

Characteristic Analysis of the Gravity Unloading Device for the Satellite Simulation Experiment

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Abstract: *With the growing complexity of space station missions, space manipulators play an increasingly important role in extravehicular operations. However, the microgravity environment imposes stringent requirements on ground verification tests, making accurate gravity unloading simulation a critical challenge. This paper proposes a theoretical design method for a gravity unloading system based on an equivalent end-stiffness mechanism for space manipulator ground testing. The manipulator topology is analyzed, and force and stiffness models including end air buoyancy are established. The effects of end air buoyancy, air-bearing spring stiffness, and unloading-position scale parameters on the unloading rate are investigated. In addition, the design principles of the ground test system are discussed, with emphasis on the consistency criterion between ground tests and space missions. The test process is optimized using an orthogonal test method to obtain comprehensive performance parameters through limited experiments while ensuring verification reliability and protecting key components. The results determine the feasible range of unloading positions and provide theoretical and engineering guidance for the structural design of manipulator unloading devices and the preliminary selection of test parameters. Future work should further improve gravity unloading efficiency and real-time monitoring accuracy over the manipulator's full workspace.*

Keywords: Space manipulator, Microgravity simulation, Ground verification test, Gravity unloading, Air flotation, Space-ground consistency.

1. Introduction

With the rapid development of aerospace technology, space manipulators have been widely applied in on-orbit servicing tasks such as space station maintenance, sample capture, and space debris removal, and have become a major research focus in the aerospace field [1–3]. Ground verification testing is a crucial step in manipulator development because it directly affects the reliability of on-orbit operations. Since space manipulators work in a microgravity environment, ground tests must satisfy the criterion of space-ground consistency to accurately evaluate motion accuracy, load capacity, and control stability. Meanwhile, because key manipulator components have limited service life, efficient test design is required to obtain sufficient performance data with a limited number of experiments [4–7].

A major challenge in ground verification is the accurate simulation of microgravity, particularly the design of an effective gravity unloading system. Existing low-gravity simulation methods mainly include air flotation, buoyancy, and suspension methods [8–10]. Among them, the air flotation method is widely used because of its high simulation accuracy and reusability. Previous studies have reported substantial progress in gravity unloading system design and test platform development [11–16]. However, due to the special structural and functional characteristics of space manipulators, existing methods cannot fully meet their testing requirements. In particular, manipulators require efficient gravity unloading over the entire workspace while maintaining real-time monitoring and precise control of test parameters [17–23].

To address these issues, this paper proposes a theoretical design method for a gravity unloading system based on the equivalent end stiffness of the mechanism, taking a manipulator demonstration platform on the space station as

the research object. The manipulator topology is analyzed, and force and stiffness models including end air buoyancy are established. The effects of end air buoyancy, air-bearing spring stiffness, and unloading-position scale parameters on unloading rate are investigated, and a feasible design range is obtained. Ground experiments are finally conducted to verify the effectiveness of the proposed method.

2. Device Structure

A space manipulator demonstration bench (hereinafter referred to as the manipulator) is a space 2-degree-of-freedom serial manipulator, which adopts the basic form of fixing the constraint end and releasing the end degree of freedom. The main components include a fixed base, a rotating joint 1, a rotating joint 2, a cantilever 1, a cantilever 2, and an end mechanical claw. It has significant structural characteristics such as light weight, long cantilever, and large aspect ratio. Therefore, it is difficult to guarantee the accuracy of the end pose and the output of the grasping force.

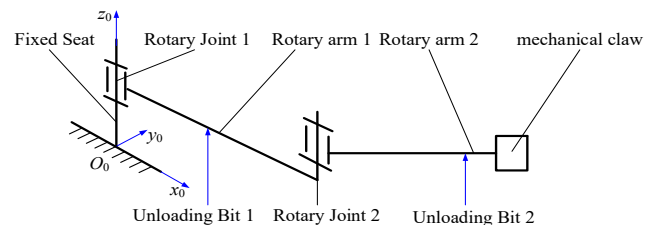


Figure 1: Mechanism diagram of the space manipulator demonstration bench

The topological relationship of the manipulator can be simplified as follows: joint 1 is fixed to the fixed base, and cantilever 1 is connected to the fixed base through joint 1 to form a revolute joint; cantilever 1 is connected to cantilever 2 through joint 2 to form a revolute pair. The end of cantilever 2 is equipped with a manipulator claw. The local degree of freedom of the manipulator claw can be set according to

different grasping design requirements, generally 3. The manipulator mechanism diagram is shown in Figure 1, in which the fixed coordinate system $O_0-X_0Y_0Z_0$ is fixedly connected to the base.

3. Static Analyses

Because the microgravity simulation device can realize each joint's separate movement and the joint's angular velocity is minimal, it can be considered a quasi-static process. The fully deployed manipulator is one of the most extreme working conditions, so this section will first analyze its stress state, as shown in Figure 2. In addition, the fully deployed manipulator can be considered a cantilever beam when examining the unloading characteristics in the vertical direction.

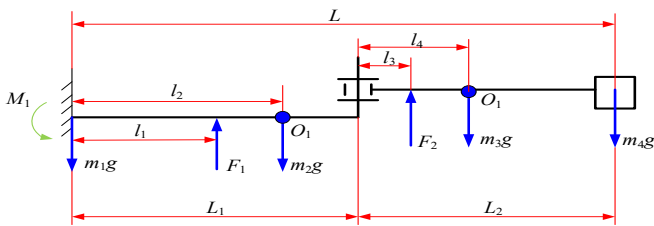


Figure 2: Manipulator arm stress state

The mass is distributed by joint mass substitution, that is, the mass of joint 2 is evenly distributed to cantilever 1 and cantilever 2.

4. Stiffness Modelling

Combined with the manipulator's structural characteristics, the mapping relationship between the end stiffness and the load is studied, and the deflection and rotation angle models of the manipulator at each position under the condition of double support are established. On this basis, the effect of the end air buoyancy is discussed.

4.1 Neglected the End Air Buoyancy

4.1.1 Deflection and rotation angle of cantilever 1

To distribute the joint mass, the cantilever 1 can be regarded as a cantilever beam with equal section. Using the superposition method, it can be seen that the total deformation of the beam can be regarded as the superposition result of the combined action of the cantilever 1 support force F_1 and the cantilever 1-joint 2 equivalent gravity m_2g . Among them, l_1 represents the unloading position of cantilever 1.

4.1.2 Deflection and rotation angle of cantilever 2

The concentrated support force F_2 , the end load gravity m_4g , and the cantilever 2 gravity joint 2 equivalent gravity m_3g cause the maximum deformation of the beam.

4.1.3 The overall deflection and rotation angle of the manipulator

Since cantilevers 1 and 2 are rotating pairs around the Z_0 axis, the degrees of freedom in other directions are constrained. Therefore, the entire manipulator can be simplified as a

cantilever beam, as shown in Figure 3.

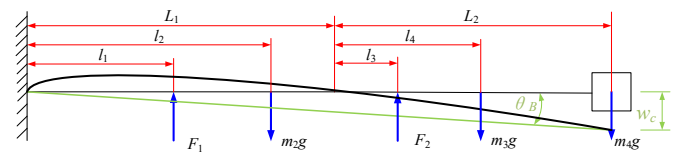


Figure 3: The deformation of the manipulator under the force $F_1, F_2, m_{11}g, m_4g$

The maximum deformation of the beam is caused by the concentrated cantilever 1 support force F_1 , the cantilever 1 gravity joint 2 equivalent gravity m_2g , the concentrated support force F_2 , the cantilever 2 gravity joint 2 equivalent gravity m_3g , and the end load gravity m_4g .

4.2 Incorporating the Terminal Air Buoyancy

According to the design requirements, the rotation angle of the mechanical claw around the y-axis in the actual ground test should be strictly controlled within 0.01° . In fact, it is difficult to achieve the working accuracy of the mechanical claw by simply relying on the force constraint of the manipulator unloading device. The method of adding a suspended balloon at the end is often used, and the buoyancy value of the balloon is only measured by experiment.

Therefore, this section intends to carry out the theoretical modeling of the terminal air buoyancy. Based on the analysis of the manipulator's structure and stress state, an air buoyancy F_3 is added at the end of the manipulator.

4.3 Unloading Rates

The unloading rate is an important index to judge whether the unloading position is reasonable. The gravity unloading device is equipped with a preset stiffness spring. When the flexible deformation of the manipulator occurs, the spring in the vertical direction will produce a certain amount of compression. Therefore, to facilitate the selection of spring stiffness in engineering, considering the influence of spring stiffness k , the unloading rate of cantilever 1 and cantilever 2 is analyzed, the rationality of the unloading point position is judged.

5. Parameter Sensitivity

Sensitivity analysis is one direct way of quickly determining the sensitivity of performance indicators to various scales and structural parameters. The differential method establishes the sensitivity expression of the manipulator's rotation angle and deflection to each parameter.

6. Conclusions

Combined with the space manipulator's design requirements, the end actuator's stiffness equivalent model is established in this study. The parametric analysis method reveals the mapping relationship between the key scale parameters and the end grasping force, and the sensitive parameters that have a dominant influence on the end stiffness are identified. The main research conclusions can be summarized as follows:

- 1) Considering the influence of the unloading position on the

rotation angle of the manipulator, the optimal design interval of the unloading position is determined to be $l_1=0.47\sim 0.60L_1$ and $l_3=0.71\sim 0.86L_2$. Within this parameter range, the theoretical attitude angle deviation of the end effector can be controlled within the technical requirements to meet the high-precision operation requirements.

2) Quantitative analysis shows that the unloading position parameters have the opposite regulation effect on the unloading rate of the cantilever system: the unloading rate of cantilever 1 is positively correlated with the unloading position, while that of cantilever 2 is negatively correlated, and the influence intensity of the two is similar, but the introductory unloading rate of cantilever 2 is lower than that of cantilever 1; it is worth noting that within the design range of spring stiffness k , the contribution rate of stiffness change to the unloading rate of the system is only 0.5 %, which can be regarded as a secondary influencing factor.

3) Air buoyancy is an important performance parameter affecting the unloading rate, which has a significant linear positive correlation with the theoretical unloading rate. For the manipulator configuration designed in this study, the optimal working range of air buoyancy is determined to be 0.5-1.5N by parameter optimization analysis, which can meet the requirements of maximizing the unloading efficiency in this range.

References

- [1] Xu W, Liang B, Xu Y. Survey of modeling, planning, and ground verification of space robotic systems[J]. *Acta Astronautica*, 2011, 68(11-12): 1629-1649.
- [2] Rybus T, Seweryn K, Oles J, et al. Application of a planar air-bearing microgravity simulator for demonstration of operations required for an orbital capture with a manipulator[J]. *Acta Astronautica*, 2019, 155: 211-229.
- [3] Prado J, Bisiacchi G, Reyes L, et al. Three-axis air-bearing based platform for small satellite attitude determination and control simulation[J]. *Journal of Applied Research and Technology*, 2005, 3(3): 222-237.
- [4] Carignan C R, Akin D L. The reaction stabilization of on-orbit robots[J]. *IEEE Control Systems Magazine*, 2000, 20(6): 19-33.
- [5] Deng Z, Liu Z, Gao H, et al. An approach for gravity compensation of planetary rovers[A]. In: 2010 3rd International Symposium on Systems and Control in Aeronautics and Astronautics[C]. Harbin, China: IEEE, 2010: 1053-1058.
- [6] Wei Y, Yang X, Xu Z, et al. Novel ground microgravity experiment system for a spacecraft-manipulator system based on suspension and air-bearing[J]. *Aerospace Science and Technology*, 2023, 141: 108587.
- [7] Jiang Z, Liu S, Li H, et al. Mechanism design and system control for humanoid space robot movement using a simple gravity-compensation system[J]. *International Journal of Advanced Robotic Systems*, 2013, 10(11): 389.
- [8] Sui Y, Sun H N, Huang W, et al. Design of a gravity compensation system for landing preview of a Mars lander[J]. *Journal of Tsinghua University (Natural Science)*, 2023, 63(3): 406-413.
- [9] Yang Q L, Yan Z H, Ren S Z, et al. Research on gravity unloading for ground deployment of a large deployable flexible solar wing driven by a sleeve[J]. *Manned Spaceflight*, 2017, 23(4): 536-545.
- [10] Yang G Y, Wang H G, Jiang Y, et al. Analysis of gravity unloading accuracy of an air-bearing test rig[J]. *Journal of Mechanical Engineering*, 2019, 55(5): 1-10.
- [11] Hu T Y, Lei H M, Wang H W, et al. Design and validation of a ground microgravity test program for a large space deployable arm[J]. *Spacecraft Engineering*, 2022, 31(4): 143-148.
- [12] Zhang J B, Wang H, Li Y, et al. Gravity unloading technology of a solar wing based on vacuum negative-pressure adsorption[J]. *Journal of Mechanical Engineering*, 2020, 56(5): 202-210.
- [13] Lu B, Tao G L, Liu H, Zhong W. Modeling and constant-pressure control of a pneumatic suspension system for zero-gravity simulation[J]. *Journal of Zhejiang University (Engineering Science)*, 2010, 44(2): 379-385.
- [14] Lin P Y, Shieh W B, Chen D Z. A theoretical study of weight-balanced mechanisms for design of spring assistive mobile arm support (MAS)[J]. *Mechanism and Machine Theory*, 2013, 61: 156-167.
- [15] Xu Z G, Wei Y Q, Lu H, et al. Ground microgravity experimental system for a spacecraft-manipulator based on suspension and air flotation[J]. *Journal of Mechanical Engineering*, 2025, 61(4): 1-11.
- [16] Gao C Q. Research on the design and control of a space truss deployable metamorphic grasping manipulator[D]. Harbin: Harbin Institute of Technology, 2023.
- [17] Guo J Q. Research on a suspended microgravity simulation system for aerospace electric tools[D]. Harbin: Harbin Institute of Technology, 2022.
- [18] Huang Y Z. Air-floating and balloon-type microgravity deployment simulation of a space deployable mechanism[D]. Harbin: Harbin Institute of Technology, 2021.
- [19] Tian D K, Fan X D, Zheng X J, et al. Current status and prospects of microgravity environment simulation for space deployable antennas[J]. *Journal of Mechanical Engineering*, 2021, 57(3): 11-25.
- [20] Moran-Armenta M, Montoya-Chairez J, Rossomando G F, et al. Neural networks meet PID control: Revolutionizing manipulator regulation with gravitational compensation[J]. *IFAC Journal of Systems and Control*, 2025, 32: 100306.
- [21] Ma Z, Li D X, Chee R K W, et al. Author Correction: Mechanical unloading of engineered human meniscus models under simulated microgravity: A transcriptomic study[J]. *Scientific Data*, 2024, 11(1): 1109.
- [22] Zhao L, Li Z, Shi Y, et al. Motion control for a multi-DOF pneumatic manipulator via angle deflection gravity compensation[J]. *Nonlinear Dynamics*, 2024, 112(18): 16257-16275.
- [23] Zhu H, Qin J, Zhu Q, et al. The angular momentum unloading of the asymmetric GEO satellite by using electric propulsion with a mechanical arm[J]. *Aerospace*, 2024, 11(4): 290.

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