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Prospects and challenges of touchless electrostatic detumbling of small bodies

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Abstract

The prospects of touchlessly detumbling a small, multiple meters in size, space object using electrostatic forces are intriguing. Physically capturing an object with a large rotation rate poses significant momentum transfer and collision risks. If the spin rate is reduced to less than 1 deg/s, relative motion sensing and control associated with mechanical docking becomes manageable. In particular, this paper surveys the prospects and challenges of detumbling large debris objects near Geostationary Earth Orbit for active debris remediation, and investigates if such electrostatic tractors are suitable for small asteroids being considered for asteroid retrieval missions. Active charge transfer is used to impart arresting electrostatic torques on such objects, given that they are sufficiently non-spherical. The concept of touchless electrostatic detumbling of space debris is outlined through analysis and experiments and is shown to hold great promise to arrest the rotation within days to weeks. However, even conservatively optimistic simulations of small asteroid detumbling scenarios indicate that such a method could take over a year to arrest the asteroid rotation. The numerical debris detumbling simulation includes a charge transfer model in a space environment, and illustrates how a conducting rocket body could be despun without physical contact.

Keywords: Remote electrostatic despin; GEO debris servicing; Asteroid retrieval

1. Introduction

Active orbital debris remediation is a challenging mission concept that often requires an active servicing vehicle to approach and mechanically interface, such as dock or tether, with a defunct target object (Couzin et al., 2013; Ogilvie et al., 2008; Xu et al., 2011). If the target object is in an uncontrolled tumble with excessive rotational kinetic energy, the mechanical interface phase becomes impractical, impossible with current technology, or hazardous for the servicing craft. References Karavaev et al. (2004) and Papushev et al. (2009) discuss the observed spin rates of debris in the Geostationary Earth Orbit (GEO) neighborhood ranging from 1–2 deg/s to many 10s of degrees per second. The advanced docking solutions being developed by MacDonald, Dettwiler and Associates (MDA) require the object to be rotating less than 1 deg/s (Couzin et al., 2012). Considering these challenges, a touchless method of detumbling is highly desirable, and would facilitate both orbital debris and orbital servicing missions with tumbling objects. In addition, NASA has recently considered retrieving a small asteroid 10s of meters in size, and returning it to the near-Earth environment. However, a significant challenge of such a mission is how to capture the tumbling asteroid. This raises the question of whether the electrostatic debris detumbling method could be applied to the small asteroid problem.

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Electrostatic actuation has been proposed as a touchless tugging solution for uncontrolled GEO debris objects (Schaub and Moorer, 2010; Moorer and Schaub, 2011b,a). More recently, fast numerical electrostatic torque models were developed to explore applying electrostatic torques on a passive object (Stevenson and Schaub, 2013a,b; Schaub and Stevenson, 2012). Touchless electrostatic detumble, illustrated in Fig. 1, requires the servicing craft to actively control the electrostatic potential of both space objects in order to impart control forces and torques. The servicing vehicle controls its own potential through use of an electron and/or ion gun. Charge control of the target object is achieved by direct charge beaming from the servicer. As seen at the top of Fig. 1, the servicing craft charges the target to attract the closest receding feature and repel the closest approaching feature of the tumbling target and detumble the target over time. Spacecraft charging, which enables electrostatic forces and torques, requires the nonlinear current balance methods described in the following sections.

This paper summarizes the challenges of performing an electrostatic detumble, including the development tools and implementation tasks that need to be addressed. For two spacecraft flying multiple craft radii apart, the electrostatic interaction is influenced by both the relative pose and the surface-charging dynamics. Electrostatic forces and torques are dictated by the complex and nonlinear effects of the relative electrostatic potential between the two craft. In a vacuum, these effects can be accurately determined using finite element methods; however, such computationally slow methods are not suitable for real-time spacecraft control, or faster-than-realtime numerical analysis. Spacecraft charge modeling for real time control applications is accomplished by the Multi-Sphere Method (MSM), introduced and explored by Stevenson and Schaub (2013a). MSM approximates the spacecraft charge distribution for a given surface potential by discretizing the spacecraft with representative conducting spheres held at the spacecraft potential. The effectiveness of electrostatic detumbling is further influenced by charging dynamics in the space environment. The control range is dictated by the Debye length, which is a property of the space plasma that restricts electrostatic spheres of influence. In High Earth Orbit (HEO) and GEO orbits the effective Debye length is on the order of hundreds of meters (Denton et al., 2005; Murdoch et al., 2008; Stiles et al., 2012), allowing control over dozens of meters. Current research is addressing the challenge of creating appropriate reduced-order analytical models of the charge transfer and control in the space plasma (Schaub and Sternovsky, 2013). Prior research demonstrates the sensitivity of charge control to relative size and geometry of the two craft (Hogan and Schaub, 2014c). The natural charge and discharge experienced in orbit (Hogan and Schaub, 2014b), the capability and limitations of charge transfer devices, and the material properties of the spacecraft.

Several other methods to touchlessly actuate an uncontrolled object have been investigated. One is the

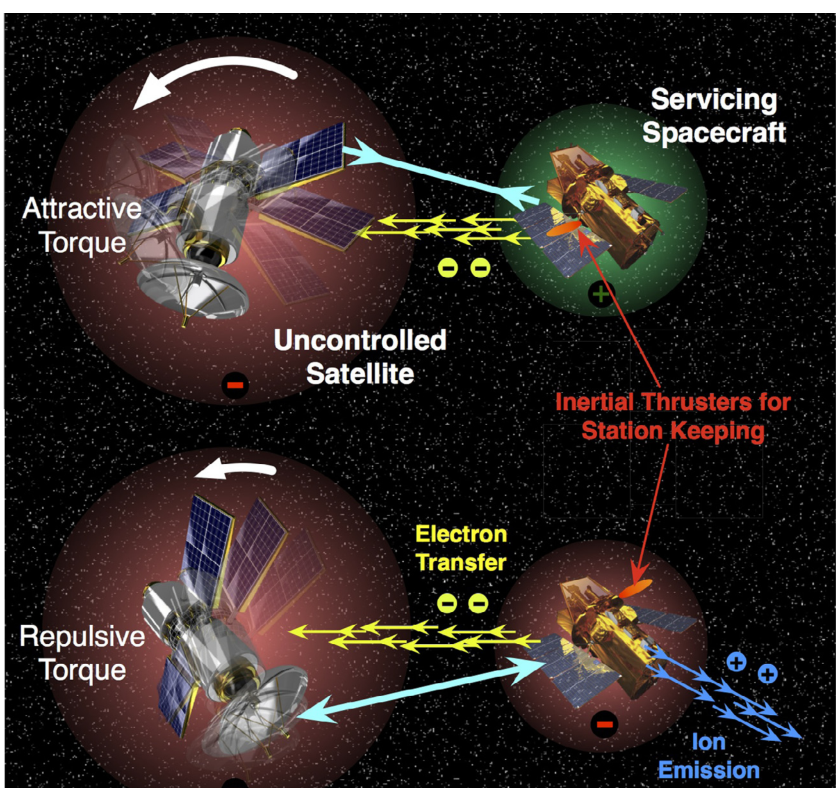


Fig. 1. Electrostatic actuation technology enabling diverse service mission profiles.

ion-sheppard method (Bombardelli and Pelaez, 2011; Kitamura et al., 2012; Bombardelli et al., 2011), where a focused exhaust cone of an ion engine is directed at the object to push it. While this approach avoids physical contact with the spinning object, the time-varying orientations will cause strong departure motions as the ion-exhaust is deflected away from the push-axis. Further, if the exhaust center of pressure is not directed at the object's center of mass, it will spin up or down. This rotational control could be used to despin a space object intentionally. However, imprecise knowledge of the exhaust characteristics and the exhaust deflecting off time-varying surfaces could render this spin control very challenging. Similarly, laser ablation applied to the deflection and attitude control small asteroids has also been considered where the ejecta acts as a propulsive force (Vatrisano et al., 2015). Laser ablation techniques are also applicable to debris detumble (Smith et al., 2013;Vetrisano and Vasile, 2013). While laser ablation is a touchless method, the target object is the fuel source which may generate additional debris particles. The electrostatic detumble method does not produce any additional particles or fragmentation which may be advantageous. An alternate method for touchless detumble is to use magnetic fields emitted from a chaser vehicle to impose braking eddy current torques on a foreign objects (Gómez and Walker, 2014; Sugai et al., 2013). This approach would require very close proximity operations and is reliant on a fully conducting foreign object.

In summary, this paper provides an overview of the exciting prospects and challenges of the ability to touchlessly detumble large space debris using electrostatic actuation, and investigates if this technology is feasible for small asteroid detumbling. Further, the question of employing this method to the asteroid detumbling problem is investigated. While each type of object has its unique set of challenges, there is also great commonality in the general tools required to analyze the complex charged relative motion and predict detumbling performance. This study identifies the core challenges in modeling the electrostatic interaction of space objects, charge transfer in the space environment, and the associated control algorithms. To demonstrate these concepts, new numerical simulations as well as proof of concept experiments are presented.

2. Overview of electrostatic detumble challenges

Table 1 provides an overview of the current challenges and investigations relevant to electrostatically detumble both GEO debris and small asteroids. The study is restricted to the GEO and deep space environments where the Debye length is sufficiently large for separation distances of several craft radii. Subsequent sections detail and discuss the challenges presented and offer current research and application methods. This study assumes a spherical conducting servicer spacecraft that uses charge control devices, has the necessary sensing capabilities, and implements relative motion control.

3. Challenges and prospects in GEO applications

3.1. Electrostatic charging

This study utilizes a charging model that accounts for the numerous current sources experienced by a satellite in the space environment by incorporating space weather conditions adapted from observed values at GEO. The electrostatic interaction is dependent on the charging that occurs on both spacecraft, which is influenced by several factors. Naturally occurring ion and electron plasma currents are collected by the spacecraft, and photoelectrons may be emitted depending on the spacecraft potential and presence of sunlight. Focused electron beam emission by the servicer

Table 1
Overview of electrostatic detumble challenges.

Challenge	GEO relevance	Asteroid relevance
CHARGE GENERATION & TRANSFER	Use focused electron and ion beams on tug to control charging of both objects	Similar to GEO debris with additional unknowns (see other challenges)
EXPECTED CHARGE LEVELS	Determined by calculating current balance. Use GEO space weather for plasma interaction. Charge sensing unnecessary because controller design is robust to uncertainties	Larger uncertainty in charge levels because of unknown asteroid material interaction with charge beams and space plasma. Deep space weather conditions
TUMBLING BODY MATERIAL PROPERTIES	Fully conducting spacecraft bus, various surfaces with differing properties	Non-uniform rocks and metals with unknown densities and conductivities, loose material possible on surface
TUMBLING BODY GEOMETRY AND INERTIA	High aspect ratio, well known geometry, comparable inertias to tug	Aspect ratios less than 2, usually unknown geometry, inertias orders of magnitude larger than tug
SENSING OF TUMBLING BODY	Accurate knowledge of the foreign object's attitude and relative position is necessary for proper charge control and station keeping. LIDAR or structured light sensors considered	Equivalent sensing methods are necessary, with the additional challenge of asteroid geometry uncertainty. Estimation of system properties may be possible
RELATIVE MOTION	Relative position movement due to Earth's gravitational field, may be harnessed to optimize torques. Thruster plume impingement must be considered. Separation distance is a tradeoff between torque generation and collision risks	Mutual attraction may influence relative orbits. Large discrepancy in size between tug and asteroid presents additional station keeping challenges. Autonomy is only option due to excessive communication distances

is used for charge control. When the electron beam is absorbed by the target object, secondary electron emission occurs as the incoming beam electrons excite and release electrons from the target surface material. The potential levels achieved by the two craft result from a balance of these various current sources, as computed by the charging model outlined by Schaub and Sternovsky (2013).

For the conducting servicer, the charging is dominated by the plasma electron current and electron beam emission. The servicer potential ϕ_S settles to a value that satisfies the approximate current balance $I_e(\phi_S) + I_t = 0$ where I_t is the actively emitted servicer current, and I_e is the environmental electron current imparted onto the servicer. This is solved analytically as

$$\phi_S = \left(\frac{4I_t}{Aqn_e w_e} - 1\right) T_e \tag{1}$$

which assumes a positive servicer potential. The servicer current balance equation remains an accurate approximation provided the beam current is the dominant current source. Full details of this GEO servicer potential approximation are found in Hogan and Schaub (2014a). The current balance on the debris object contains several more contributions, and an analytical solution does not exist. The debris potential ϕ_D is found by numerical root-solving this current relationship:

$$I_{\text{Tot}} = I_e(\phi_D) + I_i(\phi_D) + I_{\text{SEE}}(\phi_D) + I_{ph}(\phi_D) + I_D(\phi_D) = 0 \tag{2}$$

Here I_e represents the plasma electron current, I_i represents the plasma ion current, I_{SEE} is the secondary electron emission, I_{ph} is the photoelectron current, and I_D is the absorbed current from the electron beam emitted by the servicer. The presence of the photoelectron current implies the debris is in the sunlight. When in the Earth's shadow, the current balance contains all of the same terms except for I_{ph}.

3.2. Electrostatic force and torque modeling

In order to develop stabilizing charge feedback controls for the touchless spacecraft detumble, reduced-order analytical and numerical charged relative motion dynamics models must be developed. No simple analytic solution exists for the exact electrostatic interaction between charged conductors with generic geometries. Several options exist for the numerical modeling of spacecraft charging and interactions, including finite element, finite difference, boundary element, and Monte Carlo methods (Gibson, 2007; Sadiku, 2009). Each of these approaches, however, are too computationally expensive to allow for faster than real time simulations of the electrostatically influenced relative motion dynamics.

Simpler methods, such as the point charge approximation and finite sphere model, have been used for Coulomb charge control analysis in the past (Seubert and Schaub, 2010; Jasper and Schaub, 2012; Hogan and Schaub, 2013). These are limited to line-of-site forces and are not capable of predicting electrostatic torques. The recently developed Multi Sphere Model (MSM) (Stevenson and Schaub, 2013a) uses a set of conductive spheres throughout the geometry of a spacecraft to capture the 3D electrostatic effects. Specifically, Stevenson and Schaub (2013a) provide detailed analysis of the interaction between a charged cylinder and a sphere as depicted in Fig. 2. The cylinder shape is representative of many upper stage rocket bodies such as the Centaur, which may experience a tumbling motion that must be removed if any spacecraft wishes to perform a docking maneuver. The 3-sphere MSM charge distribution presented in Stevenson and Schaub (2013b) for the cylinder in Fig. 2, at separation distances considered by this survey, agrees on the order of 1% with commercial finite element analysis (FEA) software: Maxwell 3D. Capitalizing on the charge accuracy, the 3-sphere MSM cylinder system is used to study the detumble control concepts that are the basis of this manuscript.

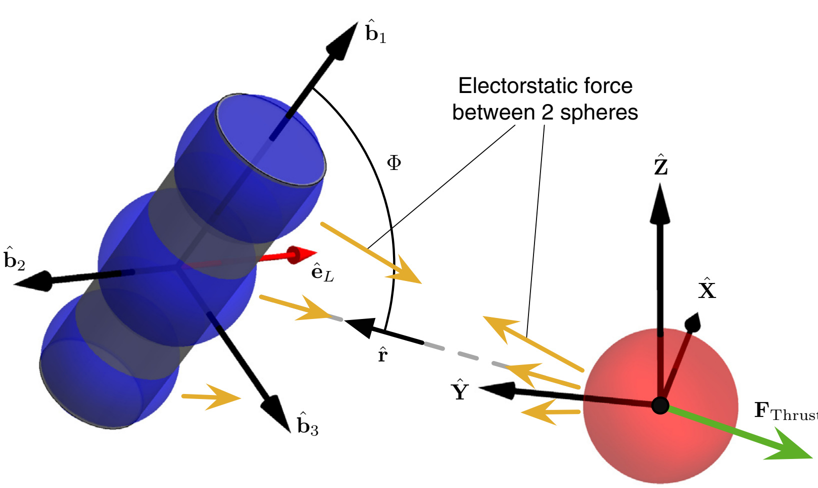


Fig. 2. Free body diagram for MSM cylinder-sphere system. The symmetrical axis projection angle is shown as Φ.

The MSM relies on the mutual capacitance relationship between charged spheres. Assuming a known potential is prescribed on each of the n spheres in the system, a linear system of equations can be constructed to relate the charges on the spheres to their potentials. Once this system is solved, Coulomb's law is used to determine the total force on each sphere, which sum to yield the total force and torque acting on each spacecraft. The choice of a spherical servicer with one sphere results in no torque on the servicer, even though the debris' rotational momentum is changed. However, the servicer must apply station keeping thrust to maintain a fixed position relative to the tumbling cylinder. Torque is expected when a servicer is modeled by additional spheres.

3.3. Electrostatic tractor power requirements

The power requirements for GEO detumble applications are only a few Watts, and easily reside within operating power limits available to GEO spacecraft. The power draw of active charge control is the product of the beam energy and current supplied. Explored extensively by Hogan and Schaub (2014c,b) are optimal beam currents and resulting electrostatic forces and torques. Power requirements in the neighborhood of 40 W are demonstrated for admissible servicer to debris size ratios if only an electron beam is employed. If both electron and ion emission methods are employed, the power requirements can reach 100s of Watts. Power draws of this magnitude do not present significant pressures on concept realization, as the power generation levels of typical GEO spacecraft can easily reach 25 kW.

3.4. Debris geometry and inertia

Mission success depends on the reduction or elimination of debris object rotational momentum. Such momentum is a direct function of the debris' geometry and inertia properties. The challenges are therefore twofold for mission design applicable to generic geometries. First, large shape protrusions such as solar arrays may interfere with proximity safety, restrict relative motion trajectories, or inhibit active charge transfer capability. However, such spacecraft geometry may be favorable to the detumble application as large torque moment arms amplify the electrostatic force effect. The servicer relative motion may be designed for debris geometry avoidance with the opportunity to increase detumble effectiveness.

Second, symmetric inertia properties may introduce momentum characteristics and detumble behavior complexities. An instance explored by Bennett and Schaub (2014) demonstrates that axi-symmetric bodies restrict what amount of the momentum can be removed. Electrostatic torques about the conducting body's axis of symmetry are impossible, resulting in incomplete reduction of the debris object's total momentum. Removal of the remaining rotation might be possible by creating differential potentials across the surface. For instances with full coupling and no shape symmetry, the reduction in angular momentum is more complete, thus achieving more desirable steady states. The axi-symmetric concern is less hindering for geometries with symmetry around the minor-axis of inertia. For example, a rocket body that has a slender axis spin to deploy a payload will begin to tumble in the presence of perturbations (an insight gained by Explorer 1). The initial maximum energy spin will transition to the lower energy tumble about the larger controllable inertia axes. The inclusion of perturbations in the detumble study would negate the minor-axis spin limitation.

3.5. Debris material properties

Inherent in the charge distribution modeling of a spacecraft via MSM techniques are the assumptions about material properties. The simulations and discussion in this study assume that the debris object is fully conducting, thus ensuring that a uniform potential can be achieved. Introducing di-electric debris surface materials will alter how the MSM models can be applied, and is still an area of on-going research. The charging behavior of dielectrics, combinations of conducting and insulating, and non-uniform conductors complicates the rapid numerical predictions of electrostatic detumble performance.

3.6. Relative motion sensing and control

Application of electrostatic actuation to debris detumble scenarios assumes that the debris object is non-cooperative. This places all station keeping and relative motion control responsibility on the servicer craft. The uncertainty in material properties and geometry, as well as any factors influencing charge control must be considered when designing robust controllers. Candidate position station-keeping control solutions have been proposed by Hogan and Schaub (2013), but these focus uniquely on the position control while electrostatically actuating the debris.

Assuming the debris-servicer electrostatic force is $\boldsymbol{F}_1$, the servicer will require a nominal open-loop thrusting force $\boldsymbol{F}_{\text{thrust}}$ to maintain a constant relative position:

$$\boldsymbol{F}_{\text{thrust}} = -\boldsymbol{F}_1\left(1 + \frac{m_1}{m_2}\right) \tag{3}$$

Thus, depending on whether attractive and repulsive forces are considered (both electron and ion emission), or only attractive forces (electron beam only), the 2-body system will be subject to secular drift.

Station keeping servo controls often have feedforward and feedback components. Here the feedforward part would be the expected electrostatic tractor force $\boldsymbol{F}_1$. However, care must be taken with the closed-loop gains for the feedback control acting in conjunction with this feedforward control. If the electrostatic force magnitude is uncertain, underestimating this force can lead to bifurcations in the resulting charged closed-loop dynamics (Hogan and Schaub, 2013). Thus, it is important to consider conservative upper bounds when implementing this station keeping control law.

3.7. Sensor suite

A servicer craft will require a proximity operations sensor suite to enable sensing of both the debris's relative position and orientation. Of primary concern is the inter-spacecraft range as it ensures a safe separation distance as well as properly predicting electrostatic force magnitudes. Relative motion accuracy only has to be in the 10s of centimeter levels. Optical and laser ranging techniques that can provide the necessary range accuracy are currently available. In addition, the debris object geometry, attitude, and tumble rates are to be supplied to the detumble controller. Knowledge of the debris attitude is crucial in order to apply the correct polarity charge control. For non-cooperative objects, attitude information and tumble rates can be acquired using structured light, visual flow methods, or flash LIDAR sensors.

3.8. Servicer thrusting consideration

The servicer's inertial thrust levels need to be in the milli-Newton range to balance the equivalent electrostatic forces, and must operate continuously over a period of weeks. It is important that the inertial thrusting solution does not interfere with the electrostatic tractor performance. That is, the charge and momentum flux must not impinge on either. This could be achieved by using neutral gas thrusters, or select types of electric propulsion systems such as field-emission electric propulsion (FEEP) thrusters. In both cases care must be taken to analyze the coupled thruster emission flow subject to the charging on the debris and servicer. Alternatively, a pulse-width modulation approach is possible, whereby the tractor is engaged while no inertial station keeping is performed. As necessary, the tractor is turned off and the thrusters are used for a finite time to perform relative position station keeping. Because it typically takes less than a second to resume the natural absolute charging at GEO, this allows for quick switching of control modes if needed. Inherently, performance may suffer depending on the duty cycle of tractor beam actuation versus inertial thrusting.

3.9. Charge control development

Developing a charge field modulation control strategy whose stability and convergence is understood for general shapes is still an area of active research. For example, no control torque can be produced on a conducting body about any axis of symmetry. However, gyroscopic rotational motion of general bodies can lead to cross-coupling where general tumbling may still be arrested.

Preliminary work has been performed considering 1-D constrained rotational motion and 3-D tumble, which are reviewed in this section. As shown in Schaub and Stevenson (2012), if the separation distance is larger than 2–3 craft radii, the potential and attitude influence on the electrostatic torque can be separated as shown in Eq. (4) where Φ represents the projection angle measure between the cylinder slender axis and the inter-spacecraft separation vector. The separated torque form is

$$L = \gamma f(\phi) g(\Phi) \tag{4}$$

The separation of the potential dependence function $f(\phi)$ and the orientation dependence function $g(\Phi)$ allows for a simplified analytic control development and analysis in-place of the matrix inversion necessary required by the MSM formulation. As shown in Bennett and Schaub (2014), approximating the MSM torque on a cylinder with Eq. (4) can introduce errors that are less than 1%. Without loss of generality, it is assumed that the non-cooperative cylinder has the same potential magnitude, that is $\phi_2 = |\phi_1|$, and is assumed to be always positive (Schaub and Stevenson, 2012). Thus, the voltage dependency function is set to:

$$f(\phi) = \phi|\phi| \tag{5}$$

The orientation angle dependency explored in Schaub and Stevenson (2012) presents Eq. (6) as the analytic representation. Bennett and Schaub (2014) also demonstrate more complicated torque surfaces at close proximity due to induced charging properties. For a cylinder, the g function is approximated through

$$g_1(\Phi) = \sin(2\Phi) \tag{6}$$

Inserting the potential and orientation dependency functions into Eq. (4) provides a separable form base function to approximate the MSM torque profile.

The following development leads to a rotation rate control to reduce or eliminate the cylinder's tumbling motion. A fixed separation distance is maintained using a continuous station keeping servo. The charging controller assumes the projection angle Φ and angle rate $\dot{\Phi}$ are measured and the servicing spacecraft potential ϕ_1 is the control variable as introduced in Schaub and Stevenson (2012). Generalized for 3-D rotation of a cylinder, the control law $f(\phi_1)$ is:

$$f(\phi_1) = -\mathrm{sgn}\left(\sum_{m=1}^{n} g_m(\Phi)\right) h(\alpha\dot{\Phi}) \tag{7}$$

where $\alpha > 0$ is a constant feedback gain and the function h is chosen for stability such that:

$$h(x)x > 0 \quad \text{if } x \neq 0 \tag{8}$$

Tumble rates that tend toward infinity necessitate a limit on physical potential. The h function proposed by Schaub and Stevenson (2012) smoothly limits, or saturates, the control at a maximum potential. Defining the h function as

$$h(\alpha\dot{\Phi}) = f(\phi_{\max})\frac{\arctan(\alpha\dot{\Phi})}{\pi/2} \tag{9}$$

demonstrates

$$\lim_{\dot{\Phi}\to\pm\infty} f(\phi_1) = \begin{cases} \pm f(\phi_{\max}) & \text{if } \sum_{m=1}^{n} g_m(\Phi) \neq 0 \\ 0 & \text{if } \sum_{m=1}^{n} g_m(\Phi) = 0 \end{cases} \tag{10}$$

As α tends to infinity, the saturation controller presented in Eq. (9) becomes the bang-bang controller

$$h(\alpha\dot{\Phi}) = f(\phi_{\max})\operatorname{sgn}(\dot{\Phi}) \tag{11}$$

The stability of this 1D despin control algorithm is discussed in detail in reference Bennett and Schaub (2014). Even with saturation considerations in the control potential being applied, asymptotic spin stability about the zero spin condition is achieved. Further, this control is shown to be robust to electrostatic force modeling uncertainties, as long as the potential sign is correctly modeled.

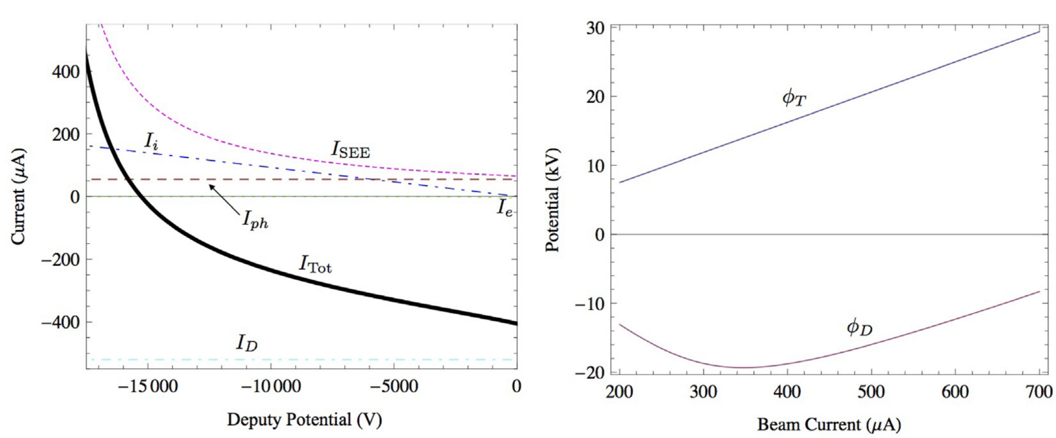
The formulation presented assumes a zero nominal potential, i.e. only detumbling is desired and no simultaneous tugging. Schaub and Stevenson (2012) further consider nominal tugging and nominal pushing potentials and explores the relative stability of all 1-D detumble. The result is that particular steady-state attitudes are achieved respective to nominal conditions. Expansion to 3-D nominal tugging and pushing is yet to be explored.

4. Analytical and experimental results for GEO-like objects

4.1. Charging studies in the GEO environment

An example charging scenario is presented in Fig. 3(a). Shown are the various currents impacting debris charging for nominal GEO space weather conditions of $n_e = 0.9\ \text{cm}^{-3}$, $n_i = 9.5\ \text{cm}^{-3}$, $T_i = 50$ eV, and $T_e = 1250$ eV. The results assume a beam energy of $E_{EB} = 40$ kV and a beam current of $I_t = 520\ \mu\text{A}$ determined to be feasible in Hogan and Schaub (2014b). Both spacecraft are treated as spheres, with radii of $r_T = 2$ m and $r_D = 0.935$ m. The deputy achieves a potential that results in $I_{\text{Tot}} = 0$. With these conditions, the servicer achieves a potential of $\phi_T = 21.5$ kV and the deputy reaches a potential of $\phi_D = -15.3$ kV. As seen in Fig. 3(a), the deputy potential results in a net zero current balance, i.e. $I_{\text{Tot}} = 0$. While the plasma electron current is included in the current balance, for the debris it provides an insignificant contribution to charging at the high potential levels achieved. The respective spacecraft potentials as a function of beam current are shown in Fig. 3(b). The servicer potential increases linearly with beam current, while the debris potential has its largest value around $I_t = 350\ \mu\text{A}$.

There are two electron beam parameters that may be used to influence charging: the beam energy and potential. Generally, a higher beam energy will result in higher debris charging. This is due to the reduced secondary electron emission that stems from the higher energy of the incoming beam electrons. As the energy of an absorbed electron increases, fewer secondary electrons are emitted. Because the secondary electrons essentially result in the loss of some fraction of the incoming beam current, reducing the number of secondary electrons emitted will improve debris charging. Thus, the beam energy is treated as constant, while the beam current is considered to be a control variable. Depending on the space weather conditions, increasing or decreasing the beam current can improve or worsen debris charging, as shown in Fig. 3(b). However, the servicer will always charge to higher potentials as the beam current is increased, up to the level of the beam energy ($\phi_T \leqslant E_{EB}$). Choosing a beam current to maximize the resulting electrostatic force requires a careful balance



(a) Currents acting on the debris (deputy) for a range of debris potentials.

(b) Servicer and debris potentials as a function of beam current.

Fig. 3. Relationship between craft potentials and currents.

between servicer and debris charging, as well as consideration of changes in space weather. Too much current will overcharge the servicer relative to the debris and result in a weaker force. Too little, and neither spacecraft will charge sufficiently.

4.2. Simulation of electrostatic detumble in GEO

A numerical simulation is performed that incorporates the active charge transfer model into a relative motion control scheme utilizing a recently developed relative orbital motion description. The debris object, represented by a 3 m long by 1 m diameter 3-sphere MSM cylinder with admissible inertias, is detumbled from an initial single axis rotation of 2 deg/s by a 2 m radius servicing spacecraft. All mass properties and control variables are detailed in Table 2. The two craft are initialized in deep space, that is without the gravitational influence of a celestial body, at a separation distance of 12.5 m and maintained by the active station keeping controller. Nominal GEO space weather conditions are used as outlined in Section 4.1. Shown in Fig. 4(d), the angular velocity of the debris object is completely and touchlessly removed in approximately 170 h.

Fig. 4(c) and (d) show the complete detumble time history while the vertical line present marks the start time of the truncated control and projection angle histories in Fig. 4(a) and (b). The smooth tangent saturation of the controller prescribes a reduced charge transfer at the end of the detumble history as the cylinder comes to rest at the final orientation with zero rotational speed. The controller does not return to the nominal zero potential in this simulation due to some numerical small residual rotation speed. However, electrostatic detumble clearly reduces the rotational kinetic energy and rotational speed to nearly zero enabling conventional methods for rendezvous and docking. Verification of the numerical results are further explored in the following experimental analysis.

Table 2
Simulation parameters for cylinder detumble system.

Parameter	Value	Units	Description
m_C	500	kg	Commanding sphere mass
R_C	2	m	Commanding sphere radius
m_D	1000	kg	Cylinder debris mass
D_D, l_D	1, 3	m	Cylinder diameter and length
I_a	125.0	kg m^2	Cylinder axial moment of inertia
I_t	812.5	kg m^2	Cylinder transverse moment of inertia
α	5×10^4	–	Gain in h function
ϕ_{max}	20	kV	Max voltage in h function

4.3. Experimental developments

In order to validate the Coulomb detumble concept, it is desirable to experimentally verify the electrostatic models and charge control algorithms. The Autonomous Vehicle Systems (AVS) lab has established an expertise in high voltage charged dynamics experiments, including

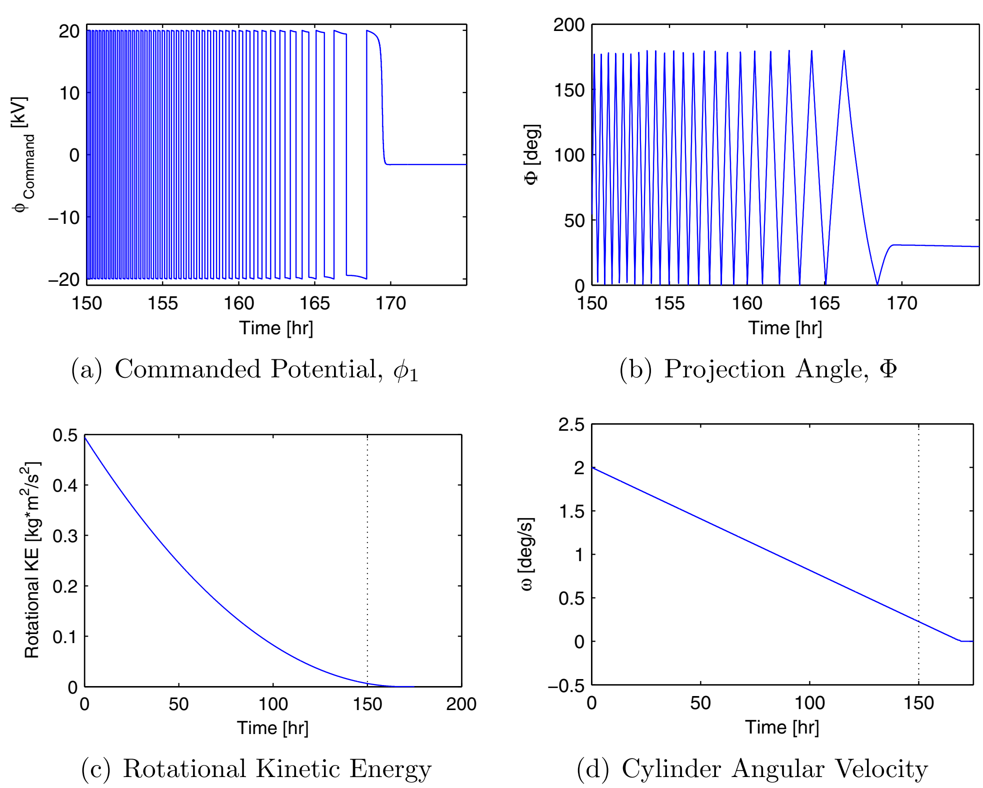


Fig. 4. Numerical simulation with initial conditions: $\dot{\Phi} = 2.0$ deg/s,$\Phi_0 = 30°$.

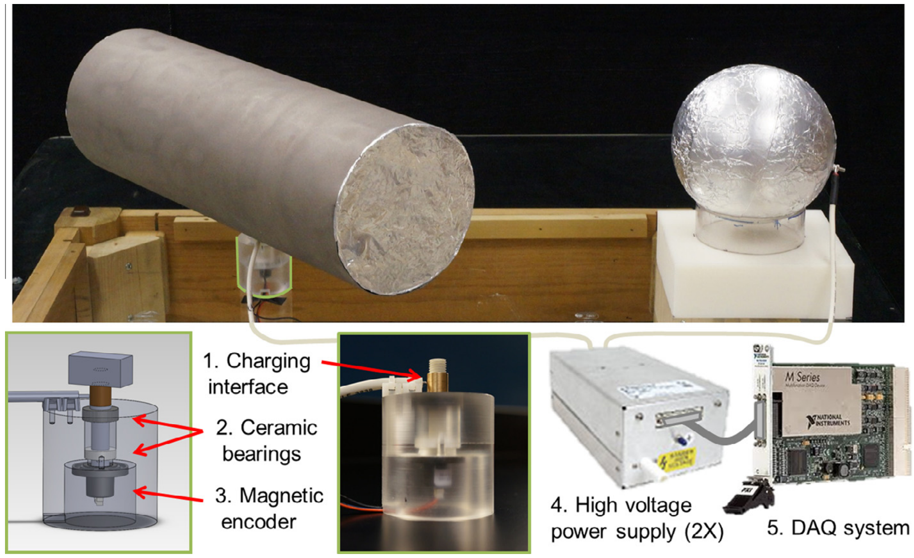


Fig. 5. Depiction of the experimental setup for charged attitude control.

Electrostatically Inflatable Membrane Structures (EIMS) research (Stiles et al., 2013) and a linear air-bearing testbed for charged relative motion experiments (Seubert and Schaub, 2009). Fig. 5 depicts the latest iteration of a rotational testbed for Coulomb attitude control experiments. The conducting surface cylinder rotates freely on a shaft constrained by two low friction ceramic bearings. Mounted to the bottom of the shaft is a directional magnet whose orientation is measured by an absolute magnetic encoder. Two high voltage power supplies are used to control the electric potential on both objects, within a range of ± 30 kV. Charge is transferred to the cylinder via the touchless interface between the charging cable and the rotating copper bushing that creates connectivity to the cylinder surface. System monitoring and control is achieved using National Instruments (NI) data acquisition components and a GUI programmed with NI Labview (Stevenson and Schaub, 2013a).

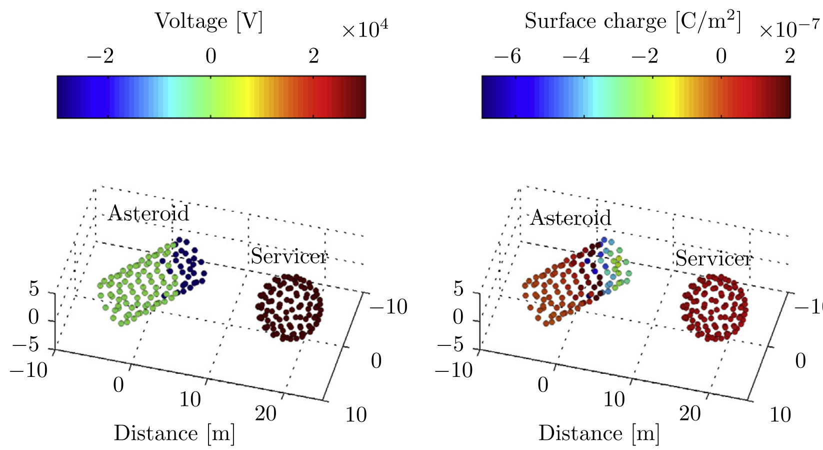
Hardware and software improvements in this experimental design allow for accurate tracking of rotation rate and exact angular position. Atmospheric drag on the rotating cylinder and the friction torque from the ceramic bearing are analytically modeled while their coefficients are empirically fit to physical results. The Coulomb torques that are produced can be modeled by the recently developed MSM technique, or approximated analytically. Nonlinear stability arguments are made for control algorithms that achieve a desired rotation rate or specific attitude control in one dimension. Besides slight deviations due to angular sensor noise, the experimental results presented in Stevenson and Schaub (2013c) match the numerical simulations extremely well. Using active charge control, a cylinder with an initial angular rate of 100 deg/s is brought to rest within 10 s, while it takes 60 s for this rotation rate to be removed by disturbance torques alone.

5. Small asteroid detumbling with an electrostatic tractor

5.1. Small asteroid capture mission considerations

In light of NASA's proposed asteroid retrieval mission (ARM), the logical question is posed whether the technology to electrostatically detumble man made objects in Earth orbit may be extended to perform a despin maneuver on a near Earth asteroid (NEA). The goal is to robotically capture a suitable asteroid within the decade and transport it to a high lunar orbit so that a crewed mission may rendezvous with it to collect and retrieve samples. According to NASA's Summer 2013 Asteroid Initiative Request for Information (RFI), "NASA is interested in concepts for systems to capture and despin an asteroid with the following characteristics: (a) Asteroid size: 5 m < mean diameter < 13 m; aspect ratio < 2/1. (b) Asteroid mass: up to 1000 metric tons. (c) Asteroid rotation rate: up to 2 rpm about any axis or all axes. (d) Asteroid composition, internal structure, and physical integrity will likely be unknown until after rendezvous and capture". A feasibility study sponsored by the Keck Institute for Space Studies proposes to capture the asteroid using a high strength 'bag' held open by several arms and a ring to constrain the asteroid position and attitude (Brophy et al., 2012). The spacecraft guidance subsystem would use Radar-Altimeter aided relative position estimates to match the surface velocity and spin state of the target during capture. Considering that these pose algorithms are largely untested, and an asteroid of the dimensions and spin rate mentioned above exhibits up to 6 MJ of rotational kinetic energy, it would be beneficial to reduce the rotation of the asteroid as much as possible.

Furthermore, a deployable capture bag is often a single attempt concept. Electrostatic tractor and detumble



(a) Prescribed voltages (b) Charge distribution

Fig. 6. Voltage and charge distribution on the servicer craft and asteroid in despin simulation.

concepts are not reliant on complex mission phases such as bag deployment, asteroid alignment, and capture. The advantages of a touchless method are evident. The following discussion provides insight into the touchless electrostatic detumble method as applied to asteroid mission concepts.

5.2. Asteroid detumble simulation

A simulation is created to estimate the time scales required to despin an asteroid with the specifications given in NASA's RFI regarding asteroid capture. Developing a realistic asteroid surface charging model is very challenging. The most optimistic case treats the surface as fully conducting. Naturally, the asteroid surface is not conducting, and only local charging of the regolith would be achieved. A balanced charging scheme where local surfaces obtain charge as described below is implemented. If this optimistic scenario leads to detumble times that are too long to be practical, it would illustrate that a more realistic charging model would only yield worse performance.

A surface populated MSM is used to determine the electrostatic interaction between a cylindrical asteroid and a nearby spherical control craft. It is assumed that the spacecraft uses a focused electron gun to induce an electric potential of -30 kV on the adjacent half of the asteroid, while using a separate charge control device pointed to deep space to maintain a $+30$ kV potential on its own body. It is assumed that the composition of the asteroid is such that the affected surface (within the field of view of the charge transfer device) will acquire the desired potential while there is sufficient insulation within the body that the rest of the asteroid maintains zero potential. The current balance for the asteroid assures that an asteroid MSM sphere not targeted by the electron gun balances to the nominal zero potential. The charge resides only on the spheres targeted by the electron gun emission. This scheme is maintained for a full rotation of the asteroid around its minor axis to determine the average achievable torque. One frame of this simulation is shown in Fig. 6, with the electrostatic potential and charge distribution visible on both bodies each populated with 107 MSM spheres.

The cylindrical asteroid is chosen to have a 12 m length and 6 m diameter, giving it a mass of 678 metric tonnes, assuming an average density of 2000 kg/m^3. The representative asteroid geometry and assumed simple density model resides in the middle of the size and weight range from the NASA RFI, with the most favorable torque aspect ratio of 2:1. The servicer craft is modeled as an 8 m diameter sphere, which is reasonable given that it is meant to capture the asteroid and transport it back to a lunar orbit. The servicer bus need not be spherical as this analysis assumes. A proposed concept would be a large inflatable sphere affixed ahead of the primary servicer bus and arrays. Such a spacecraft configuration retains insight from the assumptions made by this study. Using a surface to surface separation distance of one spacecraft diameter, an average torque of 19.5 mNm is achievable, which means that it would take 600 days, nearly 2 years, to remove one revolution per minute about the minor inertia axis of the asteroid. While adjusting certain simulation parameters might result in slight increases in performance, it is fairly unfeasible that the asteroid retrieval mission will allow for this much time for detumble operations. If long duration missions are implemented, such detumble durations can be simultaneous with a tugging effect allowing a low thrust trajectory to be simultaneously utilized. In general, the achievable torques are quite impressive and could be utilized for despin maneuvers on wayward GEO satellites in days or weeks. However, the moments of inertias involved with a rotating asteroid are simply too large, yielding detumble times of a year or longer even with the highly optimistic assumption that the surface is conducting.

6. Conclusions

This paper outlines the prospect of how an electrostatic tractor could be used to detumble a man-made space object in the geosynchronous region, and challenges that lie ahead in the technical development. Using an electron gun with an energy level in the 10s of kV, it is feasible to charge the servicer and debris to 10s of volts. This level of charging, applied to a non-spherical conducting debris object, could allow the objects to be despun over a period of days or weeks. Technical challenges include autonomous station keeping of the servicer relative to tumbling debris, robust charge control developments and relative motion sensing. While many of these technologies could also be applied to the touchless despinning of a small asteroid, the expected detumble times are orders of magnitude larger than with debris objects. The asteroid density, along with the small aspect ratios, yield an impractically small torque to inertia relationship. Models and implementation methods to apply electrostatic detumble to space objects are presented, suggesting effectiveness for GEO debris applications but unrealistic time scales for asteroid operations.

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