

# Analysis of Zero-Gravity Unloading Positions for 2-DOF Space Manipulators

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**Abstract:** *The gravity unloading mechanism using the air flotation method is a device that supports aerospace equipment by ejecting high-pressure gas from the bottom air foot to counteract most or all of the gravity in aerospace simulations. Due to the structural characteristics of the aviation manipulator, such as a large length-to-diameter ratio, light weight, and long cantilever, the unloading position is a critical factor affecting the unloading rate under the influence of gravity. Therefore, using a manipulator demonstration platform as the research object, the multi-objective optimization of the manipulator's unloading position is conducted. The rigid deformation of the manipulator serves as the optimization objective. Meanwhile, the additional bending moment, rotation angle, bending stress, and interference issues between the manipulator and other equipment are considered constraints for multi-objective optimization. The optimal unloading position is determined by comparing two different algorithms. The strain simulation of the manipulator under the optimal unloading position is to analyze the deformation of the end of the manipulator.*

**Keywords:** Space manipulator, Multi-objective optimization, Unloading position, Unloading rate.

## 1. Introduction

Space and interstellar exploration technology have been rapidly developing for the past two decades. Space stations and satellite systems are established by several countries in low Earth orbit, which are capable of conducting various scientific research tasks. Currently, astronauts mainly perform extravehicular activities such as external maintenance, sample collection, module docking, and special experiments. However, Huge challenges, such as insufficient air, low temperature, space debris, unpredictable radiation, and random impacts by meteorites, present engineering difficulties, resulting in maintenance issues and longer servicing times. Therefore, developing manipulators to assist or replace astronauts in outer space missions can improve safety while increasing efficiency and quality [1-3].

Once the manipulator is developed, it is crucial to conduct ground tests in advance to simulate the microgravity environment of space and thoroughly evaluate its performance. This ensures an accurate understanding of how the manipulator will operate on the space station. Reliable and rapid verification tests are vital for guaranteeing smooth functioning in space. At the same time, since some key components have limited service life, it is necessary to minimize unnecessary ground tests to prolong the satellite's lifespan after launch. Therefore, performing dependable and quick ground verification tests is an essential technology for maintaining the manipulator's proper operation in the space station [4-7].

In response to the insufficiency of the current studies and practical engineering requirements, this paper presents an optimization approach for the unloading force analysis in the ground test of a space manipulator. The method specifically features both the structural properties and flexibility of the

links. The remainder of this paper is organized as follows. Section 2 provides a brief introduction to the structure and working principles. In section 3, the objective functions related to the unloading and are confirmed, two algorithms are used to solve the optimization model to partially verify the effectiveness. This enables the optimization model to be implemented by tiny deflection superposition principle, in turn allowing for the analysis of vibration characteristics, in turn allowing for the analysis of gravity unloading rate and position. Section 4 simulates the static characteristics and verifies the proposed optimization model by FEM tool to determine its maximum deformation and equivalent stress. Conclusions are drawn in section 5.

## 2. Structure and Working Principle

A space manipulator demonstration bench (hereinafter referred to as the manipulator) is a space 2-degree-of-freedom serial manipulator with 3 DOFs in the end, whose structure is shown in Figure 1. The entire manipulator is composed of the shoulder, elbow, and wrist, and its primary components include: shoulder joints 1, 3, and 4; elbow joint 2; and wrist joints 5 and 6. All six joints are rotary joints.

The section connecting the shoulder to the elbow is link 1, while the section connecting the elbow to the wrist is link 2. The manipulator exhibits structural characteristics as follows, including a lightweight design, long cantilevers, and a high length-to-diameter ratio. Consequently, it is challenging to precisely guarantee both the end-effector's posture accuracy and the magnitude of its gripping force output.

## 3. Optimization Function

The above objective function and constraint conditions are combined to create the final optimization model as follows.

$$\min\left(a_1 w_c, a_2 \frac{1}{\eta}\right) = a_1 w_c + a_2 \frac{1}{\eta}$$

$$300\text{mm} \leq l_1 \leq 1090\text{mm}$$

$$200\text{mm} \leq l_3 \leq 1140\text{mm}$$

$$-45N \cdot m \leq -(m_1 + m_2)gl_1 + m_2gl_2 + m_4gL_2 + m_3gl_4 - (m_3 + m_4)gl_3 \leq 45N \cdot m$$

$$-25N \cdot m \leq m_4gL_2 + m_3gl_4 - (m_3 + m_4)gl_3 \leq 25N \cdot m$$

$$0 \leq \frac{32[-(m_1+m_2)gl_1+m_2gl_2+m_4gL_2+m_3gl_4-(m_3+m_4)gl_3]}{\pi d^3(1-\alpha^4)} \leq 60\text{Mpa}$$

$$0 \leq \frac{M_2}{W} = \frac{32[m_4gL_2+m_3gl_4-(m_3+m_4)gl_3]}{\pi d^3(1-\alpha^4)} \leq 60\text{Mpa}$$

$$-1.745 \times 10^{-3}\text{rad} \leq \frac{F_1 l_1^2}{2EI} - \frac{m_2 g l_2^2}{2EI} \leq 1.745 \times 10^{-3}\text{rad}$$

$$-1.745 \times 10^{-3}\text{rad} \leq \frac{F_2 l_3^2}{2EI} - \frac{m_3 g l_4^2}{2EI} - \frac{m_4 g L_2^2}{2EI} \leq 1.745 \times 10^{-3}\text{rad}$$

$$F_3 \geq 0, l_1 \geq 0, l_3 \geq 0, d \geq 0, k \geq 0$$

#### 4. Theoretical Optimal Solution

The common multi-objective optimization method (achieved by Matlab fmincon) uses the interior point method to solve the constrained optimization problem, which allows nonlinear constrained optimization problems to be solved quickly and efficiently. NSGA-II is a widely used method for solving multi-objective optimization problems in mechanical engineering fields. These two methods are used to employ the analysis.

For the selection of the range of air buoyancy, the resistance in the manipulator movement will increase as the balloon volume, which is influenced by the air buoyancy. Therefore, a moderate numerical range is selected.

##### 4.3 Verification

###### 1) Common optimization method

The deformation of the manipulator without and with adding the air buoyancy. The maximum deformation occurs surely at the end of the manipulator, measuring 5.29 mm without air buoyancy, and reduces to 5.11 mm when adding the air buoyancy. The results indicate that the maximum deformation still occurs at the right end, and adding air buoyancy decreases the deformation at the end of the manipulator and enhances the working accuracy.

The relationship between  $l_1$ ,  $l_3$ , and the manipulator's deflection can be thoroughly analyzed. The two unloading positions identified by MATLAB are identical. The deflection of the manipulator is 4.3 mm when the air buoyancy is loaded and 5.2 mm when the air buoyancy is not loaded.

###### 2) NSGA-II optimization method

The deformation of the manipulator with and without considering the air buoyancy. The deformation maximum occurs surely at the end of the manipulator, about 5.29mm without air buoyancy, and 5.10mm when adding the air buoyancy. The results indicate that the maximum deformation still occurs at the right end, and adding air buoyancy decreases the deformation at the end of the manipulator and enhances

the working accuracy.

The relationship between  $l_1$ ,  $l_3$ , and the manipulator's deflection is thoroughly examined. When the two unloading positions determined by NSGA-II are identical, the deflection of the manipulator is 4.7mm when the air buoyancy is loaded and 5.6mm when the air buoyancy is not loaded.

#### 5. Conclusions

1) The optimization results are  $l_1=800.2\text{mm}$ ,  $l_2=907.4\text{mm}$ ,  $F_3=1.5\text{N}$ , and  $l_1=822.6\text{mm}$ ,  $l_2=862.3\text{mm}$ ,  $F_3=1.6\text{N}$ , respectively, by the two algorithms. While the crucial dimensions need to be rounded to  $l_1=800\text{mm}$ ,  $l_2=907\text{mm}$ ,  $F_3=1.5\text{N}$ , and  $l_1=820\text{mm}$ ,  $l_2=860\text{mm}$ ,  $F_3=1.6\text{N}$ . The FEM simulation results by common optimization show that the maximum deformation of the manipulator is 5.1mm, and the air buoyancy is 1.5N. The results by the NSGA-II algorithm indicate that the maximum deformation is 5.1mm, and the air buoyancy is 1.6N.

2) The relative errors in rotation angle and deflection are analyzed under two modeling conditions: with and without air buoyancy effects. Using the conventional optimization approach, the relative error in rotation angle was approximately -15%, with a deflection error of -2% when air buoyancy was loaded. When air buoyancy was included, the rotation angle error reduced to -10%, but the deflection error increased significantly to -16%. In contrast, the NSGA-II algorithm yielded a rotation angle error of 16% and a deflection error of -6% without air buoyancy. When air buoyancy was considered, both errors decreased substantially, with the rotation angle error at 11% and the deflection error at -8%.

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