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Prospects of using a permanent magnetic end effector to despin and detumble an uncooperative target

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Abstract

Space debris, such as defunct satellites and upper stages of rockets, becomes an uncooperative target after losing its attitude control and communication ability. In addition, tumbling motion can occur due to environmental perturbations and residual angular momentum prior to the object's end-of-mission. To minimize the collision risk during docking and capturing of the tumbling target, a non-contact method based on the eddy current effect is put forward to transmit the control torque to the tumbling target. The main idea is to induce a controllable torque on the conducting surface of the tumbling target using a rotational magnetic field generated by a Halbach rotor. The radial and axial Halbach rotors are used to damp the spinning and nutation motions of the target, respectively. The normal and tangential force are evaluated concerning the relative pose between the chaser and the target. A simplified dynamic model of the nutation damping and despinning processes is developed and the influences of the asymmetrical principal moments of inertia and transverse angular velocity are discussed. The numerical simulation results show that the designed Halbach rotor stabilized the target attitude within an acceptable time. The electromagnetic nutation damping and despinning method provides new solutions for the development of on-orbit capture technology.

Keywords: Uncooperative target; Despin and detumble; Eddy current effect; Halbach rotor

1. Introduction

As a result of decades of the exploration of outer space, an increasing number of mission-relevant spacecrafts and upper stages of rockets remaining in orbit become uncooperative targets and float freely after the end of their missions. These uncooperative targets, usually called space debris, pose a great hazard to operational satellites due to collision risks and the "Kessler syndrome" chain effect (Liou, 2011; Shan et al., 2016). Therefore, the active removal of space debris is essential to control its number and reduce the associated risk. Due to the environmental perturbation torque and residual angular momentum prior to the object's end-of-mission, a tumbling motion can occur in an uncooperative target. The measured spin velocity of space debris varies from 1°/s to several tens of degrees per second (Praly et al., 2012; Lin and Zhao, 2015). The direct contact or grabbing of space debris with high spin rates by a robotic end effector cannot be achieved easily because the robotic arm has limited abilities regarding the position or velocity tracking (Flores-Abad et al., 2014). Therefore, much attention has been focused on the active detumbling of uncooperative space debris prior to capture to stabilize its attitude and facilitate the subsequent on-orbit service or deorbit missions (Fabacher et al., 2017; Ao et al., 2017; Hughes and Schaub, 2017; Hovell and Ulrich, 2017; Flores-Abad et al., 2017).

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Many nutation damping methods for uncontrolled satellites have been proposed, including contact (Matunaga et al., 2001; Nishida and Kawamoto, 2011; Wang et al., 2015; Bylard et al., 2017; Yudintsev and Aslanov, 2017; Meng et al., 2017) and non-contact methods. A direct contact between the target and the end effector might result in a large impact on the chaser if the spin rate of the target is very high. Also, using a tethered detumbling system might entangle the target and the chaser and complicate the attitude control algorithm (O'Connor and Hayden, 2017; Jaworski et al., 2017). Therefore, noncontact methods are preferred to reduce the collision risk during detumbling. Many noncontact nutation damping concepts have been proposed including an electrostatic force (Schaub and Sternovsky, 2014), an electromagnetic force (Kadaba and Naishadham, 1995; Caubet and Biggs, 2014), an ion thruster (Bombardelli, and Pelaez, 2011), a thruster plume impingement (Nakajima et al., 2016), and laser ablation (Kumar and Sedwick, 2015). Among these methods, the electromagnetic detumbling methods have attracted much attention because the electromagnetic force has been widely used in cooperative space missions, such as the concept of electromagnetic formation flying (EMFF) (Huang et al., 2014) and magnetic torques used for the attitude control of small satellites (Roldugin and Testani, 2014). Using the electromagnetic force for uncooperative target detumbling, Sugai et al. (2013) proposed an electromagnetic detumbling concept using coils to construct a moving source field but the air gap between the chaser and the target when using traditional coils is several millimeters, which limits its application. To increase the magnetic field intensity and generate a time-changing magnetic field, the concept of using high-temperature superconducting (HTS) coils with a radius of several meters was studied by Gómez and Walker (2015a, 2015b). The key component of electromagnetic detumbling or despinning is to create a moving or time-changing magnetic field relative to the target surface, thereby inducing a damping eddy current force and torque. When an electromagnetic coil is used as the source field, three-phase windings or HTS material could be used and the driving and control system might complicate the structure. In this study, the concept of using permanent magnetic (PM) arrays to despin and detumble a target is proposed. Compared with electromagnetic coils, the detumbling end effector consisting of rotational PM arrays has a simple structure and provides high magnetic field intensity. An eddy current force on the order of 0.1 N can be achieved at a separation distance of 0.1 m. Good linearity between the force and rotational velocity at low speed can be obtained, which is convenient for the controllability and ease of experimental verification for this proof-of-concept design.

Compared to the noncontact detumbling methods using an electrostatic force, ion thruster, thruster plume impingement, or laser ablation, the detumbling force created by a time-changing electromagnetic field is composed of the tangential and perpendicular component relative to the target. The influences of this coupling effect together with the non-symmetrical inertia matrix and transverse angular velocity disturbances on the stability of the target attitude are investigated. When the structure is integrated into a robotic end effector, the collision risk can be avoided by the non-contact nature and the active control of the dexterous robotic arm. In this study, two kinds of end effectors consisting of rotational PM arrays are proposed to damp the nutation angle and spinning velocity of the target. An axial flux Halbach rotor is used to damp the nutation angle passively and a radial flux Halbach rotor is used to despin the target. The two different magnetic flux directions cannot be achieved by a single type of magnet array. However, it is possible to assemble the two ring-shaped PM arrays into one end effector and the integrated co-axial structure can be either the axial magnetic coupling or the radial magnetic coupling as depicted in Li et al., (2017). After stabilization of the target, the PM array can be replaced by a grab end effector to capture the target satellite.

The remainder of the paper is organized as follows. The despinning and detumbling concepts using the rotational PM end effector are introduced in Section 2. Subsequently, the theoretical models of the electromagnetic force and the torque and attitude dynamics of the detumbling system are developed based on the single-side linear motor theory. The detumbling process simulation is conducted afterwards. Section 4 describes the simulation results and discusses the influences of non-symmetrical target inertia matrix and the transverse angular momentum component. Finally, the conclusions are drawn in Section 5.

2. Despinning and detumbling concept using rotational PM end effector

The tumbling motion of an uncooperative target depends on the residual angular momentum when it first becomes passive. If energy dissipation components exist onboard the uncooperative target, the rotation states eventually result in a steady spin about its major axis (Kaplan et al., 2010). Therefore, the tumbling motion of an uncooperative target can be classified into two types, which are single-axis spinning with a fixed angular velocity and 3-degree-of-freedom (DOF) free tumbling with time-changing angular velocity (Ge et al., 2017). In order to detumble the target dexterously within the functional working distance of the robotic arm, two types of rotational PM end effectors are designed and integrated into the end effector to accomplish the despinning and detumbling tasks. The rotational PM end effector consists of PM arrays and the driving motor to rotate the PM array. Assuming that the uncooperative target is an oblate rigid body with conducting surfaces, the relative orientation and time-varying attitude are considered in the following design of the despinning and detumbling strategies.

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