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Conceptual Design and Analysis of Space Tether Transportation System With Electrodynamic Propulsion

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Abstract. Tether transportation system can form the infrastructure for a reusable low cost space transportation architecture and can be used to carry frequent traffic between orbits. The Tether transportation facility would be sized for launch on a single large rocket vehicle to its operational orbit. This system will utilize electrodynamic tether propulsion to restore its orbit after each payload boost operation. Several technical challenges must be resolved to enable this systems to be fielded, including development of rapid rendezvous and capture capabilities and techniques for building and controlling the tether facilities. This research is applied modeling of tether dynamics, orbital mechanics, electrodynamics, and other relevant physics, to verify the orbital design of the system and investigate methods for performing electrodynamic re-boost of the platform. Using comparison for differing payload capacities of each vehicle and the dependence of launch pricing upon business factors, these research indicates that a reusable tether boost facility could enable commercial customers to reduce their launch costs by reduction of recurring costs.

Keywords: Tether, Conceptual design, Electrodynamic propulsion, Transportation system.

1. INTRODUCTION

After 58 years of space exploration, the space launch industry remains reliant only on chemical rockets. This paper will investigate if any merit exists in implementing an alternative launch assist technology with functionality of existing upper stages namely momentum transfer tethers. A space tether is a long cable used to couple spacecraft together as they orbit the central body (i.e. Earth). Tethers are usually made of thin strands of high-strength fibers such as Spectra or Kevlar. Conducting tethers offer the additional capability to interact with the earth magnetic and electrical force fields as the electrodynamic tether. [1]

Because the space tether makes it possible to transfer energy and momentum from one object to another, it can be called a form of space propulsion. There are two general categories of tethers. Tether transportation system will utilize momentum-exchange techniques and electrodynamic tether propulsion to transport multiple payloads with little or no propellant consumption. [2]

In this paper after reviewing the works has done to date in this field, the results for the development of a concept for the tether transportation architecture are presented, and discussed simulations are used to investigate the performance of the tether system.

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2. PRIOR WORKS

The field of space tethers has received very considerable attention in recent decades, with many specialist articles. The longest tether stably deployed to date has reached a length of 31.7 km, albeit unintentionally [2]. According to Aerospace America Magazine [2], in 2010, the near-term target was to achieve reliable deployment and operation of 1 km tethers, although other projects [3] succeeded with non-liberating deployment of 20 km-long tethers in 1993. In 2007 Menon [4] described in detail a tether brake used to control deployment of the 31.7 km-long tether in the SpaceMail experiment [5]. Therefore, the author concludes that current technology is sufficient to deploy 80–1000 km-long tethers in the LEO environment.

Among many rotating momentum-transfer tether configurations promoted on the Tether Unlimited site, the LEO momentum transfer tethers (rotating tether) [6] deserves special attention, as it is scalable to low tip speed.

In 2010, Williams [7] proposed using a system with two rotating tethers for orbital capture or disposable and one reusable. Unfortunately, around the Earth, the only such body is the moon, and series of tethers able to handle at least 1.6 km/s tip speed are necessary for harnessing the orbital momentum of the moon rocks. An example of momentum-neutral tether design may be found in [8] in which a range of statistical methodologies for life prediction from the literature were critically compared and a revised proposal made, with some potential for practical use highlighted.

3. 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 massive central body. It allow momentum to be transferred between objects in space, such as two spacecraft. The principle is based on the gravity gradient force. Swinging motion may be used to raise or lower the orbit of a tandem system without using any propellant. If the tether facility is placed in an elliptical orbit and its rotation is timed so that the tether will be 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 acquire a payload moving in a lower orbit, as illustrated in Figure 1 and Figure 2. [9]

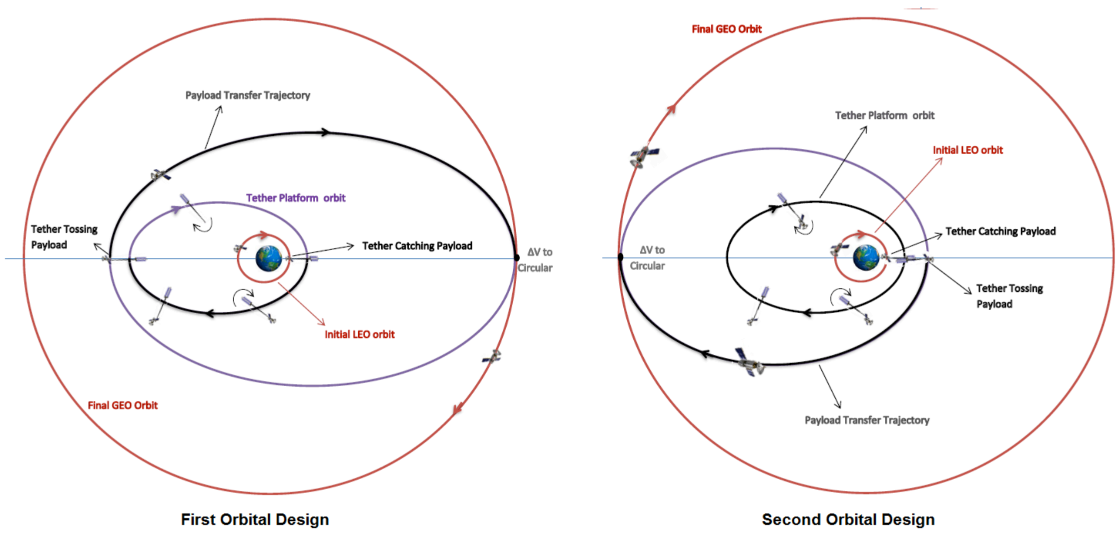

Figure 1. Momentum Exchange Tether catching payload and tossing it to GTO orbit. First orbital design implemented in this paper and second utilized by Hoyt.

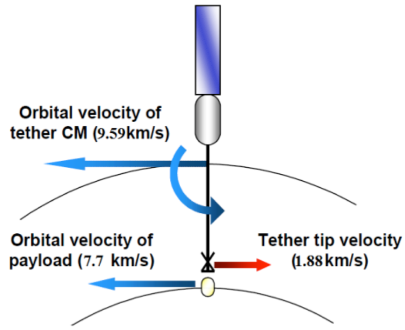

Figure 2. Tether tip velocity is configured to be equal to the difference in velocity between tether and payload. [9]

4. ELECTRODYNAMIC TETHERS

An electrodynamic tether is essentially a long conducting wire extended from the main end-body. There may be a second end-body to help deploy the bare tether. The gravity gradient field of the "spacecraft and string system" tends to orient the tether in a vertical position. A tether in Earth orbit interacts with the earth's magnetosphere due to the relative orbital velocities; the motion of the conductor across the magnetic field induces a voltage along the length of the tether. This voltage can be up to several hundred volts per km. [10]

The interaction of the tether system with the magnetosphere can be used in the design of the system to act either as an "electrodynamic power or thrust system" to boost the orbit of the spacecraft. The direction of the current flow in or out of an electrodynamic tether system determines if the interaction contributes to drag or to propulsion. In order for the tether facility to boost one payload per month, the tether must restore its orbital energy after each payload boost operation. This concept called the High strength Electrodynamic Force Tether (HEFT) Facility is illustrated in the right side of Figure 3.[11] The reboost trajectory (as shown in the left side of Figure 3) is the same of low thrust engines.

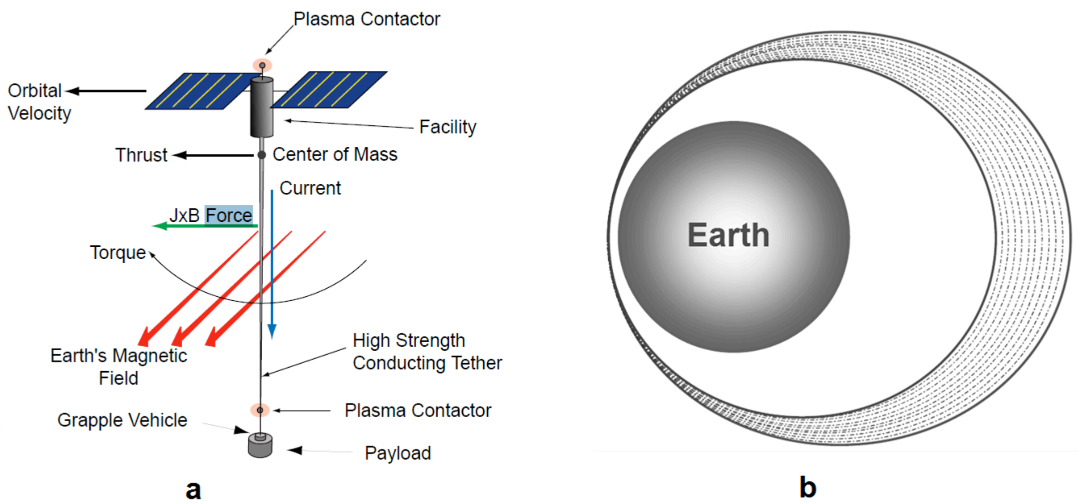

Figure 3. (a) Schematic of the HEFT Facility concept, (b) Electrodynamic reboost centered on an arc about perigee as a low thrust propulsion system. [11]

5. TETHER MISSION ANALYSIS

The fundamental rationale for this concept is to reduce the cost of transporting payloads to GEO. Figure 4 compared the final mass of tether system versus a conventional upper stage. Then the conceptual design algorithm of tether system according this concept illustrated in figure 5.

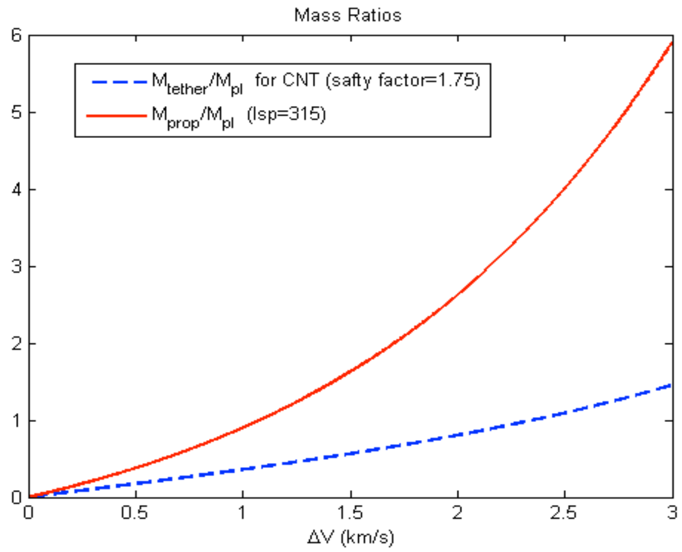

Figure 4. The mass performance of conventional chemical propulsion system comparing with tether transportation system. (CNT represents the Carbon Nanotube material for tether).

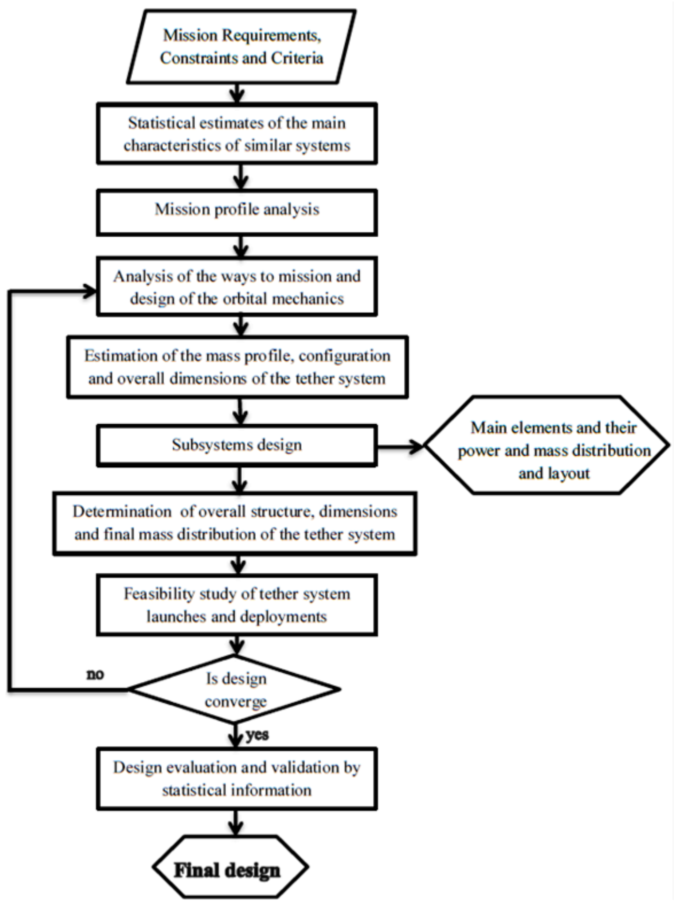

Figure 5. Algorithm design of tether transportation system

6. SYSTEM DEFINITION AND DESIGN REQUIREMENTS

The mission of the tether transportation system will be to pick 2500 kg payloads up from low- LEO to GEO altitudes. To do so, the Tether transportation system will provide the payload with a total ΔV of 3.7 km/s. The tether boost station architecture must minimize the design impacts upon payloads. In order to enable the payload to be boosted by the tether facility, a payload accommodation adapter (PAA) will be fitted to the payloads standard fixtures. The PAA will provide the rendezvous maneuvering and docking capabilities to the payload, and may also provide the apogee kick ΔV. The 2500 kg payload size was chosen primarily so that a fully operational tether facility can be launched on a single large launch vehicle. To provide ample margin for error and degradation of the tether over time, the tether structure is sized to provide a safety factor of 1.75 for the largest loads expected in the system. The largest loads will be due to transient oscillations immediately after the payload capture. [12]

Because one of the primary advantages of tethers is their reusability, to maximize the cost competitiveness of the system it will be designed to boost payloads as frequently as once every 30 days.

7. OPERATIONS CONCEPT AND FUNCTIONAL REQUIREMENTS

The functional analysis of recurring mission operations was used to identify the functional requirements to be satisfied by major system elements. This recurring missions illustrated in Figure 6. Also, the functional requirements were used to define the major subsystems and assemblies of the tether transportation system as shown in Figure 7-left side. The main subsystems of this facility are shown in Figure 7-right side.

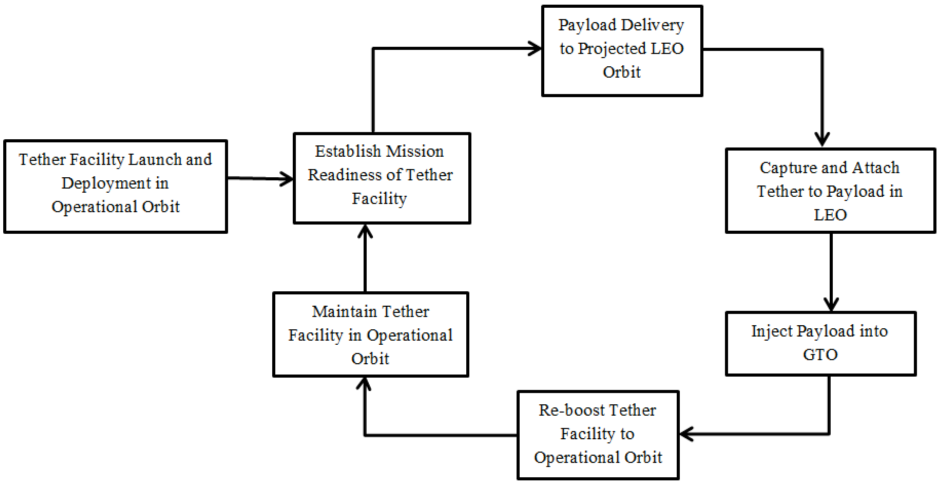

Figure 6. recurring operation algorithm of tether transportation facility.

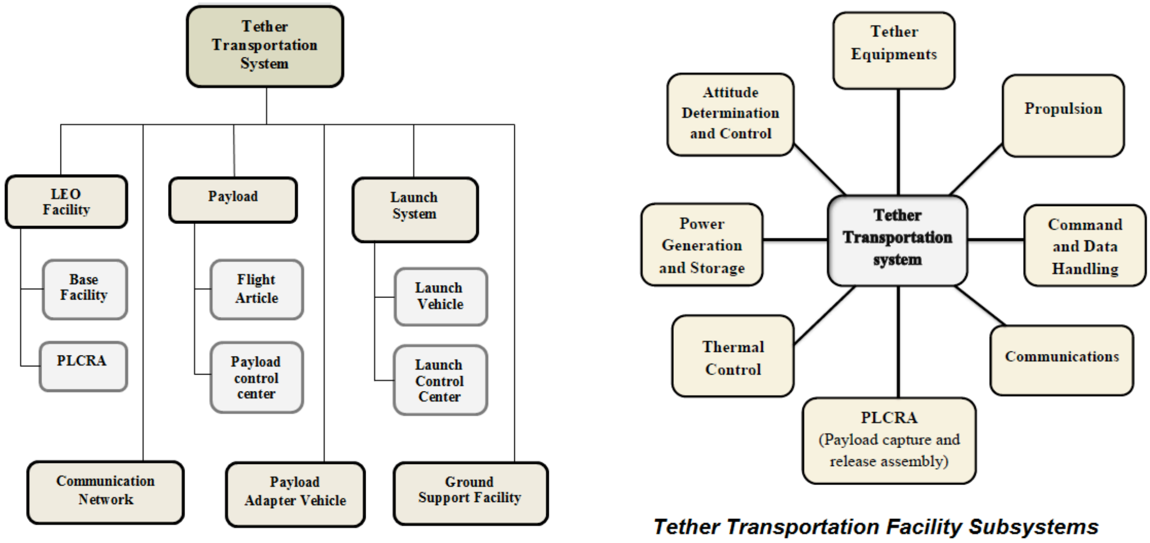

Figure 7. Architecture and subsystems of tether transportation facility.

Tether geometry must be considered with lower mass per unit length, and higher area at the point of greatest tension. Table 1 indicates the some main material characteristics that are used for tethers and their efficiency improvements by introducing the new materials. The tensile strength to density ratio in this table is a suitable criterion for tether material performances [13]. Accordingly in design process CNT is used for tether materials.

Table 1. Possible tether materials and their properties [13].

Material	Tensile Strength (GPa)	Density (kg/m3)	Tensile Strength /Density ($*10^{-6}$ s2/m2)
CNT	30	1300	23.077
Kevlar	3.6	1440	2.5
Spectra 2000	3.5	970	3.6
Zylon	5.8	1540	3.77
Current PIPD	5.3	1700	3.12
Anticipated PIPD	9.5	1700	5.59

8. ORBITAL MECHANIC SIMULATION

The first orbital designe that provided in figure 1 is utilized for platform design and simulation. Figure 8 provided the all ΔV changes for the range of platform apogee altitude. In this figure the specified sought point is related to the equal impulse in catch and toss for constant rotation velocity. Table 2 contains main orbital parameters for this design point.

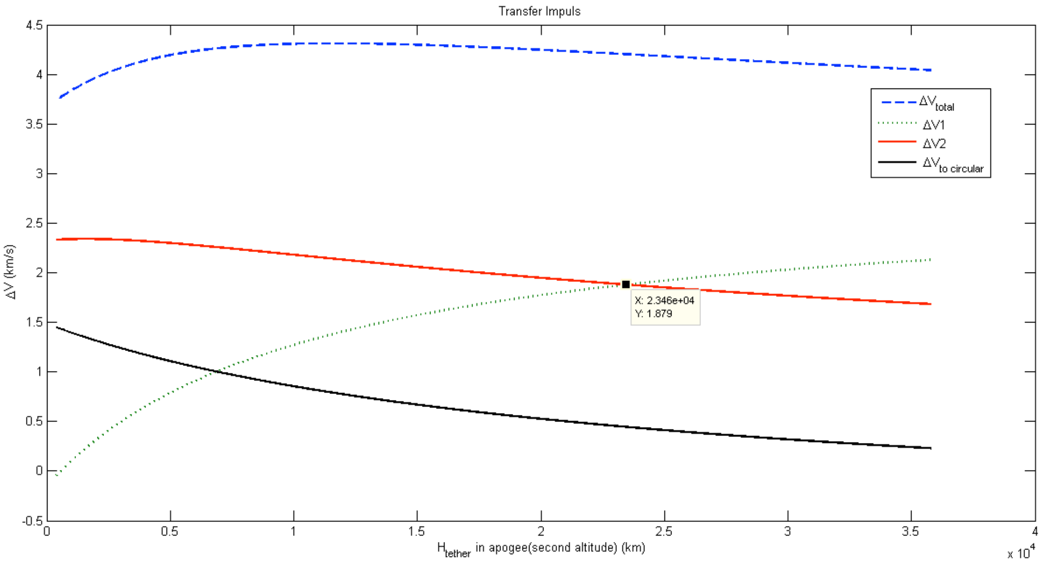

Figure 8. Transfer impulses variation by tether platform orbit altitude.

Table 2. System Orbital Design for LEO to GTO maneuver .

		Pre-Catch		Joined System	Post -Toss	
Positions & Velocities		**Payload**	**Tether**		**Tether**	**Payload**
resonance ratio	Km	50	11			
perigee altitude	Km	325	405	397	219	17957
apogee altitude	km	325	23461	17877	17869	35786
perigee radius	Km	6703	6783	6775	6597	24335
apogee radius	Km	6703	29839	24255	24247	42164
perigee velocity	m/ s	7711	9785	9590	10757	4557
apogee velocity	m/ s	7711	2224	2679	2483	2630
ΔV to Re-boost	m/ s				364	
ΔV To Circularize	m/ s					0.44
Orbital Parameters						
semi-major axis	km	6703	18311	15515	14922	33249
eccentricity		0	0.63	0.56	0.62	0.27
inclination	rad	0	0	0	0	0
Orbital Energy	GJ	-74.33	-261.22	-308.29	-320.55	-149.8
period	GJ	91	411	160	151	503

9. RESULTS EVALUATION AND VALIDATION

After implementation and simulation of the algorithm design according to the design functional requirements the major system element masses are estimated as Table 3. Some other main system elements are available in Table 4. For validation of this algorithm, the results are compared by available outputs from tether boost facility gives by Hoyt [6] for 2500 kg payload.

Table 3. Mass contribution of major system elements.

	Design result	Hoyt results	
Tether mass	1853	8274	Kg
CS Active Mass	15130	11514	Kg
CS Ballast Mass	2800	3490	Kg
PLCRA mass	650	650	Kg
Total Facility Mass	20433	23928	Kg
Total Launch Mass	20433	20438	Kg
Payload Mass	2500	2500	Kg

Table 4. Comparison of main system parameters.

		Design result	**Hoyt results**	**Percent of Variations**
Payload mass	kg	2500	2500	-
Platform mass	kg	20433	23928	-
Tether length from CM	km	80	80	-
Initial altitude	km	325	325	-
Final altitude	km	35786	35786	-
Platform altitude in apogee	km	23461	8445	-
ΔV1	km/s	1.878640	1.146583	-63 %
ΔV2	km/s	1.878642	1.140058	-64 %
ΔV for circularization	km/s	0.444272	1.448182	+69 %
ΔV total	km/s	4.201555	3.734823	-12.5 %
Transfer time	min	663.088	488.56	-35.7 %
Propellant mass for circularization	kg	333.2	931.645	+64 %
(Mprop/Mpayload)*100		13.32 %	37.26 %	Constant for all payload range
Platform Orbital Energy Pre-catch	GJ	-261.220687	-441.397849	-
Platform Orbital Energy After Toss	GJ	-320.549757	-495.427716	-
ΔE for platform Re-boost	GJ	59.329070	54.029866	+9 %
Re-boost time (by 2.7 GJ/day Ed)	day	21.973	20	+9 %

Moreover this tether transportation system has several advantages compared to conventional chemical upper stages and other advanced space propulsion systems. Zero propellant usage, short transfer times, reusability and fully testable system are some of them.

10. CONCLUSION

In this research it is shown that both momentum exchange and electrodynamics can, both separately and together, provide practical and workable propellantless propulsion. Thus the tether transportation system combines the efficiency of Electrodynamic propulsion and the delivery speed to GEO and transfer time of a chemical system. This system is flexible and can be adjusted to limit payload accelerations and can adjust for a range of payload masses. The total mass required on orbit is about 20 tons, less than the current mass of the ISS and so clearly fit within the current launch capabilities. Due to the reusability of this system and its advantages in reducing the launched mass to LEO, total cost of delivery to GEO reduced up to 30 percent.

Some technical challenges must be met to enable tether transport systems to be fielded, that among those, recently increase of the strength-to-weight ratio of CNT materials for tethers makes tether system much more attractive and accessible and presents a new generation of orbital propulsion systems with much better performance. Provided system in this paper catches payloads from LEO and injects them into GTO without fuel consumption. Compared to similar schemes designed system in this paper is able to provide a significant reduction in final impulse to circular GEO orbit, and consequently the proportion of the propellant mass in total mass of GTO payload reduces to 13%.

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