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Nanosatellite Architecture for Tethered De-Spin of Massive Asteroids

Karsten James, Robert Hoyt
Tethers Unlimited, Inc.
Bothell, WA, 98011; 425.486.0100
kjames@tethers.com

ABSTRACT

Asteroid capture and retrieval is a problem of significant scientific and commercial interest. However, de-spinning and de-tumbling massive asteroids with chemical thrusters will require hundreds of kilograms of propellant. In order to address this challenge, Tethers Unlimited, Inc. has developed a small satellite mission architecture called “Weightless Rendezvous And Net Grapple to Limit Excess Rotation” (WRANGLER), which enables significant size, complexity, and order-of-magnitude mass savings for asteroid capture, retrieval, or redirect missions. WRANGLER uses a tethered nanosatellite to de-spin a targeted asteroid by converting the asteroid’s rotational momentum into rotation momentum of the nanosatellite as it revolves around the asteroid. The leverage offered by using a tether to extract angular momentum from a rotating asteroid enables very small nanosatellite systems to de-spin massive asteroids. This paper details the analysis of the tether deployment from a spinning and tumbling asteroid, demonstrates that a tethered system can effectively de-spin and de-tumble large space objects while avoiding tether wrapping and other dynamic problems, and compares tethered de-spin mission concepts to baseline approaches. Additionally, the capture and de-spin of an upper stage rocket body is proposed as a validation demonstration of both the WRANGLER architecture and its alignment to active debris removal missions.

INTRODUCTION

Asteroid capture and retrieval is a problem of significant scientific and commercial interest. Proposed near-future Asteroid Redirect Missions (ARM) have the potential to both provide significant scientific insight and demonstrate key technologies for future planetary defense and space utilization missions. However, as seen in Figure 1, most Near-Earth Asteroids (NEAs) small enough to be candidates for near-future redirect or retrieval missions are ‘fast rotators’, with rotation periods ranging from a few hours to a few minutes.[1] Reducing the rotation rate of one of these smaller NEAs to enable a redirect or retrieval mission, such as the ‘Plan A’ option considered by NASA’s ARM program, using baselined thrusters will require a very large propellant mass. For example, even with the selection of a relatively small, slowly rotating NEA the Keck Institute for Space Studies’ Asteroid Retrieval Feasibility Study budgeted hundreds of kilograms of propellant to de-spin and capture an asteroid.[2] Additionally, the rotational and optical characteristics of NEAs indicate that many of them may be loosely bound rubble piles, or are bodies surrounded by clouds of dust or gravel.[3] The presence of small particles poses collision, contamination, and charging risks to large spacecraft attempting to capture and de-tumble asteroids. The costs and risk associated with capturing even small asteroids have driven recent ARM efforts, such as the OSIRIS-Rex and NASA’s Asteroid Retrieval Mission, to focus on regolith and ‘boulder grab’ sample return missions in lieu of wholesale asteroid redirect or retrieval.

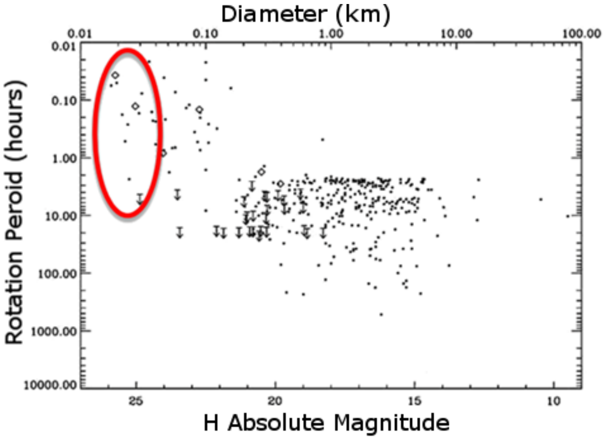

Figure 1: NEA Population Characteristics. [1] *The majority of near earth asteroids suitable for near future redirect or retrieval missions have short rotation periods.*

In order to address the needs of ARM, and similar challenges posed by Active Debris Removal (ADR) missions, Tethers Unlimited, Inc. (TUI) has developed the Weightless Rendezvous And Net Grapple to Limit Excess Rotation (WRANGLER) small satellite architecture for the capture and maneuvering of rotating space objects such as NEAs and orbital debris. The WRANGLER architecture leverages the r^2 dependence of the moment of inertia of a tethered spacecraft with respect to the target's reference frame to enable spacecraft as small as CubeSats to effectively de-spin massive asteroids. The WRANGLER system works much in the same manner a de-spin yo-yo device slows the rotation of an upper stage rocket. As seen in Figure 2, a first-order analysis demonstrates that the WRANGLER architecture can provide order-of-magnitude reductions in rotation rate using a tether with length and strength requirements well within the capabilities of current space tether technologies. With peak tension forces less than 190 N the tether required for such an operation can be extremely thin and lightweight, smaller than dental floss, enabling significant mass and volume savings over baseline ARM concepts.

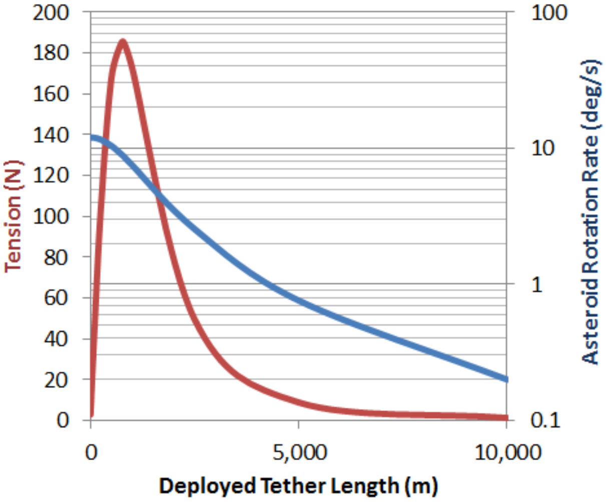

Figure 2: First Order Analysis of a 1 kg CubeSat De-Spinning a 1,000 Metric Ton Asteroid. *A very slender, lightweight tether is sufficient to de-spin a massive asteroid.*

While a first order analysis provides preliminary validation of the WRANGLER approach to de-spinning massive quickly rotating asteroids using small spacecraft, a detailed analysis provides confidence in the technical feasibility, efficacy, and value of the WRANGLER architecture. Utilizing analytical methods and detailed physics-based simulation tools, we investigated the dynamics of the tether deployment to evaluate the feasibility and performance of the WRANGLER concept and develop control algorithms to prevent unwanted contact or wrapping of the tether on the target object. Through our simulation efforts, we have demonstrated that controlled, well-behaved tether deployment is readily achievable with very simple control methodologies and that it is effective at de-spinning and de-tumbling massive asteroids. Having established the feasibility and effectiveness of the WRANGLER architecture we have developed Concept of Operations (CONOPS) for both free-flyer small satellite and tethered CubeSat systems. Through evaluation of conceptual designs aligned with the developed CONOPS and sizing of the tether required to complete the proposed missions we have demonstrated the use of a tether provides significant mass and size benefits over propellant based de-spin approaches for the majority of identified NEAs. Finally, we have evaluated the WRANGLER concept for ADR missions, and found that architectures leveraging WRANGLER technologies could enable affordable remediation of high-risk debris objects using secondary payload ride opportunities.

WRANGLER FEASABILITY ASSEMENT

Regardless of the mission specific implementation of the WRANGLER architecture, two tasks must be completed in order to de-spin and de-tumble a target object. First, the deploying spacecraft must grapple or anchor to the target object to provide a secure attachment for the end of the tether. Second, a multi-kilometer tether with an attached CubeSat endmass must be deployed while maintaining control of the dynamic behavior of the tether. While many strategies and options have been identified for grappling and securing an asteroid, including deployable bags or nets, inflatable bags or arms, and harpoons, the challenges of ensuring reliable, well-controlled tether deployment remain nearly identical across the span of potential mission architectures. The efficacy and feasibility of the tether deployment is therefore critical to the overall feasibility of the WRANGLER concept.

Tether Deployment Analysis

An often-asserted risk of tethered de-spin schemes is the potential for the dynamics of the tether to cause it to contact or 'wrap around' the target during deployment. Contact with the surface could cause snagging or cutting of the tether, and wrapping would reduce the system's effectiveness at de-spinning the object. In order to understand and mitigate the risks associated with tether deployment, we have sought to both characterize the dynamics of the tether deployment and develop strategies to mitigate risks associated with any unwanted dynamic behavior. While analytical modeling is useful to gain a first order understanding of the magnitude of the forces experienced by the tether and the length of tether required to effectively de-spin a target, intensive physics-based simulation is required in order to adequately characterize the dynamic behavior of a tethered system. Tether-Sim™ is a physics-based code developed by TUI that models both tether and spacecraft dynamics to allow for accurate modeling of the dynamics of tethered systems. Using the TetherSim software we conducted simulations of multi-kilometer tether deployments from representative target objects, such as the one shown in Figure 3, in order to determine the efficacy and feasibility of the WRANGLER approach.

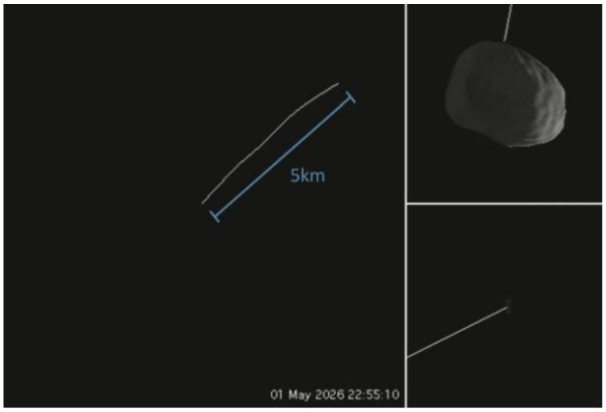

Figure 3: TetherSim Visualization of Asteroid De-Tumble. *TetherSim allows for physics based analysis of tether and endbody dynamics.*

Deployment of a multi-kilometer long tether from a spinning object poses several control challenges that must be resolved in order to successfully de-spin or de-tumble the target. The most significant concern for the deployment of a tethered endmass from a spinning object is excessive libration or 'wrapping' of the tether caused by the Coriolis and Euler forces driving the endmass away from the local vertical (in the co-rotating frame) during deployment. While some libration of the tether is necessary in order to impose a torque on the asteroid and thereby achieve a corresponding decrease in the rotation rate, excessive libration will cause the tether to contact the asteroid. This behavior is of particular concern when the tension, which acts as a restorative force on the tethered endmass, is low.

Our initial simulations of uncontrolled WRANGLER tether deployments, utilizing a representative small NEA 4.2 m in diameter with a mass of 1,000,000 kg and rotating at an initial rate of 1.2 deg/s, demonstrated that a simple constant deployment rate control scheme was insufficient to prevent the tether contacting the surface of the asteroid during deployment. Based on these results it was clear that a control scheme was needed to prevent excessive libration of the tether during deployment. From TUI's extensive experience with space tether systems a variable deployment rate control scheme was identified as the leading candidate control approach. In this control approach, varying the deployment rate of the tether will cause a corresponding change in the reaction force on the CubeSat endmass. If the tip of the tether begins to lag behind the desired libration angle, the deployment rate of the tether is slowed to bring the tether back towards the local vertical. Rate control of tether deployments has been successfully demonstrated on-orbit, most notably during the SEDS-2 tether experiment.[4] Controlling the deployment rate of the tether, whether from a deployer on the tethered endmass or from a deployer fixed to the tether attachment point, can be used to minimize dynamic behavior and maintain a desired libration angle.

Implementing a simple deployment rate control scheme, in which the tether deployment rate was slowed if the libration angle exceeded a maxium setpoint of 30 degrees, we simulated successful WRANGLER deployments beyond 10 km without the tether 'wrapping' or impacting the asteroid. The simplest case that can be used to demonstrate the WRANGLER concept is an asteroid spinning about a single principle axis of rotation. Figure 4 shows a successful WRANGLER deployment from our representative small NEA. In this scenario, a 3.8 km tether deployment reduces the spin rate to under 0.3 deg/s in less than 2 days. During this deployment the tether remains well behaved, with the maximum libration of the tether effectively limited by the control scheme to 30 degrees. Once a viable control law was established and demonstrated through simulation, we began a simulation campaign of tether deployments from asteroids of various sizes, masses, and rotation rates. Simulations representative of various small NEA candidates were conducted demonstrate that tethers can effectively de-spin a wide range of potential targets while effectively mitigating the risk of unwanted dynamic tether behavior.

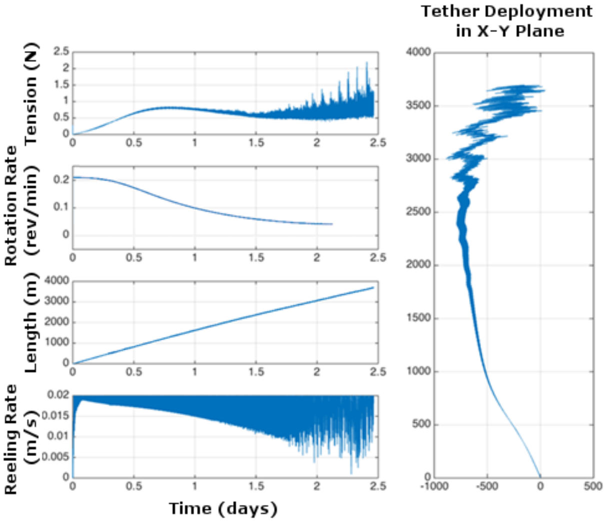

Figure 4: Tether Deployment from NEA Rotating about a Single Axis. *Implementation of reeling rate control minimized tether librations during deployment.*

The initial simulation efforts demonstrated that the control law developed control law was sufficiently robust to prevent variations in the physical characteristics of the target object from adversely impacting the performance of the tethered system. Our next simulation effort focused on determining what if any impact the location of the tether attachment has on the effectiveness of the de-spin or de-tumble effort. Simulation of de-spin efforts with varying initial tether attachment point demonstrated that attachment of the tether off of the equatorial plane of a given spin axis will drive the target into forced gyroscopic precession and result in the target's spin pole migrating to the attachment point of the tether. As seen in Figure 5, the precession of the target limits the amount of angular momentum that can be extracted from the target by the tethered endmass. Achieving attachment of the tether to the equatorial spin plane of the axis or axes of rotation is an important consideration for the design of the WRANGLER system. A design that allows for adjustment of the attachment point on the asteroid will maximize the potential benefit of the WRANGLER concept and allow for greater errors in the initial capture of the target object.

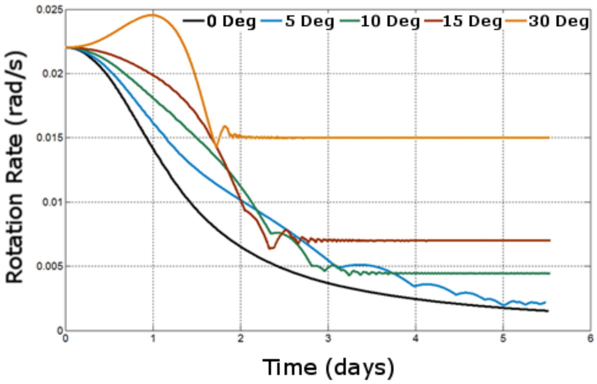

Figure 5: Off-Axis De-spin Effectiveness. *Attachment of the tether off of the equatorial spin plane of the NEA limits the effectiveness of a tethered de-spin.*

In addition to determining the effectiveness of using tethers to de-spin a target object with a single principle spin axis, we also investigated the efficacy of using tethers to de-tumble an object spinning about multiple principle axes. While the gyroscopic precession induced by tether attachments off of equatorial spin planes limits the capability of a single tether to de-tumble a target with an initial three-axis spin, tumbles that can be decomposed into two principle axes of rotation can be effectively stopped with a tether attached at the intersection of the two equatorial spin planes. Figure shows the effectiveness of a 5 km tether deployment from a 13 m diameter 1,000,000 kg de-tumbling asteroid spinning with a principle axis of rotation rate of 1.32 deg/s and a secondary principle axis of rotation rate of 0.3 deg/s. A significant reduction in the spin rate of both principle axes of rotation is achieved without the induction of gyroscopic precession or tether wrapping.

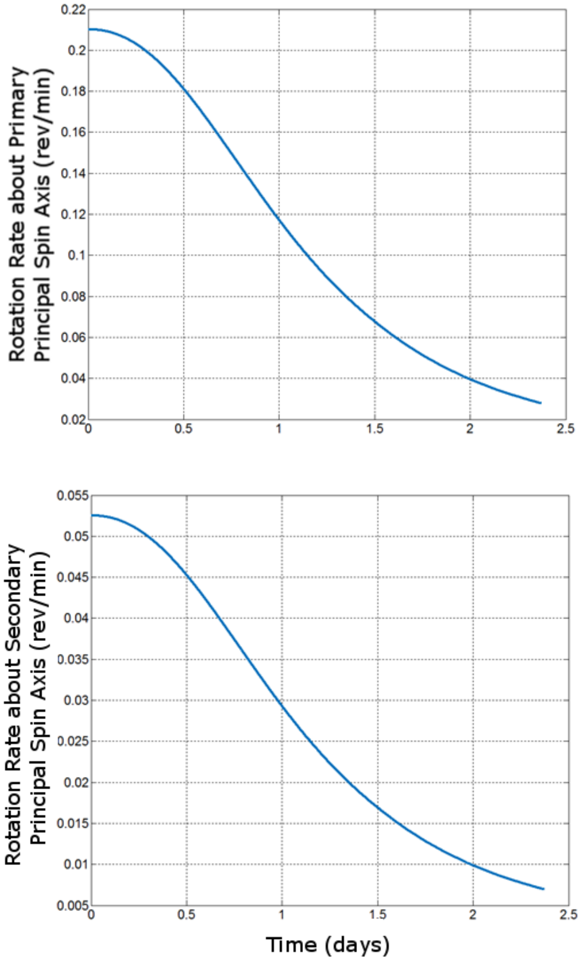

Figure 6: De-Tumble of NEA Spinning about Two Principle Axes. *Careful selection of tether attachment point allows for two-axis de-tumble of targets.*

Through the use of an extensive simulation utilizing the TetherSim Software we have demonstrated that the WRANGLER architecture is both feasible and effective. We have validated the WRANGLER concept for targets across a wide range of initial rotation rates, sizes, and masses. Using simple control schemes, we showed that the risks of unwanted tether behavior associated with deployment of the tether can be mitigated and that contact of the tether with the target object can be prevented. Furthermore we demonstrated that tethers can be used effectively on both spinning and tumbling objects provided a suitable attachment point is chosen.

Tether Design

The tether design for the WRANGLER architecture is driven by the required strength of the tether. Higher tension forces require the use of correspondingly stronger and therefore more massive tethers. However, as shown in Figure 4, the tension forces on the tether during de-spin of representative NEA objects is extremely small, on the order of 10 N. Correspondingly the tethers required to de-spin most NEA can be extremely lightweight and thin while still providing adequate strength.

The tether material used for determining the technical feasibility and performance of a representative WRANGLER tether is monofilament Dyneema SK-75 fiber. Dyneema SK-75 is a highly-oriented high molecular weight polyethylene with a tenacity of 3.5 N/Tex (1 Tex = 1 g/km). This is the thinnest yarn tow available of the highest strength-per-weight fiber commercially available. Each monofilament is 0.02 mm in diameter and has a linear mass density of 0.7 Tex. In order to provide resistance to micrometeoroid impacts multiple monofilament fibers are braided together in a Hoytether[5] structure to prevent tether severing under impact. A minimal tether is composed of 12 monofilament strands, is capable of supporting 29.4 N, and has a linear mass density of 8.4 Tex. Figure 7 shows how the mass of a 10 km WRANGLER tether scales with both the rotation rate and diameter of a target asteroid assuming an endmass of 1 kg, a target density of 2.8 g/cc, and a factor of safety, FoS=2. As evidenced by this analysis the tether required to de-spin even a massive, quickly rotating asteroid can easily be packed into a small satellite volume and provides significant mass savings over current ARM approaches.

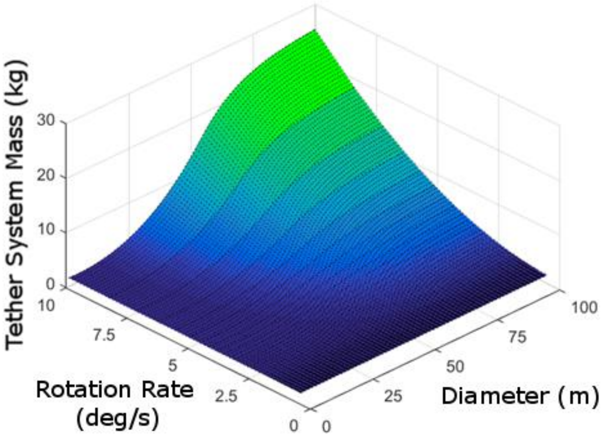

Figure 7: WRANGLER Tether Mass. *WRANGLER can de-spin massive asteroids with a lightweight tether.*

Although the tether used by the WRANGLER system is extremely thin, it is also many kilometers long. When fully deployed, the tether will be at least 5-10 km long, and deploying it in a controlled manner will likely take on the order of a week to complete. The length, exposure time, and potential fragility of the tether raise concerns of the possibility of the tether being severed by an impact. A WRANGLER system deployed to de-spin an asteroid will be exposed to both the interplanetary micrometeoroid flux and the environment in proximity to the target object. While interplanetary micrometeoroids pose distinct risks to the survival of the tether, particles in a vicinity of the asteroid will have relatively low velocities with respect to the surface of the target object and should not pose the same collision or charging dangers to tether as they might to large solar arrays or other more delicate hardware.

In order to understand the risk posed to the tether by micrometeoroid impacts the flux of particles that will be seen by the tether during a WRANGLER deployment must be determined. For the ARM use case the interplanetary micrometeoroid flux is the sole source of potential collision objects. ADR missions operating in the LEO orbital debris environment must consider the man-made debris flux as well and have a correspondingly higher risk of impact and subsequent tether damage. The Grün micrometeoroid flux model, represents the best model of the interplanetary micrometeoroid environment for typical NEO orbits of 0.9-1.4 AU.[6] The baseline WRANGLER tether, composed of 12 monofilament strands of Dyneema SK-75 arranged in an impact resistant Hoytether structure, is composed of 4 strands braided into 1 m fail safe lengths which isolate damage in each length from the rest of the tether. Each strand of the tether is composed of three monofilament strands braided together with a diameter of 0.0431 mm presenting a cross sectional area of 0.431 m^2. The entire Hoytether structure has a diameter of approximately 0.104 mm and presents a cross sectional area of approximately 1.04 m^2. Assuming a lethality coefficient of 3, each strand can be cut by an impactor 0.014 mm in diameter or larger. However in order for the tether to fail from multiple impacts all four of the strands would need to be cut. Alternatively the entire tether can be cut by a particle approximately 0.035 mm or larger. Using the cumulative flux from the Grün model[7] and multiplying by the strand area the total rate of cuts to each strand, c_s, is 2.32x10^{-8} per day and the rate of cuts to the tether, c_t, is 2.06x10^{-4} cuts per day. The probability of survival of the tether for a certian time is given by,

$$P(t) = e^{-c_t t}\left(1-\left(1-e^{-c_s t}\right)^4\right)^{10000}. \qquad (1)$$

Although 9.28x10^{-4} strands are expected to be cut each day the Hoytether structure limits the damage caused by these cuts to the local 1 m length and prevents these cuts form jeopardizing the integrity of the remainder of tether. Evaluating Equation 1 for a typical WRANGLER mission length of 5 days we find the probability of tether survival is > 99.9%. Therefore by utilizing the failsafe Hoytether we can almost guarantee that the tether used to de-spin a large asteroid will not be severed by a micrometeoroid impact.

Asteroid Grapple

In order for a tether to de-spin an object it must have a secure attachment point through which it can impart the required torque. For capturing and de-spinning NEAs this requirement imposes the need to securely grapple a potentially quickly rotating object of uncertain composition. As previously discussed several different architectures have been proposed to solve this challenge, however for the purposes of evaluating the feasibility of the WRANGLER architecture we have baselined the use of TUI's Grapple, Retrieve, and Secure Payload (GRASP) technology. GRASP is a simple, small, and readily scalable device developed by TUI to enable capture of space debris. GRASP uses lightweight, temporary inflatable tubes to deploy and expand a net or bag, and then uses a drawstring mechanism to enclose that net around a target object and cinch it down to provide a secure connection.[8] In 2004 TUI conducted testing of a subscale GRASP prototype onboard a Zero-G aircraft. These tests, shown in **Error! Reference source not found.**, successful validated the GRASP deployment mechanism, confirmed GRASPs ability to successfully capture a tumbling object, and demonstrated GRASPs tolerance to moderate relative position and velocity errors.

Figure 8: Zero-G Flight Test of GRASP Prototype. *GRASP provides a scalable solution capable of capturing tumbling objects in microgravity***.**

To aid the analysis of the WRANGLER concept we have conducted a scalability analysis for the GRASP system in order to determine the mass and volume requirements for a system capable of capturing NEAs. Concerns about the composition of NEAs, including suggestions that many NEAs may be composed of gravitationally attracted boulders covered in a surface of loosely bound regolith, have driven the use of bag to completely encapsulate target objects in current ARM architectures.[2] In light of these concerns we have baselined a GRASP design composed of four 50 mm diameter temporarily inflatable arms made of aluminized Nomex® that will open a high strength Kevlar® net backed by a thin aluminized polyethylene terephthalate bag. Figure 9 shows how this baseline GRASP system scales with the diameter of the GRASP system. A 25 m diameter GRASP bag capable of capturing a 13m tumbling asteroid was used as a baseline design for a GRASP system. Such a system would have a mass of 18 kg and stow into a volume of 18,000 cubic centimeters or 18U.

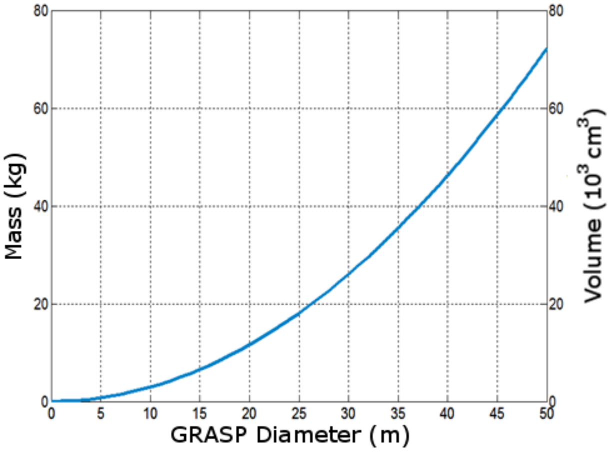

Figure 9: GRASP Sizing. *GRASP can be readily scaled to support ARM or ADR.*

Many dynamic challenges associated with grappling and securing a tumbling NEA remain unaddressed due to both the complexity of the interaction between the asteroid surface and any encapsulating net or bag and the unknowns surface and composition properties of small NEAs. While challenges must be addressed prior to the realization of ARM missions of any architecture, as evidenced by the scaling analysis of the GRASP system likely requirements for the mass and volume of a capture bag for a reasonably sized NEA do not preclude the use of a small satellite system.

WRANGLER CONOPS

Having established the feasibility of using a small tethered mass to drain angular momentum massive NEAs and other target objects, we proceeded to develop a CONOPS as a baseline for evaluating future mission implementations. For utilization of the WRANGLER concept in both the ARM and ADR roles we develop two baseline architectures to evaluate against current approaches. The first and simplest CONOPS leverages existing mission concepts utilizing a WRANGLER derived system as purely a low SWaP de-spin and de-tumble device. The second, more ambitious, CONOPS fractionates or replaces existing mission architectures through the use of a free-flying small satellite capable of independently grappling and de-tumbling space objects.

Integrated De-spin WRANGLER Subsystem

As an integrated de-spin subsystem within a larger ARM or ADR mission architecture a WRANGLER subsystem would be utilized in lieu of chemical thruster to de-spin and de-tumble a target object. Figure 10 illustrates how a WRANGLER subsystem would operate in the context of a much larger system to complete these tasks. In this simplified architecture the WRANGLER subsystem only requires the hardware needed to house and deploy the tether, control the deployment, determine relative position and communicate with the host spacecraft, and provide power for these functions.

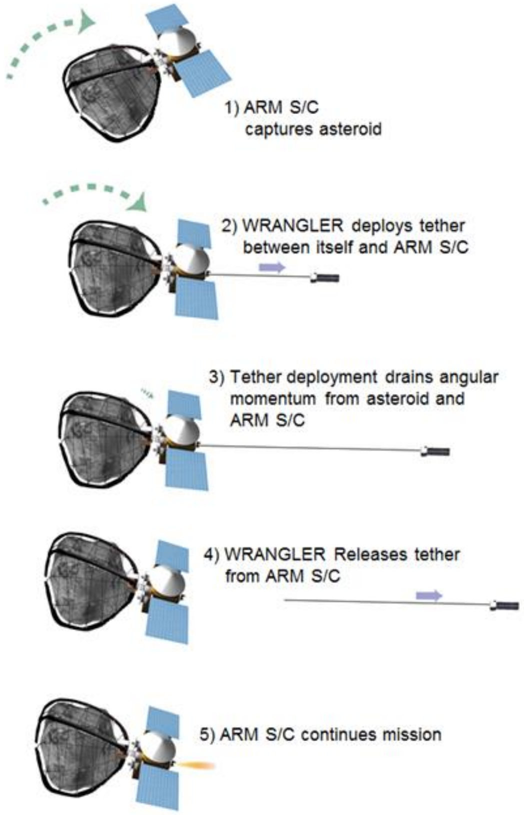

Figure 10: Integrated De-Spin System CONOPS. *WRANGLER can be deployed from ARM spacecraft to de-tumble target objects with significant mass savings.*

Table 1: Integrated De-spin Subsystem Mass.

Component	Mass
Structure & Mechanisms	0.4 kg
Avionics	0.3 kg
Batteries & EPS	0.8 kg
Tether & Deployer	0.2 kg
TOTAL	**1.7 kg**

A conceptual design of an integrated de-spin WRANGLER system serves to further validate the technical feasibility of the concept and provides SWaP estimates that can be used to compare the WRANGER concept to baseline approaches. This small 1.7 kg payload concept, a mock-up of which is shown in Figure 11, leverages TUI's existing high Technology Readiness Level (TRL) flight qualified hardware to create a system that can be integrated into ARM and asteroid mining architectures with relatively low cost and little nonrecurring engineering effort. Table 1 summarizes the estimated mass breakdown for the 2U WRANGLER design. This 2U design would be deployed by a primary ARM, asteroid mining, or ADR spacecraft and would be used to de-spin or de-tumble the coupled target and primary spacecraft, providing significant mass savings over current ARM architectures which propose using hundreds of kilograms of propellant.

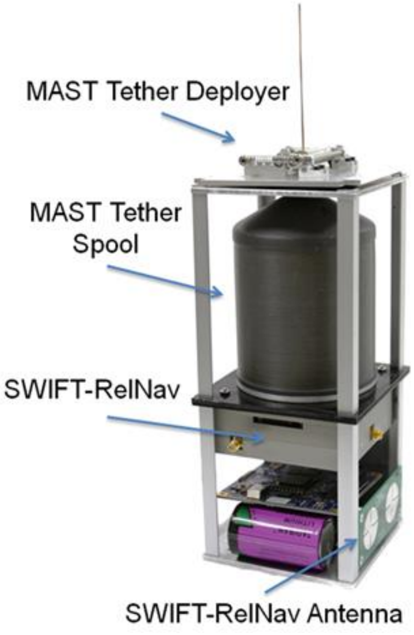

Figure 11. WRANGLER de-spin CubeSat model, assembled using all flight-qualified hardware.

The spool and tether deployment mechanism used in the WRANGLER 2U conceptual design are flight hardware developed for the Multi-Application-

Survivable-Tether (MAST) experiment. A Hoytether of the minimum viable size, capable of conducting the baseline tether deployment shown in Figure 4, provides a representative tether for mission targeted at a NEA. Despite Dyneema's relatively low density of 970 kg/m3 the 10 km tether packs into a volume of 86 cc. The MAST spool, which is contained in the first volume of the satellite, houses the tether and feeds it into the deployer on the front of the satellite. The MAST deployer is composed of a set of driven pinch rollers which provide control of the tether deployment rate and allow for control of the dynamics of the tether during deployment as previously discussed.

To provide control, communications, and relative position information the 2U design will leverage TUI's existing "SWIFT-RelNaV" radio. The SWIFT-RelNav radio is a software defined radio designed to provide small satellites cross link communication as well as measurements of relative range and position. It is capable of measuring range to ≤0.1 m, and relative position to ≤ 1 degree. SWIFT-RelNav provides more than enough accuracy to meet the needs of the WRANGLER control scheme and its onboard processing capabilities can be used to control the tether deployment.

Free-Flying WRANGLER System

An alternative implementation of the WRANGLER concept, shown in Figure 12, fractionates the ARM architecture so that the capture and de-spin operations are performed by a lower-cost nanosatellite system, reducing complexity and risk for the larger, more costly electric propulsion (EP) tug that would perform repositioning of the asteroid. For future commercial operations independent small satellite grapple and de-spin systems could also be launched in fleets in advance of primary tug spacecraft to find and prepare objects for the primary spacecraft to retrieve. A fully independent system is also closely aligned with the requirements for small satellite ADR systems which offer the potential for the removal of many debris objects per launch.

The free-flying WRANGLER system consists of two fundamental subsystems: a small tethered nanosatellite which contains the tether and tether deployment hardware, and a larger baseplate which incorporates the GRASP capture bag, propulsion, and a docking collar. In operation the tethered nanosatellite remains attached to the baseplate throughout the proximity operations and capture of the target object. Once the target has been secured in the GRASP bag the tethered nanosatellite deploys from the baseplate and de-spins the coupled system.

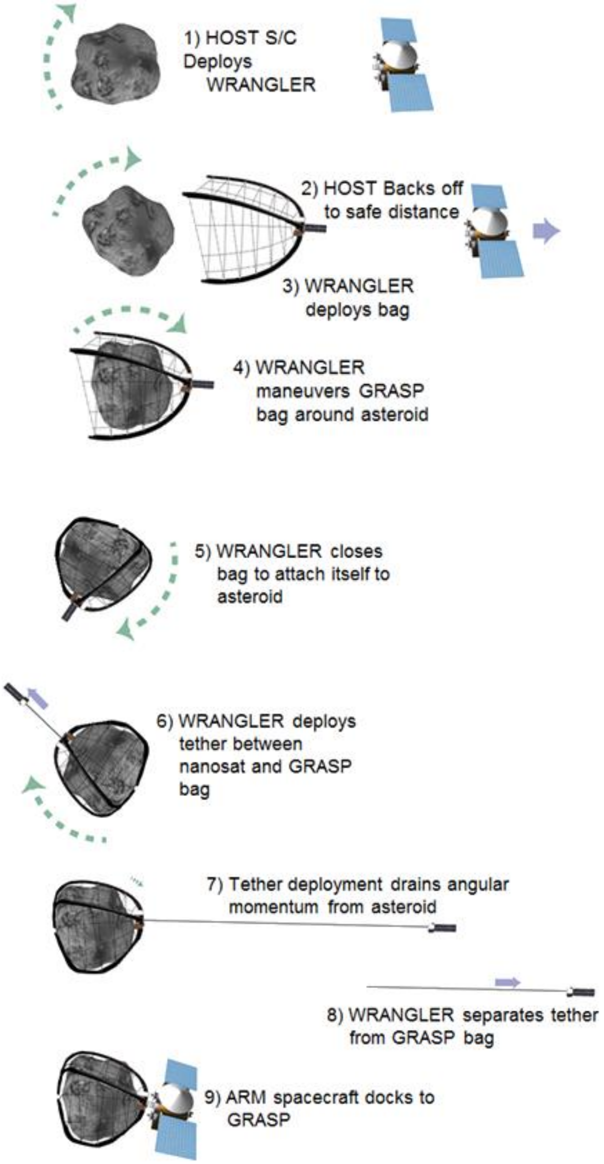

Figure 12: Free-Flying WRANGLER System CONOPS. *A nanosatellite-scale WRANGLER system can be deployed from an ARM electric propulsion tug to capture and de-spin target NEAs.*

Table 2 provides a summary of the mass budget for a free-flying WRANGLER system targeted for the same baseline 13m tumbling asteroid. The tether, tether spool, and tether deployment mechanism contained within the tethered nanosat remain unchanged from the smaller 2U WRANGLER concept and are composed of flight-qualified hardware. Propulsion is provided by TUI's HYDROS water electrolysis thruster. SWIFT-RelNav radios at both the baseplate and tethered nanosatellite to provide the communications, relative position, and processing capabilities required for execution of the WRANGLER CONOPS.

Table 2: Independent De-spin System Mass.

Component	Mass
Structure & Mechanisms	28 kg
GRASP	17.7 kg
Avionics	0.6 kg
Batteries & EPS	3.9 kg
Propulsion System	8.0 kg
Tether & Deployer	0.2 kg
TOTAL	**48.4 kg**

WRANGLER VALUE PROPOSITION

In order for the WRANGLER architecture to offer a substantive benefit to ARM and ADR missions it must not only be technically feasible but also provide a significant advantage over existing high-TRL technologies. By leveraging a low mass tether system to de-spin and de-tumble targets instead of using thrusters and the associated propellants WRANGLER can provide order of magnitude mass savings over current ARM approaches. Additionally, the ability to fractionate the ARM CONOPS offers the potential to remove the need for primary EP tug spacecraft to incur the risks and complexities associated with grappling and controlling a large asteroid.

WRANGLER Provides Significant Mass Savings

De-spinning and de-tumbling target objects is an integral part of wholesale ARM concepts, planetary defense missions, ADR architectures, and future commercial space mining operations. The majority of current concepts for these missions involve the use of thrusters to apply a torque to the target object and reduce or eliminate its rotation. In order to characterize the efficacy and mass requirements of these proposals, we developed a MATLAB model simulating the use of thrusters to conduct de-spin operations. We verified our thruster de-spin model against both an analytical first-order analysis and the results of ARM feasibility assessments including the Keck Institute for Space Studies *Asteroid Retrieval Feasibility Study*.[2] Utilizing this model, we determined the amount of propellant required to de-spin the prospective NEA candidate objects highlighted in Figure 1, given their observed diameters and rotation periods. The analysis conducted assumed the objects were rotating about a single principle axis and have a uniform density of 2.8 g/cc. The same hypergolic bipropellant reaction control system baselined for the Keck Institute Study, composed of 200N thrusters with a specific impulse of 278 s, was assumed for the comparison. As can be clearly seen in Figure 13 the majority of NEA candidates require hundreds or thousands of kilograms of propellant to de-spin. The need to launch and transfer the required propellant plus an acceptable margin drives the mass and cost of mission architectures that rely exclusively on thrusters to de-spin and de-tumble their targets.

In contrast to the prohibitive mass required to de-spin a target using thrusters, the WRANGLER system required to accomplish the same mission is orders of

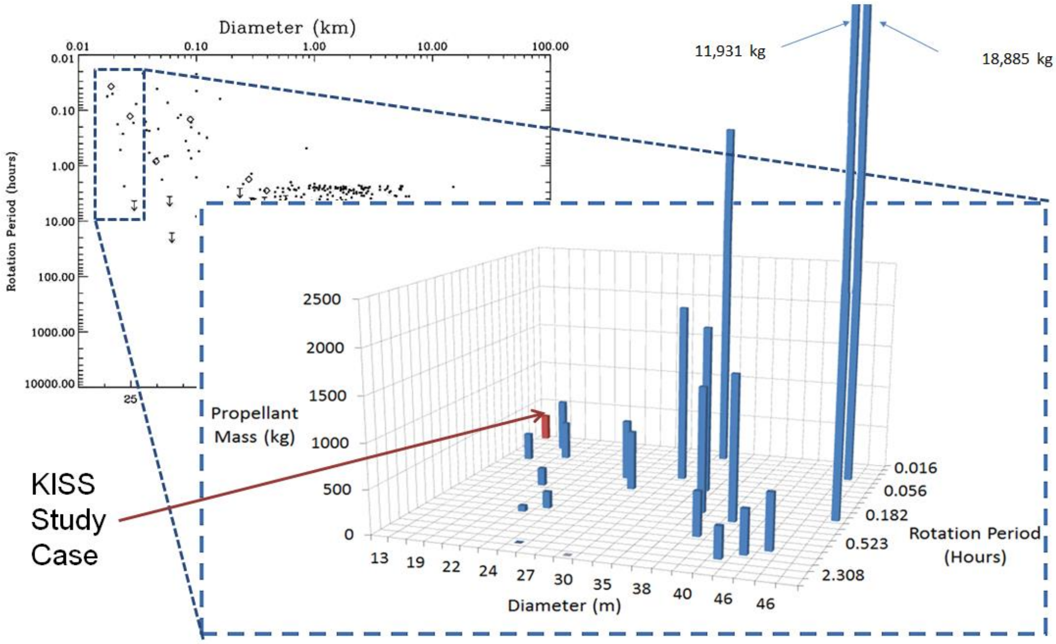

Figure 13: Propellant Requirements to De-spin NEAs. *The majority of NEAs feasible for near future recovery require massive amounts of propellant to de-spin.*

magnitude less massive. As previously discussed and shown in Figure 7 the mass of the tether scales with the tension force but remains relativity small (<10 kg) for even massive, quickly rotating NEAs. The remainder of the WRANGLER system, excluding the GRASP capture mechanism, which is not relevant to the mass required to de-spin the target, is composed of components of a fixed mass not subject to the size or rotation rate of the target. The mass of a WRANGLER system required to de-spin a target is therefore purely composed of a small fixed mass plus the mass of a tether strong and long enough to sufficiently de-spin the target.

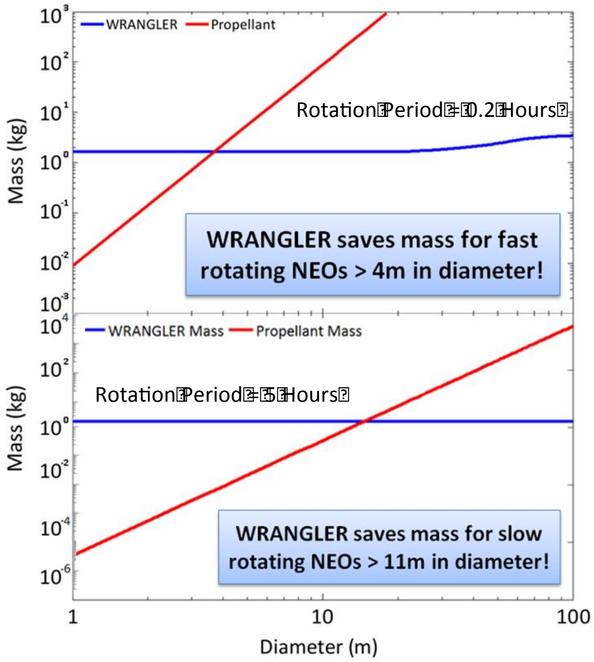

Figure 14: Comparison of a tethered WRANGLER system and the mass of propellant required to de-spin a target.

Comparing the mass of propellant required to successfully de-spin candidate NEA targets with the mass of WRANGLER systems needed to conduct the same operations clearly demonstrates the potential of the WRANGLER concept. Figure 14 clearly shows that WRANGLER provides mass advantages for objects larger than 4 meters. For objects greater than 10 meters WRANGLER provides order-of-magnitude mass savings compared to propellant intensive thrusting. Moreover, this result is likely overly-conservative since it does not consider additional propellant and tankage mass that would be required to provide an adequate safety margin. Figure 13 also demonstrates that these advantages hold for the main population of NEAs as well, indicating that WRANGLER can provide key advantages to future commercial space exploitation efforts.

WRANGLER Provides ARM Mission Risk Reduction

In addition to providing orders of magnitude mass savings over current ARM architectures, WRANGLER provides the potential to confer a significant reduction of risk to ARM, commercial mining, and ADR missions. A free-flying WRANGLER system employing the GRASP capture technology fractionates the architecture for asteroid retrieval missions, allowing the required capture and proximity operations to be conducted by a small agile spacecraft. The use of a secondary spacecraft allows the primary mission spacecraft to stand-off during these high risk operations effectively mitigating the collision, contamination, and charging risks to large solar arrays and other sensitive spacecraft components.

Removing the primary spacecraft from the capture and de-spin operations not only mitigates the challenges posed by the unknown and potentially dangerous proximity environment but also simplifies the design of the primary spacecraft by eliminating the requirement for the spacecraft to handle the dynamic loading incurred during these operations. Current architectures have identified significant risks from torques induced during these operations to the large deployable solar arrays required for near future ARM missions. Folding booms, reinforced solar arrays, or similar methods for stowing or protecting solar panels during the capture and de-spin of targets have been proposed as potential strategies to mitigate the dynamic loading on the deployed spacecraft structures. While these methods may effectively mitigate the risk imposed by dynamic loading during capture and de-spin they inherently increase the complexity, and thereby the mass and cost of the required deployable structures. For example, the NASA/LaRC 300 kW Government Reference Array (GRA) is designed to sustain 0.1 gees, and this strength requirement drives the mass of its support structure.[9] If it did not need to sustain such high acceleration, the structural mass of the array could be reduced substantially, by factors of 2-10X, and this will translate into lower launch and life-cycle costs.**Error! Reference source not found.**

WRANGLER Enables Affordable ADR Architectures

The parallels between the problems of asteroid retrieval and problems posed by potential ADR missions allows for the natural extension of ARM concepts and technologies to the ADR problem. As previously discussed the free-flying WRANGLER concept provides an extremely good baseline for a small satellite ADR architecture. A 7m Thor Agena D SLV-2 rocket body massing 670kg in an 800km near circular orbit at an inclination of 99° provides a suitable candidate for demonstrating the suitability of the free-flying WRANGLER architecture[11]. A 15m GRASP system sized to capture such a rocket body will mass 6.5 kg and pack into a 6U volume. Furthermore, based on a ΔV budget of 490 m/s for the nanosatellite to maneuver to the rocket body and 160 m/s to deorbit both the nanosatellite and target a HYDROS propulsion system would require 53 kg of water propellant.[11]

Utilizing these sizing estimates Table 3 provides a conservative mass budget for a representative ADR system based on the free-flying WRANGLER architecture. Such a system would easily meet the mass and volume criteria for an ESPA class payload. Larger objects can also be targeted by scaling the GRASP system and the amount of propellant carried.

Table 3: Mass Budget for based WRANGLER ADR System. *Small satellite ADR systems utilizing can de-orbit large debris within a mass budget compatible with ESPA class secondary payload opportunities.*

Component	Mass
Structure & Mechanisms	28 kg
GRASP	17.7 kg
Avionics	0.6 kg
Batteries & EPS	3.9 kg
Propulsion System	8.0 kg
Tether & Deployer	0.2 kg
TOTAL	**48.4 kg**

SUMMARY AND CONCLUSION

Our initial development of the WRANGLER concept has demonstrated both its feasibility and the value provided to future ARM, space exploitation, and ADR efforts. Through intensive simulation efforts we have demonstrated that tethers deployed from even the most massive ‘fast rotators’ are effective at achieving adequate reductions of the target’s body rates and can be controlled through the implementation of simple and proven control laws and tether deployment hardware. Utilizing the results of this effort, we have developed two WRANGLER system architectures capable of serving a variety of existing ARM and ADR CONOPS: the first a small 2U nanosatellite used simply as a means of de-spinning the target and the other a larger free-flying nanosatellite used to both capture and de-spin the target object. Detailed conceptual designs of both architectures have been used to demonstrate the significant mass savings afforded by the WRANGLER concept when compared to the use of propellant intensive thrusting schemes. Furthermore these concepts have highlighted the mission architecture risks that can be easily mitigated by a fractionalization of the mission architecture, reducing the requirements imposed on large primary mission spacecraft. The technologies required to provide the benefits of the WRANGLER system are all flight-qualified hardware of mid-TRL to high-TRL. TUI’s evaluation of the technology readiness of the concept indicates that a WRANGLER system that has the potential to provide order of magnitude performance improvements to ARM mission architectures could be designed and integrated with minimal effort and modest investment. While the risks of the WRANGLER system are non-trivial they are well understood and have clear and proven mitigation strategies that can be implemented with the proper engineering effort. WRANGLER provides significant benefits to ARM, ADR and future commercial space exploitation efforts by replacing hundreds or thousands of kilograms of propellant with a small, low mass, low cost system capable of allowing spacecraft to gain control of large space objects or capturing and preparing target objects ahead of future missions.

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