane is calculated by formula 8.

\[
I = \sqrt{x_p^2 + y_p^2} = 65.71\text{mm} \tag{8}
\]

Let the position of the center of mass of the fan-shaped counterweight and the required counterweight be equal, and then solve the major diameter \( R_1 \), minor diameter \( R_2 \) and vertex angle \( 2\alpha \). As shown in Figure 9, the intersection line is the solution meeting the requirements.

![Figure 9. Parameters selection of the fan-shaped counterweight](image)

Through computer simulation, the coordinates of the center of mass after the counterweight are: \( X_3 = 0.40 \), \( Y_3 = 6.30 \), and \( Z_3 = 28.20 \), which meet the requirements of the position deviation of the center of mass less than 5 mm and the mass deviation less than 1%.

| Table 2. Mass parameters of the space manipulator and the simulated manipulator |
|-----------------------------------------------|-----------------------------------------------|
| **Joint of Space Manipulator**                 | **Joint of Simulated Manipulator (After counterweight)** |
| Mass/kg                                       | \( M_1 = 67.50 \)                                | \( M_1 = 67.50 \)                                |
| barycentric coordinate                        | \( X_3 = 0.40 \)                                 | \( X_3 = 0.37 \)                                 |
|                                              | \( Y_3 = 6.30 \)                                 | \( Y_3 = 6.24 \)                                 |
|                                              | \( Z_3 = 28.20 \)                                | \( Z_3 = 28.20 \)                                |
5. Simulation and experiment

5.1. Simulation of equivalence optimized analysis
By the method described in the previous section, the centroid parameters of the actuated joint after weight optimization can be simulated and calculated. All the deviation values of the center of mass position are less than 5 mm.

5.2. Experiment
Based on the results of previous simulation calculation, the centroid platform SZX-10 was used for testing, and the testing fixture was a coordinate measuring machine. The coordinate measuring machine is fixed on the center of mass, and the balanced actuated joint is installed on the coordinate machine through the tooling. The overall center of gravity was measured by placing the activity platform of the coordinate measuring machine horizontally and at an incline of 45°, and the centroid positions of the joints in three directions were obtained. The position of the center of mass is similar to the conclusion derived from the theory and can meet the requirements that the position of the center of mass is less than 5 mm and the mass deviation is less than 1%.

6. Conclusion
In this paper, the equivalence study of the centroid is made by establishing a simulation model of the space manipulator. On the premise of ensuring constant mass, a joint counterweight scheme is designed to adjust the radial and axial centroid of the joint. And two types of counterweights, namely, fan-shaped and with a notch, are used together to ensure that the results meet the requirements of the index and the process of counterweight is simplified.

It can realize the similarity between the mass and the center of mass of the actuated joint of simulated manipulator and that of the space manipulator, effectively ensuring the feasibility of the ground zero gravity system experiment. This method can be applied to the development of the ground centroid equivalent experimental device which requires constant mass in aerospace field.

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