The μTORQUE Momentum-Exchange Tether Experiment

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Abstract. Long, high-strength tethers can provide a mechanism for transferring orbital momentum and energy from one space object to another without the consumption of propellant. By providing a highly-reusable transportation architecture, systems built upon such "momentum-exchange" tethers may be able to achieve significant cost reductions for a number of in-space propulsion missions. Before such systems could be placed into operation, however, a number of technical challenges must be met, including flight demonstration of high-strength, highly survivable tethers, demonstration of the ability to control the dynamics of a rotating tether system, and the ability for a tether system to rendezvous with, capture, and then toss a payload. In this paper, we discuss a concept design for a small momentum exchange tether experiment that is intended to serve as the first step in demonstrating these key technologies. The "Microsatellite Tethered Orbit Raising QUalification Experiment" (μTORQUE) will be designed to fly as a secondary payload on an upper stage of a rocket used to deliver a satellite to GEO. The μTORQUE experiment will remain on the upper stage left in a GTO trajectory. After the primary satellite has been deployed into GEO, the μTORQUE experiment will deploy a microsatellite at the end of a 20 km long tether. Utilizing tether reeling and/or electrodynamic propulsion, the μTORQUE system will set the tether in rotation around the upper stage, accelerating the rotation until the tip velocity is approximately 400 m/s. The experiment will then release the microsatellite when the system is at its perigee, tossing the payload into a near-minimum-energy transfer to the Moon. The microsatellite can then utilize a Belbruno weak-boundary trajectory to transfer into a lunar orbit using only a few m/s of delta-V. Preliminary analyses indicate that the tether system could be mass-competitive with a chemical propellant system for the same mission.

INTRODUCTION

Momentum-Exchange/Electrodynamic-Reboost (MXER) tethers have strong potential for providing a reusable in-space propulsion capability that can dramatically reduce the cost of many space missions (Hoyt, 2000b; 2000c; Sorensen 2001). In order for these concepts to progress towards operational service, however, flight experiments must be carried out to develop and demonstrate the key technologies needed for these systems. In this paper, we will first briefly review the concepts of momentum exchange and electrodynamic tether propulsion, describe two previous in-space demonstrations of momentum exchange, and then discuss the key technologies required for MXER systems. We will then discuss a concept for a small, low-cost flight experiment intended to perform risk reduction demonstration of several of these key technology needs.

Background: Momentum-Exchange Tethers

In a momentum-exchange tether system, a long, thin, high-strength cable is deployed in orbit and set into rotation around a central body. If the tether facility is placed in an elliptical orbit and its rotation is timed so that the tether is oriented vertically below the central body and swinging backwards when the facility reaches perigee, then a grapple assembly located at the tether tip can rendezvous with and capture a payload moving in a lower orbit, as illustrated in Figure 1. Half a rotation later, the tether can release the payload, tossing it into a higher energy orbit. This concept is termed a momentum-exchange tether because when the tether picks up and tosses the payload, it transfers some of its orbital energy and momentum to the payload, resulting in a drop in the tether facility's apogee.

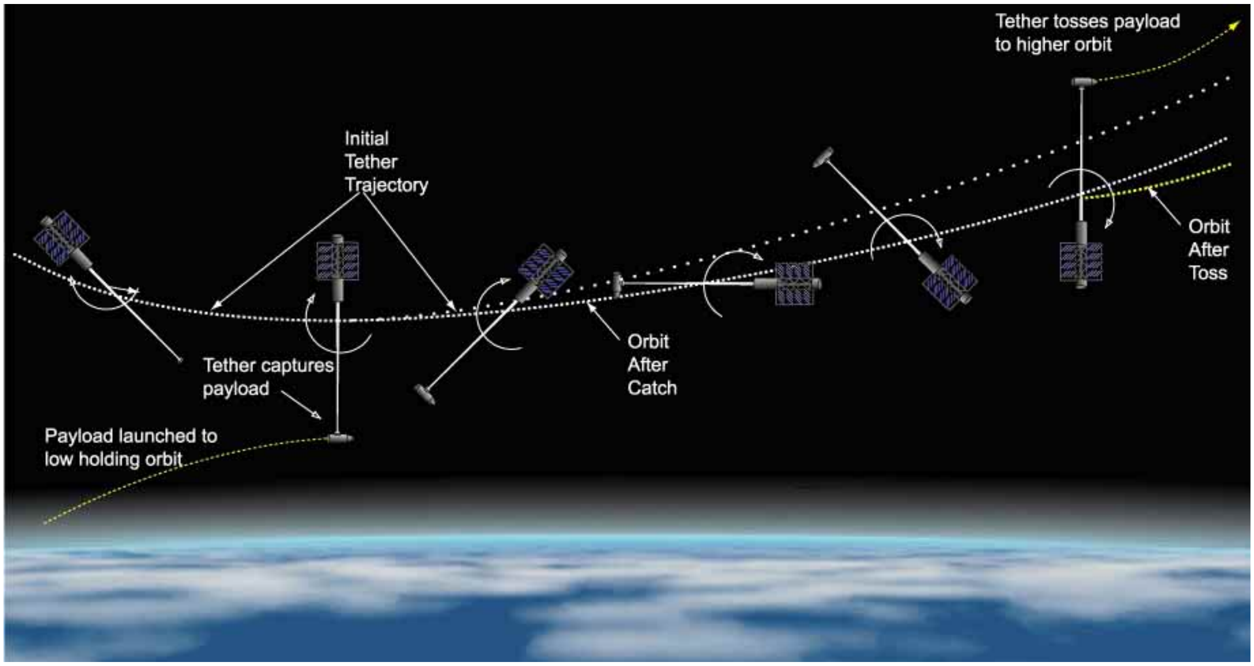

Figure 1. Concept of operation of a momentum-exchange tether facility. Orbits are depicted conceptually from the perspective of an observer on the Earth.

Electrodynamic Reboost

In order for the tether facility to boost multiple payloads, it must have the capability to restore its orbital energy and momentum after each payload transfer operation. If the tether facility has a power supply, and a portion of the tether contains conducting wire, then the power supply can drive current along the tether so as to generate thrust through electrodynamic interactions with the Earth's magnetic field. By properly controlling the tether current during an orbit, the tether facility can reboost itself to its original orbit (Hoyt, 2000a; 2001). The tether facility essentially serves as a large "orbital energy battery," allowing solar energy to be converted to orbital energy gradually over a long period of time and then rapidly transferred to the payload.

Key Advantages

A tether transportation system has several advantages compared to conventional and other advanced in-space propulsion systems:

<u>1) *(Near) Zero Propellant Usage*</u> Chief among these advantages is the ability to eliminate the need for propellant expenditure to perform payload transfers. Of course, some propellant expenditure will be needed for trajectory corrections and rendezvous maneuvering, but these requirements will be very small, a few tens of meters per second. The ability to cut several thousands of meters per second from the ΔV needed to deliver a payload to its destination can enable customers to utilize much smaller launch vehicles than would be required with a rocket-only system, greatly reducing total launch costs. For example, launching a 5 metric ton satellite into GEO, would require a Delta IVM+ (4,2) launch vehicle using an all-chemical propulsion system, at a cost exceeding \$90M. Using a tether facility, the payload could instead be launched into LEO using a much smaller Dnepr 1 (RS-20) launch vehicle, at $1/7^{th}$ the cost of the Delta launch.

<u>*(2) Short Transfer Times*</u> A momentum-exchange tether system provides its ΔV to the payload in an essentially impulsive manner. Thus the transfer times in a tether system are very short, comparable to rocket-based systems. This can be compared with electric propulsion schemes, which offer low propellant usage, but invariably require long transfer times due to their low thrust levels. The short transfer times offered by a momentum-exchange tether

system can play an important role in minimizing the lost-revenue time that a commercial satellite venture would have to accept while it waits for its satellite to reach its operational orbit and begin generating revenue.

3) Reusable Infrastructure Once deployed, a tether boost facility could transfer many, many payloads before requiring replacement. Thus the recurring costs for payload transport could be reduced to the cost of operations. A tether transportation system thus would be somewhat analogous to a terrestrial railroad or public-transit system, and might achieve comparable cost reductions for transporting many payloads.

4) *Fully Testable System* Another important but often overlooked advantage of a tether transportation system is that the components that perform the actual payload transfer operations can be fully tested *in space operations* before being used for critical payloads. In conventional rocket systems, engine components and other key elements can be tested on the ground, and many individual units can be flown to provide reliability statistics, but to date only the Shuttle has re-used rocket engines, with significant maintenance after each flight. In a tether transportation system, the tether facility could be tested many times with “dummy” payloads – or, better yet, with low inherent-value payloads such as water or fuel – to build confidence for use on high value or manned payloads. In addition, "using" a tether does not damage or "wear it out", as long as the loads placed on the tether do not approach the yield point of the tether material. This means that the tether used in the operational system is the same tether in nearly the same condition in which it underwent strength and reliability testing with the "dummy" payloads.

Previous Demonstration Missions

The use of space tethers to transfer orbital momentum and energy from one spacecraft to another has been demonstrated in a rudimentary fashion at least twice in the past, once intentionally, the other as a serendipitous outcome of a premature mission termination. In the SEDS-1 mission, a small payload was deployed below a Delta-II upper stage at the end of a 20 km long Spectra tether. The physical connection of the payload to the upper stage by the tether forced the payload to orbit the Earth with the same velocity as the upper stage. At the payload’s location, 20 km closer to the Earth, however, this velocity was less than that required for the payload to remain in orbit. After completion of the deployment, the tether was released from the upper stage. This dropped the payload into a suborbital trajectory that re-entered the Earth’s atmosphere half an orbit later (Smith, 1995). In the Tethered Satellite System Reflight Experiment carried out on the Shuttle orbiter in 1996, a satellite was deployed upwards from the Shuttle at the end of a 20 km conducting tether. Unfortunately, a flaw in the tether’s insulation allowed an arc to jump from the tether to the deployment boom, causing the tether to burn and separate near the Shuttle. Although this ended that experiment prematurely, it did unintentionally demonstrate momentum exchange, because after the tether was cut, the satellite was injected into an orbit with an apogee approximately 140 km higher than the Shuttle’s orbit.

Technology Needs

Although momentum-exchange/electrodynamic reboost tethers have strong potential for achieving significant cost reductions for a wide range of space missions, and many of the core technologies are available or at a high technology readiness level, as a system-level propulsion technology MXER tethers are currently at a relatively low TRL level. Several key challenges must be met before MXER tethers can be considered for operational use. NASA's 2000 H/READS Strategic Research and Technology Road Map for Space Transportation identified the following four technology elements key to the success of MXER tethers:

1. Highly accurate prediction and control of the tether dynamics associated with catching and tossing a payload
2. Integrated high-strength electrodynamic tethers, and improved modeling and control algorithms for electro-dynamic thrusting.
3. Efficient orbital propagators able to accurately model all of the perturbative effects on rotating space tethers, as well as methods for obtaining highly accurate orbital knowledge of tethers and their payloads.
4. Low mass, inexpensive, and reliable methods for catching payloads.

The previous flight demonstrations of momentum exchange did not address any of these issues. Consequently, in order for MXER tether concepts to advance towards operational capability, further flight demonstrations must be carried out to develop and prove these key technologies.

THE μTORQUE EXPERIMENT

In order to begin addressing these key technical challenges, we propose to develop a very small momentum-exchange tether system capable of boosting a microsatellite by a ΔV of 0.4 km/s. This "Microsatellite Tethered Orbit Raising QUalification Experiment" (μTORQUE) system will be sized to fly, along with its microsatellite payload, as a secondary payload on an upper stage rocket such as the SeaLaunch Block DM 3rd Stage. The primary goal of the μTORQUE system will be the development and low-cost demonstration of key technologies for MXER tether architectures.

The μTORQUE concept is illustrated in **Figure 2**. The μTORQUE tether system and a microsatellite payload would be integrated onto a rocket upper stage prior to launch. After the stage releases its primary payload into GTO (1), the μTORQUE system would deploy the microsatellite from the stage at the end of a high-strength conducting tether (2). The system would then use electrodynamic-drag thrusting during several successive perigee passes (3), to spin-up the tether system. This would effectively convert some of the upper stage's orbital energy into system rotational energy. Because the system utilizes electrodynamic drag to perform the spin-up of the system, it will not require the mass and complexity of a dedicated solar power supply; the system can also power its own avionics utilizing the power generated by the tether. When the tether tip velocity reaches 0.4 km/s, the μTORQUE system could then release the payload during a perigee pass (4), injecting the payload into a minimum-energy lunar transfer trajectory (5). With a 0.4 km/s ΔV capability, the μTORQUE tether system could also be useful for missions such as deploying microsatellites into high-LEO and MEO orbits as secondary payloads on launches of larger satellites into LEO.

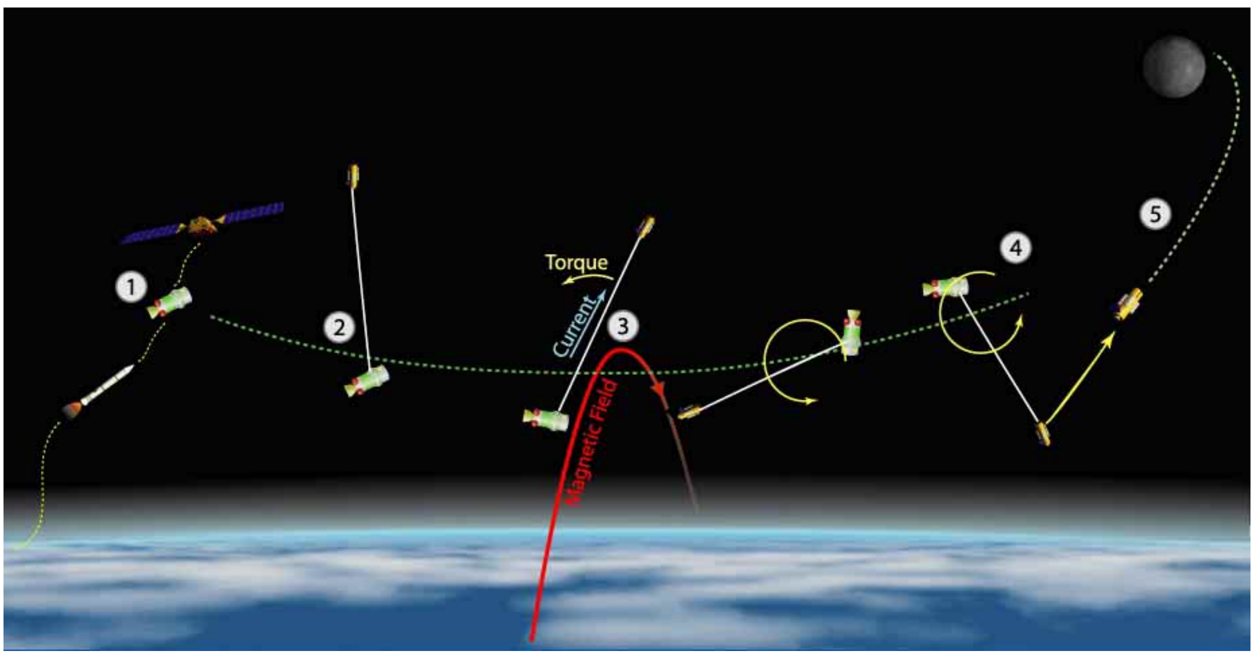

Figure 2. The "Microsatellite Tethered Orbit-Raising Qualification Experiment (μTORQUE)" concept.

System Concept

The μTORQUE system would be composed of:

- A 20 km long high-strength tether; this tether would have an integrated conductor, enabling it to carry currents for generation of electrodynamic forces. The tether would utilize an interconnected, multiline structure to ensure that it survives the orbital debris environment for the duration of the mission.
- A small, simple deployment system. The microsatellite would be ejected away from the upper stage, pulling the tether out of a deployer canister.
- An avionics package, to control deployment and operation of the tether, and to sense and control tether dynamics.
- An electron emission system, such as a hollow-cathode plasma contactor or a Field Emission Array Cathode, located on the upper stage side of the tether.
- A commandable release mechanism, enabling the tether system to release the microsatellite payload into its transfer orbit.

Preliminary System Sizing

The mass of a tapered rotating tether with tip speed V_t depends upon ratio of the tip speed to the tether material's characteristic tip speed: $V_c = \sqrt{2T/Fd}$, where T is the tensile strength of the material, F is the design safety factor, and d is the material density. For Spectra 2000, the best fiber presently available in quantity, T = 4 GPa, d = 0.97 g/cc, and thus V_c = 1.8 km/s for a safety factor of F = 2.5. In an unpublished paper, Moravec found that the mass of a tapered tether depends upon the tip mass (payload) and the tip velocity according to (Moravec 1978):

$$M_T = M_p \sqrt{\pi} \frac{\Delta V}{V_c} e^{\frac{\Delta V^2}{V_c^2}} erf\left\{\frac{\Delta V}{V_c}\right\}$$, where erf(x) is the error function of x.

Using a stepwise-tapered approximation of this ideal tapering, we have developed a preliminary design for a 0.4 km/s momentum-exchange tether system sized to boost an 80 kg microsatellite from a GTO trajectory to a minimum-energy lunar transfer orbit (LTO), using a 20 km long tether:

Tether Mass: (kg)	10.5	(2 kg of which is conductor)
Avionics & Emitter Mass: (kg)	5.5	
Deployer Mass (kg)	3.5	Max acceleration on payload: 0.83 gees
Ejection Mechanism Mass (kg)	0.5	
Total (kg)	20.0	

The initial experimental version of the system will likely include significant diagnostics for performance and dynamics verification, which will add to the system mass, but an operational version of this system with a mass on the order of 20 kg should be feasible. This (estimated) tether system mass is approximately 25% of the 80 kg microsatellite mass.

The primary objective of the proposed µTORQUE effort would be to develop a small, low-cost method for demonstrating many of the key technologies required for larger MXER tether facilities for boosting communications satellites to GTO and scientific payloads to the Moon. Using a Belbruno Weak-Boundary Transfer technique, the system may be capable of placing small payloads into lunar orbits without the need for a capture burn (Belbruno, 2000). Alternatively, it could place microsatellites into lunar-flyby-to-escape trajectories. The µTORQUE system as defined above will provide a testbed to demonstrate technologies for meeting the first three key technologies listed above (dynamics modeling, high-strength conducting tethers, and orbital propagation and sensing capabilities).

If the initial payload toss demonstration is successful, the µTORQUE system can then be augmented for a second flight demonstration to validate the fourth key technology, rendezvous and capture capability. In this second test, a grapple mechanism would be integrated at the tip of the tether. The µTORQUE experiment could then fly as a secondary payload on an upper stage that is placed into a LEO trajectory. The tether system could then be used to catch and toss a microsatellite payload, providing it with 800 km/s of total ΔV.

In addition, the µTORQUE effort will result in a small propulsion system that could be competitive with chemical propulsion for missions such as boosting secondary payloads from GTO drop-off orbits to lunar transfer or to other high-energy trajectories. A chemical-rocket stage sized to boost a microsatellite from GTO to LTO would require a propellant mass of approximately 20% of the microsatellite mass. When the necessary avionics and thruster hardware are included, a chemical-based system would likely have a mass penalty of approximately 25%, roughly equal to the (estimated) tether system mass penalty. A rocket system, however, could boost only one microsatellite. The µTORQUE system could be configured to deploy multiple payloads with zero or minimal additional mass requirements.

CONCLUSIONS

Momentum-Exchange/Electrodynamic-Reboost tether systems have strong potential for reducing the cost of in-space transportation, but several key technology challenges must be addressed before they can enter operational service. Given the large expense of conducting space demonstrations, and the relatively small amount of funding available for the development of advanced space propulsion technologies, we have sought to design a very small, affordable experiment that can achieve a significant advance in technology demonstration and risk reduction while performing a technically and scientifically significant propulsion mission. The µTORQUE concept can be flown as a secondary payload on a GEO satellite launch, enabling it to be conducted with relatively low launch costs. With a 100 kg total secondary payload mass allocation, the tether system can be sized to boost approximately 80 kg into a lunar transfer trajectory, and thus could deliver a significant science microsatellite to the Moon.

ACKNOWLEDGMENTS

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