Journal of Intelligent Systems and Control
https://www.acadlore.com/journals/JISC

# Automatic Leveling Algorithm for a Three-Degree-of-Freedom Air-Floating Platform with Uncertain Inertia

Qingtao Hou[1], Xuexu Yuan[2], Junwei Zhao[2*], Yuanyuan Zhang[2*], Hanyu Gao[3], Xiaowei Fu[2]

[1] Jinan Chaofeng Intelligent Technology Co. Ltd., 250140 Shandong, China
[2] North China Institute of Science and Technology, 101601 Beijing, China
[3] Sanhe Chenhao Geological Exploration Technology Service Co. Ltd., 065201 Beijing, China

[*] Correspondence: Junwei Zhao (shower@yeah.net); Yuanyuan Zhang (zhangyuanyuan@ncist.edu.cn)

**Received:** 10-21-2024 **Revised:** 12-03-2024 **Accepted:** 12-12-2024

**Citation:** Q. T. Hou, X. X. Yuan, J. W. Zhao, Y. Y. Zhang, H. Y. Gao, and X. W. Fu, "Automatic leveling algorithm for a three-degree-of-freedom air-floating platform with uncertain inertia," *J. Intell Syst. Control*, vol. 3, no. 4, pp. 201–212, 2024. https://doi.org/10.56578/jisc030401.



**Abstract:** A three-degree-of-freedom air-floating simulation platform is commonly used for attitude maneuver simulation and control system design. To reduce the impact of gravity on the air-floating platform, adjustments must be made to the platform's center of mass so that it coincides as closely as possible with the center of rotation (CR). For larger three-degree-of-freedom platforms, it is often different to easily obtain the moment of inertia, which presents challenges for automatic leveling. In response to this issue, an automatic leveling method was proposed in this study. This method utilizes attitude and angular velocity information, and during the leveling process, only a linear motion mechanism is required to drive a mass block for adjustment. An analysis of the uncertainties present in the model was conducted, and the uncertainties in the system were processed separately. Adaptive control techniques were then applied to design the control method. The stability of the system was demonstrated through the Lyapunov stability theorem. Finally, the algorithm was tested on a three-degree-of-freedom air-floating platform. The experimental results showed that the proposed method can achieve rapid and effective leveling of the platform.

**Keywords:** Uncertain moment of inertia; Automatic leveling; Adaptive control; Three-degree-of-freedom air-floating platform; Nonlinear control

## 1 Introduction

The development of the aerospace industry has raised higher demands for experimental simulations of microgravity, low-damping environments, and other space-related conditions on the ground. Due to the difficulties associated with testing and reconstructing spacecraft in space, ground-based simulation and testing of spacecraft are particularly critical. Many countries have established air-floating platforms equipped for full physical satellite simulation experiments [1]. These ground-based physical simulation platforms primarily use air-floating systems to replicate the microgravity and low-damping conditions found in space. The three-degree-of-freedom air-floating platform, utilizing air bearing, can achieve rotational motion in three degrees of freedom, allowing for simulations of three-degree-of-freedom attitude dynamics and control. To strictly simulate the microfriction and microgravity environment during ground testing, external disturbance torques must be minimized, with gravity's influence on the air-floating platform being the most significant obstacle [2]. To reduce the effects of gravity as much as possible, it is essential to minimize the distance between the platform's center of mass and its CR. The adjustment of the center of mass can be observed by examining its oscillatory motion. By moving the leveling mass block, the oscillation period can be increased [3]. However, this method has the drawback of requiring extensive experimentation, and the rotational angle of the three-degree-of-freedom platform is limited, making practical application difficult. Manual leveling has been studied by Peck et al. [4] and Romano and Agrawal [5], but this approach still results in time inefficiencies and significant adjustment errors.

In practical applications, the addition or replacement of loads on the air-floating platform can have a significant impact on its center of mass. Even a period of inactivity or minor changes in the platform can cause considerable shifts in the center of mass. Relying on manual leveling methods in such cases becomes a time-consuming and labor-intensive task. Given this background, the design of an automatic center of mass leveling system for the air-floating platform becomes crucial. In recent years, many three-degree-of-freedom satellite simulation platforms have been equipped with automatic leveling systems [6–9]. Several studies [10–12] have examined automatic leveling systems based on the least squares method. However, the disadvantage of this approach is that multiple adjustments are required to obtain relatively accurate results. Kim and Agrawal [13] proposed an adaptive automatic leveling method based on the least squares method. This method uses adaptive control to move the mass block for adjusting the center of mass position. While this method addresses the repeated adjustment issue, the maximum disturbance torque after leveling can reach 0.142 Nm, and the results remain suboptimal. Chesi et al. [14] designed an automatic leveling algorithm based on nonlinear adaptive control theory. This method was verified on a CubeSat, and the final results maintained the center of mass deviation within 1.5 mm. Domestically, a finite element model has been established for the air-floating platform, estimating the center of mass position by measuring the rotational speed of the platform. However, no automatic leveling solution has been proposed [15]. The center of mass has been estimated using dynamic inversion and complex pendulum methods, followed by manual leveling of the platform [16, 17]. Automatic leveling has been achieved by modeling and estimating the disturbance torque and combining it with a linear motion mechanism [18–20].

Currently, the leveling methods for three-degree-of-freedom air-floating platforms can be divided into two main categories. The first category assumes that the platform's moment of inertia is known, and automatic leveling is performed accordingly [14]. For air-floating platforms with small moments of inertia, the primary moment of inertia can be measured accurately, and the impact of the inertia product on the system can be neglected. However, for platforms with larger moments of inertia, measuring the moment of inertia becomes more challenging. This method is less practical for air-floating platforms with large moments of inertia. The second category involves estimating the moment of inertia of the platform using the least squares method [13]. This method is more suitable for platforms with large moments of inertia, but it suffers from significant estimation errors, which considerably affect the accuracy of the automatic leveling. In addition to the aforementioned issues, during the actual operation of the three-degree-of-freedom air-floating platform, changes in the platform's load can have a significant impact on the moment of inertia. Therefore, to further improve the accuracy of the automatic leveling for three-degree-of-freedom air-floating platforms, the uncertainty in the platform's moment of inertia must be taken into account.

This study focuses on a three-degree-of-freedom air-floating satellite simulation platform, which has a total mass of approximately 120 kg and is equipped with a cold gas thruster system. Its moment of inertia and mass have not been precisely measured. The platform is equipped with a linear motion mechanism on each of its three principal axes of inertia, which drives a mass block to move along the principal axis directions in order to adjust the platform's center of mass. Based on adaptive feedback control technology, the automatic leveling method proposed in this study was designed to achieve high-precision adjustment of the platform's center of mass under conditions of uncertainty in the platform's moment of inertia.

## 2 Mathematical Model of the Automatic Leveling System

### 2.1 Principle of Automatic Leveling

The automatic leveling system designed in this study consists of three mass blocks, each driven by a stepper motor, arranged along the principal inertia axes of the air-floating platform. It is assumed that the platform's body-fixed coordinate system's principal axis is aligned with the direction of the primary moment of inertia, with the origin of the coordinate system located at the CR of the air-floating platform, as shown in Figure 1. The vector $r_{off}$ represents the displacement of the center of mass relative to the CR. The goal of the automatic leveling mechanism is to adjust the position of the mass blocks in order to reposition the center of mass, bringing it as close as possible to the CR. The advantage of this system is that it achieves the leveling of the platform's center of mass without the need for additional actuators.

### 2.2 Kinematic and Dynamic Model of the Air-Floating Platform

The kinematic and dynamic model of the three-degree-of-freedom air-floating platform can be described in the two coordinate systems shown in Figure 1. The inertial coordinate system is represented by $X^i$, $Y^i$, and $Z^i$, while the body-fixed coordinate system is represented by $x^b$, $y^b$, and $z^b$. The deviation angle between the body-fixed coordinate system and the inertial coordinate system defines the relative attitude of the three-degree-of-freedom air-floating platform.

Since the three-degree-of-freedom simulation platform is fixed on the air bearing, only attitude maneuvers can be performed. It is assumed that the linear motion mechanism used to level the center of mass of the platform moves along the principal axis of the inertial coordinate system. The kinematic equation of the platform's attitude can be expressed using quaternions as follows:

$$\dot{q}_0 = -\frac{1}{2}q^T\omega \tag{1}$$

$$\dot{q} = \frac{1}{2}\left(q^{\times} + q_0 I\right)\omega \tag{2}$$

where, $\omega = \begin{bmatrix} \omega_x & \omega_y & \omega_z \end{bmatrix}^T$ denotes the rotation angle velocity of the platform in the body-fixed coordinate system, and $q = \begin{bmatrix} q_0 & q_1 & q_2 & q_3 \end{bmatrix}^T$ is the unit quaternion.

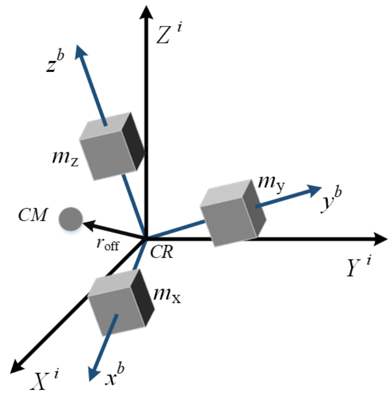


**Figure 1.** Principle and coordinate system of the automatic leveling system

The kinematic equation of the air-floating platform under the influence of gravity can be expressed by the Euler equation as follows:

$$J(\cdot)\dot{\omega} = -\omega^{\times} J(\cdot)\omega + r^{off} \times m_a g^b + \tau_c + T_d(\cdot) \tag{3}$$

where, $m_a$ is the total mass of the air-floating platform, $J(\cdot)$ is the uncertain moment of inertia of the platform, $r^{off}$ is the distance between the platform's center of mass and the CR, $g^b$ is the gravitational vector in the body-fixed coordinate system, $T_d(\cdot)$ is the external disturbance torque, and $\tau_c$ is the torque generated by the automatic leveling system.

To perform leveling of the air-floating platform, the gravitational vector must be transformed into the body-fixed coordinate system as follows:

$$g^b = R_i^b g^i \tag{4}$$

where,

$$R_i^b = \left(q_0^2 - q^T q\right) I + 2qq^T - 2q_0 q^{\times} \tag{5}$$

$$g^i = \begin{bmatrix} 0 & 0 & -9.8 \end{bmatrix}^T \ \mathrm{m/s^2} \tag{6}$$

The objective of this study is to adjust the center of mass of the air-floating platform by manipulating the mass slider on the linear motion mechanism in order to align the center of mass with the CR, thereby counteracting the disturbance torque caused by gravity.

**Assumption 1:** There exist unknown constants $c_J > 0$ and $c_f > 0$ such that the following condition holds: $\|J(\cdot)\| \le c_J < \infty$, and $\left\|\frac{dJ(-)}{dt}\right\| \le c_f < \infty$.

In order to perform the leveling of the air-floating platform's center of mass, it is necessary to first adjust the platform's attitude to an arbitrary orientation before proceeding with the leveling. This is because if the Z-axis coincides with the gravitational direction, leveling along the Z-axis would not be feasible. The desired attitude error is denoted as $(q_{e0}, q_{\theta})$, with the expected attitude represented by $(q_{d0}, q_d)$, where

$$q_{e0} = q_{d0} q_0 + q_d^T q \tag{7}$$

$$q_e = q_{d0} q - q_0 q_d + q^{\times} q_d \tag{8}$$

The rotation matrix is given by:

$$C = \left(q_{e0}^2 - q_e^T q_e\right) I + 2q_e q_e^T - 2q_{e0} q_e^{\times} \tag{9}$$

Thus, the relative angular velocity can be expressed as:

$$\omega_e = \omega - C\omega_d \tag{10}$$

The kinematic and dynamic equations for the attitude error of the air-floating platform can be expressed as:

$$J(\cdot)\dot{\omega}_e = -\omega^{\times} J(\cdot)\omega + r^{off} \times m_a g^b + \tau_c + T_d(\cdot) + J(\cdot)\left(\omega_e^{\times} J(\cdot)\omega_d - C\dot{\omega}_d\right) \tag{11}$$

$$\dot{q}_e = \frac{1}{2}\left(q_e^{\times} + q_{e0}I\right)\omega_e \tag{12}$$

$$\dot{q}_{e0} = -\frac{1}{2}q_e^T\omega_e \tag{13}$$

To derive the control system, the following sliding mode variable can be defined as:

$$s = \omega_e + \beta q_e \tag{14}$$

where, $\beta > 0$. The dynamics equation can be rewritten as:

$$J(\cdot)\dot{s} = \tau_c + \Delta(\cdot) - \beta q_e - 0.5\frac{dJ(\cdot)}{dt}s \tag{15}$$

where,

$$\begin{aligned}\Delta(\cdot) = &-\omega^{\times} J(\cdot)\omega + r^{off} \times m_a g^b + T_d(\cdot) + \beta q_e \\ &+ J(\cdot)\left(\left(\omega - C\omega_d\right)^{\times}\omega_d - C\dot{\omega}_d\right) + 0.5\frac{dJ(\cdot)}{dt}s \\ &+ \frac{1}{2}\beta J(\cdot)\left(q_e^{\times} + q_{e0}I\right)\omega_e\end{aligned} \tag{16}$$

The additional term $\beta q_e + 0.5\frac{d\boldsymbol{J}(\cdot)}{dt}s$ in the equation was introduced for the convenience of proving the stability of the controller. In addition, $\Delta(\cdot)$ can be considered as an uncertainty component of the system, which consists of two parts: a) the nonlinear term of the system, and b) the external disturbance term. A significant challenge in control system design lies in the presence of similar uncertainty components within the dynamics of the system. The core idea in this study is not to focus on the structure or specific content of $\Delta(\cdot)$, but rather to design the control system by determining the upper bounds of $\Delta(\cdot)$. Under the consideration of external disturbances and gravitational interference, the following assumptions can be made:

**Assumption 2:** The external disturbance torque $T_d(\cdot)$ satisfies the condition $T_d(\cdot) \leq c_g + c_d\|\omega\|^2$, where $c_g \geq 0$ and $c_d \geq 0$ are constants.

**Assumption 3:** $\omega_d, \dot{\omega}_d, q_d$, and $\dot{q}_d$ are bounded, and the following relation holds:

$$\left\|\left(q_e^{\times} + q_{e0}I\right)\omega_e\right\| = \left\|\left(q_e^{\times} + q_{e0}I\right)\left(\omega - C\omega_d\right)\right\| \leq \|\omega\| + c_\omega \tag{17}$$

where, $c_\omega \geq 0$ is a constant.

Since $\|q_e^{\times} + q_{e0}I\| = 1$ and $\|C\| = 1$, Assumption 3 holds.

**Assumption 4:** $\left\|\frac{dJ(\cdot)}{dt}s\right\| \leq c_f\left\|\left(\omega - C\omega_d\right) + \beta q_e\right\| \leq c_f\|\omega\| + c_0$, where $c_0 \geq 0$ is a constant.

For the gravitational disturbance torque component $r^{off} \times m_a g^b$ in $\Delta(\cdot)$, the platform is usually manually leveled before automatic leveling is performed, and $r^{off}$ is typically small. Therefore, $r^{off} \leq c_r$ and $c_r \geq 0$ can be assumed to be constants. Furthermore, $m_a$ and $\left\|g^b\right\|$ can be treated as constants, leading to the following assumption:

**Assumption 5:** $\left\|r^{off} \times m_a g^b\right\| \leq c_g$, where $c_g \geq 0$ is a constant.

Based on these assumptions, it can be concluded that, despite the presence of nonlinear terms, uncertainty components, and time-varying factors in $\Delta(\cdot)$, the following equations still hold:

$$\|\Delta(\cdot)\| \leq b_0 + b_1\|\omega\| + b_2\|\omega\|^2 \leq b\Phi \tag{18}$$

$$\Phi = 1 + \|\omega\| + \|\omega\|^2 \tag{19}$$

These assumptions form the foundation of the proposed algorithm. Under the conditions of external disturbances and uncertainties in the rotational inertia, the algorithm ensures the rapid automatic leveling of the three-degree-of-freedom air-floating platform.

## 3 Automatic Leveling Algorithm

The algorithm presented in this study is derived based on angular velocity information. If the gravitational disturbance torque is zero, the system's angular velocity will no longer change. Conversely, an angular velocity increment will occur. The objective of the automatic leveling algorithm is to adjust the positions of the mass blocks via three linear motion mechanisms, such that the angular velocity increment of the air-floating platform becomes zero.

The torque generated by the linear motion mechanisms can be expressed as follows:

$$\boldsymbol{\tau}_c = m_m \sum_i \boldsymbol{r}_i \times \boldsymbol{g}^b \tag{20}$$

where, $m_m$ is the mass of the block, and $r_i (i = 1, 2, 3)$ represents the position of the $i$-th slider relative to the CR, which is the control variable to be designed.

### 3.1 Algorithm Design

**Theorem 1:** For the dynamical system described by the equation above, under the control structure specified as follows:

$$\begin{aligned} \tau_c &= -\left[k_0 + \kappa(t)\right] s, \quad \kappa(t) = \frac{\hat{b}\Phi}{\|s\| + \varepsilon} \\ \dot{\hat{b}} &= -\sigma_1 \hat{b} + \sigma_2 \frac{\|s\|^2 \Phi}{\|s\| + \varepsilon}, \quad \varepsilon = \frac{\mu}{1 + \Phi} \end{aligned} \tag{21}$$

The closed-loop system is globally stable, and the system's state tracking error is bounded, i.e., $r_i (i = 1, 2, 3)$ and $\|\omega_e\| \leq \varepsilon_2$, where $k_0 > 0, \mu > 0, \sigma_1 > 0$, and $\sigma_2 > 0$ are the controller parameters to be designed.

**Proof:**

A Lyapunov function was selected as follows:

$$V = \frac{1}{2} s^T J(\cdot) s + \frac{1}{2\sigma_2} (b - \hat{b})^2 + \beta \left[ q_e^T q_e + (1 - q_{e0})^2 \right] \tag{22}$$

Given that $q_e^T q_e + q_{e0}^2 = 1$ and $\dot{q}_{e0} = -\frac{1}{2} q_e^T \omega_e$, the derivative of $V$ can be computed as follows:

$$\dot{V} = \frac{1}{2} s^T \frac{dJ(\cdot)}{dt} s + s^T \left( \tau_c + \Delta(\cdot) - \beta q_e - \frac{1}{2} \frac{dJ(\cdot)}{dt} s \right) - \frac{1}{\sigma_2} (b - \hat{b}) \dot{\hat{b}} + \beta \omega_e^T q_e \tag{23}$$

It further leads to:

$$\dot{V} = s^T \left( \tau_c + \Delta(\cdot) \right) - \frac{1}{\sigma_2} (b - \hat{b}) \dot{\hat{b}} - \beta^2 q_e^T q_e \tag{24}$$

The controller described by the equation can be substituted into this expression to obtain:

$$\begin{aligned} \dot{V} &= -s^T \left[k_0 + \kappa\right] s + s^T \Delta + \frac{1}{\sigma_2} (b - \hat{b})(-\dot{\hat{b}}) - \beta^2 q_e^T q_e \\ &\leq -k_0 s^T s - \kappa s^T s - \beta^2 q_e^T q_e + \|s\| b \Phi + \frac{1}{\sigma_2} (b - \hat{b})(-\dot{\hat{b}}) \\ &= -k_0 s^T s - \beta^2 q_e^T q_e - \frac{\hat{b}\Phi}{\|s\| + \varepsilon} s^T s + \|s\| b \Phi + \frac{1}{\sigma_2} (b - \hat{b})(-\dot{\hat{b}}) \\ &\leq -k_0 s^T s - \beta^2 q_e^T q_e + (b - \hat{b}) \frac{\|s\|^2 \Phi}{\|s\| + \varepsilon} + \varepsilon b \Phi + \frac{1}{\sigma_2} (b - \hat{b})(-\dot{\hat{b}}) \\ &\leq -k_0 s^T s - \beta^2 q_e^T q_e + \mu b + \frac{\sigma_1}{\sigma_2} (b - \hat{b}) \hat{b} \end{aligned} \tag{25}$$

where,

$$\frac{\sigma_1}{\sigma_2} (b - \hat{b}) \hat{b} = \frac{\sigma_1}{\sigma_2} \left( b\hat{b} - \hat{b}^2 \right) = -\frac{\sigma_1}{\sigma_2} \left( \hat{b} - \frac{b}{2} \right)^2 + \frac{\sigma_1 b^2}{4\sigma_2} \tag{26}$$

Substituting the expression into the equation yields:

$$\dot{V} \leq -k_0 s^T s - \beta^2 q_e^T q_e + \mu b - \frac{\sigma_1}{\sigma_2}\left(\hat{b} - \frac{b}{2}\right)^2 + \frac{\sigma_1 b^2}{4\sigma_2} \leq -k_0 s^T s - \beta^2 q_e^T q_e + \mu b + \frac{\sigma_1 b^2}{4\sigma_2} \tag{27}$$

Let $\varepsilon^* = \mu b + \frac{\sigma_1 b^2}{4\sigma_2}$, when s and $q_e$ are outside the set below, then $\dot{V} < 0$.

$$S_1 \triangleq \left\{ (s, q_e) : \|s\| \leq \sqrt{\frac{\varepsilon^*}{k_0}}, \|q_e\| \leq \frac{\sqrt{\varepsilon^*}}{\beta} \right\}$$

It can be deduced from the above that when $s$ and $q_e$ are bounded, $w_e$ remains bounded as well.

$$S_2 \triangleq \left\{ \omega_e : \|\omega_e\| \leq \sqrt{\varepsilon^*} \right\}$$

End of proof.

### 3.2 Torque Distribution

In the previous section, the theoretical control torque $\tau_c$ was designed to be generated by the movement of the mass blocks on the linear motion mechanism. The torque produced by the sliders is directed perpendicular to both the direction of motion and the gravity direction. In practical applications, the actual control variable is the displacement $r$ of the mass block. To obtain the actual control variable, the control torque $\tau_c$ needs to be transformed into $r$. This can be expressed as:

$$\tau_c = m_m \left( -g^b(t) \times r \right) \tag{28}$$

Since the main diagonal elements of the cross-product matrix are always zero, the matrix $\left[-g^b(t)\times\right]$ becomes singular. Therefore, the vector $r$ cannot be obtained through the inversion of $\left[-g^b(t)\times\right]$. The solution of $r$ provided in this study is:

$$r = \frac{g^b \times \tau_r}{\|g^b\|^2 m_m} \tag{29}$$

The output $r$ of the automatic leveling system can be given by the equation.

## 4 Simulation Results

This section presents the simulation verification of the automatic leveling algorithm proposed in this study. The simulation parameters are based on the three-degree-of-freedom air-floating simulation platform developed by the Beijing Institute of Control Engineering. The simulation parameters are provided in Table 1.

**Table 1.** Simulation parameters

| Simulation Parameter | Value |
|---|---|
| Moment of inertia | diag(12818) $\mathrm{kg \cdot m^2}$ (estimated value) |
| Total mass | 120 kg (estimated value) |
| Slider mass | 0.8 kg |
| Slider stroke | $\pm 260$ mm |
| Mass center offset | $r_{\text{eff}} = \left[\ 1 \quad 1.2 \quad 0.8\ \right]$ mm |
| Initial attitude | $q = \left[\ 0.51 \quad 0.52 \quad 0.48\ \right]$ |
| Desired attitude | $q = \left[\ 0.5 \quad 0.5 \quad 0.5\ \right]$ |

Figure 2 shows the response curve of the mass block's displacement under the proposed automatic leveling algorithm. From the figure, it can be observed that the displacement of the mass block remains within the maximum stroke at all times, and the leveling process is completed within 15 seconds, demonstrating a rapid leveling response.

Figure 3 shows the angular velocity response curve of the three-degree-of-freedom air-floating platform during the automatic leveling process. It can be observed that under the drive of the proposed algorithm, the angular velocities of all three degrees of freedom tend towards zero, which also demonstrates the stability of the algorithm.

The following method was designed to further prove the effectiveness of the leveling algorithm. After the automatic leveling was completed, an arbitrary angular velocity was applied to the three-degree-of-freedom air-floating platform. The total energy of the platform can then be expressed as the sum of kinetic energy and potential energy:

$$E_{sum} = E_d + E_s \tag{30}$$

where, $E_d = 0.5\omega^T J\omega$ represents kinetic energy and $E_s$ represents potential energy. If the system is in equilibrium, then $E_s \approx 0$, meaning that the system's rotational kinetic energy is conserved, i.e., $E_d(t) = E_d(0)$. Therefore, the variation curve of the system's rotational kinetic energy can reflect the performance of the automatic leveling algorithm.

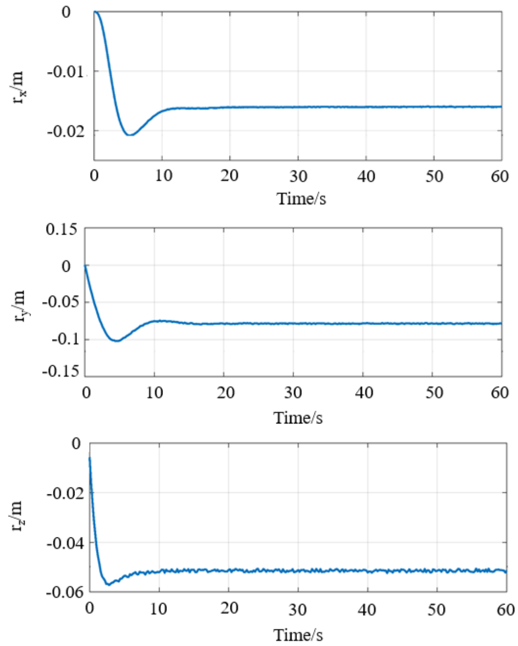


**Figure 2.** Response curve of the mass block displacement

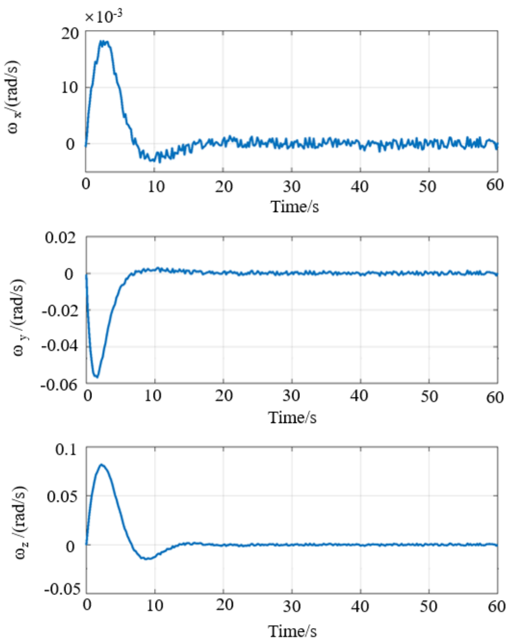


**Figure 3.** Angular velocity response curve of the three-degree-of-freedom air-floating platform

Figure 4 presents the system's kinetic energy response curves before and after leveling. In the figure, $E_d^a$ represents the kinetic energy response curve after the platform after leveling, while $E_d^b$ represents the kinetic energy response curve before leveling. When the platform is not leveled, the system's kinetic energy and potential energy continuously transform into each other, resulting in the periodic variation seen in the figure. After leveling, the kinetic energy no longer transforms into potential energy, and the kinetic energy curve stabilizes. Therefore, it can be clearly observed from the figure that after leveling, the potential energy of the air-floating platform decreases significantly, which is sufficient to demonstrate the effectiveness of the leveling algorithm.

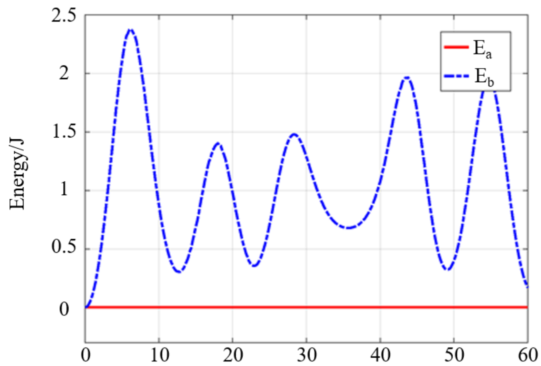


**Figure 4.** Kinetic energy response curve of the system

## 5 Experimental Results

### 5.1 Experimental Platform

The algorithm proposed in this study was validated on a three-degree-of-freedom air-floating simulation platform developed by the Beijing Institute of Control Engineering, as shown in Figure 5. The automatic leveling system consists of three linear motion mechanisms and a mass block. The mass block is driven by a stepper motor, with a maximum motion speed of 100 mm/s. The air-floating platform is capable of rotating freely around the Z-axis by 360°, while the rotation angles around the other two axes are ±30°.

As shown in the figure, the platform is equipped with a three-axis high-precision fiber-optic gyroscope to accurately measure angular velocity information. Additionally, a dual-axis inclinometer is mounted to precisely measure the attitude information along the $X$ and $Y$ axes, while the $Z$-axis attitude information is obtained through the integration of the angular velocity measured by the gyroscope. Due to the platform's integration of a cold gas thrust system, the research on automatic leveling algorithms with uncertain moment of inertia becomes imperative.

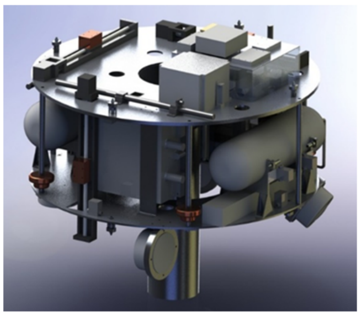

**Figure 5.** Three-degree-of-freedom air-floating platform

### 5.2 Control Parameter Settings

There are two types of automatic leveling methods: hardware-based and software algorithm-based leveling methods. Hardware-based leveling methods involve a larger number of control parameters, such as the configuration of stepper motors, the layout of air-floating units, the selection and installation locations of sensors, and the construction of electrical control systems. The leveling method studied in this research is of the software algorithm type. It calculates the position of the slider based on the attitude and angular velocity information of the air-floating platform, aiming to adjust the center of mass so that it aligns as closely as possible with the CR. The experiment was conducted using a three-degree-of-freedom air-floating simulation platform developed by the Beijing Institute of Control Engineering, with the hardware control parameters already being set. Therefore, no new settings are required for this experiment, and only a few parameters need to be configured. Table 2 shows the automatic leveling test parameters for the three-degree-of-freedom platform.

Figure 6 presents the sliding position response curve of the mass block during the experiment. Compared to the simulation curve in Figure 2, the distance travelled by the slider in the experiment is shorter. This suggests that the simulation parameters were slightly conservative, while the actual deviation of the center of mass remains well within the capacity of the automatic leveling system.

**Table 2.** Automatic leveling test parameters for the three-degree-of-freedom platform

| Simulation Parameter | Value |
|---|---|
| Slider mass | 0.8 kg |
| Slider stroke | ±260 mm |
| Initial attitude | $q = \begin{bmatrix} 0.1022 & 0.0951 & -0.012 \end{bmatrix}$ |
| Desired attitude | $q = \begin{bmatrix} 0.0868 & 0.0868 & -0.0076 \end{bmatrix}$ |

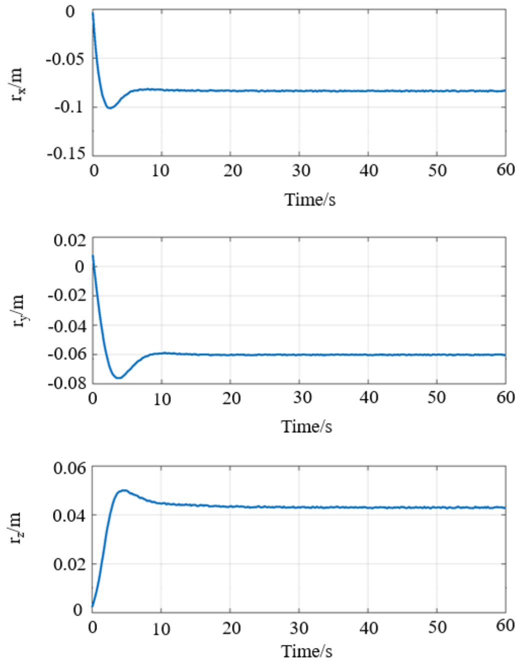


**Figure 6.** Sliding position response curve of the mass block

Figure 7 shows the response curve of the angular velocity during the experiment. It can be observed that the angular velocity ultimately stabilizes at zero, and the system completes the automatic leveling process within 20 seconds. This confirms the effectiveness of the method from an experimental perspective.

Figure 8 displays the kinetic energy response curve $E_d^a$ after applying an angular velocity excitation to the three-degree-of-freedom air-floating platform following automatic leveling. The platform's kinetic energy response curve $E_d^b$ before leveling is also shown. It is evident from the figure that automatic leveling significantly reduces kinetic energy fluctuations, thereby mitigating the influence of gravity on the angular velocity of the three-degree-of-freedom air-floating platform. If the effect of gravity on the angular velocity is negligible, it indicates that gravity's influence on the angular momentum of the platform is minimal. Consequently, during attitude maneuver simulations, the gravitational impact on the platform can be ignored.

### 5.3 Comparison with Other Leveling Methods

Leveling methods are generally classified into three main categories: hardware leveling methods, software algorithm leveling methods, and manual leveling methods. Hardware leveling methods involve the layout of air-floating units, selection and installation of sensors, as well as the construction of electrical control systems. For example, capacitive sensor-based leveling methods utilize changes in capacitance to accurately measure the platform's position, angle, and load variations, thus achieving leveling.

Software algorithm leveling methods involve data processing, error compensation, and control strategies, such as Proportional-Integral-Derivative (PID) control, to achieve precise leveling of the platform [21–23].

The leveling method studied in this research falls under the software algorithm category. Experiments were conducted on the three-degree-of-freedom air-floating simulation platform developed by the Beijing Institute of Control Engineering. A review of publicly available literature on leveling methods (references 1-39) was conducted, and the results are summarized in Table 3.

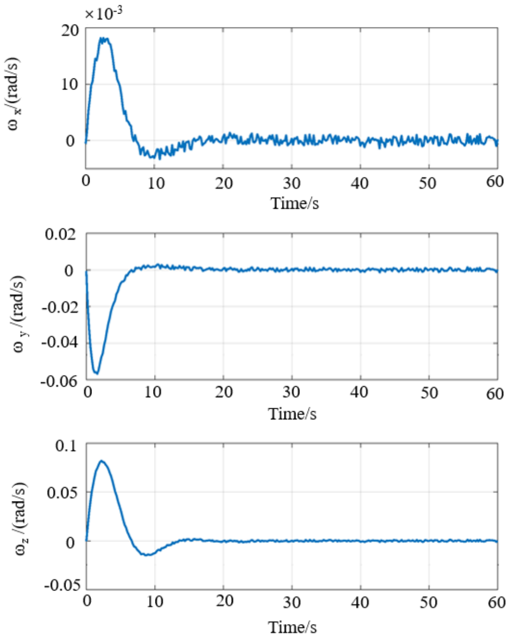


**Figure 7.** Angular velocity response curve of the three-degree-of-freedom air-floating platform

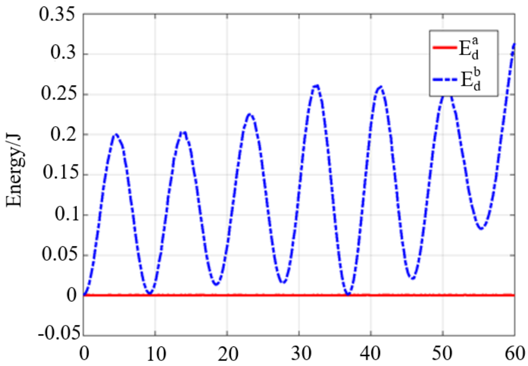


**Figure 8.** Kinetic energy response curve of the three-degree-of-freedom air-floating platform

Six key evaluation criteria were selected [24–27], as follows:
• Leveling time, i.e., speed or response time.
• Leveling accuracy, i.e., sensitivity.
• Leveling stability.
• Dynamic range of leveling, which refers to the system's capability range.
• Manufacturing cost, which refers to the cost of implementation.
• Ease of operation.

**Table 3.** Comparison with other leveling methods

| Method | Time | Accuracy | Stability | Dynamic Range | Cost | Operation |
|---|---|---|---|---|---|---|
| Manual | Long | Low | Low | Large | Low | Complex |
| Hardware category | Medium | Low | Medium | Medium | High | Simple |
| Algorithm category | Medium | Medium | Medium | Medium | Low | Simple |
| Proposed algorithm | Short | High | High | Large | Low | Simple |

### 5.4 Potential Limitations

The automatic leveling algorithm studied in this research is suitable for small-scale fine adjustments of the attitude of small or medium-sized satellites. Due to the limitations imposed by the mass of the leveling slider and the sliding distance, it is not suitable for large-scale attitude adjustments of heavier satellites. For example, the method cannot be used to adjust the attitude of an Earth observation satellite, such as when the camera is facing away from the Earth. In this case, the method would be unable to reposition the satellite's camera to face the Earth for surface imaging.

### 5.5 Potential Applications in Other Scenarios

The three-degree-of-freedom air-floating satellite simulation platform serves as an effective means for verifying satellite attitude control devices and methods. This study can also be applied to modern high-end manufacturing fields, such as precision measurement, micro-nano fabrication, and optical systems.

## 6 Conclusion

The automatic leveling method studied in this research is based on adaptive feedback control technology, which enables high-precision adjustment of the platform's center of mass under conditions of uncertainty in the moment of inertia of the three-degree-of-freedom air-floating satellite simulation platform.

An automatic leveling algorithm was proposed for the platform in situations where the moment of inertia of the three-degree-of-freedom air-floating satellite simulation platform is unknown. The algorithm drives the mass block via a linear motion mechanism, allowing for real-time adjustment of the distance between the platform's center of mass and its CR. To overcome the leveling challenges induced by uncertainties in the platform's moment of inertia and mass, an automatic leveling algorithm was designed. The stability of this method was proven using the Lyapunov stability principle. Finally, both mathematical simulations and physical experiments were conducted, with the results demonstrating that the method can quickly and effectively achieve automatic leveling of the three-degree-of-freedom air-floating satellite simulation platform.

The innovations of this study are as follows: First, the uncertainty in the moment of inertia within the three-degree-of-freedom air-floating satellite simulation platform model was analyzed and separately addressed. Second, adaptive control technology was applied in the design of the control method, using attitude and angular velocity information to calculate the position of the mass block to be adjusted. This allows for the adjustment of the platform's center of mass to align as closely as possible with the CR. During the leveling process, the mass block is only driven by the linear motion mechanism for leveling.

In terms of practical applications, this study is not only applicable to the simulation of satellite attitude motion on the ground using the three-degree-of-freedom air-floating platform, enabling effective satellite ground simulation, but also has potential applications in modern high-end manufacturing fields, such as precision measurement, micro-nano fabrication, and optical systems.


## Data Availability

The data supporting our research results are deposited in Hanyu Gao and Shengchen Yu at email address: 200600737ysc@ncist.edu.cn.

## Conflicts of Interest

The authors declare no conflict of interest.


## References


[1] J. L. Schwartz, M. A. Peck, and C. D. Hall, "Historical review of air-bearing spacecraft simulators," *J. Guid. Control Dyn.*, vol. 26, no. 4, pp. 513–522, 2003. https://doi.org/10.2514/2.5085

[2] G. A. Smith, "Dynamic simulators for test of space vehicle attitude control systems," in *Virginia Polytechnic Institute Proceedings of the Conference on Role of Simulation in Space Technology*, 1965.

[3] R. R. Fullmer, "Dynamic ground testing of the skipper attitude control system," in *34th Aerospace Sciences Meeting and Exhibit*, Reno, NV, U.S.A., 1996, p. 103. https://doi.org/10.2514/6.1996-103

[4] M. A. Peck, L. Miller, A. R. Cavender, M. Gonzalez, and T. Hintz, "An airbearing-based testbed for momentum control systems and spacecraft line of sight," *Adv. Astronaut. Sci.*, vol. 114, pp. 427–446, 2003.

[5] M. Romano and B. N. Agrawal, "Acquisition, tracking and pointing control of the bifocal relay mirror spacecraft," *Acta Astronautica*, vol. 53, no. 4-10, pp. 509–519, 2003. https://doi.org/10.1016/S0094-5765(03)80011-5

[6] J. J. Kim and B. Agrawal, "System identification and automatic mass balancing of ground-based three-axis spacecraft simulator," in *AIAA Guidance, Navigation, and Control Conference and Exhibit*, 2006, p. 6595.

[7] J. J. Kim and B. N. Agrawal, "Automatic mass balancing of air-bearing-based three-axis rotational spacecraft simulator," *J. Guid. Control Dyn.*, vol. 32, no. 3, pp. 1005–1017, 2009. https://doi.org/10.2514/1.34437

[8] J. Prado, G. Bisiacchi, L. Reyes, E. Vicente, F. Contreras, M. Mesinas, and A. Juárez, "Three-axis air-bearing based platform for small satellite attitude determination and control simulation," *J. Appl. Res. Technol.*, vol. 3, no. 3, pp. 222–237, 2005.

[9] Y. Yang and X. B. Cao, "Design and development of the small satellite attitude control system simulator," in *AIAA Modeling and Simulation Technologies Conference and Exhibit*, Keystone, Colorado, U.S.A., 2006, p. 6124. https://doi.org/10.2514/6.2006-6124

[10] Y. Li and Y. Gao, "Equations of motion for the automatic balancing system of 3-DOF spacecraft attitude control simulator," in *3rd International Symposium on Systems and Control in Aeronautics and Astronautics*, Harbin, China, 2010, pp. 248–251. https://doi.org/10.1109/ISSCAA.2010.5633650

[11] D. Jung and P. Tsiotras, "A 3-DOF experimental test-bed for integrated attitude dynamics and control research," in *AIAA Guidance, Navigation, and Control Conference and Exhibit*, Austin, Texas, U.S.A., 2003, p. 5331. https://doi.org/10.2514/6.2003-5331

[12] J. L. Schwartz and C. D. Hall, "System identification of a spherical air-bearing spacecraft simulator," *AAS Paper, Tech. Rep. 122*, 2004.

[13] J. J. Kim and B. N. Agrawal, "Automatic mass balancing of air-bearing-based three-axis rotational spacecraft simulator," *J. Guid. Control Dyn.*, vol. 32, no. 3, pp. 1005–1017, 2009. https://doi.org/10.2514/1.34437

[14] S. Chesi, Q. Gong, V. Pellegrini, R. Cristi, and M. Romano, "Automatic mass balancing of a spacecraft three-axis simulator: Analysis and experimentation," *J. Guid. Control Dyn.*, vol. 37, no. 1, pp. 197–206, 2014. https://doi.org/10.2514/1.60380

[15] Apache Hive. http://hive.apache.org

[16] Big Data. http://en.wikipedia.org/wiki/Big_data

[17] Apache Hadoop. http://hadoop.apache.org

[18] S. G. Mallat, "Multiresolution approximations and wavelet orthonormal bases of L2 (R)," *Trans. Amer. Math. Soc.*, vol. 315, pp. 69–87, 1989. https://doi.org/10.1090/S0002-9947-1989-1008470-5

[19] S. G. Mallat, "A theory for multiresolution signal decomposition: The wavelet representation," *IEEE Trans. Pattern Anal. Mach. Intell.*, vol. 11, no. 7, pp. 674–693, 1989. https://doi.org/10.1109/34.192463

[20] S. Mallat and W. L. Hwang, "Singularity detection and processing with wavelets," *IEEE Trans. Inform. Theory*, vol. 38, no. 2, pp. 617–643, 1992. https://doi.org/10.1109/18.119727

[21] M. Frischi and H. Messer, "The use of the wavelet transform in the detection of an unknown transient signal," *IEEE Trans. Inform. Theory*, vol. 38, no. 2, pp. 892–897, 1992. https://doi.org/10.1109/18.119748

[22] B. Macq and I. Pitas, "Special issue on watermarking," *Signal Process.*, vol. 66, no. 3, pp. 281–282, 1998.

[23] J. J. K. Ó Ruanaidh, W. J. Dowling, and F. M. Boland, "Watermarking digital images for copyright protection," *IEE Proc. Vis. Image Signal Process.*, vol. 143, pp. 250–256, 1996.

[24] Z. W. Wang, Y. B. Li, and G. Bao, "Study on the mechanics property of three degrees of freedom air-bearing testbed- analysis on unbalance torque acted on gravity," *J. Mech. Eng.*, vol. 42, no. 4, pp. 179–184, 2006.

[25] X. Dong, Q. J. Yang, B. Gang, and et al., "Auto-balancing system for three-axis air-bearing based platform," *J. Dalian Maritime Univ.*, vol. 2008, no. 3, pp. 25–28, 2008.

[26] X. Dong, X. Jian, Q. J. Yang, and et al., "Research on quality characteristic influence for three axis air-bearing table," *Chinese Hydraul. Pneumat.*, no. 10, pp. 70–74, 2009.

[27] D. Lu and J. Guang, "Research and simulation on a method for automatic mass balancing of a three-axis attitude control test bed," *J. Tsinghua Univ.*, vol. 51, no. 8, pp. 1063–1071, 2011.