Using permanent magnetic array device to detumble and despin defunct spacecraft

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Abstract. For the mission of detumbling and despinning the space debris, like defunct satellites, it is highly reliable and safe to use the permanent magnetic array device (PMAD). Based on the electromagnetic principle, the target’s attitude dynamics is analysed, the electromagnetic torque is studied, the formula of electromagnetic force is simplified, and the stability of the nutation Angle is obtained. The rotation speed and attitude of PMAD are controlled by a dual-manipulator space robot to ensure that the component of the torque on the spin axis is zero. So the target will be only affected by the transverse component of the torque, and then the nutation angle decreases gradually to zero. When mission completed, the dual-manipulator space robot can deorbit or maintain on-orbit servicing, which is a significant exploration.

1. Introduction
With the development of space activities, lots of space debris are generated, such as defunct satellites and upper stages of rocket. On-orbit servicing and active removal of space debris have become the vital means to protect the space environment. In order to improve the safety of missions, detumbling and despinning the target have become a hot point. Many institutes proposed a variety of methods. According to whether the device is in contact with the target, they can be divided into contact and non-contact methods [2]. The contact method can only be applied to the target with low spin angular velocity. And its potential collision risk has great negative influence on the service spacecraft. The non-contact method mainly uses gas [3], electrostatic force [4], and electromagnetic force [5], which greatly improve the safety. In recent years, the method of electromagnetic force has received a great attention. Sugai [6-7] proposed using electromagnetic coils to detumble the target, but the air gap is very small and its power consumption is high. Gomez and Walker [8] proposed that using superconducting coils to provide high-intensity magnetic field, the working distance can reach meter. However, in order to control superconducting coils, complicated additional system support is required. Liu[9] proposed using a rotating permanent magnetic array, but the electromagnetic force is a nonlinear function with a complex mathematical expression, which is difficult to be applied in practical engineering.

To obtain a more efficient and practical scheme, this paper, based on the PMAD, studies the applied electromagnetic torque, the simplified formula of electromagnetic force and the stability of nutation angle. And the simulation verification of detumbling and despinning is implemented.
2. The design of the detumbling and despining scheme

The mission is divided into two steps. First, the nutation angle is eliminated into zero, so that the tumbling motion turns into a spinning motion. Second, the spin angular velocity is eliminated into zero. A dual-manipulator space robot [7] is equipped with PMAD to detumble the target, as shown in figure (1). In this way, the negative influence of the single manipulator can be offset and the detumbling torque can be increased. In addition to applying detumbling torque to the target, the single manipulator will also generate a thrust force, which will drive the target to move in the direction of thrust force. So the service spacecraft and the manipulator have to track the target in time. Therefore, the dual-manipulator is applied. As for the magnetic field source, eight blocks of 42*42*42mm N52-NdFeB permanent magnet are selected to construct a Halbach array. Its gradient magnetic circuit configuration can improve the external intensity magnetic field of PMAD. PMAD, as shown in figure (2), is simple and doesn’t require power supply and other additional system. So its energy consumption is much lower than the electromagnetic coil.

![Figure 1. Dual-manipulator space robot.](image1)

![Figure 2. The permanent magnetic array device](image2)

2.1. The direction of the detumbling torque.

Gomez and Walker [10] created the ‘magnetic tensor’ \( \mathbf{M} \) to describe the electromagnetic torque, as in equation (1). It only depends on the inherent physical parameters of the target and only needs to be computed once. Equation (1) is expanded by applying the vector algorithm and rewritten into the component expression, as in equation (2). The direction of the electromagnetic torque \( \mathbf{T} \) is always opposite to the direction of the angular velocity \( \mathbf{\omega} \).

\[
\mathbf{T} = (\mathbf{M}\mathbf{\omega} \times \mathbf{B}) \times \mathbf{B}
\]

\[
\mathbf{T} = -\mathbf{M} |\mathbf{B}| \mathbf{\omega} = -\begin{pmatrix} T_x \\ T_y \\ T_z \end{pmatrix} \mathbf{\omega} / |\mathbf{\omega}|
\]

2.2. The magnitude of the electromagnetic torque

Electromagnetic torque is mainly determined by electromagnetic force \( \mathbf{F} \) and arm of force \( \mathbf{r} \). Electromagnetic force \( \mathbf{F} \) is related to the relative distance \( d \) and relative velocity \( v \) between the target and PMAD, and it is a complex nonlinear function [11]. So that the theoretical calculation is large and it is difficult to meet the real-time requirements in engineering. If the simplified formula with high accuracy is used, the real-time performance of the system can be greatly improved. Therefore, the electromagnetic force generated by the PMAD specifically was measured and fitted, as in equation (4). Coefficients of the simplified electromagnetic force has 95% confidence bounds.
F(d, v) = -\frac{432.5\ddot{v}}{d^2 - 82.81d + 2483} (mN) \tag{3}

In the mission of detumbling and despinning the target, the relative velocity \( \ddot{v} \) is the vector sum of the PMAD’s \( \ddot{v}_{mag} \) and the target surface’s \( \ddot{v}_{target} \), as in equation (4). The size and direction of \( \ddot{v}_{mag} \) are determined by the angular velocity and the attitude of PMAD relative to the body coordinate system. \( \ddot{v}_{target} \) is the vector sum of three components.

\[ \ddot{v} = \ddot{v}_{target} - \ddot{v}_{mag} \tag{4} \]

\[ \ddot{v}_{target} = \ddot{v}_x + \ddot{v}_y + \ddot{v}_z = \ddot{\omega}_t \times \dddot{r}_a + \dddot{\Omega} \times \dddot{R}_{cy} \tag{5} \]

Where \( \ddot{\omega}_t \) is the transverse angular velocity; \( \dddot{\Omega} \) is the spin angular velocity; \( \dddot{R}_{cy} \) is the radius of target; \( \dddot{r}_a \) is the distance from the point of the electromagnetic force to \( \ddot{\omega}_t \). When the target is in the tumbling motion, \( \dddot{r}_a \) is a time-varying periodic function.

2.3. The expression of the applied torque

When the detumbling torque acts directly on the target, the three components of angular velocity will decrease simultaneously. However, the nutation angle \( \tan \theta = I_t \ddot{\omega}_t / I_z \dddot{\Omega} \). In this method, it may increase first and then decrease. So measures should be taken to avoid it, otherwise the system may be unstable. Since the spinning motion equation is independent and not coupled with the tumbling motion, keeping the spin angular velocity \( \dddot{\Omega} \) constant and eliminating the transverse angular velocity \( \ddot{\omega}_t \) will make the nutation angle decrease stably. Combined with the electromagnetic torque, the dual-manipulator space robot drives the PMAD to make \( \ddot{v}_{mag} = \dddot{\Omega} \times \dddot{R}_{cy} \). So that the relative velocity of the spin axis component can be reduced to zero, as in equation (6). Consequently, the electromagnetic torque on the spin axis component is equal to zero. Therefore, we only need to consider the influence of the detumbling torque on the nutation angle.

\[ \ddot{v} = \ddot{v}_{target} - \ddot{v}_{mag} = \ddot{\omega}_t \times \dddot{r}_a \tag{6} \]

Where \( \ddot{\omega}_x, \ddot{\omega}_y, \ddot{\omega}_z \) is the component of the target’s angular velocity vector \( \ddot{\omega} \) in the body coordinate system \( \mathbf{Ox}_y y_z z_b \), as in equation(7).

\[ \ddot{\omega} = \omega_x \dddot{x}_b + \omega_y \dddot{y}_b + \omega_z \dddot{z}_b = \ddot{\omega}_t + \dddot{\Omega} \tag{7} \]

The calculation of the torque needs to obtain the relative distance \( d \) and arm of force \( \dddot{r} \) under the current state. Both parameters are periodic functions related to the tumbling motion. And, \( d = A_t \cos \Omega_\theta t + B_1 \), \( r(t) = -A_t \cos \Omega_\theta t + (R - B_1) \). According to \( \ddot{v}_i = \ddot{\omega}_t \times \dddot{r}_i \), the relative velocity \( \ddot{v} \) in equation (8) is separated by parameters, and substitute equation (3) into equation (8). The expression of the torque is obtained, as shown in equation (9).

\[ T = \dddot{r} \times \dddot{F} = -r(t) \cdot F(d, v) \cdot \frac{\ddot{\omega}}{\dddot{\omega}} (mN \cdot mm) \tag{8} \]
\[ T = -f(r,d) \cdot r(t) \begin{bmatrix} \dot{\omega}_x \\ \dot{\omega}_y \\ 0 \end{bmatrix} \]  

(9)

Where, \( r(t) \) is a periodic function related to tumbling motion, and \( r(t) = A_2 \cos \Omega t + B_2 \). In addition, \( f(r,d) \) is a time-varying function of relative distance \( d \) and arm of force \( \vec{r} \), which is determined by geometric parameters.

\[
 f(r,d) = \frac{432.5 \cdot (-A_4 \cos \Omega t + (R - B_3))}{C_1 \cos^2 \Omega t + C_2 \cos \Omega t + C_3}
\]

(10)

Where \( A_1 = 42.97 \), \( B_1 = 82.81 \), \( A_2 = 176.72 \), \( B_2 = 195.63 \), \( C_1 = A_1^2 \), \( C_2 = 2A_1B_1 - 82.81A_1 \), \( C_3 = B_1^2 - 82.81B_1 + 2483 \), \( R = 873.21 \).

3. Simulation verification and analysis

3.1. Dynamics of the target

The spacecraft is usually weighted before launch, and the inertia of each axis are similar. Therefore, the target can be simplified to a dynamical symmetric cylindrical rigid body. The mass and related motion parameters of the spacecraft are shown in table (1), and the inertia matrix is shown in equation (11).

| Features         | Values          |
|------------------|-----------------|
| Geometry         | \( R_y 750mm \times L1000mm \) |
| Mass             | 1378.55kg       |
| Spin angular velocity | 20degs\(^{-1}\) |
| Nutation angle   | 20deg           |

\[
 I = \begin{bmatrix} I_x & 0 & 0 \\ 0 & I_y & 0 \\ 0 & 0 & I_z \end{bmatrix} = \begin{bmatrix} 3.087 \\ 3.087 \\ 3.877 \end{bmatrix} \times 10^7 \text{(kg \cdot mm}^2) \]

(11)

3.2. Attitude motion analysis and simulation

First, the attitude angle about the body coordinate system is used to describe the attitude of the target in the inertial coordinate system. According to the Euler equation, the attitude dynamics equation of the target is shown in equation (12). Then the expression of the nutation angle can be obtained, as in equation (13). It is worth noting that this equation has made some mathematical simplification, which cannot be used to calculate the magnitude of instantaneous nutation angle. In equation (13), \( \Delta \Omega t \) is a periodic part whose amplitude does not drift with time, and meanwhile the other part is a negative exponential form, which will cause the nutation angle to decrease stably with time. Therefore, the system is stable and effective. The dynamics model and the control model are established respectively in ADAMS and SIMULINK. The Co-Simulation results are shown in figure 3, 4. The transverse angular velocity \( \omega_x, \omega_y \) decrease to zero gradually, and the nutation Angle decreases stably without fluctuation, as in figure 5. Results are consistent with the theoretical analysis. When the transverse
angular velocity becomes zero, the nutation angle also turns to be zero, and the target is changed from tumbling motion to spinning motion.

Then, PMAD’s rotation axis is controlled to be parallel to the angular momentum axis of the target. So that the despining torque is in the opposite direction to the spin angular velocity, as in figure 6. When the angular velocity is greater than 1deg/s, the torque is maintained to be a constant. And when the angular velocity is less than 1deg/s, the PMAD will no longer rotate. The despinning torque will only depend on the residual spin angular velocity of the target. The mission is completed.

\[ \dot{\mathbf{\omega}} + \Omega \cdot \mathbf{\omega} = \mathbf{\varepsilon} \cdot \mathbf{\omega} \]
\[ \dot{\mathbf{\omega}} = 0 \]

Where \( \Omega = \frac{I - I_f}{I_f} \), \( \mathbf{\varepsilon} = -\mathbf{f} \cdot \mathbf{r}_a \cdot \mathbf{r}_i / I_f \).

\[ \mathbf{\theta} = \frac{\lambda \Omega}{\mathbf{r}_a(t) \mathbf{B}_i / I_f - \lambda \Omega} \mathbf{\omega}_i(0) e^{-\frac{B_i}{\mathbf{\lambda}(t)} + \lambda \Omega t} \]

Comparing with other contactless methods. As for the mission time, the scheme of PMAD spends about 3.4h, while the ion beam and the electrostatic method take about 680h and 170h, respectively. And as for the cost of mission. The electromagnetic coil requires the support of the control system, and the power consumption is large. The compressed gas will consume a large amount of fuel, which limits its application. Since the PMAD’s weight is about 7kg, its launch cost will be high. But it can work constantly after the successful launch. Therefore, the scheme of the PMAD is safe, reliable and highly cost effective.

Figure 3. The Component \( \omega_x \) of angular velocity \( \mathbf{\omega} \).

Figure 4. The Component \( \omega_y \) of angular velocity \( \mathbf{\omega} \).
4. Conclusion and future work
This paper proposed an electromagnetic scheme based on the PMAD. Dual-manipulator space robot equipped with PMAD approaches the target at a distance of about 30mm. Then the target is detumbled and despanned. This scheme is a significant exploration in non-contact methods. The future work will focus on the attitude control of the manipulator, the dynamic attitude research on the inertia asymmetric target and the change trend of nutation Angle.

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