DETUMBLING ROCKET BODIES IN PREPARATION FOR ACTIVE DEBRIS REMOVAL

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1.ABSTRACT

The focus of this analysis is on the difficult, yet critical, step of preparing derelicts for removal from orbit by grappling and de-tumbling the object. If the objects are made stable (i.e. not tumbling) and have a common attachment point, then the active debris removal process by another system can be enabled. The approach of this study is to identify possible applications for a microsatellite (less than 100 kg) to detumble large derelict objects as a precursor to active debris removal. This satellite size is small enough to deploy many of them into an orbital regime from a single launch, but large enough to create a reasonable physical effect on a derelict. Two mechanisms investigated to reduce the tumble rate are applying a retarding torque and/or increasing the moment of inertia. Three potential solutions in each of these two general categories are investigated in detail.

2.PROBLEM STATEMENT

The collision risk to operational satellites is driven by the lethal fragments (1-10 cm) that may number 600,000 objects in Low Earth Orbit (LEO). However, it is problematic to remove this dispersed swarm that cannot be seen reliably from the ground. Analysis has shown that the future debris population may best be constrained by removing hundreds of large derelict rocket bodies and payloads in earth orbit in order to prevent them from colliding with each other. Unfortunately, it is likely that most of these derelict objects have some tumbling motion which will complicate the grappling and subsequent moving of the objects. These derelicts appear in altitude and inclination clumps in LEO as seen by Fig. 1. [1]

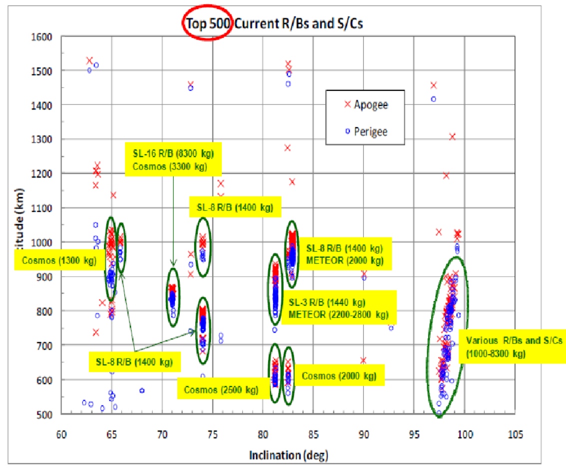

Figure 1. The top 500 LEO large debris is clustered by altitude and inclination

Three of the types of derelict objects that represent a majority of the mass in LEO orbit are the 31 SL-3 Vostok, the 204 SL-8 Kosmos, and the 19 SL-16 Zenit rocket bodies. Objects of each type are often located in similar orbits due to the similarity of the payload missions. A disposing device that can affect multiple objects is advantageous in these altitude and inclination bands since the amount of propulsion needed to move between derelicts is reduced by their proximity. The focus of this analysis is on the difficult, yet critical, step of preparing derelicts for removal from orbit. This step involves the grappling and de-tumbling of the derelict. If the objects are made stable (i.e. not tumbling) and have a common attachment point, then the active debris removal process by another system can be enabled. Significant work has been performed in pursuit of such systems over the years. [2-4]

3.TECHNICAL APPROACH

The approach of this study is to identify possible applications for a microsatellite (less than 100 kg) to detumble large derelict objects as a precursor to debris

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removal. This satellite size is small enough to deploy many of them into an orbital regime from a single launch, but large enough to create an appropriate effect on a derelict. The typical area-to-mass ratio for large derelict objects is likely too small to contribute to the deorbit of objects in the 775-975km altitude range for most derelict rocket bodies. However, we strive to use microsatellites to attach to objects (possibly providing a common interface for a larger "deorbiters") and slow down their rotation rate.

3.1 Attach to Derelict (Grappling Concepts)

Three simple attachment techniques are examined: hook/harpoon, net, and perch.

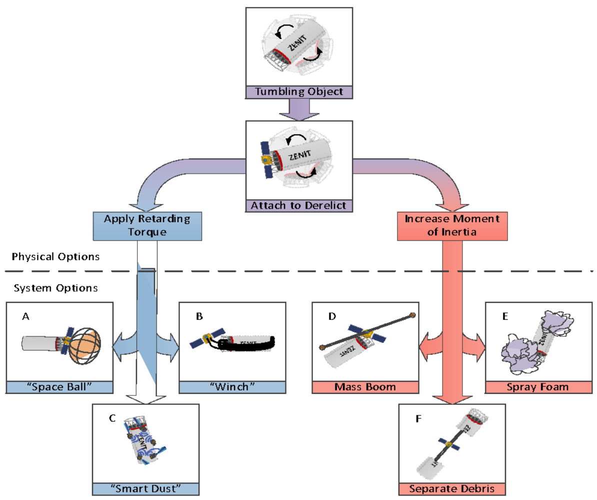

Figure 2. Options for decreasing the tumbling rate of a derelict are grouped into two major categories: either apply a retarding torque or increase the moment of inertia.

Hook/Harpoon

A hook/harpoon is an object launched at the derelict object that somehow connects to hook onto or through the derelict while remaining connected to the parent satellite by a lanyard, as depicted in Figure . This concept requires knowing the physical characteristics of the derelict and identifying a "soft" spot either ahead of time or during rendezvous with the object. An advantage of this approach is that a generic design for the harpoon portion of the device could be applicable to a variety of objects. It will be difficult to properly time the release of the harpoon such that it impacts the desired location on the derelict. If the incorrect portion of the derelict is hit, it may trigger an explosion or knock pieces off of the derelict.

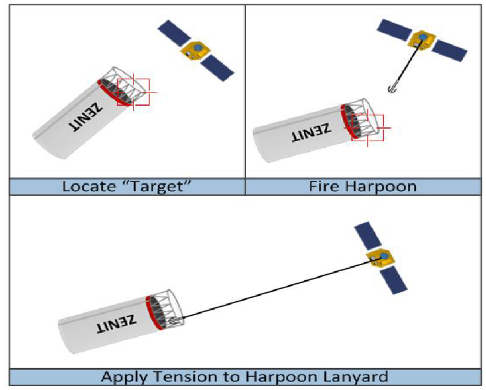

Figure 3. The notional hook/harpoon concept will be difficult to engage with a derelict reliably.

Another difficult aspect of this approach is how the final docking occurs between the satellite deploying the harpoon and the derelict object. As the end of the cable wraps around the tumbling debris, it will likely pull the satellite deploying the cable towards the derelict at a high speed. The system would have to be designed to account for this.

Net

A net is similar to a harpoon except the wider area of the net increases the probability of success of coupling to the derelict. A notional depiction of this concept is shown in Fig. 4. The net will likely be stabilized by masses pulling at the corners of the net as it rotates. Once it makes contact with the derelict object, these spinning masses will aid in wrapping the net around the derelict. Once the net is positioned, a similar problem exists in which the satellite still needs to "reel in" the derelict and perform a final docking. If the derelict is spinning at a reasonably fast rate, this could prove very difficult. The net will also need to be designed to limit the structural challenges for the net when dealing with rotating derelicts.

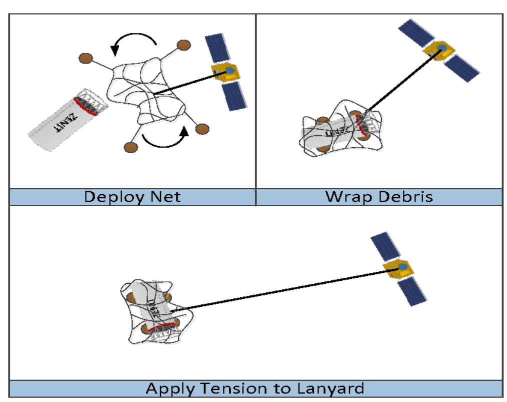

Figure 4. The notional net concept does not provide a set attachment point.

Perch

The “perch” solution is proposed to use stiff lanyard arms with microspines that are deployed as the parent object approaches the derelict object. This is an extension of concepts used for wall climbing robots and perching UAVs. [5] The approach speed and the characteristics of the microspines would need to be tuned to the specific type of object being encountered. A device using this concept, modified for UAV perching, is shown in Fig.5

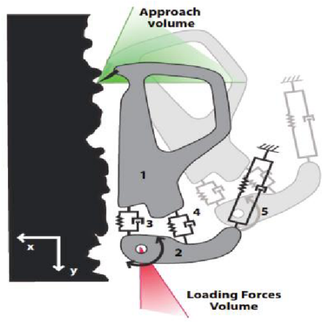

Figure 5. This "claw" uses microspines to perch an unmanned aerial vehicle (UAV) on a wall. [6]

A notional application of this concept to perching on a derelict rocket body is shown in Figure . Since this device relies on surface asperities of the object being landed on, the specific landing point will be challenging to control. However, in contrast to the hook/harpoon concept, the landing is of the entire vehicle on the derelict, which eliminates some of the challenges. Much testing is required to determine the appropriate closing velocities and feature sizes for the microspines to maximize their effectiveness in gripping onto the derelict. Tab. 1 summarizes the pros and cons of each of the three grappling concepts.

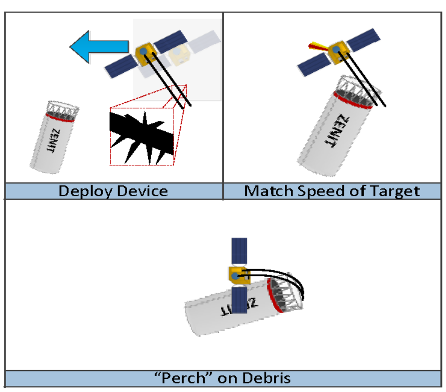

Figure 6. The notional perch concept requires the approaching craft to match speed with the derelict rocket body.

Table 1: Presentation of the pros and cons of the three grappling concepts shows that none of them are easy or foolproof.

Grappling Method	PROS	CONS
Hook/ Harpoon	-Functional from a distance -Works equally well for large or small objects	-May trigger explosion or knock pieces off -May not penetrate or attach sufficiently -Lanyard wrapping around tumbling debris may cause a high speed collision
Net	-Functional from a distance -Does not require specific target point on the debris	-Complex deployment to ensure the net is expanded when it hits the debris -Still need to “dock” satellite after the derelict is captured with the net
Perch	-Provides a solid landing of the entire spacecraft -Does not require specific target point on the debris	-Complex deployment to ensure the device is properly aligned -Would have to optimize spine size and characteristics -Not a precise, pre known location of the attachment point

3.2 Decrease Tumble Rate

To detumble an object a retarding torque must be applied to the object. This may be done by exerting a force at a radial location from the spin axis in the proper direction, or by increasing the object’s moment of inertia, or both. We will examine a means to bring these forces to the derelicts and to leverage natural phenomena (such as the Earth’s magnetic field).

Space Ball

A device is proposed that inflates a sphere that has crisscrossing conducting wires embedded into it. Once inflated, the coils of wire act as a magnetic field sensor which in turn determines the rotation rate of the combined system (i.e. derelict with the “space ball”). The “space ball” then provides a current in the appropriate coil to create a torque against the existing rotation. This concept uses a simple principle and makes use of an available resource in the target environment (Earth’s magnetic field, B). It also can act as both a sensor of the tumbling rate and the actuator.

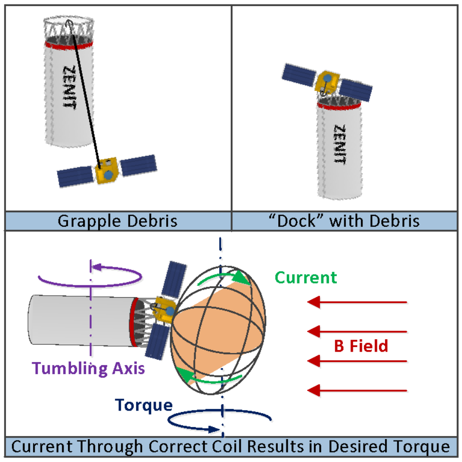

Figure 7. The notional "space ball" concept uses Earth's magnetic field to slow derelict tumble.

To calculate the time that it would take this concept to null the tumbling rate (ω) of the derelict, assume a constant deceleration rate, α, and use Eq. 1.

$$time = \frac{\omega}{\alpha} \quad (1)$$

Next, the deceleration rate due to a constant torque (τ) can be calculated with Eq. 2, using the moment of inertia ($I_{Inertia}$) of the rocket body.

$$\alpha = \frac{\tau}{I_{Inertia}} \quad (2)$$

Substituting Eq. 2 into Eq. 1 gives Eq. 3.

$$time = \frac{\omega I_{Inertia}}{\tau} \quad (3)$$

Calculation of the torque created by an armature of wire with area A, number of turns n, and current $I_{current}$, turning in a magnetic field B can be done using Eq. 4.

$$\tau = I_{current} A B n \quad (4)$$

The development of moment of inertia for the space ball is detailed in Appendix A and provided in Eq. 5.

$$I_{Inertia} = L^2\left(\frac{M_{tube}}{12} + \frac{M_{endcap}}{2}\right) + R^2\left(\frac{M_{tube} + M_{endcap}}{2}\right) \quad (5)$$

Substituting the moment of inertia from Eq. 5 and the torque calculation from Eq. 4 into Eq. 3 gives the calculation for the time as shown in Eq. 6.

$$time = \frac{\omega\left[L^2\left(\frac{M_{tube}}{12} + \frac{M_{endcap}}{2}\right) + R^2\left(\frac{M_{tube} + M_{endcap}}{2}\right)\right]}{I_{current} A B n} \quad (6)$$

A calculation of this time is shown using a set of base parameters for an SL-8 rocket body is shown in Table 1.

Table 1. Calculation of time to null rates for SL-8 using the balloon concept.

omega (deg/sec)	3
omega (rad/sec)	0.05235988
omega (RPMs)	0.5
Total Mass	1400
mass of cylinder tube (kg)	1166.66667
mass of cylinder endcap (single) (kg)	116.666667
length of cylinder (m)	6
radius of cylinder (m)	1.2
moment of Inertia (kg*m^2)	6524
bus voltage (V)	26
solar array output (W)	100
current (A)	3.85
Diameter of Balloon (m)	10.00
area of loop (m^2)	78.5398163
magnetic field strength (T)	0.000023
number of coils	1
time (sec)	49166.38
time (min)	819.44
time (hr)	13.66
time (days)	0.57

The time required to damp a 3 degrees/sec tumble (i.e. spin period of 2 min) of an SL-8 rocket body is less than a day so it would take a week to slow down a tumble period of 10 sec. In an effort to determine the sensitivity of the nulling time, four of the parameters were varied and the results plotted. This is shown in Fig. 8, with the baseline value for each parameter highlighted by the purple line.

Space Winch

It is proposed that the end of a spooled up lanyard is attached to a derelict. As the derelict tumbles, the host satellite can thrust to "pull" on the other end, slowing down the tumble of the derelict. The friction internal to the spool may also be used to help dissipate the angular momentum of the derelict. As the conductive lanyard wraps around the derelict, a large armature is created that will function similarly to the space ball described earlier. However, the wrapping of the conducting lanyard will not be predictable so the concept of operations must be flexible to the possible ways in which the "armature" will be created, as shown in the upper right panel of Figure 9.

This concept shares most of the pros and cons of the Space Ball concept, except that this concept only works in the orientation when the axis of rotation is aligned with the axis of effect of the armature. This makes the use of it less predictable, since it will have to wait to be used until the rotation axis precesses and the proper alignment occurs. Also, as the wire is deployed, the satellite will have to thrust in the opposite direction to counter any resistance in the device unwinding the wire.

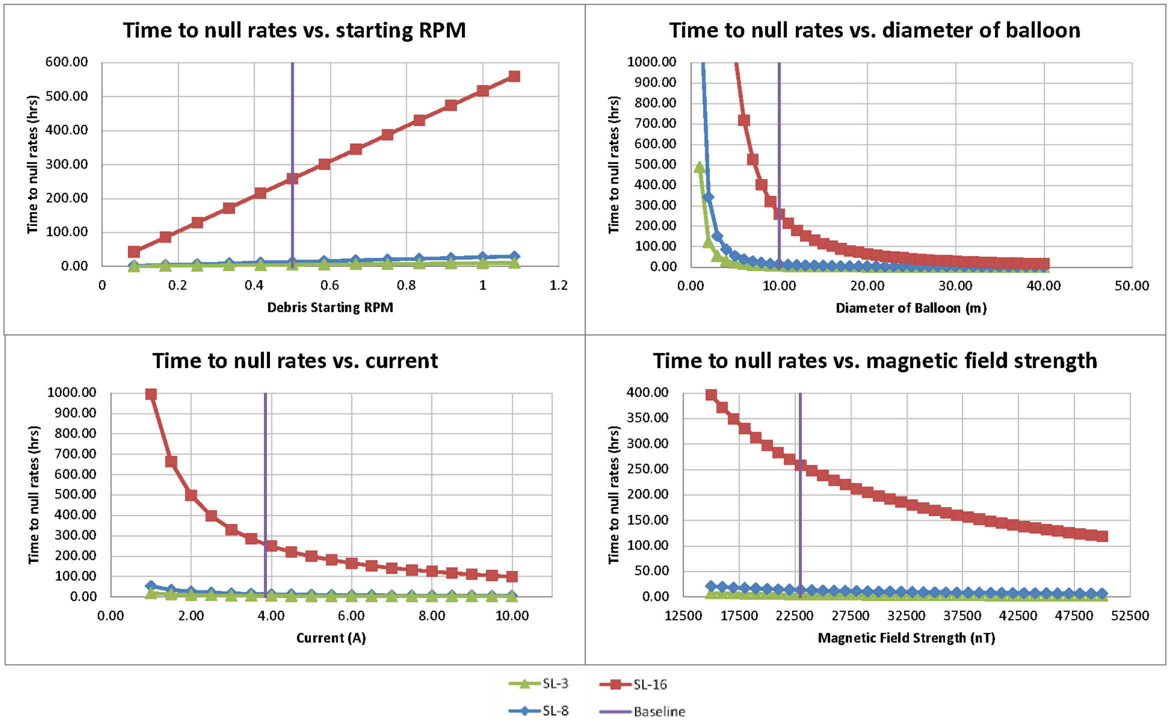

Figure 8. Sensitivity study for space ball concept, with baseline values of ω = 0.5 RPM, diameter = 10m, current = 3.85A, and a magnetic field of 23,000nT.

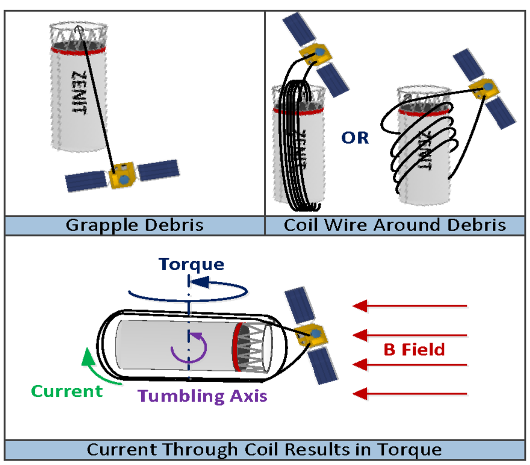

Figure 9. Notional "Space Winch" Concept

Using the active coils (i.e. power a current in the wires) of the "space ball" and "winch" systems under the influence of Earth's magnetic field, the retarding torque can be calculated. At 0.5 deg/sec (0.008 RPM), it is determined that the rotation of an SL-8 rocket body can be eliminated within 73 minutes.

It is assumed that 10 coils are perpendicular to a magnetic field of 23,000 nano Tesla (600km altitude) and each coil is a circle with the radius of 1.2 m (radius of SL-8 rocket body), which is the least optimistic configuration for the retarding torque. The current is created from a 26V bus voltage powered by a 100W solar array. This could also be provided by an on board battery of 122 Whr, which is likely less than 1 kg. [7] Table 2 was created using Eq. 6 and shows these calculations. This single scenario is realistic but a sensitivity study will be necessary to refine the system design and expected operational performance. A start to this study can branch from the sensitivity graphs below.

Table 2. Sample calculation for the winch concept shows 1.22 hours to null the tumbling rates.

*for SL-8	
omega (deg/sec)	0.5
omega (rad/sec)	0.00872665
omega (RPMs)	0.00833333
mass of cylinder tube (kg)	1000
mass of cylinder endcap (single) (kg)	200
length of cylinder (m)	6
radius of cylinder (m)	1.2
moment of Inertia (kg*m^2)	7464
bus voltage (V)	26
solar array output (W)	100
current (A)	3.85
area of loop (m^2)	16.8
magnetic field strength (T)	0.000023
number of coils	10
time (sec)	4382.84
time (min)	73.05
time (hr)	1.22
time (days)	0.05

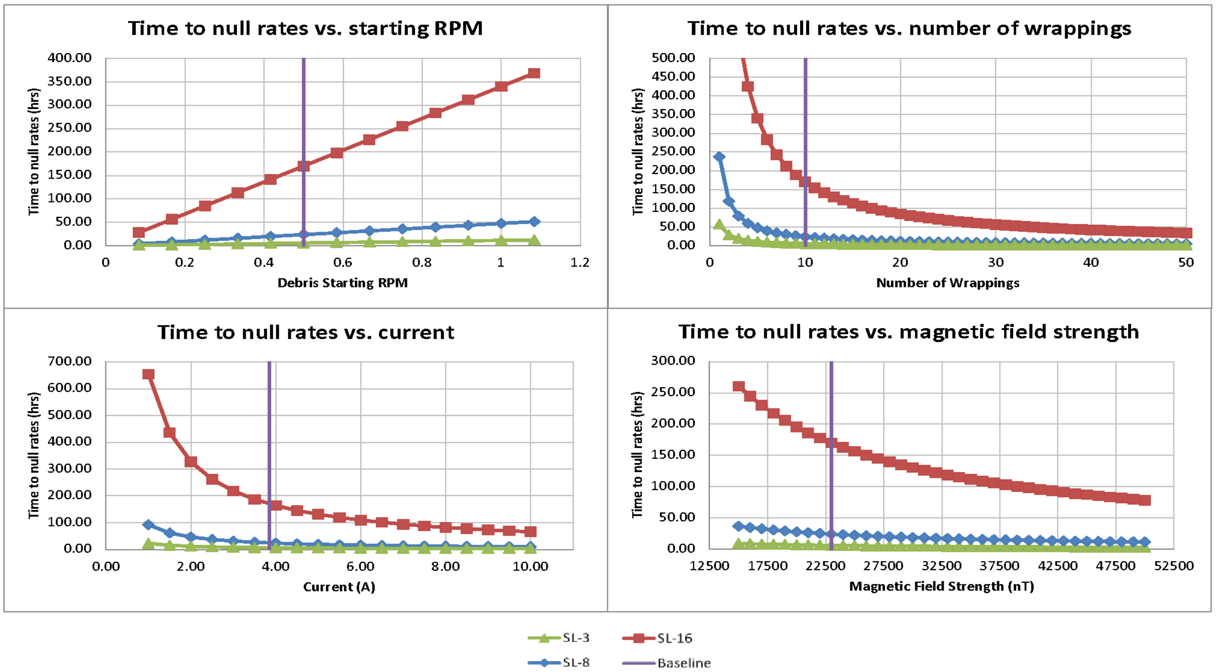

Figure 10. Sensitivity study for armature, with baseline values of ω = 0.5 RPM, 10 wrappings, current = 3.85A, and magnetic field of 23,000nT. The armature area stays consistent at 6.7m^2 for SL-3, 4.5m^2 for SL-8, and 11.9m^2 for SL-16.

"Nano-tugs"

A third method to add torque to the rocket body is the use of networked propulsive nano-satellites (i.e. "nano-tugs") adhered to the sides of the rocket body. This is similar in principle to the Smart Dust program developed by DARPA, with the addition of a small electric ion thruster and space rated components. The grappling stage of this concept is effectively the "sticking" of these nano-satellites to the side of the rocket body. The specific location of each deployed nano-satellite does not need to be specified, as long as they are dispersed over a large part of the derelict object. After networking together to identify their relative locations and rotation rates on the derelict, the appropriate nano-satellites can be commanded to fire their ion thrusters to apply a torque and slow the rotation rate.

This concept's main advantage is that the nanosatellites do not need to target specific locations on the derelict, since statistically, some will land in locations that can provide the desired effect. Also, after detumbling, any remaining propellant can be used to move the derelict to reduce the orbital lifetime. One of the main problems would be missing the derelict and floating on by, creating more space debris. However, it may be possible to use the thruster to perform a slow de-orbit of the nanosatellite, based on a simple attitude control scheme.

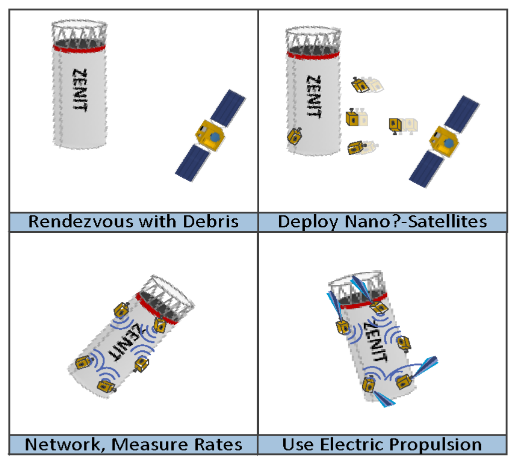

Figure 11. A swarm of "nano-tugs" could attach, determine orientation, and then use its propulsive capability to despin the derelict.

In order to evaluate this concept, we performed a sizing of the propulsion system required. Ideally, this system would fit in a nanosatellite (~10cm cube, 10 kg). The first simplifying assumption is that exactly one thruster is positioned midway between the center and the end of the derelict and able to create the desired retarding torque on the derelict. In operation, it is likely that there will be more than one thruster, but in even less optimal places to apply the torque.

Using a thruster similar to those produced by Busek, [8] with an ISP of 800 sec and a thrust of 0.7mN. To calculate how long it would take to stop rotating an SL-8 rocket body, we can use Eq. 7.

$$time = \frac{\omega I_{Inertia}}{\tau} \quad \textbf{(7)}$$

The torque produced in this concept is Eq. 8.

$$\tau = \mathrm{F} * \mathrm{d} \quad \textbf{(8)}$$

Where *d* is the distance of the thruster from the CM (*L/4*). Substituting gives Eq. 9.

$$time = \frac{4\omega I_{Inertia}}{FL} \quad \textbf{(9)}$$

Solving this equation for time for an SL-8 gives 325,329 seconds to completely null the rates. The next step is to calculate the amount of Xenon gas that is required to operate the thruster for this long. The first step is to calculate the mass flow rate using Eq. 10.

$$F_{thrust} = I_{sp} * \dot{m} * g_0 \quad \textbf{(10)}$$

Solving for the mass flow rate and multiplying by the time gives the total mass used, as shown in Eq. 11.

$$\mathrm{m} = \frac{F_{thrust} * time}{I_{sp} * g_0} \quad \textbf{(11)}$$

Using thrust of 0.7mN, ISP of 800sec, and g of 9.8 m/s^2, the equation yields a Xenon mass needed of 0.029 kg. To ensure that the required tank is of a reasonable size, we first calculate the density of the gas, using Eq. 12.

$$\rho = \frac{MW * P}{R * T} \quad \textbf{(12)}$$

Where MW is the molecular weight of the Xenon gas (131.29 g/mol), P is the pressure in the storage tank (~2500 psi or 272.2 atm is standard), R is the gas constant (0.0821 L*atm/K*mol) and T is the tank temperature in Kelvin (assume 293K). Dividing the density by the mass required (after converting it to grams) gives Eq. 13.

$$\mathrm{V} = \frac{MW * P}{R * T * m} \quad \textbf{(13)}$$

Substituting values gives a required volume of 0.02 L. Assuming a spherical tank, with Eq. 14, gives a tank radius of 0.02m.

$$\mathrm{V} = \frac{4\pi r^3}{3} \quad \textbf{(14)}$$

This is a reasonable size to fit into a nanosatellite. The battery weight is also important. Using a metric of 150 Whr/kg from Clyde Space, [7] the calculation that the thruster needs to run for 90.4 hr and requires 9W to operate, we will need 813 Whr, or 5.4 kg of battery. This is about half of the weight of the nanosatellite, but is probably achievable. A summary of these calculations is shown in Table 3.

Table 3. Sample calculation for the networked propulsion concept shows 90.4 hours to null the tumbling rates.

***for SL-8**	
omega (deg/sec)	3
omega (rad/sec)	0.052359878
omega (RPMs)	0.5
Total Mass	1400
mass of cylinder tube (kg)	1166.67
mass of cylinder endcap (single) (kg)	116.67
length of cylinder (m)	6
radius of cylinder (m)	1.2
moment of Inertia (kg*m^2)	6524
battery density (W*hr/kg)	150
power needed (W)	9
Isp (sec)	800.00
Thrust (N)	0.0007
mass flow rate (kg/sec)	8.93E-08
distance of thruster from CM (m)	1.5
torque applied (Nm)	0.00105
battery capacity needed (W*hr)	813.32
battery weight (kg)	5.42
time (sec)	325329.37
time (min)	5422.16
time (hr)	90.37
time (days)	3.77
Xenon mass needed (kg)	0.029
Xenon tank pressure (psi)	4000.00
tank pressure (Pa)	27579029.16
Xenon molecular weight (g/mol)	131.29
Xenon tank temperature (K)	293.00
Xenon density (kg/m^3)	1487.14
Xenon tank volume needed (m^3)	1.95E-05
Xenon tank diameter (m) - assume sphere	0.017

Mass Extension

A spinning object whose moment of inertia (I) is increased will slow its rotational rate. We will investigate three ways to produce a higher I: (1) add new mass to the derelict that is subsequently extended out, (2) sever the derelict object into two halves and move them apart, and (3) add mass to the derelict ends using a spray foam system. The first concept utilizes the extension of the mass of the attached microsatellite onto long booms, as shown in Fig. 11.

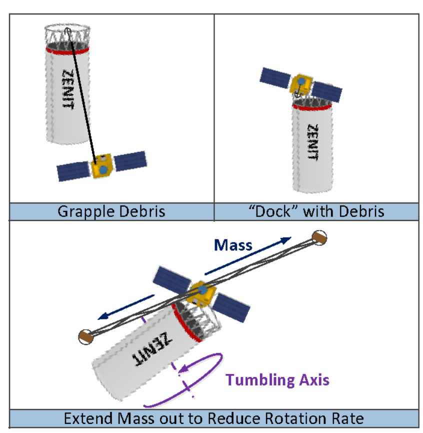

Figure 12. Notional Mass Extension Concept

This concept is an application of a simple principle, and would likely require little power after docking with the derelict. The centrifugal force could be used to "pull" the masses out from the satellite. A drawback is that this concept will never fully reduce the rate to zero, even with infinite mass at an infinite distance will only asymptotically approach a null rotation rate. Analysis has shown that by deploying two 50kg masses 40m from the SL-8 rocket body, the rotational rate can be decreased by 80%, as shown in Tab. 5.

The inertia before and after the deployment of the mass is shown in Eqs. 15 and 16.

$$I_{Inertia(before)} = L^2\left(\frac{M_{tube}}{12} + \frac{M_{endcap}}{2}\right) + R^2\left(\frac{M_{tube} + M_{endcap}}{2}\right) \quad \textbf{(15)}$$

$$I_{Inertia(after)} = L^2\left(\frac{M_{tube}}{12} + \frac{M_{endcap}}{2}\right) + R^2\left(\frac{M_{tube} + M_{endcap}}{2}\right) + D^2\left(M_{deployed}\right) \quad \textbf{(16)}$$

The kinetic energy of a rotating object is shown in Eq. 17.

$$E_{rotational} = \frac{1}{2} I_{inertia}\omega^2 \quad \textbf{(17)}$$

Using the conservation of energy, the energy of the system after deployment of the mass must be the same as before the mass was deployed, giving Eq. 18. Solving for the new rotation rate gives Eq. 19.

$$I_{inertia(before)}\omega_{(before)}{}^2 = I_{inertia(after)}\omega_{(after)}{}^2 \quad \textbf{(18)}$$

$$\omega_{(after)} = \sqrt{\frac{I_{inertia(before)}\omega_{(before)}{}^2}{I_{inertia(after)}}} \quad \textbf{(19)}$$

Table 4: Sample calculation for mass extension concept shows an 80% reduction in rotation rate.

***for SL-8**	
omega (deg/sec) before	3
omega (rad/sec) before	0.05236
omega (RPMs) before	0.5
total mass	1400
mass of cylinder tube (kg)	1166.667
mass of cylinder endcap (single) (kg)	116.6667
length of cylinder (m)	6
radius of cylinder (m)	1.2
moment of Inertia (kg*m^2) before	6524
length of each deployment (m)	40
number of deployments	2
mass of each deployment (kg)	50
moment of Inertia (kg*m^2) after	166524
omega (rad/sec) after	0.010364
omega (deg/sec) after	0.593799
omega (RPMs) after	0.098967

A sensitivity study to starting RPM, mass deployed, and length deployed is shown in Figure 13

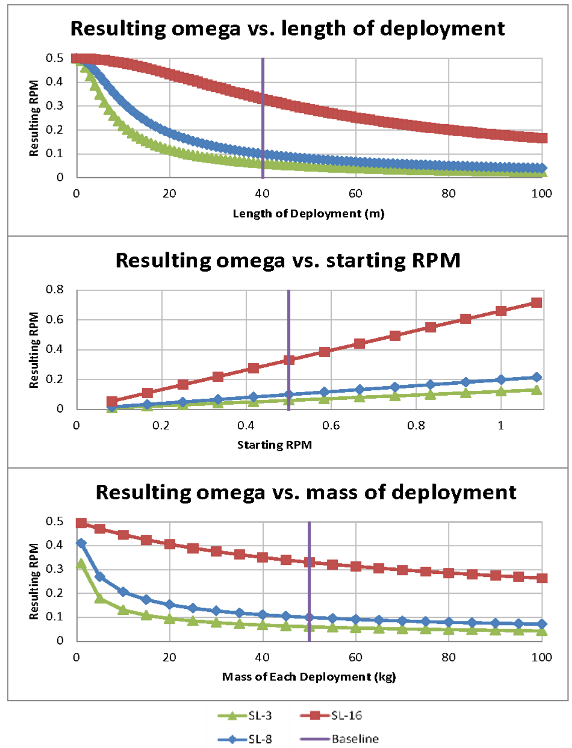

Figure 13. Sensitivity study for mass deployment, with baseline values of ω = 0.5 RPM, two 50kg deployments of 40m each.

Separate Debris

Similarly, by cutting the rocket body in half, and separating the pieces by a 24m "strut", the rotational rate will be decreased by 80% as shown in the figure below. Details are provided in Table 5, using the equations generated for the mass extension concept.

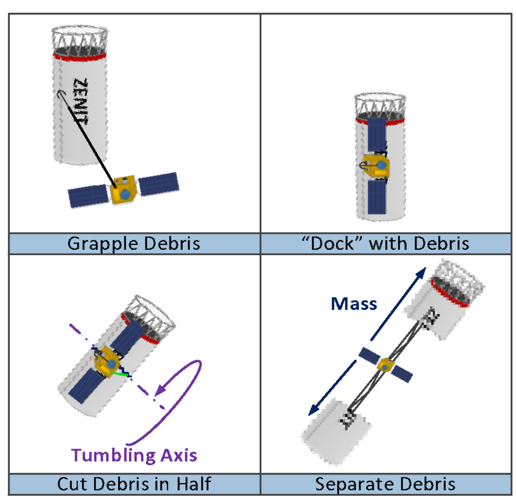

Figure 14. Notional "sever and separate" concept

Table 5. Sample calculation for debris separation concept shows an 80% reduction in rotation rate.

***for SL-8**	
omega (deg/sec) before	3
omega (rad/sec) before	0.05236
omega (RPMs) before	0.5
total mass (kg)	1400
mass of cylinder tube (kg)	1166.667
mass of cylinder endcap (single) (kg)	116.6667
length of cylinder (m)	6
radius of cylinder (m)	1.2
moment of Inertia (kg*m^2) before	6524
effective radius	1.127346
length of each deployment (m)	12
new effective radius	13.12735
number of deployments	2
mass of each deployment (kg)	700
moment of Inertia (kg*m^2) after	201600
omega (rad/sec) after	0.009419
omega (deg/sec) after	0.539676
omega (RPMs) after	0.089946

A sensitivity to the separation length and the starting RPM is presented in Fig. 15.

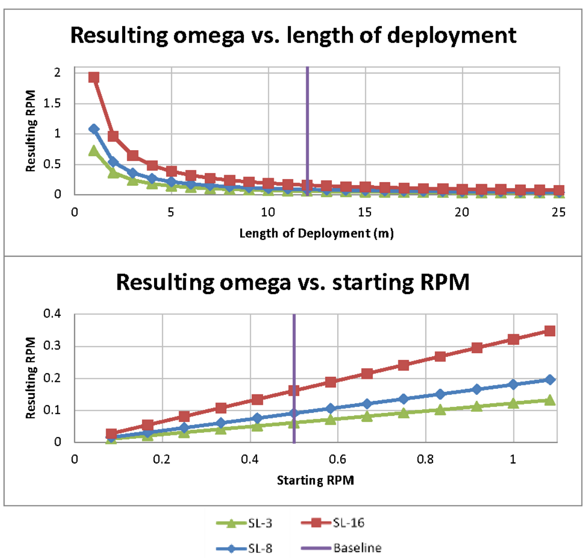

Figure 15. Sensitivity study for sever and separate, with baseline values of ω = 0.5 RPM, and two deployments of 12m each.

Foam

A third mode by which the inertia of the rocket body can be increased is to spray adhesive foam onto the ends of a rotating rocket body. This is a purely mechanical and kinetic approach that is less effective, but removes the step of docking the host satellite to the derelict. If the foam is applied such that the foam direction of motion is opposite of the rotation of the end of the derelict, then there will be some additional retardation of the spin rate.

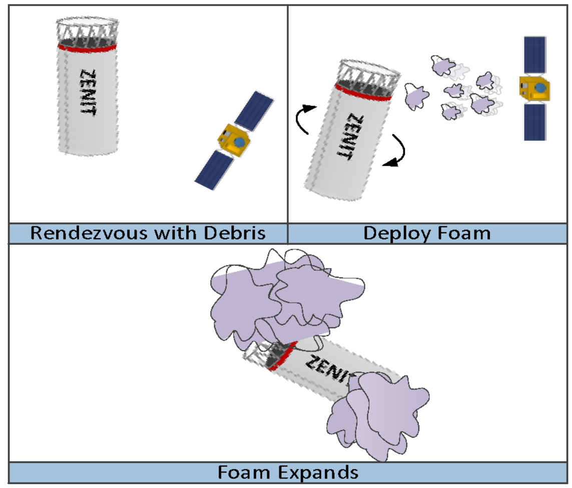

Figure 16. Notional foam concept

This concept's main advantage is that the docking procedure is limited to the foam getting stuck to the derelict. Research is needed to determine the correct formulation to create the right sticking effect.

Before foam impact on the derelict, each has its own kinetic energy (KE), as shown in the Eqs. 20 and 21:

$$KE_{Derelict} = \frac{1}{2} I_o \omega_o^2 \quad \textbf{(20)}$$

$$KE_{Foam} = \frac{1}{2} m_{foam} v_{foam}^2 \quad \textbf{(21)}$$

If applied to oppose rotation rate, the energy of the foam will directly reduce the kinetic energy of the rotating derelict. The individual effects of each foam application can be added together, so we will use the total mass of the application of foam for the calculations. Assuming a perfect transfer of this energy, the kinetic energy of the final system will be as shown in Eq. 22.

$$KE_{Final} = KE_{Derelict} - KE_{Foam} \quad \textbf{(22)}$$

This new system has a new moment of inertia (I_f) and a new rotation rate (ω_f) as calculated in Eqs. 23-26.

$$\frac{1}{2} I_f \omega_f^2 = \frac{1}{2} I_o \omega_o^2 - \frac{1}{2} m_{foam} v_{foam}^2 \quad \textbf{(23)}$$

$$I_f \omega_f^2 = I_o \omega_o^2 - m_{foam} v_{foam}^2 \quad \textbf{(24)}$$

$$\omega_f^2 = \frac{I_o \omega_o^2 - m_{foam} v_{foam}^2}{I_f} \quad \textbf{(25)}$$

$$\omega_f = \sqrt{\frac{I_o \omega_o^2 - m_{foam} v_{foam}^2}{I_f}} \quad \textbf{(26)}$$

A sample calculation using this equation is shown in 6, with graphs showing sensitivity of the effect to application velocity, total mass applied, and starting rotation rate shown in Fig. 17.

Table 6. Sample calculation of resulting rotation rate after foam application.

omega (deg/sec)	3
omega (rad/sec)	0.05236
omega (RPMs)	0.5
Total Mass (kg)	1400
mass of cylinder tube (kg)	1166.667
mass of cylinder endcap (single) (kg)	116.6667
length of cylinder (m)	6
radius of cylinder (m)	1.2
moment of Inertia (kg*m^2)	6524
total mass of foam (kg)	24.5
deployment velocity (relative to CM of debris) (m/s)	0.5
instantaneous rotational energy of foam (J)	3.0625
radius of applied foam (assume end) (m)	3
new moment of inertia (kg*m^2)	6744.50
omega new (rad/sec)	0.04
omega new (RPMs)	0.40

The following figures provide insights into the efficacy of this approach.

4.CONCLUSION

We looked at methods for both applying torque to the debris to completely stop the rotation and increasing the moment of inertia to decrease the rotation rate within acceptable limits. A summary of the concepts and their relative comparisons across key categories is presented in Table 7.

The examination of a series of innovative means to slow tumbling derelict objects has provided insights into the engineering challenges that must be overcome to perform this mission. However, this analysis has also laid the foundation for the next stage of active debris removal (ADR) design and development. It is expected that the functionality described in this paper may be integrated with a debris removal system to create an end-to-end capability. The primary conclusion is that a 100 kg mass budget is likely sufficient to provide a detumbling capability for a wide range of derelict objects, but especially for the critical spent body population

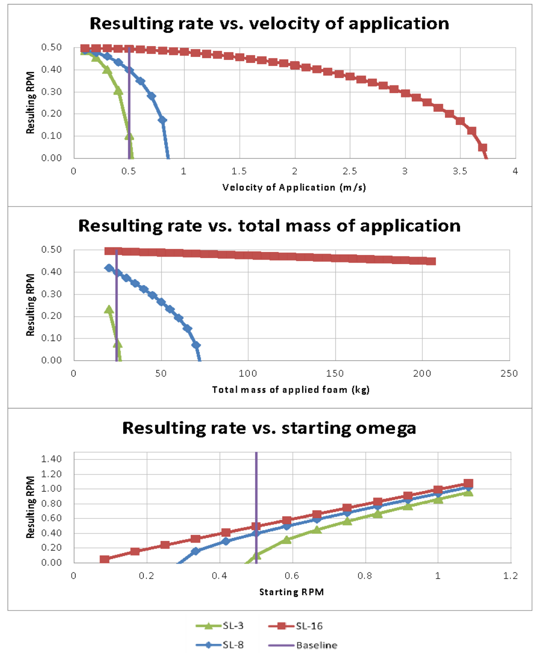

Figure 17. Sensitivity study for foam application,

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Table 7. Summary of results for all six options to detumble a spinning derelict shows no clear "winner." Scale is 1-10, 10 being favorable

Concept	Applicable			Simple	Speed	Key Limiting Technology	Power Needed	Repeatability	Total
	SL-3	SL-8	SL-16						
Space Ball	10	10	6	8	7	Inflatable material with conductive loops	5	9	50
Space Winch	10	10	7	5	8	Strong, conductive lanyard	5	4	49
Nano-Tugs	9	9	9	6	6	Docking design and thruster orientation	6	7	52
Mass Extension	9	9	5	7	9	Stiff extendable boom	5	8	52
Sever and Separate	9	9	7	4	5	Cutting derelict in half	3	7	44
Foam	10	5	1	5	7	Chemical formulation and use	9	7	44

Table 8: Presentation of the pros and cons of detumbling concepts.

Detumbling Concept	Pros	Cons
Space Ball	-Uses Earth's magnetic field and power from battery or solar arrays; Simple principle -Works in any docking orientation -Increases drag on object similar to inflatable de-orbit devices	-Requires conductive traces on inflatable material -Requires knowledge of direction of Earth's magnetic field (magnetometer, or we could also use the coils to sense the magnetic field) and switching "on" the correct circuit for that instant in time.
Space Winch	-Tumbling of derelict wraps wire into a large armature -Uses Earth's magnetic field and power from battery/solar arrays. -Simple principle	-Might be difficult to close the current loop: need to "re-grab" wire attached to the "grappling" device. -Torque is perpendicular to the axis of rotation that causes the wrapping. Want torque in the same axis as the wrapping: will the axis of rotation precess around and make them aligned? -Requires knowledge of direction of Earth's magnetic field and switching "on" when in the correct orientation.
Nano-tugs	-Simple, imprecise attaching -Can also use the propulsion to reduce orbital lifetime	-Need battery/solar array and consumables -Needs a sensor to determine its position on the debris -Unclear how to handle "missing" derelict with nano-tugs
Mass Extension	-Small amount of power required, no consumables -Simple principle	-Will not reduce tumble rate to zero -Requires knowledge of rotation axis and control to deploy mass perpendicular to that axis
Sever and Separate	-Simple principle -Uses mass already contained in the system	-Will not reduce tumble rate to zero -Requires knowledge of rotation axis and control to deploy mass perpendicular to that axis -Requires cutting object in half
Foam	-Simple, imprecise docking -Attach at high rotation rates -No power/consumables needed to use foam	-Large amount of foam needed to create desired effect -Chemical formulation of foam and deployment difficult

Appendix A: Development of "Space Ball" Moment of Inertia

The generic calculation for an object's moment of inertia is shown in Eq. a, where *dM* is an infinitesimally small amount of mass in the object and *x* is that mass's distance from the axis of rotation.

$$I_{Inertia} = \int x^2\, dM \qquad \textbf{(a)}$$

For a hollow, thin walled cylinder rotating about the axis perpendicular to the cylinder's axis, the distance of the mass from the axis is as shown in Fig. A1.

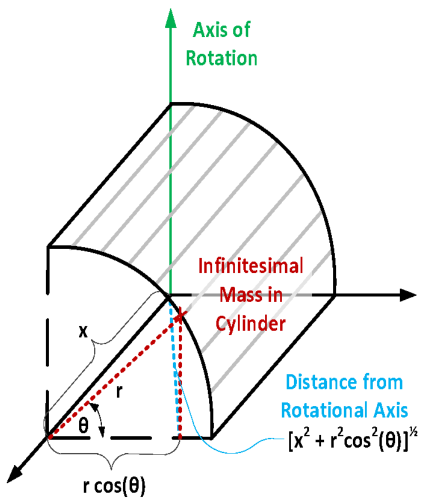

Figure A1. Calculation of the Distance of the Infinitesimal Mass from the Axis of Rotation for the Hollow Tube

The mass of the infinitesimal mass is given in Figure, where ρ is the density and *t* is the thickness.

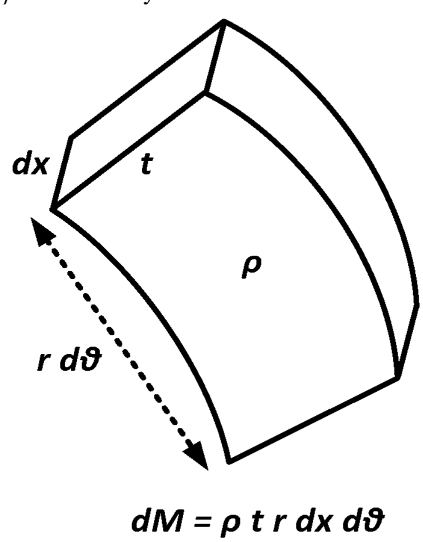

Figure A2. Mass of the Infinitesimal Mass for the Hollow Tube

Substituting the mass and the distance from the axis into Eq. a(a) gives Eq.b.

$$I_{Inertia} = \iint (x^2 + r^2cos^2\theta)\rho\, t\, rdxd\theta \qquad \textbf{(b)}$$

There are eight symmetrical pieces to the cylinder like the piece shown in Fig A2, so the overall moment of inertia for the cylinder can be calculated by adding the limits as shown in Eq. c, where *L* is the length of the cylinder.

$$I_{Inertia} = 8\rho t \int_0^{\frac{\pi}{2}}\int_0^{\frac{L}{2}} (rx^2 + r^3cos^2\theta)\, dxd\theta \qquad \textbf{(c)}$$

Integrating along the length gives Eq. d.

$$I_{Inertia} = 8\rho t \int_0^{\frac{\pi}{2}} \left(\frac{rx^3}{3} + xr^3cos^2\theta\right)\Big|_0^{\frac{L}{2}} d\theta \qquad \textbf{(d)}$$

Substituting gives Eq. e.

$$I_{Inertia} = 8\rho t \int_0^{\frac{\pi}{2}} \left(\frac{rL^3}{24} + \frac{Lr^3cos^2\theta}{2}\right) d\theta \qquad \textbf{(e)}$$

Integrating along the angle gives Eq. f.

$$I_{Inertia} = 8\rho t \left(\frac{rL^3\theta}{24} + \frac{Lr^3\theta}{4}\right)\Big|_0^{\frac{\pi}{2}} \qquad \textbf{(f)}$$

Substituting gives Eq. g.

$$I_{Inertia} = 8\rho t \left(\frac{rL^3\pi}{48} + \frac{Lr^3\pi}{8}\right) \qquad \textbf{(g)}$$

The density of the tube of the cylinder is given by Eq. h.

$$\rho = \frac{M_{tube}}{2\pi rLt} \qquad \textbf{(h)}$$

Substituting this into Eq. g, gives the solution in Eq. i. This matches the formula as derived by others. [9]

$$I_{inertia(tube)} = M_{tube}\left(\frac{L^2}{12} + \frac{R^2}{2}\right) \qquad \textbf{(i)}$$

For the thin walled cylinder "endcap" rotating about the same axis, the distance from that axis is shown in Fig. A3.

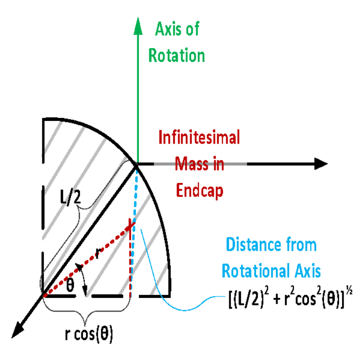

Figure A3. Calculation of the Distance of the Infinitesimal Mass from the Axis of Rotation for the Endcap

The mass of the infinitesimal mass is given in Fig. A4, where ρ is the density and t is the thickness.

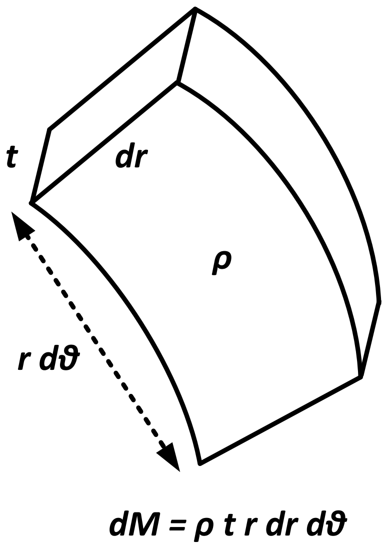

Figure A4: Mass of the Infinitesimal Mass for the Endcap

Substituting the mass and the distance from the axis into Eq. a gives Eq. j.

$$I_{Inertia} = \iint \left(\frac{L^2}{4} + r^2 cos^2\theta\right) \rho\ t\ r\ drd\theta \qquad \textbf{(j)}$$

There are eight symmetrical pieces to the cylinder like the piece shown in Fig. A3, so the overall moment of inertia for the cylinder can be calculated by adding the limits as shown in Eq. k.

$$I_{Inertia} = 8\rho t \int_0^{\frac{\pi}{2}} \int_0^R \left(\frac{L^2 r}{4} + r^3 cos^2\theta\right) dr\ d\theta \qquad \textbf{(k)}$$

Integrating along the radial direction gives Eq. l.

$$I_{Inertia} = 8\rho t \int_0^{\frac{\pi}{2}} \left(\frac{L^2 r^2}{8} + \frac{r^4 cos^2\theta}{4}\right) \Big|_0^R\ d\theta \qquad \textbf{(l)}$$

Substituting gives Eq. m.

$$I_{Inertia} = 8\rho t \int_0^{\frac{\pi}{2}} \left(\frac{L^2 R^2}{8} + \frac{R^4 cos^2\theta}{4}\right) d\theta \qquad \textbf{(m)}$$

Integrating along the angle gives Eq. n.

$$I_{Inertia} = 8\rho t \left(\frac{L^2 R^2 \theta}{8} + \frac{R^4 \theta}{8}\right) \Big|_0^{\frac{\pi}{2}} \qquad \textbf{(n)}$$

Substituting gives Eq. o.

$$I_{Inertia} = 8\rho t \left(\frac{L^2 R^2 \pi}{16} + \frac{R^4 \pi}{16}\right) \qquad \textbf{(o)}$$

The density of the endcap of the cylinder is given by Eq. p.

$$\rho = \frac{M_{endcap}}{\pi R^2 t} \qquad \textbf{(p)}$$

Substituting this into Eq. o, gives the solution in Eq. q. This matches the formula as derived by others. [9]

$$I_{inertia(endcaps)} = M_{endcap} \left(\frac{L^2}{2} + \frac{R^2}{2}\right) \qquad \textbf{(q)}$$

Adding the inertia for the hollow tube (Eq. i) to the inertia for the endcaps (Eq. q) gives the total inertia for the thin walled cylinder as shown in Eq. r.

$$I_{Inertia} = L^2 \left(\frac{M_{tube}}{12} + \frac{M_{endcap}}{2}\right) + R^2 \left(\frac{M_{tube} + M_{endcap}}{2}\right) \qquad \textbf{(r)}$$