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Survey of the electrostatic tractor research for reorbiting passive GEO space objects

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ABSTRACT

The number of operational satellites and debris objects in the valuable geosynchronous ring has increased steadily over time such that active debris removal missions are necessary to ensure long-term stability. These objects are very large and tumbling, making any mission scenarios requiring physical contact very challenging. In the last 10 years, the concept of using an electrostatic tractor has been investigated extensively. With the electrostatic tractor concept, active charge emission is employed to simultaneously charge the tug or services vehicle, while aiming the charge exhaust onto the passive space debris object to charge it as well. The resulting electrostatic force has been explored to actuate this debris object to a disposal orbit or to detumble the object, all without physical contact. This paper provides a survey of the related research and reviews the charging concepts, the associated electrostatic force and torque modeling, and the feedback control developments, as well as the charge sensing research.

KEYWORDS

electrostatics

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Review Article

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1 Introduction

The electrostatic tractor (ET) is a concept for remote actuation of objects in space. It is particularly well-suited for reorbiting of debris objects at geosynchronous earth orbit (GEO). The tractor works by utilizing the Coulomb force between two charged bodies. Figure 1 shows the electrostatic tractor concept of operations. In this sample configuration, a servicing craft approaches a debris object, such as a defunct satellite or rocket body, and directs an electron beam at the target. The target accumulates excess electrons, therefore charging negatively, while the tug charges positively because of electron emission. This results in a net attractive force between the two spacecraft acting along the line of sight between the two centers of charge. While maintaining this charge differential, the tractor can use its own inertial thrusters to slowly tug the target into a new orbit, using the electrostatic attraction between the craft to pull the target along. The charge transfer via electron beam is essentially propellantless, so the only fuel used for reorbiting is that used by the inertial thrusters on the tractor. Though the magnitude of the force is typically small (on the order of 0.1–10 mN), the force can be modulated or established in a steady state and is sufficient for tugging the debris [2]. Hogan and Schaub [3] show that the ET can raise the semi-major axis of an object at GEO by 300 km using 11 m/s of ΔV in approximately 2 months depending on mission parameters.

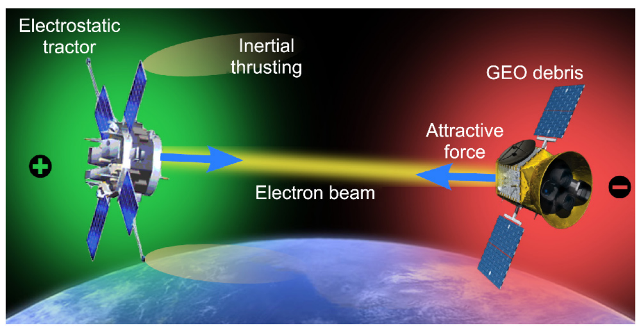

Fig. 1 Electrostatic Tractor concept of operations. Adapted from Ref. [1].

The space environment is a plasma containing both free electrons and ions which will interact with the charged spacecraft [4]. When a charged body is introduced in a plasma, the mobile charge carriers

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of opposite sign are attracted to the body. The additional charge carriers near the body act to screen the charge and cause the electric field around it to drop off more rapidly with distance than in vacuum, a phenomenon known as Debye shielding. The shielding is characterized by the Debye length, which describes the e-folding distance of the electric potential and depends on the plasma density and temperature [5]. In low earth orbit (LEO), the Debye length is on the order of centimeters because the plasma is cold and dense. As a result, the potential of a craft is shielded over a very short distance, which prevents Coulomb forces from being viable for relative motion control in this regime. However, at GEO the plasma is significantly hotter and more tenuous, resulting in a Debye length of approximately 180–200 meters for standard solar conditions [6, 7]. For nominal GEO space weather conditions, this large Debye length allows electrostatic interactions between craft to be effectively unscreened at distances of tens of meters, enabling one craft to exert milli-Newton-level forces remotely on another over distances of several craft radii [2]. At distances beyond the Debye length, the charges are effectively screened out, so the tractor will have no effect on other objects in orbit. This classical Debye length value assumes the space object potential is much smaller than the plasma energy level. This is not the case with such GEO conditions, and the effective Debye length must be considered in estimating the plasma shielding property [8–10]. For meter-sized GEO objects, the effective Debye length is estimated to be 5–6 times larger than the classical Debye length parameter, enabling electrostatic actuation even in such conditions [8]. The ET concept over dozens of meters is highly applicable to the geosynchronous regime because of the plasma environment and pressing need for active remediation, as is discussed in the following section. It is also viable for any High Earth Orbit outside the Van Allen belts or for deep space scenarios.

The concept of electrostatic actuation was first explored as early as 1966 to inflate membranes [11]. Later in the early 2000s, electrostatic charge manipulation was considered for cooperative spacecraft formation flying where each craft could manipulate its own charge. Traditional ion or chemical thrusters for position control are undesirable in close proximity formations on the order or multiple craft radii because the thruster plumes can impinge upon and contaminate other craft in the formation [12]. Forces on the order of tens of milli-Newtons (corresponding to potential levels up to 20 kilo-Volts and watt levels of power) are found to be sufficient for maintaining High Earth Orbit formations of spacecraft with spacings less than 100 meters, ideal for forming the sparse apertures needed for interferometry applications [12, 13]. These concepts for relative motion control are appealing, as they are effectively propellantless, use less power than any available electric thrusters, and avoid potential contamination of nearby spacecraft that could be detrimental to delicate sensors. The dynamics and control of such formations, which range from simple 2 craft formations to complex N-body configurations, are discussed further in Refs. [14–19]. The electrostatic tractor concept is first proposed as a mechanism for debris reorbiting in GEO by Schaub and Moorer in 2011 [1, 20, 21]. Numerous papers have been published investigating the various challenges and further developing the technology, as is discussed throughout this survey paper. Though much work on the ET focuses on operation at GEO, the concept has also been proposed as a means for deflecting small asteroids in deep space, similar to the gravity tractor concept [9, 22]. However, this research concludes that the required power levels and inadequate resultant force would make the electrostatic tractor unfeasible for the small asteroid application. Therefore, the remainder of this paper focuses on application of the ET for reorbiting of debris in GEO, a problem for which the ET is a particularly elegant solution.

The paper is structured as follows. Section 2 establishes the need for debris mitigation at GEO and overviews proposed debris removal technologies, Section 3 summarizes the physics of spacecraft charging, Section 4 explains how spacecraft charging results in useful forces and torques, Section 5 reviews both position and attitude control strategies for the ET, and Section 6 introduces ongoing work for touchlessly sensing the potential of a space object.

2 Motivation for active debris removal at GEO

GEO is a unique region in space used for communication and Earth observation satellites. Many organizations have highly valuable assets in GEO, yet the region is becoming increasingly contaminated with debris.

Whereas natural forces such as atmospheric drag exist in Low Earth Orbit which will deorbit objects over time, no such forces exist in GEO and objects in orbit will remain indefinitely [23]. The number of active satellites in GEO is steadily increasing along with the number of mission-related debris, such as rocket bodies or kick motors. The risk of collision has been identified as a hazard for operational and future missions. In an effort to reduce the congestion in GEO, the Inter-agency Space Debris Coordination Committee (IADC), an international governmental forum, has established end-of-life disposal guidelines for satellites in GEO, recommending a minimum altitude boost of at least 235 km be performed [24]. These guidelines, however, are only followed on a voluntary basis by operators. End-of-life orbit-raising maneuvers can be costly and operators must decide between extending operations and risking not being able to reorbit, or voluntary reorbiting [25]. Further, there are often uncertainties in the remaining propellant mass and satellites commonly do not achieve the desired altitude. Between 1997 and 2003, approximately 2 out of every 3 retired satellites were either reorbited to an insufficiently high altitude or not reorbited at all [26]. More recently the compliance rate with GEO operators has improved where in 2013 the 20 satellites that reached end-of-life status were all attempted to be moved to the disposal orbit [27]. However, only 15 such disposal maneuver were fully successful.

Whereas much orbital debris research focuses on the Low Earth Orbit (LEO) regime, Oltrogge shows that the spatial densities in GEO can be as high as those in LEO [28]. Anderson [29, 30] determines that, in light of the imperfect mitigation efforts, the number of near-miss events near gravitational wells will double in 50 years. Multiple studies conclude that mitigation measures must be combined with active debris removal (ADR) to ensure the long-term safety and usability of the geosynchronous ring [31–34].

There are significant technical, financial, and legal challenges associated with ADR [27]. To be financially effective, a single ADR mission should be able to reorbit multiple objects. Therefore, the method should be adaptable to any target size, shape, or attitude. Further, any proposed ADR technology should also have a very low risk of colliding with the debris or generating additional debris in the event of a mission failure.

Many studies propose using a net [35] or harpoon [36–38] to capture debris and then tug it to a higher orbit. A recent experiment launched from the International Space Station performed on-orbit testing of net and harpoon systems [39]. Other studies investigate the dynamics of the physical tether which must be able to withstand a high-force tugging [40–42]. These methods present a number of advantages and disadvantages. While lightweight and low-cost, the net or harpoon challenges being investigated include the capture dynamics and reliability. Even in the event the capture system hits the target, it may not fully capture it. The structural integrity of retired satellites is uncertain and the debris is only pulled at a single point of contact, so there is also a risk that the target object would breakup, thereby worsening the debris situation. The number of objects which can be deorbited with this method is also limited by the number of dispensables on board the chief craft.

Other work focuses on developing robotic grapplers to interface with debris objects [43–47]. Whereas the disadvantages of firing objects at the debris are avoided with this method, it is extremely challenging, thus financially expensive, to grapple with an uncooperative object which may have unknown mass characteristics. Extremely close proximity operations are also required, which carries a high risk of creating large amounts of additional debris in the event of a mission failure. Again, the structural integrity of the debris may be unknown and solar panels or antennas may break off during the grappling process. Finally, robotic arms cannot grapple objects with rotations rates greater than a few degrees per second, whereas debris objects are commonly rotatating at 10s of degrees per second, so significant propellant mass may be required to match the relative rotation rate of a tumbling object, thereby limiting the financial effectiveness of such a mission [48, 49]. As another solution, missions have been proposed to distribute reorbiting kits, add-on propulsion modules which would be attached via robotic arm and then provide the required thrust for reorbit [50, 51]. Disadvantages of this method are the difficulty in placing the module and the need for pointing control to provide the proper thrust vector.

Methods have been proposed for touchless detumbling of space debris, including electrostatic actuation, laser ablation of surface material such that the resulting ejecta provides an impulse to alter the target's attitude [52], eddy currents in the target induced by a magnetic field generated by a servicing craft [53], as well as the ion-shepherd method that employs the ion engine exhaust to push the debris object [54].

Touchless methods for reorbiting are advantageous because they are agnostic to the target being steady or tumbling. Further, there is lower risk for collision and no possibility for the generation of additional debris. Recent studies [54–56] propose a concept called the ion beam shepherd in which the target is bombarded with ions to transfer momentum in a pusher configuration. This paper presents a review of another touchless concept: the electrostatic tractor. This concept only requires propellant for approaching the object and thrusting to raise the orbit, therefore it can reorbit numerous objects in a single mission. The ET has an advantage over the ion beam shepherd in that it can operate in a puller configuration which has lower risk of collision than the pusher configuration [57]. The tractor concept can also be used to touchlessly detumble a debris object [58].

3 Spacecraft charging

A space object is subject to many currents from the space plasma and the sun as shown in Fig. 2. The object is in equilibrium when the net current to it is zero, and its total charge Q changes when there is a net current [4, 59, 60].

$$I_{\mathrm{e}}(\phi) + I_{\mathrm{i}}(\phi) + I_{\mathrm{SEE}_e}(\phi) + I_{\mathrm{SEE}_i}(\phi) + I_b(\phi) + I_{\mathrm{ph}}(\phi) + I_{\mathrm{beam}} = \frac{\mathrm{d}Q}{\mathrm{d}t} \tag{1}$$

The thermal currents $(I_{\mathrm{e}}(\phi), I_{\mathrm{i}}(\phi))$ are a result of electrons impacting the spacecraft and sticking, and ions removing an electron as they bounce off [4, 61].

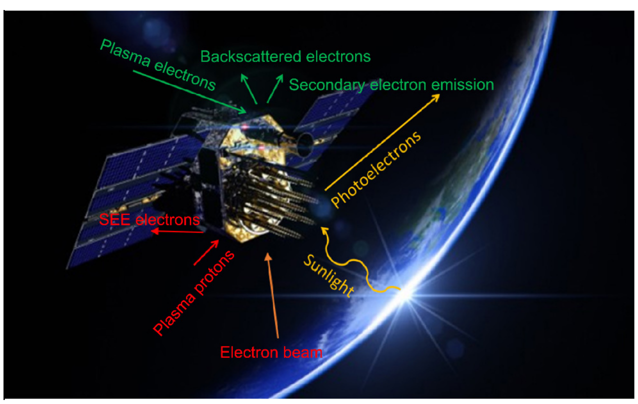


Fig. 2 Electrical currents acting on an object in geosynchronous orbit.

When either particle impacts the spacecraft, it can impart some of its energy to electrons in the first few nanometers which can subsequently leave the system. This phenomenon is called Secondary Electron Emission (SEE) and can occur with incident ions or electrons $[I_{\mathrm{SEE}_e}(\phi) + I_{\mathrm{SEE}_i}(\phi)]$. An incident electron can also bounce rather than stick, which is called backscattering (I_b). Energy from the sun can energize electrons on the surface so that they leave the material via the photoelectric effect (I_{ph}) [62, 63]. Finally, the electron beam (I_{beam}) is a positive current for the tug but a negative current for the debris. It also has an associated SEE and backscattering current. All these currents are functions of the object's voltage ϕ as well as many other material parameters such as the secondary emission and backscatter coefficients, work function, and surface roughness. Equation 1 is solved for either an equilibrium solution $(\frac{\mathrm{d}\phi}{\mathrm{d}t} = 0)$ or a transient charging solution $[\phi(t)]$. If the beam is continuous $(I_{\mathrm{beam}} = \mathrm{const.})$, the equilibrium solution is sufficient, but if the beam is pulsed $[I_{\mathrm{beam}} = f(t)]$ then the time varying solution may have to be used depending on the pulse period to charging time relationship.

The currents on each spacecraft are functions of their voltages, which are determined by the charges. For the case where both debris and tug are modeled as single spheres, a mapping between charges and voltages is given by the elastance matrix [8, 64, 65] as

$$\begin{bmatrix} \phi_{\mathrm{T}} \\ \phi_{\mathrm{D}} \end{bmatrix} = \frac{1}{4\pi\epsilon_0} \begin{bmatrix} 1/R_{\mathrm{T}} & 1/\rho \\ 1/\rho & 1/R_{\mathrm{D}} \end{bmatrix} \begin{bmatrix} q_{\mathrm{T}} \\ q_{\mathrm{D}} \end{bmatrix} \tag{2}$$

where ϕ_{T} and ϕ_{D} are the tug and debris voltages, respectively, q_{T} and q_{D} are the charges, R_{T} and R_{D} are the craft radii, and ρ is the center-to-center separation for the tug and debris, respectively. In a simulation, the voltage is computed using the charges on both craft, then the currents are computed and the charges on each craft are updated at each timestep.

We also note that charged particles moving in a magnetic field experience a Lorentz force. However, the relatively low charge levels of the tractor craft, weak geomagnetic field, and small relative velocity in GEO mean that the Lorentz force is several orders of magnitude smaller than the Coulomb force. Therefore, effects of the Earth's magnetic field on the tractor are neglected.

Naturally charged spacecraft typically charge a few

Volts postive in sunlight because of the dominant photoelectric current and can reach kilo-Volt level negative potentials in eclipse [4]. To achieve reasonable force levels, many ET studies consider potentials on the order of 10 s of kilo-Volts. This requires that the servicing craft be designed to mitigate the risk of arcing or electrostatic discharge between spacecraft components which may float at different potentials. Reference [66] discusses how, alternatively, a large conducting sphere is well-suited to this application. Increasing the radius of a sphere increases its capacitance, which results in a higher charge level for a given potential, consequently producing larger forces and torques. Additionally, a large conducting sphere would act as a Faraday cage to protect the internal electrical components from electrostatic discharge.

3.1 Charging with a continuous beam

Early work in charging for the ET assumes a continuous beam. The continuous beam is simple to implement and holds the best charge possible subject to hardware and power usage limitations. Schaub and Sternovsky in Ref. [2] use a charging model that includes ion and electron plasma currents, the photoelectric current, the beam current, and its associated SEE current. However, the SEE and backscattering from the thermal currents are neglected, as well as backscattering for the beam.

Hogan and Schaub in Ref. [67] further develop the ET charging model by considering the Maxwellian thermal currents at planetary K-indices of $K_P = 1.5$ and 6. Additionally, they account for SEE and photoelectrons from the debris that enrich the plasma in the vicinity of the tug and change the current. The performance of the ET improves when both the storm-time currents and back flux from the debris to the tug are considered. The simultaneous emission of an electron and ion beam by the tug also improves tractor performance and enables charge transfer for scenarios in which using only an electron beam would be unfeasible, for example when the debris is much larger than the tug. The theoretical maximum electrostatic force that is possible with simultaneous emission is computed, and the results indicate that emitting both an electron and ion beam enables smaller tug vehicles to tow larger objects that could not otherwise be towed with only an electron beam.

Hogan and Schaub in Ref. [68] also investigate the performance of the ET with normal variations in the plasma parameters throughout an orbit. More force is produced in the early morning sector (local times between 1 and 6) due to the high temperature electron plasma in that region. They find that although the optimal balance of current and voltage does vary over an orbit, the gains from changing that voltage and current are small. Thus, a set voltage and current could be picked for the entire orbit with minimal loss of performance.

3.2 Charging with a pulsed beam

The pulsed beam is considered as some electron guns can achieve high-energy electron emission, but only over short periods of time due to power limitations. The question whether the pulsed or continuous charging strategy is better suited is mission constraint specific, and still an open area of research. If the beam is pulsed then I_{beam} is a function of time, and the charge on the tug and debris spacecraft $[q_{\mathrm{T}}, q_{\mathrm{D}}]^T$ must be propagated through time. This is shown explicitly below:

$$\begin{bmatrix} \dot{q}_{\mathrm{T}} \\ \dot{q}_{\mathrm{D}} \end{bmatrix} = \begin{bmatrix} \sum I_{\mathrm{T}}(q_{\mathrm{T}}, q_{\mathrm{D}}, t) \\ \sum I_{\mathrm{D}}(q_{\mathrm{T}}, q_{\mathrm{D}}, t) \end{bmatrix} \tag{3}$$

where, q_{D} and q_{T} are the charges of the debris and tug spacecraft, and I_D and I_T are the total currents on the debris and tug spacecraft. The beam is a time-varying current when it is pulsed. The currents on each spacecraft are functions of the voltage of each, which are determined by the charges.

Hughes and Schaub in Ref. [69] provide the first study looking at a pulsed beam for the ET. Sensing and thrusting maneuvers are more easily executed when the tractor beam is not operating, and the pulsed charging can lead to higher force levels for the same electrical power used in particular conditions. Reference [69] has a Monte-Carlo analysis to study the mean electrostatic force considering a range of beam currents, voltages, pulsing duties cycles, and vehicle sizes. In all these scenarios the pulse duration is held short enough such that the debris charging time matters. In the resulting study, power limited regions are identified where the pulsed tractor has a magnitude that is comparable or greater than the mean force associated with the continuous beam. This creates interesting alternate methods to implement the ET while having periodic off cycles. The tractor performance is illustrated through the debris reorbiting scenario. A detailed equal power analysis determines that even duties cycles as low as 10%–20% can lead to forces comparable to the continuous beam performance, or even do better at some power levels. The charging model used in this work includes SEE and backscattering for the thermal currents, and uses a more advanced model for SEE than is used in prior work.

Reference [70] performs a similar analysis to Ref. [68] to see how the performance of the pulsed ET changes when analyzed over an orbit rather than with just one set of plasma parameters as well as during a solar storm. The average pulsed force varies over an orbit, but the optimal balance between current and voltage does not change significantly. During a storm, the forces are much higher, which would decrease the re-orbit time.

4 Fast numerical electrostatic force and torque approximations

For many electrostatic actuation concepts, fast and accurate methods for predicting the electrostatic forces and torques are needed. Whereas analytical analysis is possible for highly simplified scenarios with point charges or isolated spheres, the analytical approximations break down with complex three-dimensional space object geometries and small separation distances. Therefore, fast numerical approaches are required to model and predict the electrostatic forces and torques. These models can also be used for control purposes, but must be fast to evaluate. In particular, since many of the candidate objects are tumbling at a few degrees per second, the methods need to execute quickly.

There are many methods for numerically evaluating the electrostatic force and torque on a body due to a nearby charged object. These are divided into numerical and analytic methods. Figure 3 illustrates a range of numerical electrostatic force and torque modeling techniques and shows the relative computational challenge versus the force accuracy. The simplest approach is to approximate both satellites as point charges and compute the force between them using the Coulomb force law given by

$$\boldsymbol{F} = k_c \frac{Q_1 Q_2}{R^3} \boldsymbol{R} \tag{4}$$

where Q_1 and Q_2 are the charges on the bodies, $\boldsymbol{R}$ is the relative position vector, and $k_c = \frac{1}{4\pi\epsilon_0}$ is the Coulomb constant. If the bodies are approximated as spheres

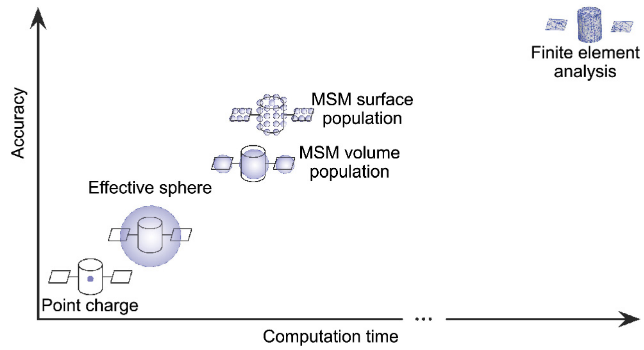


Fig. 3 Comparison of various electrostatic modeling methods [71].

rather than as point charges, their charges can be found as a function of their voltages using the position dependent capacitance matrix or the method of images [72], which are typically easier to estimate and measure than the charges [1]. This is because on the surface of a conductor the potential is the same everywhere and is determined through the charge balance equation in Eq. (1). The voltage to charge relationship can be expanded to include contributions from neighboring craft, meaning that the charge on a spacecraft is not just a function of its own voltage, but also the voltage of its neighbors.

If the spacecraft is represented by more than one sphere, or a single sphere not coincident with the center of mass, torques can also be modeled using the Multi-Sphere Method (MSM), an elastance-based method for predicting the force and torque on conductors [64,65]. A conceptual MSM representation of a satellite is shown in Fig. 4 [65]. It is similar to the Method of Moments (MoM) [73] in its linear form, but differs in that the size and location of the nodes are hand-tuned rather than derived from first principles. This tuning is done by an optimizer to match forces and torques [65] or fields

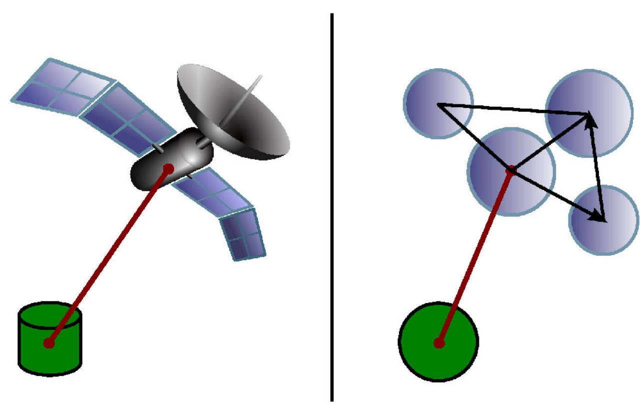


Fig. 4 Depiction of Multi-Sphere Method [65].

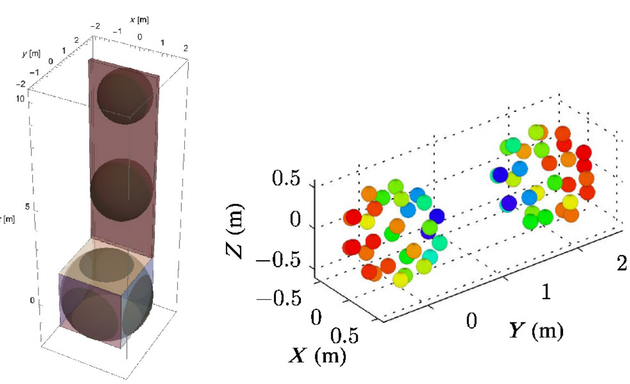
[74] which are computed using a high-fidelity Finite Element Method (FEM) or MoM software. Because of this, MSM can predict Coulomb forces and torques very quickly at accuracies of 1%–2% or better depending on the separation distance of the charged objects. Recent work largely automates the process of generating MSM models using local optimizers [74, 75]. The force and torque are found by computing the Coulomb force shown in Eq. (4) for each pair of spheres on the two spacecraft. The torque is found from summing the individual torque for each pair of spheres by crossing the vector from the origin to the sphere location:

$$\boldsymbol{F} = -k_c q_B \sum_{i=1}^{n} \frac{q_i}{{r_{i,b}}^3} \boldsymbol{r}_{i,b} \tag{5}$$

$$\boldsymbol{L}_O = -k_c q_B \sum_{i=1}^{n} \frac{q_i}{{r_{i,b}}^3} \boldsymbol{r}_i \times \boldsymbol{r}_{i,b} \tag{6}$$

MSM can be categorized as Volume MSM (VMSM), which uses a small number (1–5) of spheres placed throughout the volume of the object as shown in Fig. 5(a), and Surface MSM (SMSM), which places a large number of equidistant spheres on the surface of the spacecraft as illustrated in Fig. 5(b) [76]. While VMSM requires both the size and locations of the spheres to be tuned by an optimizer, SMSM finds the location for the spheres automatically using the equidistant criteria, and tunes only the radius of the spheres to match the self capacitance of the object being modeled.

Analytical formulae for the electrostatic two-body problem are found for the special case of two conducting spheres using the Method of Images [72, 77, 78]. If the bodies are not spherical, the multipole expansion method can be used to find the electric potential in the vicinity of a charge distribution by expanding the charge distribution in powers of $1/R$ [78]. The potential energy of two charged molecules can also be found and differentiated with respect to position attitude to find force and torque [79]. These expansions use terms similar to the inertia integrals used by Hou [80]. Hughes and Schaub [81] introduce a similar method for finding the electrostatic force and torque between two charged spacecraft as functions of the spacecraft voltages which differs in that it does not find the potential but finds the force and torque directly. This method for predicting force and torque is called the Appropriate Fidelity Measures (AFM) method, named for the measures of the charge distribution that appear due to the appropriate fidelity truncation of the binomial series.



(a) Volume MSM or VMSM illustration (b) Surface MSM or SMSM illustration

Fig. 5 Multi-Sphere Method modeling examples [76].

5 Electrostatic control

5.1 Position control

Active position control of the tractor relative to the target object is achieved through modulation of the inter-craft Coulomb force and inertial thrusters. This problem is closely related to the work done on Coulomb formation flying, which begins with Ref. [12] and continues to be an active field of research [3]. Initial work on Coulomb formation control focuses on multi-craft configurations arranged in a lattice structure, with electrostatic forces acting as virtual tethers linking spacecraft at each node [14]. A chief at one node would use inertial thrusters to maintain a prescribed orbit and the remaining craft would vary their electrostatic potential to maintain the desired relative orbits. Additionally, free-flying missions using only electrostatics are studied for 2 and 3 craft formations in Refs. [17, 18], 4 craft formations in Ref. [19], larger static formations up to 9 spacecraft in Ref. [82], and N spacecraft in Ref. [83]. References [84] and [16] discuss controllers for a two craft Coulomb configuration where only separation distances and rates are known. Spinning charged spacecraft clusters are investigated in Refs. [85–87]. In particular, invariant configurations for a spinning system are discussed in Refs. [88, 89], while Ref. [90] investigates novel configurations that yield naturally stable in-plane motion.

The electrostatic tractor concept can be considered a specific case of 2 craft Coulomb formation flying, in which a chief maintains the electrostatic force between itself and an uncooperative deputy, and also uses inertial thrusters to perform an orbital maneuver. The electrostatic force between the craft can be attractive or repulsive, so either a pushing or pulling configuration could be implemented for reorbiting debris with the tractor. Schaub and Jasper in Ref. [91] favor the pulling configuration because it is simpler to implement, more stable, more robust to failures (if the charge control devices fail, the tractor will simply pull away from the target), and has significantly higher performance. Pusher and puller ET concepts are investigated further in Refs. [92,93], while the pusher configuration dynamics is explored in Ref. [94]. The first experimental validation of controllers for relative motion Coulomb control is described in Refs. [95, 96], in which a charged sphere supported on an one dimensional air-bearing track is free to move relative to a fixed, charged sphere. Although experiments were conducted in atmosphere, increasing the track inclination effectively mimicked the dynamics of two craft on orbit. Stable position control was successfully demonstrated using a simple PID controller, even in cases of controller charge saturation.

Hogan and Schaub [3] develop a Lyupanov feedback controller which uses the charges of the two bodies to stabilize the relative positions of the tug and debris during an orbit raising maneuver. This reference also assesses the robustness of the controller to debris charge uncertainty. It is found that for overestimation of the charge, the controller is stable but the target settles to an equilibrium distance which is greater than the optimal distance. This decreases the magnitude of the electrostatic force and therefore increases the time required to re-orbit. However if the charge is underestimated, the system can become unstable, increasing the risk of a collision between the debris and the tractor.

5.2 Attitude control

As discussed previously, debris objects are often tumbling at rates up to 10 s of deg/s [49]. These high rotational rates pose a significant hazard to performing close proximity spacecraft operations and also prevent docking with the target for servicing or salvaging missions, as even advanced docking systems require rotational rates of less than 1 deg/s [22, 48]. Therefore, it is highly desirable to have a means of controlling the attitude of another body remotely.

Whereas most work on electrostatic manipulation of objects has focused on relative position control opportunities, there is growing interest in electrostatic attitude control. King *et al.* [14] analyze a scenario with two naturally-charged spacecraft separated by 10 meters at GEO. They found that significant torques, as high as 100 μNm, exist between the craft, resulting from the non-spherical electrical field around each object. This concept is explored for attitude control purposes in Ref. [15], where it is suggested that electrostatically-induced torques can be used to generate attitude changes in a nearby spacecraft.

Schaub and Stevenson [58] extend the idea of electrostatic attitude control to detumbling uncontrolled space debris. Figure 6 shows a concept of operations for electrostatic detumbling of a defunct satellite [22]. This work assesses the feasibility of using a spherical tractor, which exerts only forces, to detumble a cylinder-like object such as a spent rocket body or a dual-spinner satellite. By manipulating the charges on the bodies to potentials up to ±20 kV, the system was able to remove rotation rates of tens of deg/s in days. This was achieved using only attractive forces (as would be experienced if the tractor was using an electron or ion gun to modulate charge) and inertial thrusting by the tractor to counteract the forces required to arrest the rotational motion. Bennett and Schaub [97] consider a generic 3D detumbling scenario. They develop a detumbling controller and use simulations of a cylinder in deep

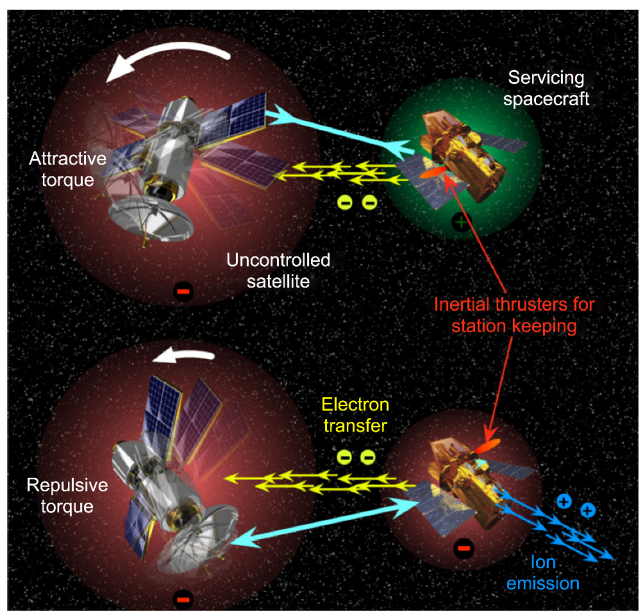


Fig. 6 Concept of operations for remote electrostatic detumbling. Image from Ref. [22].

space to analyze its performance. A smoothly saturating controller is used to control the charge on the servicing craft which eliminates chatter issues seen with bang-bang controllers while maintaining good performance. In Ref. [98], relative motion trajectories are explored to facilitate the E-torque effectiveness in detumbling an object. Criteria are developed to illustrate when the lead-follower formation is the optimal relative motion solution. Aslanov in Ref. [99] investigates adiabatic invariants that occur with electrostatic detumbling.

A laboratory experiment to validate the electrostatic detumbling concept was performed using a 15 cm diameter stationary sphere and a rotating cylinder 15 cm in diameter and 45 cm in length as illustrated in Fig. 7 [100]. The cylinder was charged to a fixed potential prior and given an initial rotation rate about 1 axis. The potential on the sphere was actively modulated to ± 30 kV. The system successfully arrested the cylinder using electrostatic forces, removing rotational rates of 100 deg/s in 1/6 the time required for disturbance torques from the bearings and air resistance to remove the same initial angular rate [101].

5.3 Thruster requirements

The inertial thrusters for the electrostatic tractor concept must be able to provide a nominal thrust to at least match the electrostatic tractor force in the range of 1–10 mN with a resolution of 10–50 μN and operate continuously for 2–3 months [102]. The mission life time is expected to be at least 10 years. The total thrust magnitude is driven by the magnitude of the electrostatic force between the debris and the tug, while the thrust resolution is required to mitigate variation in

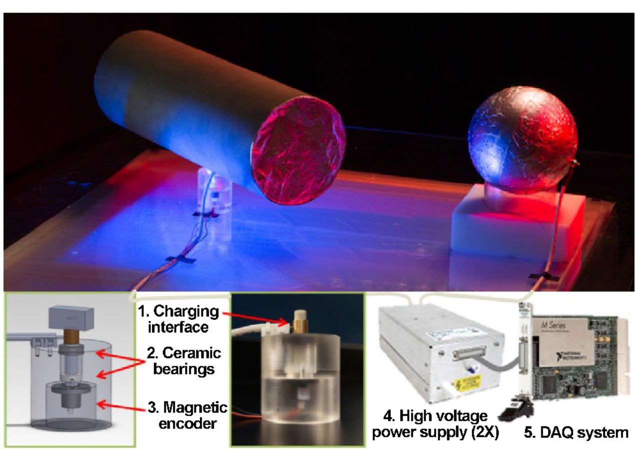


Fig. 7 Electrostatic Rotational Testbed within the Autonomous Vehicle Systems Lab [100].

the electrostatic attraction as the target tumbles. Small chemical or cold-gas thrusters were determined to be the most promising candidates as they would operate independently of the high electrostatic potentials and ensure that plume impingement on the target would not undermine the tractor operation. This analysis covers only the tractor concept and does not address thruster requirements for detumbling.

If the ET is not operating continuously, but in a pulsed manner as described earlier in this manuscript, then other propulsion solutions could be considered [70, 103]. The off-pulse duration of the charging beam creates windows during which the tug would not be highly charged, and there are less concerns with attracting expelled fuel particles.

Low thrust levels translate to low maneuverability and a decreased ability to avoid potential conjunctions during re-orbiting, an effect that is examined in Ref. [104]. Though the risk posed by collisions with other space debris during the reorbiting maneuver is found to be high, the risk can be significantly reduced if the maneuver is timed correctly to minimize conjunctions.

6 Electrostatic sensing

When active charging with the electron beam is carried out during ET operation, it is desirable to know the potential or charge which has accumulated on the target craft. Potential can be measured directly by physically contacting the target object, however, this would defeat the purpose of using a touchless method for reorbiting. Therefore, touchlessly sensing potential is an area of active research related to the ET. The Coulomb force depends on the charges of both craft, so a feedback stabilization and control law which considers the charging dynamics for the two craft formation requires knowledge of the target craft potential, as discussed by Hogan and Schaub [3]. As discussed previously, some studies propose a control strategy in which only the separation distances and relative velocities are used to stabilize the formation [16, 84]. Though it may be possible to use only relative motion feedback for tugging operations, the charge transfer physics is closely coupled to the relative motion. Therefore, knowledge of both craft potentials will allow for more efficient charge transfer and more robust control strategies. Additionally, Bennett establishes that knowledge of the electrostatic potential is required for detumbling operations [105].

Several methods for remotely sensing potential have been proposed. Ferguson *et al.* consider various techniques to remotely monitor charging or arcing events, including surface glows, bremsstrahlung x-rays, and radio or optical emission from arcing [106]. This reference concludes that arc detection may be possible from ground based on telescopes, but co-orbiting satellites would be needed to remotely sense the charge. Bennett [105] discusses how the charge can actually be estimated from the relative motion dynamics using range and range rate measurements. However, this method can provide only a single charge measurement for the entire target (i.e., an effective sphere model) and updates the charge estimate on the order of minutes. Therefore, a method with higher spatial and temporal resolution is desired. Engwerda [107, 108] proposes a method for sensing the charge by directly measuring the electric field around an object. This work focuses on how to use the voltage measurements to obtain a charge estimate and then develop an MSM model of the target. However, the challenges of obtaining a direct electric field measurement near the tractor system in GEO are not considered.

Another possible method involves measuring the energy of secondary electrons generated at the target by the interactions between the electron beam and the surface. Secondary electrons are created at the target with very low energies and then accelerated toward the tractor. The energy with which they arrive is equal to the potential difference between the two craft. Therefore, by knowing the electrical potential of the tractor, the potential of the target can be inferred. This method requires that the debris be charged negatively and the tractor be charged positively, which is consistent with the proposed operating scheme. A similar method of using secondary electrons has been used to remotely sense the charge distribution on the lunar surface [109, 110].

A final method operates by measuring bremmstrahlung x-ray radiation emitted by the debris surface when bombarded with the electron beam. When energetic electrons interact with a surface, x-ray radiation is emitted when electrons are slowed down or change direction (bremmstrahlung means "braking radiation"). The highest energy x-ray, corresponding to the case when an electron is completely stopped and a single photon is emitted, is directly proportional to the landing energy. Therefore, knowing the landing energy and the energy at which the electrons were fired, the target potential can be inferred. The characteristic peaks of the x-ray spectrum are also indicative of the elemental composition being targeted. Though this technique has not been used to determine the electrostatic potential, instruments to measure the x-ray fluorescence of atoms excited by solar radiation have flown on numerous scientific missions.

7 Conclusions

In light of the unique value of the geosynchronous ring, it is imperative that this orbital region be stabilized and maintained such that future space operations will not face an unreasonably high risk of debris collision. It is no longer sufficient to simply mitigate the creation of future debris. Instead, steps must be taken to actively remove those debris objects which pose the greatest threat of collision. This is among the most important and challenging problems in modern aerospace engineering, especially when one considers the legal and financial aspects in addition to the technical challenges. The electrostatic tractor is an innovative and elegant solution to this problem. Among the various proposed concepts, it has a very low risk of creating additional debris because it fires no physical objects and will simply pull away from the debris in the event of a mission failure. The ET makes no physical contact with the uncooperative object and therefore does not require risky, fuel-expensive docking maneuvers. Further, the ET is agnostic to the debris size, shape, attitude, or spin rate.

To further advance the ET concept into reality, future research will continue in several topics. Remote potential sensing research is necessary to enable more feedback control of the charging transfer. To increase the forces and torques, methods such as using inflatable conducting spheres to increase the craft charges without increasing the mass should be considered. This technology may allow a small satellite bus within a larger inflatable conducting sphere to tug much larger objects. Finally, experimental validations of the charge transfer physics, force and torque modeling, and sensing methods would help advance the electrostatic tractor toward realization.

This survey paper presents an overview of the concept, completed work, and current status of the electrostatic tractor, which will prove useful as efforts continue to increase the technological readiness and ultimately implement an on-orbit mission.

References

[1] Schaub, H., Moorer, D. F. Jr. Geosynchronous large debris reorbiter: challenges and prospects. *The Journal of the Astronautical Sciences*, **2012**, 59(1–2): 161–176.

[2] Schaub, H., Sternovsky, Z. Active space debris charging for contactless electrostatic disposal maneuvers. *Advances in Space Research*, **2014**, 53(1): 110–118.

[3] Hogan, E. A., Schaub, H. Relative motion control for two-spacecraft electrostatic orbit corrections. *Journal of Guidance, Control, and Dynamics*, **2013**, 36(1): 240–249.

[4] Lai, S. T. Fundamentals of spacecraft charging: spacecraft interactions with space plasmas. Princeton University Press, **2011**.

[5] Chen, F. F. Introduction to plasma physics and controlled fusion: volume 1: plasma physics, 2nd ed. Plenum Press, **1984**.

[6] Schaub, H., Sternovsky, Z. Active space debris charging for contactless electrostatic disposal maneuvers. The 6th European Conference on Space Debris, **2013**.

[7] Denton, M. H., Thomsen, M. F., Korth, H., Lynch, S., Zhang, J. C., Liemohn, M. W. Bulk plasma properties at geosynchronous orbit. *Journal of Geophysical Research*, **2005**, 110(A7): A07223.

[8] Seubert, C. R., Stiles, L. A., Schaub, H. Effective coulomb force modeling for spacecraft in earth orbit plasmas. *Advances in Space Research*, **2014**, 54(2): 209–220.

[9] Murdoch, N., Izzo, D., Bombardelli, C., Carnelli, I., Hilgers, A., Rodgers, D. Electrostatic tractor for near earth object deflection. The 59th International Astronautical Congress, **2008**.

[10] Murdoch, N., Izzo, D., Bombardelli, C., Carnelli, I., Hilgers, A., Rodgers, D. The electrostatic tractor for asteroid deflection. The 58th International Astronautical Congress, **2008**.

[11] Cover, J. H. Jr., Knauer, W., Maurer, H. A. Lightweight reflecting structures utilizing electrostatic inflation: USA, 3546706. 1970-12-08.

[12] King, L. B., Parker, G. G., Deshmukh, S., Chong, J. H. Spacecraft formation-flying using inter-vehicle coulomb forces. NASA Institute for Advanced Concepts, **2002**.

[13] Kong, E. M. C., Miller, D. W., Sedwick, R. J. Exploiting orbital dynamics for aperture synthesis using distributed satellite systems: applications to visible earth imager system. Proceedings of AAS/AIAA Space flight Mechanics Meeting, **1999**.

[14] King, L. B., Parker, G. G., Deshmukh, S., Chong, J. H. Study of interspacecraft coulomb forces and implications for formation flying. *Journal of Propulsion and Power*, **2003**, 19(3): 497–505.

[15] Schaub, H., Parker, G. G., King, L. B. Challenges and prospect of coulomb formations. *The Journal of the Astronautical Sciences*, **2004**, 52(1–2): 169–193.

[16] Natarajan, A., Schaub, H. Linear dynamics and stability analysis of a two-craft coulomb tether formation. *Journal of Guidance, Control, and Dynamics*, **2006**, 29(4): 831–839.

[17] Berryman, J., Schaub, H. Analytical charge analysis for two- and three-craft coulomb formations. *Journal of Guidance, Control, and Dynamics*, **2007**, 30(6): 1701–1710.

[18] Schaub, H., Hall, C. D., Berryman, J. Necessary conditions for circularly-restricted static coulomb formations. *The Journal of the Astronautical Sciences*, **2006**, 54(3–4): 525–541.

[19] Vasavada, H., Schaub, H. Analytic solutions for equal mass four-craft static coulomb formation. *The Journal of the Astronautical Sciences*, **2008**, 56(1): 17–40.

[20] Moorer, D. F., Schaub, H. Hybrid electrostatic space tug: USA, 8210480. 2012-07-03.

[21] Moorer, D. F., Schaub, H. Electrostatic spacecraft reorbiter: USA, WO/2011/019830. 2011-02-17.

[22] Bennett, T., Stevenson, D., Hogan, E., Schaub, H. Prospects and challenges of touchless electrostatic detumbling of small bodies. *Advances in Space Research*, **2015**, 56(3): 557–568.

[23] Yasaka, T., Hanada, T., Hirayama, H. Geo debris environment: a model to forecast the next 100 years. *Advances in Space Research*, **1999**, 23(1): 191–199.

[24] IADC. Proceedings of the 15th Inter-Agency Space Debris Coordination Committee Meeting, NASA JSC, Houston, TX, **1997**.

[25] Johnson, N. L. Protecting the GEO environment: policies and practices. *Space Policy*, **1999**, 15(3): 127–135.

[26] Jehn, R., Agapov, V., Hernndez, C. The situation in the geostationary ring. *Advances in Space Research*, **2005**, 35(7): 1318–1327.

[27] Schaub, H., Jasper, L. E. Z., Anderson, P. V., McKnight, D. S. Cost and risk assessment for spacecraft operation decisions caused by the space debris environment. *Acta Astronautica*, **2015**, 113: 66–79.

[28] Oltrogge, D. L., Kelso, T. S. Getting to know our space population from the public catalog. AIAA/AAS Astrodynamics Specialist Conference, **2011**.

[29] Anderson, P. V., Schaub, H. Local orbital debris flux study in the geostationary ring. *Advances in Space Research*, **2013**, 51(12): 2195–2206.

[30] Anderson, P. V., Schaub, H. Local debris congestion in the geosynchronous environment with population augmentation. *Acta Astronautica*, **2014**, 94(2): 619–628.

[31] McKnight, D. S., Di Pentino, F. R. New insights on the orbital debris collision hazard at GEO. *Acta Astronautica*, **2013**, 85: 73–82.

[32] McKnight, D. Pay me now or pay me more later: start the development of active orbital debris removal now. Advanced Maui Optical and Space Surveillance Technologies Conference, **2010**.

[33] Chrystal, P., McKnight, D., Meredith, P. L., Schmidt, J., Fok, M., Wetton, C. Space debris: on collision course for insurers? Swiss Reinsurance Company Ltd, **2011**.

[34] Oltrogge, D. L., Alfano, S., Law, C., Cacioni, A., Kelso, T. S. A comprehensive assessment of collision likelihood in geosynchronous earth orbit. The 68th International Astronautical Congress, **2017**.

[35] Carlson, E., Casali, S., Chambers, D., Geissler, G., Lalich, A., Leipold, M., Mach, R., Parry, J., Weems, F. Final design of a space debris removal system. NASA-CR-189976, NASA, **1990**.

[36] Reed, J., Barraclough, S. Development of harpoon system for capturing space debris. The 6th European Conference on Space Debris, **2013**.

[37] Dudziak, R., Tuttle, S., Barraclough, S. Harpoon technology development for the active removal of space debris. *Advances in Space Research*, **2015**, 56(3): 509–527.

[38] Loughman, J. J. Overview and analysis of the soldier satellite concept for removal of space debris. AIAA Space 2010 Conference & Exposition, **2010**.

[39] Forshaw, J. L., Aglietti, G. S., Salmon, T., Retat, I., Roe, M., Burgess, C., Chabot, T., Pisseloup, A., Phipps, A., Bernal, C. et al. Final payload test results for the removedebris active debris removal mission. *Acta Astronautica*, **2017**, 138: 326–342.

[40] Jasper, L. Z., Schaub, H. Input shaped large thrust maneuver with a tethered debris object. The 6th European Conference on Space Debris, **2013**.

[41] Jasper, L. E. Z., Seubert, C. R., Schaub, H., Trushkyakov, V., Yutkin, E. Tethered tug for large low earth orbit debris removal. AAS/AIAA Astrodynamics Specialists Conference, **2012**.

[42] Jasper, L., Schaub, H. Input shaped large thrust maneuver with a tethered debris object. *Acta Astronautica*, **2014**, 96: 128–137.

[43] Nishida, S. I., Kawamoto, S., Okawa, Y., Terui, F., Kitamura, S. Space debris removal system using a small satellite. *Acta Astronautica*, **2009**, 65(1–2): 95–102.

[44] Nishida, S. I., Kikuchi, N. A scenario and technologies for space debris removal. The 12th International Symposium on Artificial Intelligence, Robotics and Automation in Space, **2014**.

[45] Castronuovo, M. M. Active space debris removal—a preliminary mission analysis and design. *Acta Astronautica*, **2011**, 69(9–10): 848–859.

[46] Smith, D. A., Martin, C., Kassebom, M., Petersen, H., Shaw, A., Skidmore, B., Smith, D., Stokes, H., Willig, A. A mission to preserve the geostationary region. *Advances in Space Research*, **2004**, 34(5): 1214–1218.

[47] Lennon, J. A., Henshaw, C. G., Purdy, W. An architecture for autonomous control of a robotic satellite grappling mission. AIAA Guidance, Navigation and Control Conference and Exhibit, **2008**.

[48] Couzin, P., Teti, F., Rembala, R. Active removal of large debris: rendez-vous and robotic capture issues. The 2nd European Workshop on Active Debris Removal, **2012**.

[49] Karavaev, Y. S., Kopyatkevich, R. M., Mishina, M. N., Mishin, G. S., Papushev, P. G., Shaburov, P. N. The dynamic properties of rotation and optical characteristics of space debris at geostationary orbit. *Advances in the Astronautical Sciences*, **2004**, 119: 1457–1466.

[50] DeLuca, L. T., Bernelli, F., Maggi, F., Tadini, P., Pardini, C., Anselmo, L., Grassi, M., Pavarin, D., Francesconi, A., Branz, F. et al. Active space debris removal by a hybrid propulsion module. *Acta Astronautica*, **2013**, 91: 20–33.

[51] Schonenborg, R. A. C., Schoyer, H. F. R. Solid propulsion de-orbiting and re-orbiting. In: Proceedings of the 5th European Conference on Space Debris, **2009**.

[52] Vetrisano, M., Thiry, N., Vasile, M. Detumbling large space debris via laser ablation. 2015 IEEE Aerospace Conference, **2015**.

[53] Ortiz Gómez, N., Walker, S. J. I. Eddy currents applied to de-tumbling of space debris: analysis and validation of approximate proposed methods. *Acta Astronautica*, **2015**, 114: 34–53.

[54] Bombardelli, C., Peláez, J. Ion beam shepherd for contactless space debris removal. *Journal of Guidance, Control, and Dynamics*, **2011**, 34(3): 916–920.

[55] Bombardelli, C., Urrutxua, H., Merino, M., Ahedo, E., Peláez, J., Olympio, J. Dynamics of ion-beam-propelled space debris. The 22nd International Symposium on Space Flight Dynamics, **2011**.

[56] Merino, M., Ahedo Galilea, E., Bombardelli, C., Urrutxua, H., Pélaez Álvarez, J., Summerer, L. Space debris removal with an ion beam shepherd satellite: target-plasma interaction. The 47th AIAA/ASME/SAE/ASEE Joint Propulsion Conference & Exhibit, **2011**.

[57] Schaub, H., Jasper, L. E. Z. Circular orbit radius control using electrostatic actuation for 2-craft configurations. AAS/AIAA Astrodynamics Specialists Conference, **2011**.

[58] Schaub, H., Stevenson, D. Prospects of relative attitude control using coulomb actuation. *The Journal of the Astronautical Sciences*, **2013**, 60(3–4): 258–277.

[59] Garrett, H. B., Whittlesey, A. C. Guide to mitigating spacecraft charging effects. Wiley, **2012**.

[60] Lai, S. T. Spacecraft charging. American Institute of Aeronautics & Astronautics, **2011**.

[61] Whipple, E. C. Potentials of surfaces in space. *Reports on Progress in Physics*, **1981**, 44(11): 1197–1250.

[62] Mullen, E. G., Gussenhoven, M. S., Hardy, D. A., Aggson, T. A., Ledley, B. G., Whipple, E. Scatha survey of high-level spacecraft charging in sunlight. *Journal of Geophysical Research*, **1986**, 91(A2): 1474–1490.

[63] Lai, S. T., Tautz, M. F. Aspects of spacecraft charging in sunlight. *IEEE Transactions on Plasma Science*, **2006**, 34(5): 2053–2061.

[64] Smythe, W. R. Static and dynamic electricity, 3rd ed. McGraw-Hill, **1968**.

[65] Stevenson, D., Schaub, H. Multi-sphere method for modeling spacecraft electrostatic forces and torques. *Advances in Space Research*, **2013**, 51(1): 10–20.

[66] Peck, M. A. Prospects and challenges for lorentz-augmented orbits. AIAA Guidance, Navigation, and Control Conference and Exhibit, **2005**.

[67] Hogan, E. A., Schaub, H. Impacts of hot space plasma and ion beam emission on electrostatic tractor performance. *IEEE Transactions on Plasma Science*, **2015**, 43(9): 3115–3129.

[68] Hogan, E. A., Schaub, H. Space weather influence on relative motion control using the touchless electrostatic tractor. *The Journal of the Astronautical Sciences*, **2016**, 63(3): 237–262.

[69] Hughes, J., Schaub, H. Prospects of using a pulsed electrostatic tractor with nominal geosynchronous conditions. *IEEE Transactions on Plasma Science*, **2017**, 45(8): 1887–1897.

[70] Hughes, J., Schaub, H. Orbital and solar storm analysis of the pulsed electrostatic tractor. The 7th European Conference on Space Debris, **2017**.

[71] Stevenson, D. Optimization of sphere population for electrostatic multi sphere model. The 12th Spacecraft Charging Technology Conference, **2012**.

[72] Lekner, J. Electrostatics of two charged conducting spheres. *Proceedings of the Royal Society A*, **2012**, 468: 2829–2848.

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

[74] Ingram, G., Hughes, J., Bennett, T., Reily, C., Schaub, H. Autonomous volume multi-sphere-model development using electric field matching. AAS Spaceflight Mechanics Meeting, **2017**.

[75] Chow, P., Hughes, J., Bennett, T., Schaub, H. Automated sphere geometry optimization for the volume multi-sphere method. AAS/AIAA Spaceflight Mechanics Meeting, **2016**.

[76] Stevenson, D., Schaub, H. Optimization of sphere population for electrostatic multi-sphere method. *IEEE Transactions on Plasma Science*, **2013**, 41(12): 3526–3535.

[77] Maxwell, J. C. A treatise on electricity and magnetism. Clarendon Press, **1873**.

[78] Jackson, J. D. Classical electrodynamics. John Wiley & Sons, **1999**.

[79] Price, S. L., Stone, A. J., Alderton, M. Explicit formulae for the electrostatic energy, forces and torques between a pair of molecules of arbitrary symmetry. *Molecular Physics*, **1984**, 52(4): 987–1001.

[80] Hou, X. Y., Scheeres, D. J., Xin, X. S. Mutual potential between two rigid bodies with arbitrary shapes and mass distributions. *Celestial Mechanics and Dynamical Astronomy*, **2017**, 127(3): 369–395.

[81] Hughes, J., Schaub, H. Spacecraft electrostatic force and torque expansions yielding appropriate fidelity measures. AAS Spaceflight Mechanics Meeting, **2017**.

[82] Berryman, J., Schaub, H. Static equilibrium configurations in GEO coulomb spacecraft formations. The 15th AAS/AIAA Space Flight Mechanics Meeting, **2005**.

[83] Schaub, H. Stabilization of satellite motion relative to a coulomb spacecraft formation. *Journal of Guidance, Control, and Dynamics*, **2005**, 28(6): 1231–1239.

[84] Wang, S. Q., Schaub, H. Spacecraft collision avoidance using coulomb forces with separation distance and rate feedback. *Journal of Guidance, Control, and Dynamics*, **2008**, 31(3): 740–750.

[85] Hussein, I. I., Schaub, H. Invariant shape solutions of the spinning three craft coulomb tether problem. *Celestial Mechanics and Dynamical Astronomy*, **2006**, 96(2): 137–157.

[86] Hussein, I., Schaub, H. Stability and control of relative equilibria for the three-spacecraft coulomb tether problem. *Acta Astronautica*, **2009**, 65(5–6): 738–754.

[87] Schaub, H., Hussein, I. I. Stability and reconfiguration analysis of a circularly spinning two-craft coulomb tether. *IEEE Transactions on Aerospace and Electronic Systems*, **2010**, 46(4): 1675–1686.

[88] Hogan, E. A., Schaub, H. Collinear invariant shapes for three-spacecraft coulomb formations. *Acta Astronautica*, **2012**, 72: 78–89.

[89] Hogan, E. A., Schaub, H. Linear stability and shape analysis of spinning three-craft coulomb formations. *Celestial Mechanics and Dynamical Astronomy*, **2012**, 112(2): 131–148.
[90] Jasch, P. D., Hogan, E. A., Schaub, H. Out-of-plane stability analysis of collinear spinning three-craft coulomb formations. *Acta Astronautica*, **2013**, 88: 89–97.
[91] Schaub, H., Jasper, L. E. Z. Orbit boosting maneuvers for two-craft coulomb formations. *Journal of Guidance, Control, and Dynamics*, **2013**, 36(1): 74–82.
[92] Stevenson, D. Remote spacecraft attitude control by coulomb charging. Ph.D. Dissertation, University of Colorado at Boulder, Boulder, CO, **2015**.
[93] Shibata, T., Bennett, T., Schaub, H. Prospects of a hybrid magnetic/electrostatic sample container retriever. The 9th International Workshop on Satellite Constellations and Formation Flying, **2017**.
[94] Aslanov, V. S., Yudintsev, V. V. Relative motion control of space pusher-tug during debris removal by a coulomb force. *Journal of Guidance, Control, and Dynamics*, **2017**.
[95] Seubert, C. R., Schaub, H. Closed-loop charged relative motion experiments simulating constrained orbital motion. *Journal of Guidance, Control, and Dynamics*, **2010**, 33(6): 1856–1865.
[96] Seubert, C. R., Schaub, H. Electrostatic force model for terrestrial experiments on the coulomb testbed. The 61st International Astronautical Congress, **2010**.
[97] Bennett, T., Schaub, H. Touchless electrostatic three-dimensional detumbling of large axi-symmetric debris. The Journal of the Astronautical Sciences, **2015**, 62(3): 233–253.
[98] Bennett, T., Schaub, H. Capitalizing on relative motion in electrostatic detumble of axi-symmetric geo objects. The 6th International Conference on Astrodynamics Tools and Techniques, **2016**.
[99] Aslanov, V. S. Exact solutions and adiabatic invariants for equations of satellite attitude motion under coulomb torque. *Nonlinear Dynamics*, **2017**, 90(4): 2545–2556.
[100] Stevenson, D., Schaub, H. Terrestrial testbed for remote coulomb spacecraft rotation control. *International Journal of Space Science and Engineering*, **2014**, 2(1): 96–112.
[101] Bennett, T., Stevenson, D., Hogan, E., McManus, L., Schaub, H. Prospects and challenges of touchless debris despinning using electrostatics. The 3rd European Workshop on Space Debris Modeling and Remediation, **2014**.
[102] Hogan, E. A., Schaub, H. Space debris reorbiting using electrostatic actuation. The 35th Annual Guidance and Control Conference, **2012**.
[103] Hughes, J., Schaub, H. Monte-carlo analysis of the pulsed electrostatic tractor strength. The 14th Spacecraft Charging Technology Conference, **2016**.
[104] Anderson, P. V., Schaub, H. Conjunction challenges of low-thrust geosynchronous debris removal maneuvers. *Acta Astronautica*, **2016**, 123: 154–164.
[105] Bennett, T. J. On-orbit 3-dimensional electrostatic detumble for generic spacecraft geometries. Ph.D. Dissertation, University of Colorado at Boulder, Boulder, CO, **2017**.
[106] Ferguson, D. C., Murray-Krezan, J., Barton, D. A., Dennison, J. R., Gregory, S. A. Feasibility of detecting spacecraft charging and arcing by remote sensing. *Journal of Spacecraft and Rockets*, **2014**, 51(6): 1907–1913.
[107] Engwerda, H. J. A., Hughes, J., Schaub, H. Remote sensing for planar electrostatic characterization using the multi-sphere method. Final Stardust Conference, **2016**.
[108] Engwerda, H. J. A. Remote sensing for spatial electrostatic characterization using the multi-sphere method. Master Dissertation, Delft University of Technology, Delft, The Netherlands, **2017**.
[109] Halekas, J. S., Mitchell, D. L., Lin, R. P., Hood, L. L., Acua, M. H., Binder, A. B. Evidence for negative charging of the lunar surface in shadow. *Geophysical Research Letters*, **2002**, 29(10): 1435.
[110] Halekas, J. S., Delory, G. T., Lin, R. P., Stubbs, T. J., Farrell, W. M. Lunar prospector observations of the electrostatic potential of the lunar surface and its response to incident currents. *Journal of Geophysical Research*, **2008**, 113(A9): A09102.

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