PROSPECTS AND CHALLENGES OF TOUCHLESS SPACE DEBRIS DESPINNING USING ELECTROSTATICS

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Touchless electrostatic actuation is investigated for actively detumbling orbital debris. Such methods are desired because physically capturing a tumbling object raises significant issues with relative motion sensing and control, collision avoidance, and the associate fuel usage. However, if the spin rate could be reduced to less than 1 degree per second, this would facilitate the use of mechanical docking concepts. The prospects and challenges of touchless electrostatic detumbling in the GEO region are discussed. Active charge transfer models and considerations in the orbital environment are presented and applied. Using kilo-Volt levels of potentials, it is feasible to reduce the spin of a tumbling upper stage rocket over a period of weeks. Numerical simulations demonstrate the effectiveness of a 1D depin control algorithm. Terrestrial experimentation and validation of the employed models are discussed.

INTRODUCTION

Active orbital debris remediation is a challenging mission concept that often requires an active servicing vehicle to approach and mechanically interface, through either a hard-dock or a tether attachment, with a defunct satellite.[1,2,3] If the debris object is in an uncontrolled tumble, the mechanical interface phase can become impractical due to demanding relative motion sensing and control accuracy requirements, collision avoidance concerns, as well as the significant fuel usage associated with close-proximity closed-loop operations. The advanced docking solutions being developed by MDA requires the object to be tumbling less than 1 degree per second.[4] Considering these challenges, a touchless method of detumbling or deorbiting is highly desirable, and would facilitate both orbital debris and orbital servicing missions.

Electrostatic actuation provides a touchless tugging solution for uncontrolled GEO debris objects[5,6,7] as illustrated in Figure 1. Using the mutual electrostatic forces shown, the debris is moved to a disposal GEO orbit over a period of 2-3 months without having to despin the satellite. However, if physical docking were feasible, the debris object could be reorbited over a shorter period, or the defunct satellite could be serviced, thereby motivating touchless detumbling research. References 8 and 9 discuss the observed spin rates of GEO debris which can range from 1-2 deg/sec to many 10's of degrees per second. Thus, the question on whether despinning and docking is favored over touchlessly tugging while spinning is a function of the debris' rotational energy. Another method to touchlessly actuate a debris object is the ion-sheppard method.[10,11,12] Here a focused exhaust cone of an ion engine is directed at the debris to push it. While this approach avoids physical contact with

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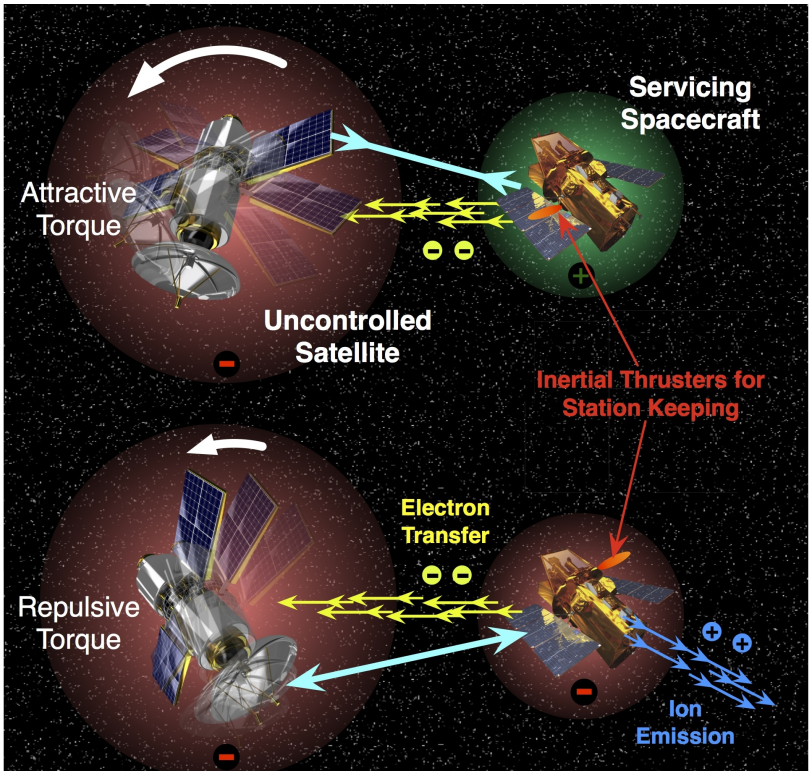


Figure 1: Electrostatic actutation technology enabling diverse service mission profiles

spinning debris, 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 debris center of mass, the debris will spin up or down. This rotational control could be used to depin a space object intentionally. However, imprecise knowledge of the exhaust characteristics and the exhaust deflecting off time-varying surfaces could cause this spin control to be very challenging. Electrostatic detumble research, as detailed through this paper, does not require the precise knowledge of the target debris in many categories of operation representing a clear advantage over other techniques.

The prospects of electrostatic actuation have been explored by several authors.[13,14,15,16,17] The electrostatic interaction between two craft in a vacuum is accurately determined using finite element methods; however, these methods are not suitable for real-time spacecraft control. Spacecraft charge modeling for real time control applications is accomplished by the Multi-Sphere Method (MSM), introduced and explored by References 18 and 19. The Multi-Sphere Method accurately captures the spacecraft charging dynamics by discretizing the spacecraft with representative conducting spheres held at the spacecraft potential. Applying the MSM reduces the computational time by orders of magnitude over finite element models and enables faster-than-realtime simulation of charged attitude control solutions.

Electrostatic forces and torques are dictated by the complex and nonlinear effects of the relative electrostatic potential and charge distribution between the two craft. This study identifies the core challenges of electrostatic interaction to include the charge modeling in the space environment, charge modeling of the space debris object, and control algorithms. The effectiveness of electrostatic despinning is influenced by the space environment. The charged control actuation range is dictated by the Debye length, which is a property of the space plasma that restricts electrostatic spheres of influence. In HEO and GEO orbits the effective Debye length,[20,21] is on the order of hundreds of meters, allowing control over dozens of meters. Thus, current research is addressing the challenge of creating appropriate analytical models of the charge transfer and control in a space plasma.[22] Prior research demonstrates the sensitivity of charge control to relative size and geometry of the two craft,[23] the natural charge and discharge experienced in orbit,[24] the capability and limitations of charge transfer devices, and the material properties of the spacecraft.

This paper outlines the prospects and challenges of electrostatically detumbling debris. During despin, the servicer vehicle will maintain a relative position several craft radii apart from the tumbling space debris. This greatly relaxes the relative motion navigation and control requirements. To be able to dock onto the spacecraft, the tumbling rate does not have to be completely arrested to use in-development docking solutions by MDA/SSL.[4] For example, a homogenous conducting cylinder cannot have torques applied about it's rotational axis of symmetry. The proposed concept applies to a generic debris object. This study outlines research challenges associated with the three-dimensional control of a spinning GEO body. To demonstrate this concept, both proof of concept experiments and sophisticated numerical simulations are presented.

ELECTROSTATIC DEBRIS DESPINING

Concept Description

Figure 1 illustrates how an orbital servicer could employ charge transmission to create attractive and repulsive electrostatic forces and torques. This process requires the servicing craft to actively control the electrostatic potential of both 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, whose primary emission is aimed at the space debris. As seen at the top of Figure 1, in a simple 1-D rotation scenario the servicing craft charges the debris to attract the closest receding feature and repel the closest approaching feature of the tumbling debris, thus detumbling the debris over time. Charge control is achieved by direct charge beaming to the space debris object.

Overall, touchless actuation of the space debris requires only servicing craft charge control capability and enables despinning and orbital transfer towing capabilities beyond current mechanical interfacing capability. However, due to the electrostatic forces creating net forces onto the servicer, the servicer will require a relative position station keeping requirement. The concept treats the servicer as ideally being at a fixed separation distance from the tumbling object. The closer this separation distance is, the stronger the electrostatic torques will be. However, the closer proximity also increases the collision risks.

Implementing attractive electrostatic forces can be achieved via a targeted electron beam emission that causes the servicer to charge positively, and as a result the debris will charge negatively. Repulsive forces require the servicer to also emit an ion beam (directed away from the debris) to overcome the electron beam charging and make the servicer negative as well. High energy electron emission devices are much simpler devices to implement compared to a corresponding ion emitter. Therefore, the concept considers scenarios where only attractive forces are implemented (simpler to implement at the cost of despin performance), or when both attractive and repulsive forces (more complex with better performance).

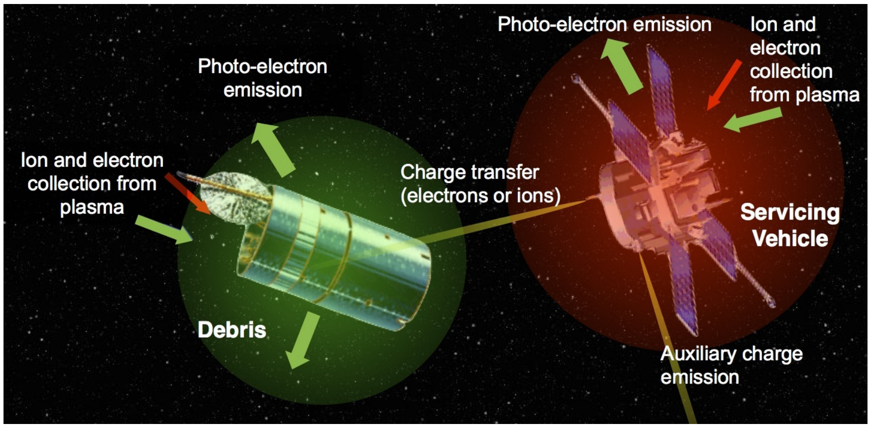


Figure 2: Illustration of the Spacecraft Charging Currents

Electrostatic Force Generation

The study utilizes a charging model that accounts for the numerous current sources experienced by a satellite in the space environment, incorporates space weather conditions adapted from observed values at GEO, and combines the charging model into a relative motion control scheme utilizing a recently developed relative orbital motion description. The electrostatic tugging force used for towing is dependent on the charging that occurs on both the tug and deputy. Several factors influence this charging process as shown in Figure 2. 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 tug is used for charge control. When the electron beam is absorbed by the deputy, secondary electron emission occurs as the incoming beam electrons excite and release electrons from the deputy surface material. The potential levels achieved by the tug and deputy result from a balance of these various current sources.

To compute these potentials, the charging model presented in Reference 22 is applied. For the tug, the charging is dominated by the plasma electron current and electron beam emission. The tug settles to a potential that satisfies the current balance $I_e(\phi_T) + I_t = 0$. This is solved analytically as

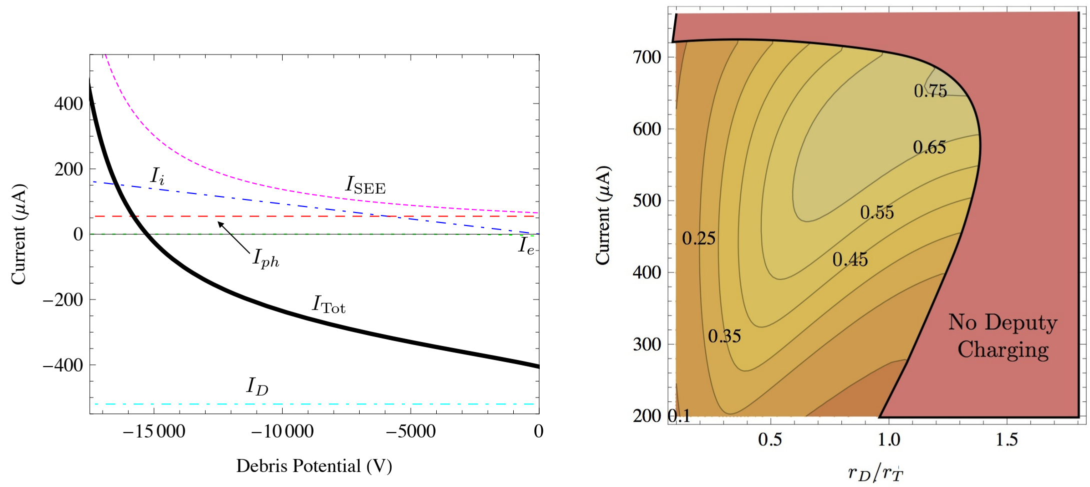
$$\phi_T = \left(\frac{4I_t}{Aqn_e w_e} - 1 \right) T_e, \tag{1}$$

which assumes a positive tug potential. This will be the case provided the beam current is sufficient. The current balance on the deputy object contains a few more contributions, and an analytical solution does not exist. The deputy will achieve a potential that satisfies

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

where 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 tug. The presence of the photoelectron current implies the deputy is in the sunlight. When in the Earth's shadow, the current balance contains all of the same terms except for I_{ph}.

Figure 3 illustrates how the use of a directed 40keV electron beam on the servicer leads to charging on the debris, as well as the resulting net electrostatic forces between them. The various currents



(a) Sample scenario illustrating currents on the debris causing a potential of about 14.5kV

(b) Net electrostatic forces assuming nominal GEO space weather, a 2m radius tug, and a 40keV electron gun.

Figure 3: Electrostatic Force Generation Illustration.

are illustrated in Figure 3(a) where the debris achieves a potential that yields a net current of zero. Figure 3(b) shows the expected electrostatic forces between a r_T =2m radius servicer and a spherical debris object of varying radii r_D. Note that if the servicer is small relative to the debris, the charge transfer does not lead to an electrostatic force. This is due to smaller servicer charging up too quickly, thus limiting the amount of current that actually reaches the debris. Directing an electron beam at a conducting body in space does not necessarily yield a high potential. Rather, a critical current level must be achieved to compensate for the photo-electron current and the secondary electron emission. This results in the sharp drop off to regions of no debris charging in Figure 3(b).

If in addition to the electron beam the servicer emits some ions to reduce its potential, the electrostatic tractor force can be slightly increased in strength.[25] Such auxiliary charge emission has a stronger performance impact if the servicer is small compared to the debris object.

Electrostatic Force Modeling

There is no simple analytic solution for the electrostatic interaction between charged conductors with generic geometries. Several options exist for the numerical modeling of spacecraft charging and interactions, including finite element methods, finite difference methods, boundary element methods, and Monte Carlo methods.[26,27] Each of these approaches, however, are too computationally expensive to allow for faster-than-realtime simulations of the electrostatically induced relative motion dynamics.

Simpler methods such as the point charge approximation and finite sphere model that have been used for Coulomb charge control analysis in the past[28,29,30] are limited to line-of-site forces and not capable of predicting electrostatic torques. The recently developed Multi-Sphere Method (MSM)[18] uses a set of body-fixed conductive spheres throughout the geometry of a spacecraft to capture the 3D electrostatic effects. Specifically, this reference provides detailed analysis of the interaction between a charged cylinder and a sphere as depicted in Figure 4, and this system will be used

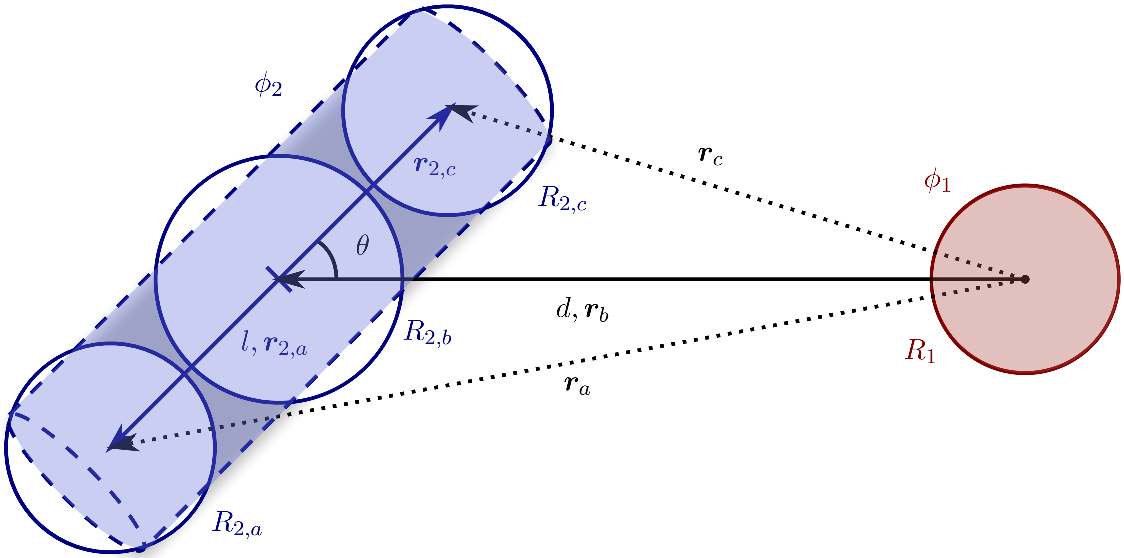


Figure 4: Free body diagram for MSM cylinder-sphere system

to study the de-spin control concepts that are the basis of this manuscript. 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. While it is possible to capture the induced charge effects that occur with very close proximity scenarios with a larger set of spheres distributed on the surface of the objects,[19] three spheres are sufficient to capture the torques exerted on the cylinder at larger separation distances.

A remaining research challenge is developing MSM models for non-cylindrical spacecraft geometries. Determination of the optimal sphere locations and radii requires complex numerical optimizations to be performed. However, once obtained, the MSM representation of the corresponding shape yields very fast electrostatic torque and force evaluations with errors (relative to FEM solution) often less than a percent at the separation distances considered.

Without presenting the complete mathematical development, 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 of the spheres to their potentials. Once this system is solved, one can sum Coulomb's law to determine the total force F_i on each sphere, which sum to yield the total force and torque acting on each body.

Flexible Body Considerations

Not all debris objects are a single rigid body, but can have flexible appendages. Already demonstrated for rigid bodies, another potential application for the MSM is the modeling of thin flexible structures such as solar panels, solar sails, gossamer structures, and other deployable inflatable structures. That the MSM can be applied to flexible structures has not been validated thus far, but the hypothesis is as follows. The thin structure is populated by equi-distant, equi-radii spheres to represent the actual charging the surface could experience in the space environment. The net force acting on each sphere is due to the contributions of the charges on every other sphere in the model.

Once the net force on each sphere is determined, the equations of motion for the system can be numerically integrated to find the dynamic response of each sphere and determine the position vector of any sphere at any given time. Therefore, the changing size and shape of a membrane structure due to charging and other dynamic contributions could be modeled over time. Such a development would allow for a significant numerical simulation speed-up as the complex Poisson partial differential equations do not have to be solved simultaneously with the structural flexing partial differential equations. Rather, the charge distribution can be solved as a fast linear algebra problem with the MSM formulation.

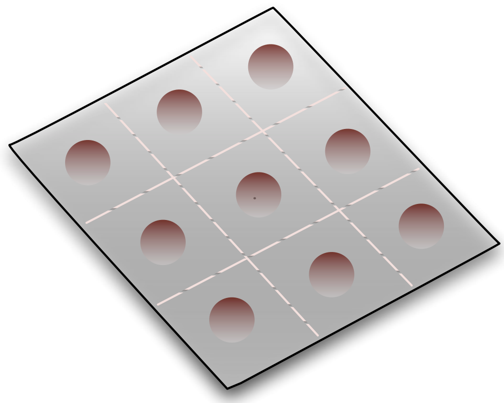


Figure 5: Illustration of hypothesized MSM model for a thin, flexible spacecraft component.

The research status of this work is as follows. Initially a 2-dimensional model has been created to explore the potential of applying the MSM to a flexible object. This model has been compared to electrostatic finite element analysis (FEA) solutions using Maxwell Finite Element Software. Initial results have shown that the membrane should be populated with spheres centered in square grids, as shown in Figure 5. The sphere radii should be selected in order for the sphere surface area to match the total surface area of each square grid. If this model is successfully validated though further comparison to FEA and experiments, then the concept can be extended to apply the MSM to fully 3-dimensional flexible objects.

Power Requirements

The power requirements for GEO detumble applications reside within reasonable operating power limits available to GEO spacecraft. The power draw of active charge control is the product of the beam energy and current supplied, both design variables. Explored extensively by Reference 24 and 23 are optimal beam currents and resulting electrostatic forces and torques. Demonstrated for admissible tug to debris size ratios are power requirements in the neighborhood of $40W$ if only an electron beam is employed. If both electron and ion emission methods are employed, the power required can reach 100's of Watts. Power draws of this magnitude do not present significant pressures on concept realization. The power generation levels of typical GEO spacecraft can easily reach 25kW.

Tumbling Body Geometry and Inertia

Mission success depends on reduction or elimination of debris object momentum. Such momentum is a direct function of debris object geometry and inertia properties. The challenges are therefore two-fold for mission design applicable to generic geometries. First, particular geometries such as large solar arrays about a particular axis interfere with proximity safety, restrict relative motion trajectories, or inhibit active charge transfer capability. However, the spacecraft geometry may be favorable to detumble application as large torque moment arms amplify the electrostatic force effect.

Second, particular inertia properties introduce momentum characteristics and detumble behavior coupling. An instance explored by Reference 31 demonstrates that axi-symmetric bodies restrict the quantity of momentum that can be removed. In instances such as the axi-symmetric debris object, electrostatic torque about the axi-symmetric axis is not possible, resulting in incomplete reduction of the debris object's total momentum. For instances with full coupling, the reduction in angular momentum is more complete, thus achieving more desirable steady states. While the total angular momentum can be reduced, the momentum of a conducting body's symmetry axes cannot be reduced without creating differential potentials across the surface.

Tumbling Body Material Properties

Inherent in the charge distribution modeling of a spacecraft via MSM techniques are the assumptions about material properties. Assumed by the simulations and discussion in this study is that the debris object is fully conducting ensuring that a uniform potential can be achieved. Introduction of more complex spacecraft constructions with localized material properties challenges the assumptions made thus far. Charging behavior of dielectrics, combinations of conducting and insulating surfaces, and non-uniform conductors present challenges to characterize and significant alteration in electrostatic detumble performance. Exploration into charging dynamics of various materials and combinations is required for full implementation of the electrostatic detumble mission concept.

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 tug or servicer vehicle. The uncertainty in material properties, geometry and additional factors influencing charge control present challenges in the design of robust controllers. The feedback control must be designed to account for differential gravitational forces and the electrostatic interaction. Candidate position control solutions have been proposed in Reference 30.

Assuming the cylinder experiences no active translational control, a nominal open-loop thrusting force on body 1 is necessary to maintain a constant relative position within the system:

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

Thus, depending on if 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.

The relative motion control incorporates a feed forward estimate of the spacecraft charging to determine the open-loop $\boldsymbol{F}_1$ compensation. Using the expected current balance described and an approximation of the deputy craft charging properties, the relative motion control can predict and feedback on separation distance measurements. 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.[30] Thus, it is important to consider conservative upper bounds when setting up this station keeping control law.

Tug Thrusting Consideration

Inertial thrust requirements are small in magnitude to balance the milli-Newton electrostatic forces, even over a period of weeks. It is important that the inertial thrusting solution does not interfere with the electrostatic tractor performance. This can be achieved by using neutral gas thrusters, or select types of electric propulsion systems such as FEEP thrusters. In both cases care must be taken to analyze the coupled thruster emission flow subject both to the charging on the debris and servicer. The charge and momentum flux cannot impinge on either. The other option is use use a pulse-width modulation approach. Here the tractor is engaged for a period of time while no inertial station keeping is performed. Next, the tractor is turned off and the thrusters are used for a finite time to perform relative position station keeping. Because it takes less than a second to resume the natural charging at GEO, this allows for quick switching of control modes if needed. Of course, depending on the tractor beam versus inertial thrusting duty cycle, the performance will decrease.

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, an axis of symmetry on a conducting body's shape provides an axis about which no control torque can be produced. However, gyroscopic rotational motion of general bodies can lead to cross-coupling where this rotation motion may still be arrested.

Preliminary work has been performed considering 1-D constrained rotational motion, and reviewed in this section. As shown by Reference 32, if the separation distance is sufficiently large, 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 vector.

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

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 required by the MSM formulation. As References 32 and 31 have shown, approximating the MSM torque on a cylinder with Eq. (4) introduces errors less than 1%. Without loss of generality, it is assumed the non-cooperative cylinder has the same potential magnitude, that is $\phi_2 = |\phi_1|$, and is assumed to be always positive.[32] Thus, the voltage dependency function is set to:[32]

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

The orientation angle dependency explored by Reference 32 presents Eq. (6) as the analytic representation. Reference 32 also demonstrates more complicated torque surfaces characterized at close proximity due to induced charging properties which can be accounted for by further approximation terms.[31] Implementation at a separation distance of $d = 15\ m$ accurately approximated the torque surface with a correlation of $R^2 = 0.9998$ and the tuned scaling parameter $\gamma = 2.234 \times 10^{-14}$.[32]

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

Using the potential and orientation dependency functions in Eq. (4) provides a separable form base function to approximate the MSM torque profile. Setting $\Phi = 0$ when the slender axis of the cylinder is aligned with the inter-spacecraft vector allows for the rate controller function $f(\phi)$ to be developed.

The following feedback control development uses rotation rate control to reduce or eliminate the cylinder's tumbling motion. A fixed separation distance is maintained using the inertial thrusting scheme described above. The controller assumes the projection angle Φ and angle rate $\dot{\Phi}$ are measured and the commanding spacecraft potential ϕ_1 is the control variable similar to Reference 32. Generalized for 3-D motion 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:[32]

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

Tumble rates that tend toward infinity necessitate a limit on physical potential. The following h function proposed by Reference 32 smoothly limits, or saturates, the control at a maximum potential.

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

that is

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

The saturation controller presented in Eq. (9) becomes the bang-bang controller in Eq. (11) as α tends to infinity.

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

The stability of this 1D despin control algorithm is discussed in detail in Reference.[31] 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 sign is correctly modeled.

The formulation presented assumes a zero nominal potential, i.e. only despinning is desired and no simultaneous tugging. Reference 32 further considers 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.

Sensor Suite

A viable spacecraft will require a proximity operations sensor suite to enable both station keeping as well as detumble control. Of primary concern is the inter-spacecraft range as it ensures safety ranges as well as electrostatic force magnitudes. Relative motion accuracy only has to be in the 10's of centimeter levels. Currently available are optical and laser ranging techniques that can provide the necessary range accuracy. In addition, the debris object geometry, attitude, and tumble rates are to be supplied to the detumble controller. For non-cooperative objects, attitude information and tumble rates can be acquired using structured light, visual flow methods, or flash LIDAR sensors.

ANALYTICAL AND EXPERIMENTAL RESULTS FOR GEO-LIKE OBJECTS

Numerical Simulation of Electrostatic Detumble in GEO

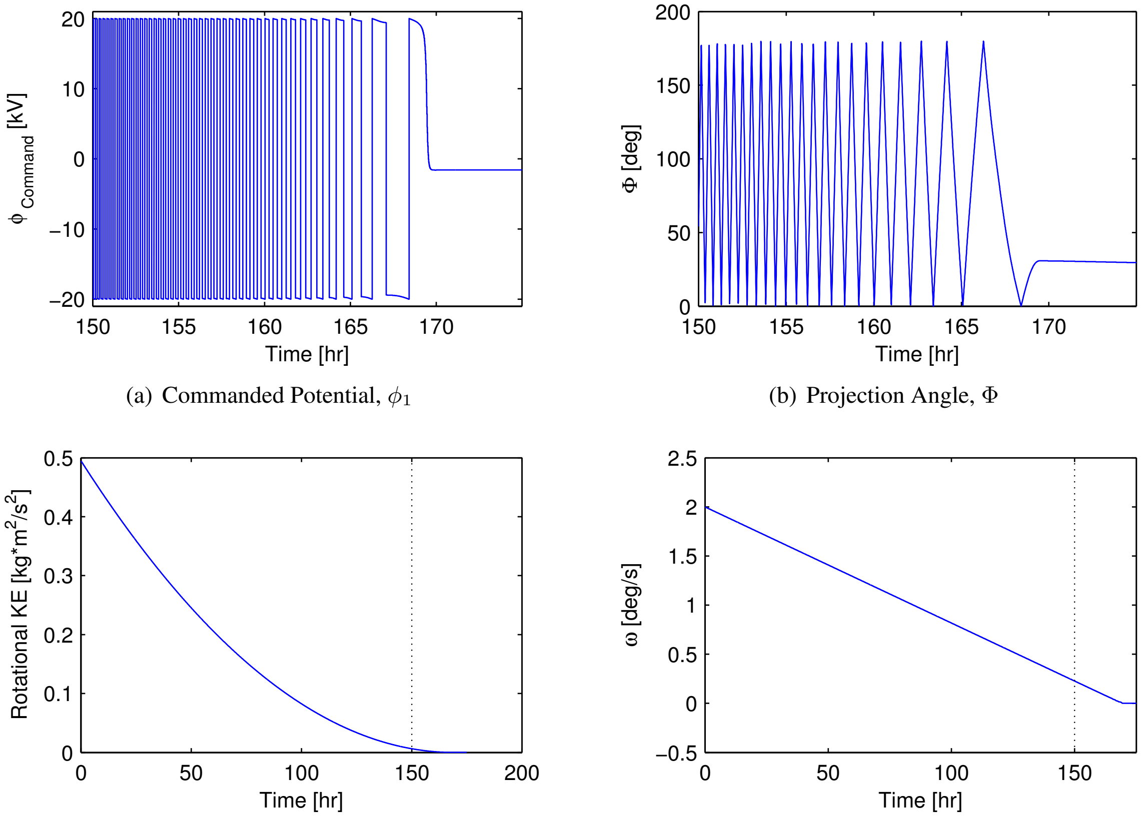
A numerical simulation is performed that encapsulates the active charge transfer process[22] and detumble controller discussed earlier in this paper. The debris object, represented by a 3 m long by 1 m diameter cylinder with admissible inertias, is detumbled from an initial single axis rotation of 2°/sec by a 2m radius servicing spacecraft. All mass properties and control variables are detailed in Table 1. The two craft are initialized in deep space, that is without gravitational influences of a celestial body, at a separation distance of 12.5 m maintained by the active station keeping controller. Representative of nominal GEO conditions, the space weather conditions assume an electron density of $n_e = 0.9$ cm^{-3}, ion density of $n_i = 9.5$ cm^{-3}, and temperatures of $T_i = 50$ eV and $T_e = 1250$ eV respectively. The results assume a beam energy of $E_{EB} = 40$ keV and a beam current of I_t=520 μA. Shown in Figures 6(c) and 6(d), the rotational energy and angular velocity of the debris object is completely removed, without requiring physical contact, in approximately 170 hours or about a week.

The command voltages are illustrated in Figure 6(a). 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 1D rotation angle Φ is shown in Figure 6(a). While the cylinder comes to rest, as predicted, it will come to rest at a random final orientation. This control only feeds back on the rate, not orientation.

Table 1: 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
R_D, l_D	1, 3	m	Cylinder radius 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



(a) Commanded Potential, ϕ_1

(b) Projection Angle, Φ

(c) Rotational Kinetic Energy

(d) Cylinder Angular Velocity

Figure 6: Numerical simulation with initial conditions: $\dot{\Phi} = 2.0°/s$, $\Phi_0 = 30°$.

Experimental Developments

In order to validate the Coulomb de-spin concept, it is desirable to experimentally verify the electrostatic models and charge control algorithms. The Autonomous Vehicle Systems lab has established an expertise in high voltage charged dynamics experiments, including Electrostatically Inflatable Membrane Structures research[15] and a linear air-bearing testbed for charged relative motion experiments.[35] Figure 7 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. The hardware and software improvements in this experimental design allow for precise attitude control where the previous setup was merely capable of rotation rate control.[18]

This test bed has successfully been used to validate the MSM models employed for the cylinder, as well as to demonstrate electrostatic despin and pointing control. Further, this test bed has been

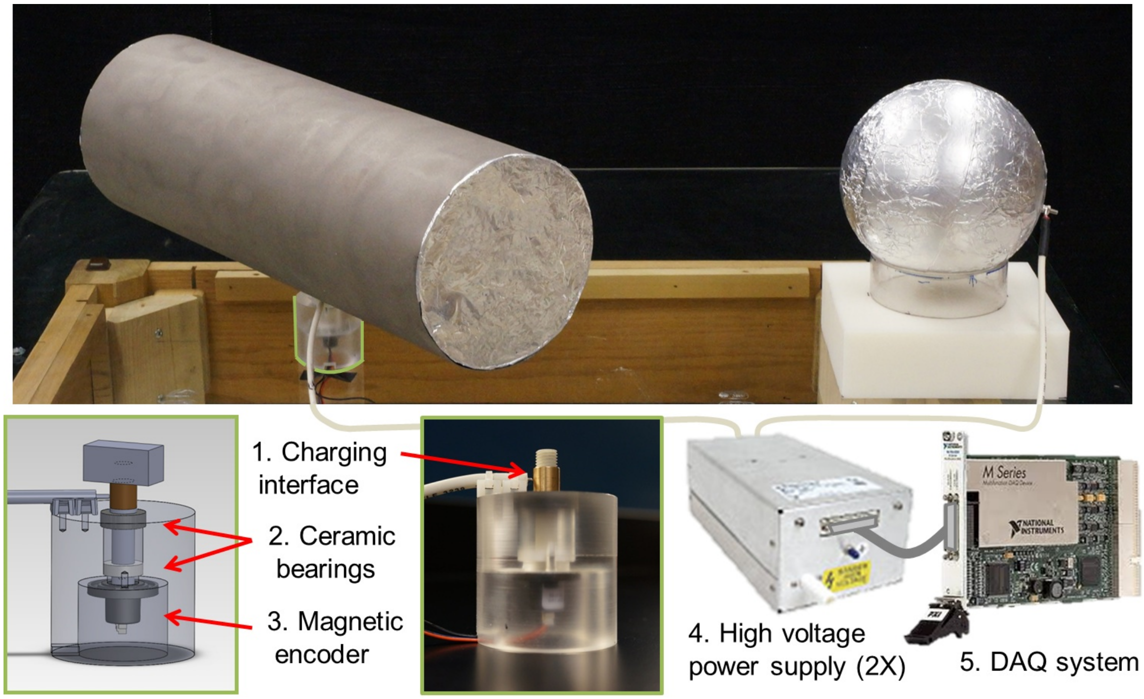


Figure 7: Depiction of the experimental setup for charged attitude control.

valuable in validating predicted charge attitude equilibrium behaviors in tugging and non-tugging scenarios. The rotation bearing friction is low, but will depin the satellite on its own over a period of minutes. With the charge control active, the cylinder will despin over a period of 10's of seconds for similar initial spin rates.

CONCLUSIONS

The prospects of touchless electrostatic despin control on large, tumbling GEO objects are discussed. The conceptual challenges are outlined and current research efforts into electrostatic actuation are reviewed. While this technology is still in it's infancy, the results to date look very promising. The robustness of the charge control to uncertainties in debris potential indicate a simple, and thus cost effective solution is feasible. Future work will investigate the complex 3D rotation motion that can result, the associated station keeping requirements as a function of the separation distance, as well as how effective this despin method is on non-cylindrical shapes.

REFERENCES

[1] P. Couzin, F. Teti, and R. Rembala, "Active Removal of Large Debris: System approach of deorbiting concepts and Technological issues," *6th European Conference on Space Debris*, Darmstadt, Germany, April 22–25 2013. Paper No. 6a.P-17.

[2] A. Ogilvie, J. Allport, M. Hannah, and J. Lymer, "Autonomous satellite servicing using the orbital express demonstration manipulator system," *Proc. of the 9th International Symposium on Artificial Intelligence, Robotics and Automation in Space (i-SAIRAS'08)*, 2008, pp. 25–29.

[3] W. Xu, B. Liang, B. Li, and Y. Xu, "A universal on-orbit servicing system used in the geostationary orbit," *Advances in Space Research*, Vol. 48, No. 1, 2011, pp. 95–119, 10.1016/j.asr.2011.02.012.

[4] P. Couzin, F. Teti, and R. Rembala, "Active Removal of Large Debris : Rendez-vous and Robotic Capture Issues," *2nd European Workshop on Active Debris Removal*, Paris, France, 2012. Paper #7.5.

[5] H. Schaub and D. F. Moorer, "Geosynchronous Large Debris Reorbiter: Challenges and Prospects," *The Journal of the Astronautical Sciences*, Vol. 59, No. 1–2, 2014, pp. 161–176, 10.1007/s40295-013-0011-8.

[6] D. F. Moorer and H. Schaub, "Hybrid Electrostatic Space Tug," US Patent 0036951-A1, Feb. 17 2011.

[7] D. F. Moorer and H. Schaub, "Electrostatic Spacecraft Reorbiter," US Patent 8,205,838 B2, Feb. 17 2011.

[8] Y. S. Karavaev, R. M. Kopyatkevich, M. N. Mishina, G. S. Mishin, P. G. Papushev, and P. N. Shaburov, "The Dynamic Properties of Rotation and Optical Characteristics of Space Debris at Geostationary Orbit," *Advances in the Astronautical Sciences*, Vol. 119, 2004, pp. 1457–1466. Paper No. AAS-04-192.

[9] P. Papushev, Y. Karavaev, and M. Mishina, "Investigations of the evolution of optical characteristics and dynamics of proper rotation of uncontrolled geostationary artificial satellites," *Advances in Space Research*, Vol. 43, No. 9, 2009, pp. 1416 – 1422, http://dx.doi.org/10.1016/j.asr.2009.02.007.

[10] C. Bombardelli and J. Pelaez, "Ion Beam Shepherd for Contactless Space Debris Removal," *AIAA Journal of Guidance, Control, and Dynamics*, Vol. 34, May–June 2011, pp. 916–920, 10.2514/1.51832.

[11] S. Kitamura, Y. Hayakawa, K. Nitta, S. Kawamoto, and Y. Ohkawa, "A Reorbiter for Large Geo Debris Objects Using Ion Beam Irradiation," *63rd International Astronautical Congress*, Naples, Italy, 2012. Paper No. IAC-12-A6.7.10.

[12] C. Bombardelli, H. Urrutxua, M. Merino, E. Ahedo, J. Pelaez, and J. Olympio, "Dynamics of Ion-Beam Propelled Space Debris," *International Symposium on Space Flight Dynamics*, Sao Jose dos Campos, Brasil, Feb. 28 – March 4, 2011 2011.

[13] L. B. King, G. G. Parker, S. Deshmukh, and J.-H. Chong, "Spacecraft Formation-Flying using Inter-Vehicle Coulomb Forces," tech. rep., NASA/NIAC, January 2002. `http://www.niac.usra.edu`.

[14] C. R. Seubert, S. Panosian, and H. Schaub, "Analysis of a Tethered Coulomb Structure Applied to Close Proximity Situational Awareness," *AIAA Journal of Spacecraft and Rockets*, Vol. 49, Nov. – Dec. 2012, pp. 1183–1193.

[15] L. A. Stiles, H. Schaub, K. K. Maute, and D. F. Moorer, "Electrostatically inflated gossamer space structure voltage requirements due to orbital perturbations," *Acta Astronautica*, Vol. 84, Mar.–Apr. 2013, pp. 109–121, 10.1016/j.actaastro.2012.11.007.

[16] S. Wang and H. Schaub, "Nonlinear Charge Control for a Collinear Fixed Shape Three-Craft Equilibrium," *AIAA Journal of Guidance, Control, and Dynamics*, Vol. 34, Mar.–Apr. 2011, pp. 359–366, 10.2514/1.52117.

[17] B. Streetman and M. A. Peck, "New Synchronous Orbits Using the Geomagentic Lorentz Force," *AIAA Journal of Guidance, Control, and Dynamics*, Vol. 30, Nov.–Dec. 2007, pp. 1677–1690.

[18] D. Stevenson and H. Schaub, "Multi-Sphere Method for Modeling Electrostatic Forces and Torques," *Advances in Space Research*, Vol. 51, Jan. 2013, pp. 10–20, 10.1016/j.asr.2012.08.014.

[19] D. Stevenson and H. Schaub, "Optimization of Sphere Population for Electrostatic Multi Sphere Model," *IEEE Transactions on Plasma Science*, Vol. 41, Dec. 2013, pp. 3526–3535, 10.1109/TPS.2013.2283716.

[20] N. Murdoch, D. Izzo, C. Bombardelli, I. Carnelli, A. Hilgers, and D. Rodgers, "The Electrostatic Tractor for Asteroid Deflection," *58th International Astronautical Congress*, 2008. Paper IAC-08-A3.I.5.

[21] L. A. Stiles, C. R. Seubert, and H. Schaub, "Effective Coulomb Force Modeling in a Space Environment," *AAS Spaceflight Mechanics Meeting*, Charleston, South Carolina, Jan. 29 – Feb. 2 2012. Paper AAS 12-105.

[22] H. Schaub and Z. Sternovsky, "Active Space Debris Charging for Contactless Electrostatic Disposal Maneuvers," *Advances in Space Research*, Vol. 43, No. 1, 2014, pp. 110–118, dx.doi.org/10.1016/j.asr.2013.10.003.

[23] E. A. Hogan and H. Schaub, "Impacts of Tug and Debris Sizes on Electrostatic Tractor Charging Performance," *International High Power Laser Ablation and Beamed Energy Propulsion*, Santa Fe, New Mexico, April 21–25 2014.

[24] E. Hogan and H. Schaub, "Space Weather Influence on Relative Motion Control using the Touchless Electrostatic Tractor," *AAS/AIAA Spaceflight Mechanics Meeting*, Santa Fe, New Mexico, Jan. 26–30 2014. Paper AAS 14-425.

[25] E. A. Hogan and H. Schaub, "Impacts of Solar Storm Events and Ion Beam Emission on Electrostatic Tractor Performance," *13th Spacecraft Charging Technology Conference*, Pasadena, CA, June 23–27 2014.

[26] W. C. Gibson, *The method of moments in electromagnetics*. Chapman & Hall, November 28 2007.

[27] M. N. Sadiku, *Monte carlo methods for electromagnetics*. CRC Press;, April 9 2009.

[28] C. R. Seubert and H. Schaub, "Electrostatic Force Model for Terrestrial Experiments on the Coulomb Testbed," *61st International Astronautical Congress*, Prague, CZ, International Astronautical Federation, Sept. 2010. Paper IAC-10.C1.1.9.

[29] L. E. Z. Jasper and H. Schaub, "Effective Sphere Modeling for Electrostatic Forces on a Three-Dimensional Spacecraft Shape," *Adventures on the Interface of Dynamics and Control* (K. T. Alfriend, M. Akella, J. E. Hurtado, J. Juang, and J. D. Turner, eds.), pp. 267–298, Duluth, Georgia: Tech Science Press, 2012.

[30] E. Hogan and H. Schaub, "Relative Motion Control for Two-Spacecraft Electrostatic Orbit Corrections," *AIAA Journal of Guidance, Control, and Dynamics*, Vol. 36, Jan. – Feb. 2013, pp. 240–249.

[31] T. Bennett and H. Schaub, "Touchless Electrostatic Three-Dimensional Detumbling of Large GEO Debris," *AAS/AIAA Spaceflight Mechanics Meeting*, Santa Fe, New Mexico, Jan. 26–30 2014. Paper AAS 14-378.

[32] H. Schaub and D. Stevenson, "Prospects Of Relative Attitude Control Using Coulomb Actuation," *Jer-Nan Juang Astrodynamics Symposium*, College Station, TX, June 25–26 2012. Paper AAS 12–607.

[33] P. V. Anderson and H. Schaub, "Local Debris Congestion in the Geosynchronous Environment With Population Augmentation," *Acta Astronautica*, Vol. 94, Feb. 2014, pp. 619–628, 10.1016/j.actaastro.2013.08.02.

[34] H. Schaub and L. E. Z. Jasper, "Circular Orbit Radius Control Using Electrostatic Actuation for 2-Craft Configurations," *AAS/AIAA Astrodynamics Specialist Conference*, Girdwood, Alaska, July 31 – August 4 2011. Paper AAS 11–498.

[35] C. R. Seubert and H. Schaub, "Closed-Loop One-Dimensional Charged Relative Motion Experiments Simululating Constrained Orbital Motion," *AIAA Journal of Guidance, Control, and Dynamics*, Vol. 33, Nov.–Dec 2009, pp. 1856–1865, 10.2514/1.48274.