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DRAG ENHANCEMENT FOR SPACECRAFT USING NUMEROUS ULTRA-THIN WIRES ARRANGED INTO DRAG-WIRE WEBS OF VARIOUS CONFIGURATIONS

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Abstract

The concept and design of a novel drag enhancement system called the Ultra-thin Wires Drag Enhancement System (UWDES), is presented. The UWDES uses numerous ultra-thin wires to form a three dimensional (3D) web through electrostatic charging. UWDES is designed with the objective of mitigating space debris, particularly in low altitude Earth orbits (LEOs) for pico/nano/micro-satellites by causing their rapid orbital decay. The ultra-thin drag-wires are stowed inside the container module of UWDES and at the end of spacecraft's mission life, deployed by releasing the container lid, followed by electrostatic charging. In comparison to drag sails, the UWDES drag-wires provide more effective area experiencing drag (EAED) for a given mass and size of the material used to fabricate the drag enhancing structure. For a unit cube of side 1 cm, (i) beaten into a square sheet of 1 micron thickness and (ii) drawn into a round wire of same thickness, the EAED for (i) is 1 m^2 and (ii) is 1.2732 m^2. The ultra-thin drag-wires of the UWDES are held straight in a tuft with all strands fused together at both ends. When they are electrostatically charged, due to mutual repulsion on acquiring like charges, they unwind from spool and deploy out of container module to gradually arrange into a 3D web structure. With this, all the individual ultra-thin drag-wire strands are exposed to incoming atoms and ions of space atmosphere and thus augment the effective area experiencing drag (EAED) of the host spacecraft and the resultant aero drag. As the drag wires are electrostatically charged, they mutually repel with like-charged particles of space atmosphere that collide with them resulting in Coulomb drag. Hybrid-drag effect of both Aero drag and Coulomb drag are responsible for stretching the ceiling altitude for UWDES application up to 6000 km. Based on the amount of charges supplied to the wires, the UWDES is designed to arrange itself into various 3D configurations (boat-shape, spindle/pear, globe and flower), resulting in varying EAED. It may be argued that the deployment mechanism of UWDES, which involves a lid release relay followed by electrostatic charging, is simpler in operation and has a lesser chance of deployment failure compared to drag-sails that employ moving parts like motors. Varying in the way ultra-thin wires deploy from container, UWDES has two variants namely fixed-spool and deployable-spool. Also, based on charging, UWDES is categorised into passive- and active-charging variants.

Keywords: Ultra-thin drag wires, Electrostatic charging, UWDES, Drag enhancement system, Aerodynamic drag, Coulomb drag

1. Introduction

Space debris or the orbiting debris around Earth consists mainly of spent upper stages of rockets, defunct satellites, exploded or collided spacecraft & their fragments,etc., ranging in sizes from a small paint-fleck to a huge rocket stage or a giant communication satellite[1]. A small paint fleck is all that takes to punch a hole through a satellite or even an astronaut performing EVA (Extra-Vehicular Activity, or simply space-walk), as it travels at nearly 25 times the speed of sound while in a low-altitude Earth orbit (LEO) of about 350 km altitude, where its kinetic energy is nearly equal to or greater than that of a fired rifle-bullet. Every object orbiting in space, whether small or large, when unused or not necessary there, unless de-orbited, is a potential space debris that constantly endangers the lives of astronauts as well as spacecraft, and hence the urgency to tackle them.

Space debris pose another grave threat in the form of 'burgeoning', i.e., rapidly multiplying in numbers[2]. This happens through collision with one another or through explosion because of unused on-board propellants, heated batteries & other components, etc., shattering into many smaller pieces of debris that are both difficult to track as well as keep spreading into wide belts in orbit, but are still hazardous, just like their parent debris (objects). This multiplication also takes place regularly at a more rapid pace with the rise in number of space missions being taken up day-by-day as well as number of satellites getting defunct or lost and the abandoned rocket upper-stages that are piling up in the precious orbits, particularly in LEOs [3],[4].

Finally, things are taking a concrete shape as to determining who is responsible for space debris and how. And, what stringent actions need to be taken to control this orbiting menace as can be seen by setting up of regulatory bodies by various space agencies worldwide, e.g.- Space Debris Office of ESA (European Space Agency)[5],[6],[7]. Also, there is the establishment of global monitoring & coordinating authorities like UNCOPUOS by United Nations which came up with the space debris mitigation guidelines that is agreed upon internationally by many space agencies [8]. These are solid proofs for consensus that's building up among multitude space-faring nations and organizations that space debris is a serious problem which really exists / is happening and can quickly go out of control, if not taken care of in time.

Some deorbiting mechanisms for debris mitigation like drag sails and electrodynamic tethers that deorbit satellites from LEO at the end of their life in a certain stipulated time are being developed.[9],[10],[11]. Other methods for end of life deorbiting of satellites like use of drag balloons are being experimented with[12]. These methods have their own pros and cons that determine their usability and reliability.

In this paper is presented a novel method (UWDES) of deorbiting spacecraft, in particular micro- and nano-satellites, in LEOs for their post-mission life disposal (PMLD). This novel mechanism constitutes the utilization of numerous ultra-thin wires in specified arrangements for enhancing the drag force acting on the host spacecraft. Unlike the conventional way of using thin large sheets/membranes as drag sails/gossamers for increasing the aerodynamic drag force acting on the spacecraft when deployed, in this case of UWDES the numerous ultra-thin wires cumulatively contribute to augmenting the net effective area experiencing drag (EAED) or simply drag area and hence the resultant rise in drag force on the spacecraft. As the role of these ultra-thin wires as part of UWDES is to create drag effect, they are referred to here as 'drag wires". Though initially when this idea of drag wires was conceived for increasing the aerodynamic drag effect on spacecraft, it was later found during the course of study, design and development of UWDES concept that these drag wires also contribute for another form of drag effect known as Coulomb drag because these drag wires are electrostatically charged. Polarizing these drag wires is another novel feature designed for deployment of drag wires as part of UWDES using a simple principle of mutual repulsion of like-charged objects. This novel design feature of deployment of drag-enhancing structure, which is drag wires, based on their mutual repulsion on being like-charged electrostatically also is conceived along with the above idea of using numerous ultra-thin wires for increasing the drag area. Therefore, both aerodynamic drag and Coulomb drag generated together are responsible for making UWDES a hybrid-drag enhancing system (HDES) for spacecraft. And because of these two radically new features of employing ultra-thin wires for drag generation and electrostatic charging (of drag wires) for deployment of drag-enhancing structure (drag wires) of UWDES, this UWDES is being proposed here as an entirely new class of deorbiting mechanisms for spacecraft in LEOs.

2. Rationale for using UWDES

Consider a regular solid cube of side 1 cm and is made of gold. Here, the volume of cube is 1 cm^3, total surface area (TSA) is 6 cm^2. Say now it's beaten into a sheet of side 1 m and thickness 1μm, its TSA increased to 2 m^2 and its maximum possible cross-sectional area (MPCA) is ≈1 m^2 (neglecting its thickness) while the volume remained 1 cm^3. This MPCA of ≈1 m^2 for the square sheet here is what is responsible for the maximum drag effect generated by conventional drag sails/gossamers when their (sheets/membranes) plane is oriented normal to the velocity vector of host spacecraft.

Moving on, when this square sheet of 1m^2 is further drawn into a wire of 1μm thickness, which is same as that of the sheet from which it's drawn, the volume is constant at 1 cm^3 while the TSA and MPCA both rise up to 4.23 m^2 and 1.414 m^2 respectively. We can understand that the long ultra-thin wire has greater TSA (111.5% rise) and MPCA (27.32% rise) than its parent object (the square sheet) of same thickness from which it is derived keeping the object's volume constant.

Ultimately the ultra-thin round-wire has a significant 27.32% increment in MPCA when drawn from a square sheet of same thickness and mass. Thus, ultra-thin wires when employed as drag wires for drag enhancement of a spacecraft and oriented with their length normal to velocity vector of spacecraft contribute to greater drag area (EAED) and the resultant greater aero drag effect in comparison to drag sails/gossamers having membranes of same thickness and are of same mass and material as drag wires and are also oriented with their plane normal to the spacecraft's velocity vector (maximum drag-generating orientation).

2.1 Aerodynamic drag effect of drag wires

By now it's clear that these ultra-thin drag wires increase the drag area/ECA of the spacecraft in LEOs for experiencing greater drag force. The near Earth space is not a complete vacuum but, still has some considerable number of residual gas molecules/atoms, ions and particles (neutral or charged) which are present as part of the extremely low dense atmosphere at Low-altitude Earth orbits (LEOs). These ions and particles (of the near-Earth space atmosphere) are responsible for the aerodynamic drag effect on the spacecraft in LEO. When a spacecraft is present in these LEOs and has the drag wires deployed from but, still anchored to, UWDES on-board the host spacecraft the drag wires are oriented such that their length is normal to the spacecraft's velocity vector. Because the host spacecraft and the drag wires are moving through this near-Earth space atmosphere with very high velocities, there will be significant number of nano-scale collisions of drag wires with the particles/ions present there. This ramming into and collision of ultra-thin drag wires with those particles/ions with high relative velocities can be likened to numerous tennis balls being thrown at a round cylindrical pillar that is far wider than the balls hitting it. When the balls hit the pillar, there will be momentum transfer between the both during their collision with each other. In a similar fashion, the particles/ions colliding with the incoming drag wires cause momentum transfer between them thereby slowing down the ultra-thin drag wires and this effect is the aero drag. This causes the drag wires to exert a pulling force on the host spacecraft in a direction opposite to its motion as they are still anchored to it, which in turn causes the entire system of the host spacecraft and the attached drag wires to keep slowing down gradually resulting in their deorbiting.

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2.2 Coulomb drag effect of drag wires

Irrespective of the UWDES variant employed, the ultra-thin drag wires are electrostatically charged or polarized with like-charges either by passive or active means. These charged drag wires, when moving through the space atmosphere (space plasma) present in those orbits, face some resistance force acting upon them. This is because these electrostatically charged drag wires mutually repel with the like-charged particles of space plasma and inner Van Allen radiation belt that are in the path of these fast moving charged drag wires.[13] Whenever any of the charged ultra-thin wire strands of the drag wires tuft encounters a like-charged particle, when they come close to each other they mutually repel with electrostatic force and due to their relative high velocity, there will be a momentum exchange between both causing the speeding drag wires to lose some of their momentum to that charged particle with which it interacted/collided resulting in its slowing down which in turn slows down the host spacecraft. This resistance offered by the charged particle in space to the like-charged or polarized ultra-thin drag wire causing it to lose momentum partially is known as the Coulomb drag effect as the resistance force is the result of mutual repulsion between two like-charged objects. Here, the greater the mass and charge of the encountered like-charged particle, the greater will be the momentum exchange between it and the colliding ultra-thin drag wire strand. And the higher the number of such collisions, the higher the net momentum transfer and the resultant deceleration of the system comprising of 3D-drag wires web, UWDES and the host spacecraft towards a rapid orbital-decay.

3. UWDES Design and Configurations

The UWDES is a tuft of ultra-thin drag-wires wound around a spindle (bobbin) and stowed (stored) in a container module. The tuft of ultra-thin drag-wires along with their anchor wires are stowed in a manner as to prevent entangling, reduce damage during launch or otherwise and facilitate smooth deployment process. A mechanical design of the spindle with the tufts of wound wires and the storage container are shown in Fig. 1. The storage container is designed in the CubeSat form factor and may be integrated into a host satellite.

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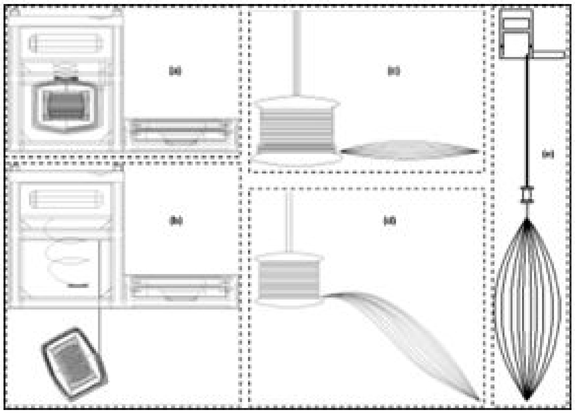

Fig. 1. UWDES Design and Arrangement

The design is novel by virtue of the use of ultra-thin wires to form drag enhancing structures through electrostatic charging. A simple lid release mechanism for activation is followed by electrostatic charging to deploy the tuft out of the storage of UWDES. The electrostatic charging causes the tuft of wires to mutually repel and form a three dimensional (3D) structure as shown in Fig. 1. This method of deployment in comparison to previously implemented mechanical means/moving parts like motors, minimizes the risk of failure of the device[14],[15] For a given amount of material, these ultra-thin drag wires can produce more effective area experiencing drag (EAED) in comparison to drag-sails and other drag-enhancing devices. Also, considering only the aerodynamic drag, the UWDES can be used in Lower-LEO region (400-1000 km) with nominal performance and the inherent design-features of this new Drag-Enhancing System (DES) allow its effective use in Upper-LEO region (1000-2000 km) as well with appreciable performance. But, with the inclusion of its Coulomb drag effect the ceiling altitude for utilization of UWDES can be raised to 6000 km, which is the outer limit of inner Van Allen radiation belt. Additionally, the design allows for an optimal range of drag force to be experienced in any configuration of the payload and the host satellite

3.1. Arrangement and deployment of drag wires

In the above example of a square sheet of side 1m and thickness 1μm, when it is drawn into ultra-thin square-wire of same thickness, it will measure 1000 km in length, whereas when drawn into ultra-thin round-wire of same thickness, it scales 1273.2 km long and provides an MPCA of 1.2732m^2. It's understandable that using ultra-thin drag wires of that long length deployed from UWDES is not practical as they are limited by their tensile strength as well as they pose a threat to other spacecraft. Therefore, the long ultra-thin wires have to be cut into numerous strands of short length and bundled together into a tuft. They have to be arranged in the tuft in a straight fashion and then the ends of all ultra-thin wire strands are fused (clamped) together at each end of the tuft. The ultra-thin drag wires tuft is to be placed (stowed) in a container with a lid as part of the UWDES. Here, before stowing in the container, the tuft is twisted about its long axis into a single wire with multi-stranded core and is wound about a tapered-spindle shaped barrel/core of a spool inside the container. When the UWDES is activated for deorbiting the spacecraft and after the lid opens, the tuft of drag wires are supposed to come out of the container as shown in Fig. 1. But, these wires being very sensitive and fragile to the forces and stresses acting upon them, extra caution is required for their deployment. This renders conventional means of deployment used for drag sails like using motors, booms or centrifugal effect directly pull the drag-enhancing payload structure out of its housing container unemployable for ultra-thin drag wires. Therefore, with this necessity in mind, the second novel feature of UWDES was conceived of which is the employment of the principle of mutual repulsion of like-charged objects for deploying the ultra-thin drag wires. This works by polarizing gradually with like-charges the tuft of ultra-thin wires and the interior of the container in which they are stowed so that the wires repel with the container and the central barrel of the spool, unwind and move out of it (deploy) gently. This constitutes the fixed-spool variant of UWDES. A diagram of the UWDES container with the fixed spool variant is shown in Fig. 2. The fixed spool variant will be discussed further in subsection [3.3]

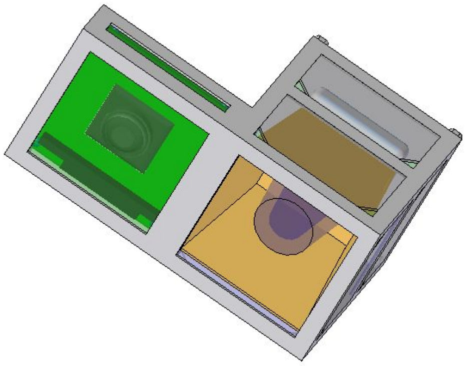

Fig. 2. Fixed-spool variant of UWDES showing the core/barrel of the spool at the center of the container with the lid open. Drag wires are not shown here.

Once out of the container, the single wire tuft untwists and stretches lengthwise and finally unfurls by the mutual repulsion between individual wire strands of the tuft which are all like charged. The strands move away from each other due to mutual repulsion and that exposes each individual strand to the incoming particles of space atmosphere for collision with them generates aerodynamic drag effect acting on them. This finishes the process of deployment of ultra-thin drag wires of UWDES. Here, as all the individual wire strands are clamped together at both ends of the tuft, they arrange/configure themselves into various shapes/configurations based on the strength of mutual repulsion between them, the drag force acting upon them, number of wire strands present and the effect of gravity-gradient stabilization. Also one end (node) of the wire tuft is anchored to the container of UWDES via an anchor wire, which is a wire of higher gauge that acts as an anchoring connection between the container and the drag wires tuft. Anchor wire helps in preventing the cutting of ultra-thin wire strands by eliminating the direct contact of the sensitive ultra-thin wire strands with the mouth of the container and the nearby components or structure of the spacecraft.

3.2 3D web configurations of drag wires

Boat configuration for deployed drag wires tuft is achieved when electrostatic repulsive force is less, allowing flexible and free movement of the wire strands in the web as shown in Fig 3. With further electrostatic charging, the individual wires in the boat configuration tend to move away radially and settle into the spindle configuration. Globular configuration can be attained by utilizing more charge than that of the spindle configuration. The drag area can be maintained nearly constant in this particular configuration irrespective of its attitude in space.

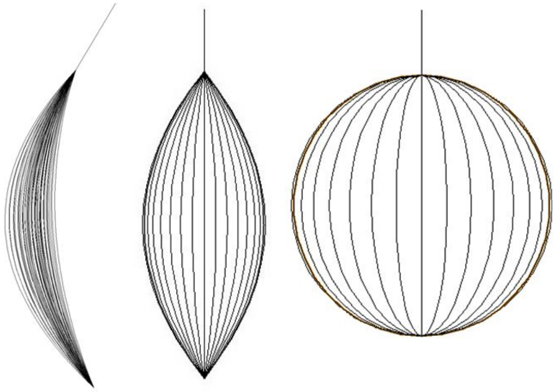

Fig. 3. 3D-drag wires web in boat, spindle and globe configurations.

Upon maximum charging, the drag wires settle into the flower configuration as indicated by Fig. 4. This configuration is the most stable amongst all. This is particularly evident when the host satellite is at lower altitudes where it encounters high atmospheric density.

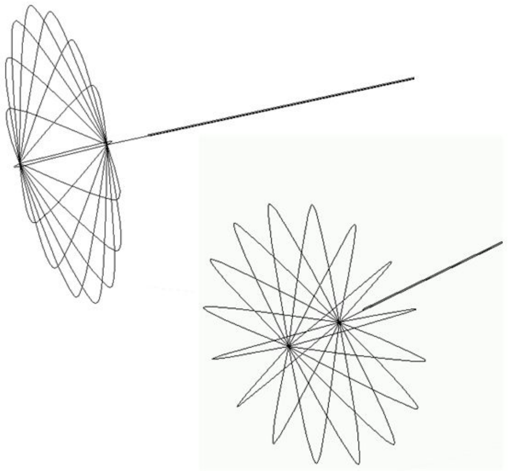

Fig. 4. Oblique views of 3D-drag wires web of UWDES in flower configuration.

3.3. Variants of UWDES based on the method of deployment

In due course of study, design and development of UWDES model, it was realized that the charged wires can come into accidental contact with either the host spacecraft or the UWDES that might lead to damage of the wires or even the host spacecraft as the wires are charged electrostatically which affects the components on-board. Also, it's difficult for the drag wires to deploy as well as maintain in a deployed state, if the spacecraft is tumbling, which might lead to wrapping around of the spacecraft by the drag wires. For these reasons, the design of the UWDES system was altered to come up with a new variant known as 'Deployable spool' model wherein a tape-spring boom (TSB) is incorporated.

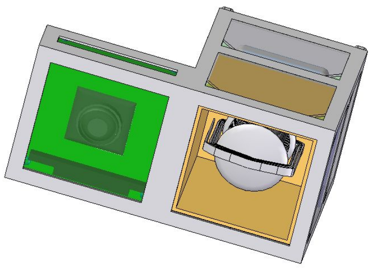

Fig. 5. Deployable-spool variant of UWDES showing TSB and spool in stowed position in container but, with the lid open.

In this model, a TSB preferably of double-element type is used and it is positioned such that one end of it is fastened in a socket present over one of the walls of the container and its other end is attached to a spool at the center of one of the spool flanges. The spool has a spindle-shaped hollow core with two hollow biconvex discs acting as its flanges present at either ends of spindle-shaped core all of which (core/barrel and flanges) act as Gaussian surfaces because of their convexity. The drag wires are wound about the spindle shaped core of the spool. The TSB is wound perpendicular to that over the groove in biconvex discs of the spool and stowed (placed) inside the container. Fig 5. Shows the placement of the tape spring within the UWDES module. While placing inside the container, the spool is pressed against helical spring, to hold it under tension, which acts as an ejection spring that assists in ejecting the spool out of the container on lid opening on the activation of UWDES. Once the TSB fully unwinds and straightens, the drag wires, spool and TSB are polarized by a charge generator on-board the UWDES. This causes the drag wires tuft wound about the spool to mutually repel with it and unwind, followed by untwisting and unfurling to complete the deployment process by forming into a 3D drag wires web structure. The presence of TSB in this variant of UWDES helps keep the charged and deployed drag wires away and distant from the spacecraft to prevent accidental contact and damage to either of them (host spacecraft and drag wires). TSB employed UWDES variant also presents the advantage of it being used for deorbiting a spacecraft in LEOs that is in uncontrolled tumbling because on activation of UWDES, the TSB is deployed along with the spool and drag wires wound about the spool both of which act as a mass at the outer/distant end of TSB, thus causing it to absorb some amount of angular momentum of the host spacecraft. This results in reduction of its rate of tumbling and finally stabilizing it (passive stabilization) by deploying the drag wires on charging them.

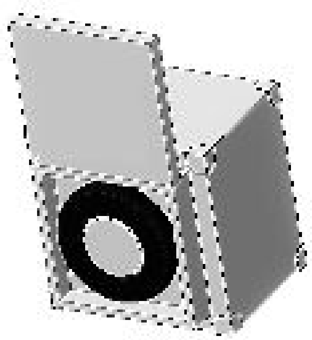

Fig. 6. Fixed-spool variant of UWDES showing drag wires (black) in stowed state wound around the core of the spool at the center of the container with the lid open. Here the UWDES is of pizza-box form factor.

The model/design of the UWDES where the wires are directly wound about a tapered-spindle shaped core of the spool that is fixed at the center of the container's floor and it doesn't employ a TSB is considered as 'Fixed spool' variant of UWDES. It was discussed before the description of 'Deployable spool' variant.

3.4 Variants of UWDES based on the method of charging drag wires

Charging the drag wires is critical for their deployment on UWDES activation. Following are the two models of UWDES that differ in how the drag wires on-board are charged.

3.4.1 Active charging of drag wires

Charging the drag wires is critical for their deployment on UWDES activation. In case of 'fixed-spool' variant, after lid opens the drag wires are polarized gradually, while still inside the container, along with the spool and the interior walls of the container causing their mutual repulsion for deployment to happen.

Whereas in 'deployable-spool' variant of UWDES, after the lid opens, the spool and its two windings (drag wires and TSB) are ejected out of the container. The TSB unwinds and, straightens by virtue of its shape memory and that positions the spool and the still wound drag wires farthest from the spacecraft. This leads to the charging of ultra-thin drag wires tuft, the spool and the TSB, facilitating the drag wires to unwind from the spool for deployment into 3D drag wire web structure. While in fixed-spool model, both the drag wires and their associated components are charged directly, in deployable-spool model, the TSB is polarized first which in turn polarizes the spool and drag wires by acting as a bridge to transfer the charges.

Irrespective of which UWDES variants (deployment based) are employed, the charging of drag wires and other required components is thought to be performed for deployment to happen as follows when UWDES was conceptualized at first. To begin with, before the activation of UWDES, drag wires and associated components are neutral (ignoring the little static charges acquired by them during a prolonged stay in space). Immediately after its (UWDES) activation, the lid opens and signals a charging device on-board the UWDES to be powered on. This device is meant for polarizing the drag wires and related components by either adding to or removing from them the (electric) charges (positive or negative) thereby polarizing them by acquiring the like-charges and forcing them to mutually repel. This addition or removal of charges from the drag wires and other components is accomplished by the above said charging device by it driving or transferring the charges from them to either the spacecraft/UWDES chassis acting as ground (electrical), which is a source as well as a sink or by emitting the charges into space. It being an open-circuit configuration, for this polarization of wires and other structures to happen an electrostatic charge generator (ECG) fits the job well. In simple, when powered on, the ECG device polarizes or builds-up electrostatic charges on the wires and their surrounding structures with like-charges for their mutual repulsion as in a gold-leaf electroscope where the leaves mutually repel and deflect on acquiring like-charges that are static. This method of mutual repulsion based deployment of drag wires on electrostatic charging with like-charges was experimented extensively and proven using a VDG.

3.4.2 Passive charging of drag wires

Another interesting possibility that has come up during the course of our development of UWDES and is now being explored for use as an alternative method is by electrostatically charging the drag wires and other required structures on-board the UWDES by making use of space plasma in low-altitude Earth orbits (LEOs) and the trapped charged particles like ions present in the Inner Van Allen radiation belt[13]. As the space atmosphere in these LEOs has plenty of charged particles (that either come through the solar wind and get trapped there or are generated by ionization of atoms there on interaction with solar and cosmic radiation), when the host spacecraft along with UWDES is breezing through them, some of these charges are acquired by them either by losing to or gaining from on interaction with these charged particles.

Considering the case of fixed-spool variant first, when the spacecraft hosting the UWDES on-board is passing through this charged space environment in LEOs, the excess charges acquired by it on interaction with the charged particles move to the outer chassis/structural frame of the spacecraft and UWDES which acts as their (electric) ground[15]. But, on activation of UWDES, once the lid opens it will establish an electrical contact between the spacecraft's chassis having excess charges and the container's interior walls along with the spool and stowed drag wires. With this there will be a flow of some excess charges to the drag wires and the container causing them to mutually repel for deployment on acquiring these static charges. In addition, the drag wires and the container also keep getting polarized with like-charges directly on interaction with the charged particles in space once the lid is open making way for the gradual deployment of the tuft of ultra-thin drag wires.

Whereas in case of deployable spool UWDES model, once it is activated and lid opens, just like in the fixed-spool variant, there will be an electrical contact will get established between the spacecraft's chassis (acting as ground) and the TSB directly instead of the container unlike in fixed-spool model where the container and its contents (spool and drag wires) get charged on direct electrical contact with chassis. Until the TSB fully unwinds, though the drag wires tuft, spool and TSB itself acquire excess like-charges on their electrical connection with spacecraft's ground, the innermost windings of TSB above prevent the unwinding of the outermost layers/windings of the drag wires below. In addition to excess like-charges acquired from spacecraft's ground, the deployed (completely unwound and straightened) TSB along with the spool with the drag wires all act as plasma collectors that absorb or accumulate like charges on interaction with space plasma facilitating the complete deployment of drag wires and maintaining them in the completely unfurled 3D wire-web configuration for drag enhancement of spacecraft hosting them on-board.

3.5 Passive stabilization and ceiling altitude

Drag sails, another kind of drag-enhancing device also work by aerodynamic drag. They have a ceiling altitude of about 700 km to attain their highest functional efficiency to provide maximum possible drag at a given altitude[16],[17],[18]. As most of them rely on passive aero-stabilization without involving any active attitude control/maintenance for orienting the drag sails, they generate maximum aero-drag effect.

In contrast, considering only the ultra-thin drag wires of UWDES can have a ceiling altitude of up to 1000 km as they are of extremely lightweight and flexible structures (the 3D drag wire web along with anchor wire) that can easily conform and reorient to provide maximum aero drag effect without necessitating the entire spacecraft to reorient for facilitating considerable amount of drag generation but, can be a follow on effect (reorientation of spacecraft due to pulling of 3D drag-wires web).

But, by adding Coulomb drag as well into the picture, it is thought that the ceiling altitude for application of UWDES can get pushed up to 6000 km, which is the outer border of the inner Van Allen radiation belt.

This is because the Coulomb drag force can be experienced by charged drag wires on repelling and colliding with charged particles that are in plenty throughout the inner Van Allen radiation belt, in particular the high energy positive charges that are higher in number.

3.6 Drag sails/gossamers versus drag wires (UWDES)

The comparison of drag-sails/ gossamers with drag wires (UWDES) is indicated in Table 1.

Table 1. Comparison of drag-sails/ gossamers with drag wires (UWDES) and its analysis

Drag sails/gossamers	**Drag wires (UWDES)**
For a given amount of material, moderate drag area can be produced	For the same quantity of material, greater drag area can be produced
Coulomb drag is not part of the design. So, negligible scope for use in 1000-2000 km altitude orbits based on current technology.	With Coulomb drag adding to the aero drag, the ceiling altitude can stretch up to 6000 km.
Because of their dependence on aero-stabilization, their ceiling altitude is limited to 700 km.	As they are not reliant on passive stabilization, their ceiling altitude with respect to aero drag alone can be up to 1000 km
Higher chances of getting torn or cut while being pulled out of container during deployment using conventional mechanical means.	The deployment based on mutual repulsion by electrostatic charging is gradual as they are slowly charged and so, less prone to damage.

Drag sails/gossamers	**Drag wires (UWDES)**
With this method of deployment, drag sail sheets/membranes of thickness below 1-5 micron can’t be employed safely without getting damaged. It’s is a significant design limitation of this method.	There’s no limitation as to what minimal thickness what minimal thickness of the wires can be employed except for the advancement in materials science that can provide them. With advances in Nanotechnology, the application of drag wires can advance too.
Depend on passive aero stabilization for effective functioning as most of them don’t have active attitude control.	Doesn’t require passive stabilization for optimum drag generation. But, can still make use of it.
Limited scope to explore or modify the concept on further research	Huge scope to kick start a whole new study area in deorbiting technology for spacecraft.
Break-even point keeps shifting higher proportionately with quantity (size and mass) of drag producing sail/sheet structure	Break-even can be reached very early and only rises by a little even with significant increase in size and mass of the drag wires tuft

4. Calculations, simulations and experiments

4.1 Rationale for using drag wires over drag sails

Consider a square metal sheet with sides measuring, ‘x’ meters and let the thickness be ‘y’ meter. Now the volume of this sheet is given by:

$$v_{sheet} = x^2 y \qquad (1)$$

If the square sheet is used as a drag sail, the effective cross sectional area experiencing drag varies from a maximum of $a_{max} = x^2$ to $a_{min} = xy$, depending on the orientation of the sail with respect to the velocity vector. If we can draw ‘n’ wires of thickness ‘y’ from the same volume as that of the sheet, we can obtain wires of length ‘l’ each. The volume of ‘n’ drag wires is given by:

$$v_{wires} = x^2 y = \frac{n\pi y^2 l_{wire}}{4} \qquad (2)$$

Now, the length of each drag-wire (from Eq. (2)) is given by:

$$l_{wire} = \frac{4x^2}{n\pi y} \qquad (3)$$

Consider the longitudinal axis of the drawn wires to be oriented perpendicular to the direction of velocity vector. At any instant of time, the surface area of a single strand experiencing drag is effectively half of the total surface area of that strand. The total drag-area (a_{drag}) from all drawn wires is given by:

$$a_{drag} = nyl \qquad (4)$$

i.e., from Eq. (3),

$$a_{drag} = \frac{4x^2}{\pi} \qquad (5)$$

It can be seen from Eq. (5) that the effective area experiencing drag increases by 1.2732 times that of a drag sail, which is fabricated from the same mass/volume of material.

4.2 Orbital analysis & simulations using STK for UWDES

The orbital analysis was performed on Systems Tool Kit to simulate the time taken for a specimen satellite with an enhanced drag area for utilizing atmospheric aerodynamic drag. Scenario consisted of a typical nanosatellite with corresponding increments in drag area. Mass of this satellite was 5.25kg, and an additional 1.5kg was chosen for the UWDES module.

Table 2. Model nano-satellite’s orbital parameters

Semi-major Axis	7047.65203592
Eccentricity	0.00048404
Inclination	98.16506757
Right Ascension of Ascending Node	328.83138775
True Anomaly	82.4214
Apogee	672.926406
Perigee	666.103665

For all the simulations, Drag Coefficient was chosen to be 2.2 and Reflectivity Coefficient being 0.5.

The value of drag coefficient is widely accepted as 2.2 for most compact satellites. Reflectivity coefficient signifies the acceleration due to pressure exerted by solar radiation.

Table 3. Drag area of a model nanosatellite (with and without DES) versus its orbital lifetime

Drag area	Orbital Lifetime
$0.0525m^2$ (Satellite without DES)	415 years (2254850 orbits)
$1m^2$	6.5 years (35082 orbits)
$2m^2$	5.5 years (29900 orbits)
$3m^2$	4.8 years (26189 orbits)
$4m^2$	4.2 years (22481 orbits)
$10m^2$	1.2 years (6640 orbits)

A satellite without an effective drag enhancement system spends huge amount of time in space after its primary functions are served. During this time, it is a potential threat to other working satellites. The above simulation takes only atmospheric aerodynamic drag into consideration. So, if Coulombic drag was also involved, it could deorbit a satellite quicker.

4.3 Experimentation with Van de Graaff generator (VDG) as ECG to charge the drag wires

For a proof of concept of deployment of drag wires using mutual repulsion on electrostatically charging them, a VDG was used as ECG and metallic yarn was used as drag wires. The VDG generated an output of about 100 kV DC regularly, measured using sphere-gap method.

In the first experiment, when a tuft of about 20 metallic yarn wire strands of 40 cm long each are tied at both ends and placed in a plastic container with a metallic base, which is connected to the dome of VDG, the tuft use to raise straight upwards moving out (deploy) of container on powering on VDG. This is due to the mutual repulsion of tuft of wires with container on acquiring like charges.

In the second experiment, when a tuft of about 45 metallic yarn wire strands of 2 m long each are tied at both ends and suspended from a ceiling in closed room, initially they were all vertical and stayed close due to gravity. The tuft is connected at the top end through a 5 m long insulated copper wire to the dome of VDG and this wire acts as an interface transferring charges from the dome of VDG to the wire tuft. When the VDG is powered on, after a few seconds it was always observed that the wire strands tried to move away from each other forming into a 3D wire web structure of various shapes (spindle, pear, orb and flower) based on the how much charges they acquired.

These experiments were repeated many times with various candidate materials for drag wires in various arrangements for improving the system.

5. Results and Discussion

The calculations presented in 4.1 are enough proof that for a given amount material to fabricate a drag-enhancing structure, drag wires can provide more EAED than drag sails.

From the two experiments briefly described in subsection 4.3, we can say that on electrostatic charging with an ECG, using UWDES we can deploy a tuft of drag wires out of a container and after moving out of the container they completely unfurl in into a 3D wire web of various configurations based on the amount of charging and other factors and finally enhance the drag area of the spacecraft by finishing the deployment process.

Also the orbital simulations data presented briefly in subsection 4.2 states clearly that with augmentation of drag area (EAED) of a spacecraft, its orbital lifetime can be reduced. Further simulations and analysis are to be carried including Coulomb drag to provide better data for deorbiting times of spacecraft using UWDES.

6. Conclusions

UWDES offers unique advantages like hybrid drag effect (including both aero and Coulomb drag), possible ceiling altitude of up to 6000 km, less chances of deployment failure, etc., unlike other deorbiting mechanisms like drag sails and electrodynamic tethers and so, is a strong candidate for deorbiting micro- and nanosatellites in LEOs. UWDES with its novel and radical design features like utilization of ultra-thin wires for hybrid drag and electrostatic charging for deployment of drag wires can be classified as a new class of deorbiting mechanism for space debris mitigation. The full potential of UWDES can be realized with the advent of nanotechnology where long and strong nanowires and nanotubes can be utilized as drag wires for generation of enormous hybrid drag effect with minute amounts of drag-enhancing payload material which is not so far in future.

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