

Scientists study mode switching control for drag-free satellite based on region of attraction

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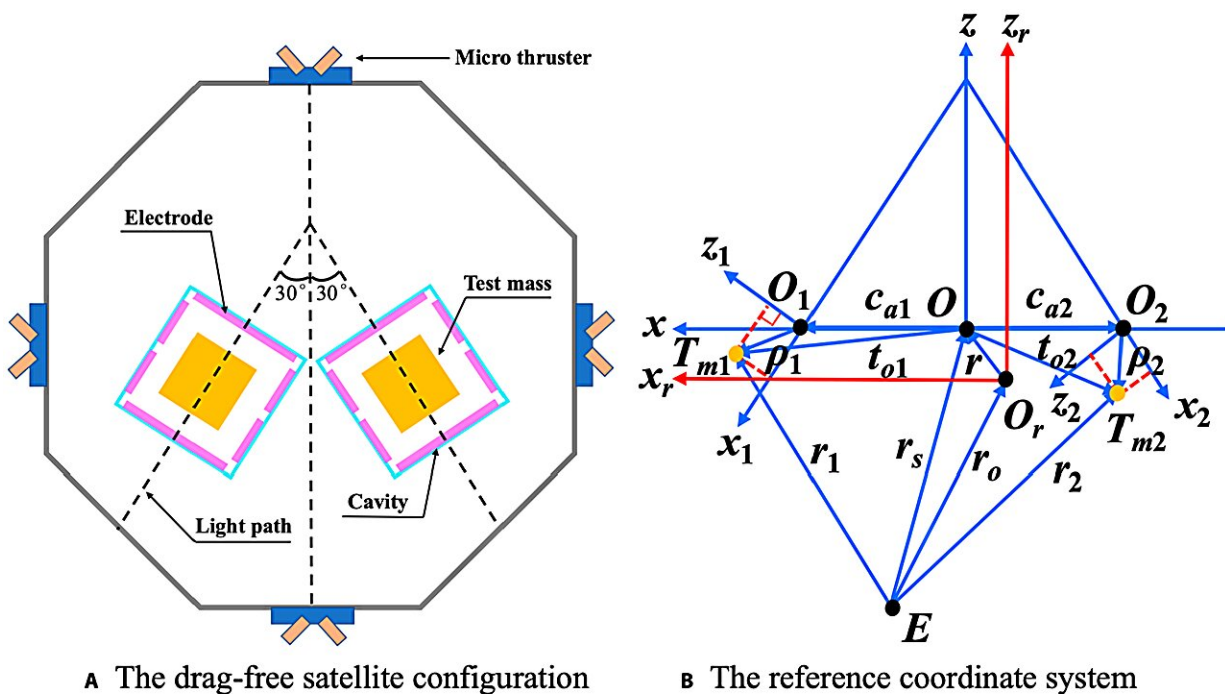


Fig.1. The drag-free satellite system with 2 TMs. (A) The drag-free satellite configuration. (B) The reference coordinate system.

Fig.1 The drag-free satellite system with 2 TMs. Credit: Space: Science & Technology

In recent decades, drag-free satellites have been used in high-precision missions, such as testing the general relativity, verifying the geodetic and frame-dragging effects, measuring Earth's gravity field, etc. In space

gravitational wave detection, drag-free satellites play an important role.

Previous research on the drag-free satellite has focused on the drag-free control algorithm. Nevertheless, science mode and nonscience mode have different control forces, sensor measurement range, measurement noise, and reaction force noise. Therefore, the different controllers for the capture control mode and the high-accuracy control mode of the test mass (TM) need to be designed.

However, it is easy to cause system instability or even uncontrollability when switching between different controllers. Research on the switching control between different modes is very important. In the drag-free satellite, there is little research on the switching control between different modes. Multi-degree of freedom strong coupling and controller saturation remains an urgent problem to be solved.

In a [research paper](#) recently published in *Space: Science & Technology*, researchers from Shanghai Institute of Satellite Engineering, China, Sun Yat-sen University, China, and Tohoku University, Japan, together propose a switching rule to improve the efficiency and stability of the mode switching process for the drag-free satellite system after TM releases.

First, authors give the reference coordinate system and dynamics models. In space gravitational wave detection, the drag-free satellite has 2 cubic TMs with an angle of 60° between them (see Fig. 1A). Three reference coordinate systems are used (see Fig. 1B). The inertial reference coordinate system is the Earth mean equator J2000 coordinates.

Orbit Coordinate System (OCS) originates at the satellite mass center O_r on the ideal orbit, with z_r -axis pointing from Earth's mass center to the satellite's mass center and the x_r -axis perpendicular to the z_r -axis in the

orbit plane and coinciding with the velocity.

Cavity Coordinate System (CCS) originates at the center of the satellite cavity, with x_i -axis directing toward the laser link and z_i -axis perpendicular to the x_i -axis in the orbital plane. As for dynamics and motion models, the motion model of the satellite relative to the ideal orbit is established in the inertial coordinates, considering the error vector $r = [x, y, z]^T$ of the satellite relative to the ideal orbit, the control vector $u_s = [u_{sx}, u_{sy}, u_{sz}]^T$ acting on the satellite, and the interference vector $d_s = [d_{sx}, d_{sy}, d_{sz}]^T$ acting on the satellite.

The motion model of the TM relative to the cavity is given in OCS, with the position vector $\rho_i = [x_i, y_i, z_i]^T$ from the cavity center to the TM's mass center, the vector $c_{ai} = [c_{aix}, c_{aiy}, c_{aiz}]^T$ from the satellite's mass center to the cavity center, the control vector $u_i = [u_{ix}, u_{iy}, u_{iz}]^T$ acting on the TM, and the interference vector $d_i = [d_{ix}, d_{iy}, d_{iz}]^T$ acting on the TM. Besides, the solar radiation pressure, the reaction force, the position measurement noise, and the reaction force noise are formulated.

Then, authors investigate the controller design, and analyze the stability in view of the Lyapunov function and the region of attraction. Unlike traditional satellite control systems, the drag-free satellite's control system includes the inner loop and the outer loop (see Fig. 2).

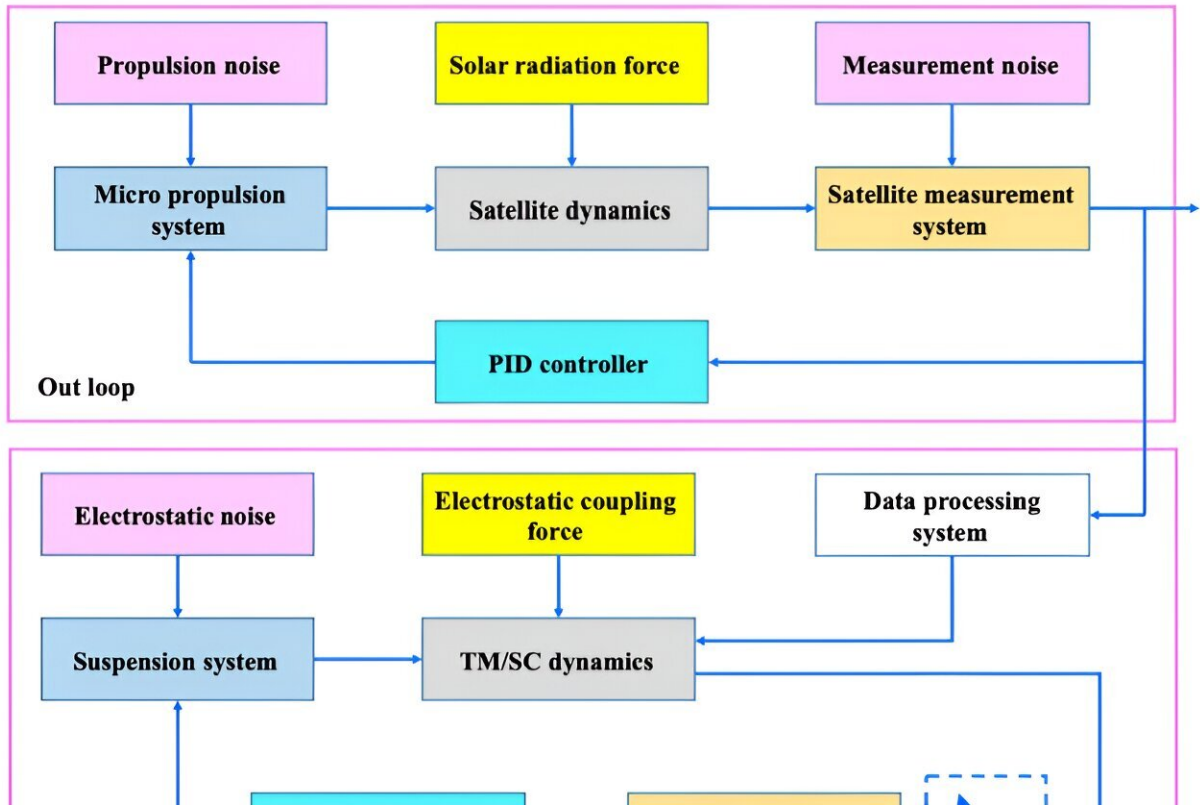


Fig. 2 The control flow diagram of drag-free satellite system. Credit: Space: Science & Technology

The inner loop is used to control the TM including the TM's capture control and the TM's high-precision control, while the outer loop is used to control the satellite. For the drag-free satellite, the PID control law u_s is designed and the thruster model P_m is obtained by polynomial fitting with the anode voltage and the mass-flow rate. For the TM's capture controller, the sliding mode control is selected due to its good robustness.

According to the state equation of the TM movement model relative to the cavity and the exponential approach law, the 3-axis control law u_i of the TM is obtained. After capture, the H_∞ mixed-sensitivity controller is designed to improve the control accuracy and reduce the noise effect.

By linearizing the state equation of the TM movement model and decoupling the system with the inverse matrix of the plant, the mixed-sensitivity problem is expressed as an optimization problem and the system control law is obtained. The sliding mode controller (i.e., subsystem 1) and the H_∞ mixed-sensitivity controller (i.e., subsystem 2) can be respectively proved stable via their the Lyapunov function V_{t1} and V_{t2} .

Furthermore, letting $V_{t1}(t_f) > V_{t2}(t_f)$ where t_f is the switching time, the switching system is global stable according to the piecewise Lyapunov function method. Although the system satisfies the global stability requirements, it cannot guarantee the local stability of the nonlinear system after switching. In order to avoid system instability, Subsystem 1 is required to switch after entering the ROA of Subsystem 2.

The ROA is defined as $\Omega(\rho, t) = \{X_h \in R^n \mid 0 \leq V_h(X_h, t) \leq \rho(t)\}$ where R^n is the Euclidean space, $V_h(X_h, t)$ is the Lyapunov function of the nonlinear Subsystem 2, and $\rho(t)$ is the continuously differentiable function. The sum of squares (SOS) method is used to calculate the ROA of Subsystem 2. Through calculation, the ROA is $V_{t2} \leq 3.129 \times 10^{-15}$, and V_{t1} is made greater than 3.129×10^{-15} at time t_f , which ensures the system is globally stable.

Finally, authors show the numerical results and draw the conclusion. To test the performance of the switching control method, the numerical simulation is carried out. In simulation, the initial states of the TM relative to the cavity are (200 μm , 5 $\mu\text{m/s}$, 200 μm , 5 $\mu\text{m/s}$, 200 μm , 5 $\mu\text{m/s}$). The initial relative states of the satellite are (0, 0, 0, 0, 0, 0).

The position coordinates of the TM1 and TM2 are (0.3 m, 0, 0) and (-0.3 m, 0, 0) in OCS, respectively. The maximum root mean square voltage of the Subsystem 1 and Subsystem 2 are 96 and 7 V, respectively. Results show that the relative motion errors of the satellite

on the 3 axes are controlled within 0.1 nm and the control force is always within the thrust range, and there is no saturation.

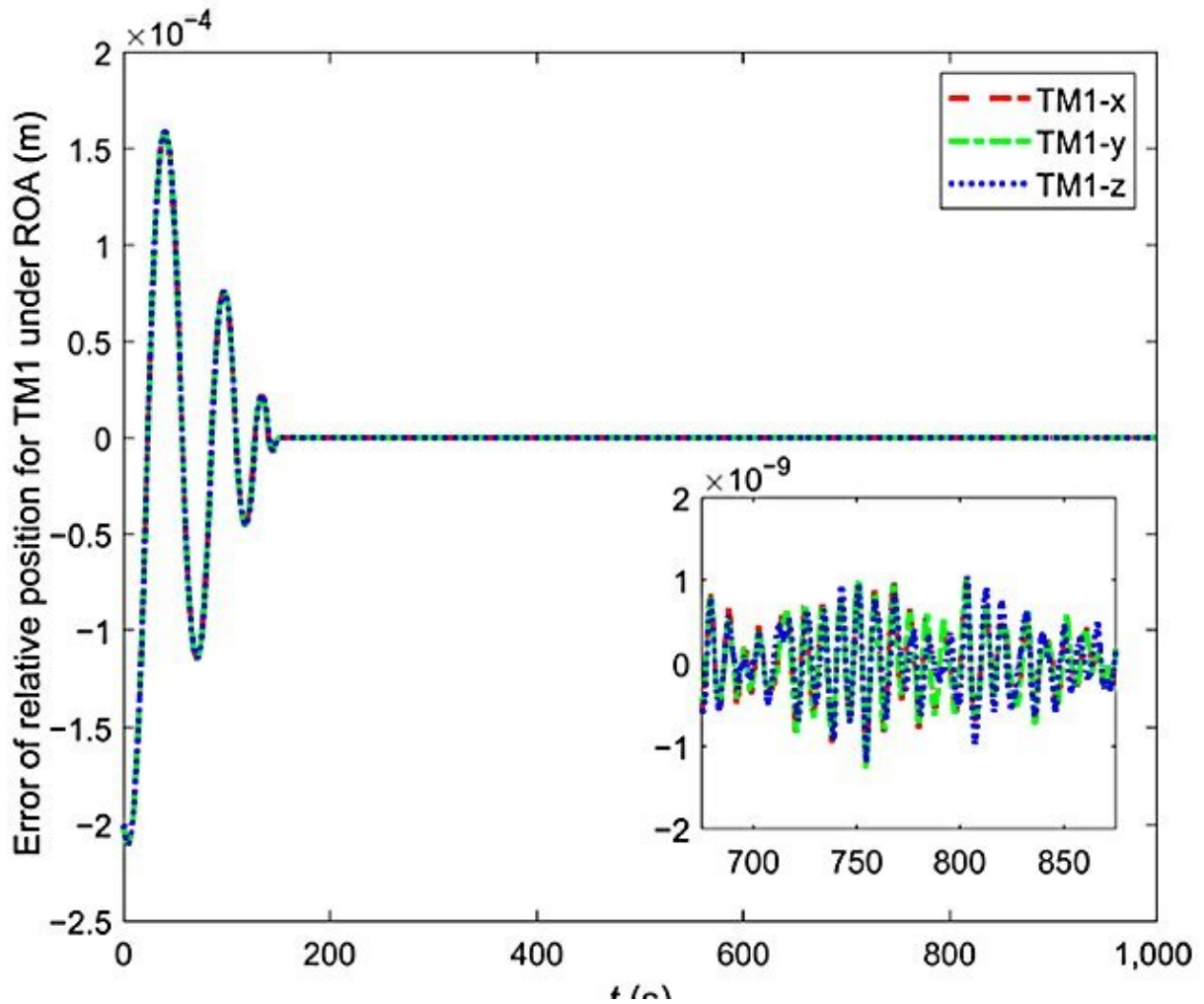
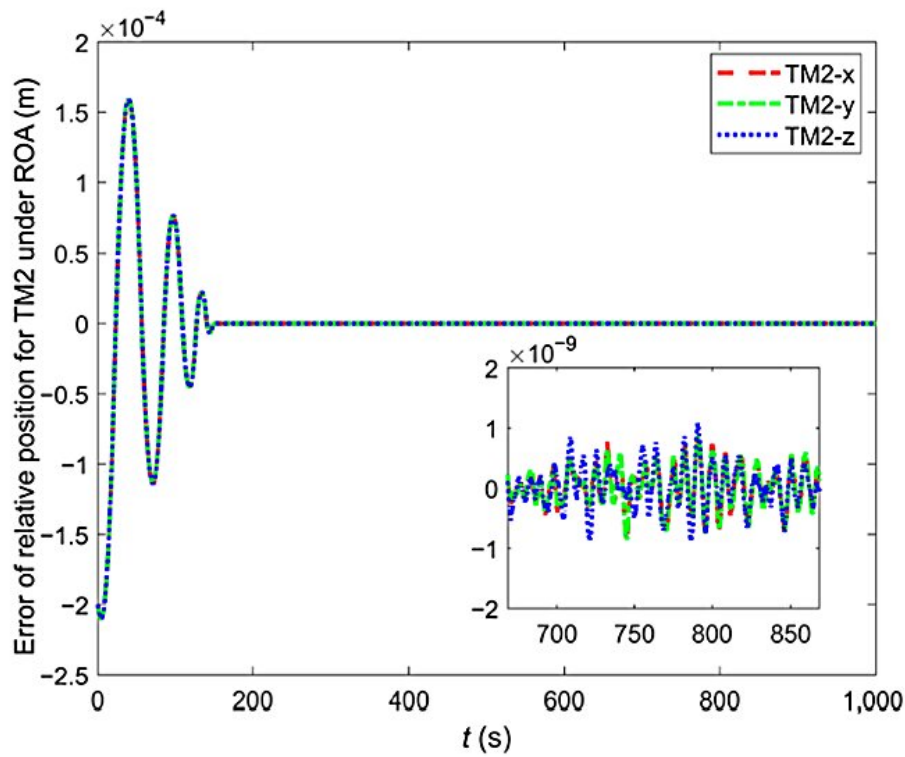
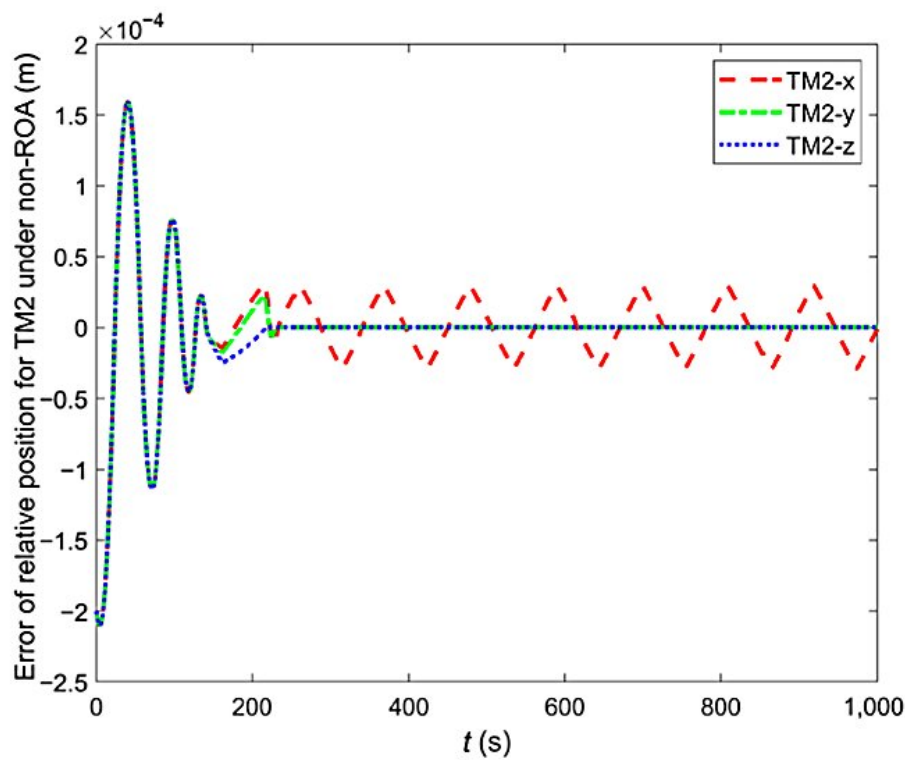


Fig. 7 The relative motion error of TM1 under the switching rule of the ROA and the non-ROA. Credit: Space: Science & Technology



A The relative motion error of TM2 under ROA



B The relative motion error of TM2 under non-ROA

Fig. 8. The relative motion error of TM2 under the switching rule of the ROA and the non-ROA. (A) The relative motion error of TM2 under ROA. (B) The relative motion error of TM2 under non-ROA.

Fig. 8 The relative motion error of TM2 under the switching rule of the ROA and the non-ROA. Credit: Space: Science & Technology

To study the performance of the proposed switching rule, the control errors of TM1 and TM2 under the switching rule of the ROA and the non-ROA are compared and analyzed, as shown in Figs. 7 and 8. It can be seen that Subsystem 1 is switched to Subsystem 2 under the constraints of the switching rule, the accuracy of the controlled system is improved and remaining stable for a long time after switching, and the relative motion error of the TM1 and TM2 is controlled within 2 nm.

By comparison, the system of the non-ROA switching rule frequently switches after the initial switching, and the control accuracy is low. In conclusion, the design of switching rules is important, and the research in this paper will provide a reference for the switching rule design of the drag-free [satellite](#).

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