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TETHER TRANSPORT FROM LEO TO THE LUNAR SURFACE

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Abstract

Moravec showed in 1977 that a rotating tether in orbit around the Moon or any small airless planet could be made to touch down to the surface six times an orbit, simultaneously dropping off and lifting up payloads weighing a reasonable fraction of the tether mass. The tether length should be one-third the diameter of the planetoid. Using Kevlar tether material with reasonable safety margins, Moravec estimated that a tether for the Moon would have a total length of 1160 km, and mass 13 times the mass of the payloads at each end. Using the improved tether material Spectra 1000, Carroll carried out in 1991 a preliminary design of a rotating tether Earth transport node facility designed to provide a ± 1 km/s ΔV to massive payloads. A 290 km long tether for handling 5-ton payloads would only mass 4.7 tons. The central station of the tether node facility would require a mass of 150 tons, however, to prevent the tether from deorbiting when handling 5 ton payloads. In this paper I combine the two systems of Moravec and Carroll to propose a method of transporting 5-ton payloads from low Earth orbit (or even sub-orbital trajectories reachable by the National Aerospace Plane) directly to the surface of the Moon without the use of any propellant. There would be two Earth tethers, and one lunar tether. The lower Earth tether facility would be placed in a circular 400 km orbit and the other in a highly elliptical orbit with a 4:1 period resonance. Payloads would be picked up from 130 km earth altitude by the lower tether facility and tossed into an elliptical orbit with an orbital period twice the lower facility and half the upper facility. There the payloads would be picked up by the higher tether facility and tossed toward the Moon. At the Moon, the 5-ton payloads would be retrieved by a 65 ton, 580 km rotating tether and deposited on the surface of the Moon. It is essential for this concept that equal amounts of mass flow in both directions, so that a tether picks up as much mass as it releases. First, this means the Earth tether facility masses can be order of magnitude less than the mass estimates in the Carroll studies, which assumed the 5 ton payloads would be added or subtracted without exchanging a compensating mass. With equal mass flow, the Earth tether transport facilities can mass as low as 30 tons. Second, with equal mass flow, the system would be self-powered. Bags of lunar dirt moving down the tether system into the Earth's gravity well would be the "fuel" needed to move payloads from LEO to the surface of the Moon. Since 1 kg moved from the lunar surface to LEO generates 27 MJ of energy, a small excess of lunar dirt would provide makeup energy to compensate for reel friction, cable stretch, and atmospheric drag losses.

Introduction

Tethers[1] are long cables in space that are used to couple spacecraft to each other, to other masses, such as a spent booster, space station, or asteroid, and to electric, magnetic, and gravity force fields in space. The tether coupling allows the transfer of energy and momentum from one object to another, and so are a form of space propulsion.

Tethers are now being seriously considered for use with the Space Shuttle and the Space Station for raising or lowering payloads for various scientific and engineering purposes. Rotating tethers have also been considered for transporting payloads to and from the Moon, Mars, and other bodies in the solar system.[1-7] This paper proposes the use of three rotating tethers, two in orbit around the Earth and one in orbit around the Moon, to transport payloads from low Earth orbit (LEO) directly to the surface of the Moon, without requiring the expenditure of any propellant, except for moving the payloads back and forth between the surface of the Earth and LEO.

Tether Performance

The characteristic velocity of the material in a tether is given by the square root of the ratio of the design tensile strength T of the tether to the density D of the tether material.

$$u = (T/D)^{1/2} \tag{1}$$

In an ideal system using perfect material with no safety margin, the design tensile strength is equal to the Young's modulus and the characteristic velocity is equal to the velocity of sound in the material. This ranges from 5 km/s in most metals to 20 km/s in diamond and graphite. In practice, the design tensile strength is usually chosen to be one-half the measured strength for metals and one-fourth the measured short-term individual fiber strength for other materials. Thus, using imperfect materials with reasonable safety margins, the characteristic velocity of most metals and fibers is around 1 km/s, with optimistic predictions for graphite and improved polymers reaching 3 km/s.

The "characteristic length" L of a material usually used by tether engineers is related to the "characteristic velocity" u of the material by the equation:

$$L = \frac{u^2}{g} \tag{2}$$

where $g=9.8$ m/s^2 is the gravitational acceleration of the earth. The length of a tether can be made longer than the characteristic length of the cable by tapering the cross-sectional area of the cable. The cross-sectional area of the tether would be largest near the deploying station, where the strains are the maximum, since the tether must not only support the mass of the payload, but also the mass of the cable needed to reach to the payload.

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Rotating Tether Parameters

The area A(r) of a rotating tether as a function of distance r from the center of the tether is given by:[2,4]

$$A(r) = \frac{M\,v^2}{T\,R} \exp(1 - \frac{r^2}{R^2})v^2/2u^2 \quad , \qquad (3)$$

where R is the radius of the rotating tether, v is the tip velocity with respect to the center, and M is the mass to be supported at each end.

The ratio of the mass of a rotating tether launcher to the mass of the payload it can throw was derived by Moravec[4] by integrating the area of the cable derived in his previous paper[2] and multiplying by the density.

$$\frac{M}{m} = 2.51\,\frac{V}{u}\,e^{V^2/2u^2}\,\mathrm{erf}(V/1.41\,u) \qquad (4)$$

where erf(V/1.41 u) is the error function associated with the normal probability function. It varies from 0.68 for $V/u=1$, to 1.00 for $V/u>3$, so is effectively unity for nearly all values of V/u of interest.

This launcher to payload mass ratio for a rotating tether payload launching system can be compared to the launcher to payload mass ratio of a rocket propulsion launching system. For the case of the rocket, the ratio of the rocket launcher mass to payload mass is given by:

$$\frac{M}{m} = e^{V/u} - 1 \qquad (5)$$

where V is the maximum payload velocity while u is now the "exhaust velocity" of the fuel. Note that for large values of V/u, the launcher to payload mass ratio of the rocket is exponential in the first power of V/u, while the rotating cable launcher to payload mass ratio is exponential in the square of V/u.

Moravec Lunar Rotovator

Moravec first used Equation 4 to determine if it was possible to design a rotovator for the Earth and other planets.[2] Unfortunately, his analysis showed that unless very strong tether materials can be found, the mass ratio of a rotovator for the Earth or other large planet becomes too high to be practical to build. This is unfortunate, because otherwise, it would be possible to build tether transport systems that would allow travel between the surface of the Earth and the surface of any solid body in the solar system without requiring fuel, provided the mass flow inward slightly exceeds the mass flow outward.

Moravec did find that rotovators were feasible for the Moon and other small airless bodies. He showed that rotovators could be designed that would touch down from one to n times per orbit, but the tether mass was minimum for a rotovator that had a total length one-third the diameter of the body, was in an orbit at an altitude of one-sixth the diameter of the body, and rotated so that it touched down six times per orbit. In a later, unpublished paper,[3] Moravec used Equation 4 to design a rotovator made of the Dupont fiber Kevlar for use around the Moon.

The Moravec Lunavator assumed the use of Kevlar with a density of 1.44 g/cc and a tensile strength of 2.8 GPa (3.8×10^5 psi). The design tensile strength was assumed to have a safety factor of two, so that the rotovators were stressed to at most half the tensile strength of the Kevlar. A Kevlar Lunavator would have an area taper ratio of 3.6 (diameter taper ratio of 1.90). The ratio of the tether mass to the largest payload that could be supported at each end would be 13. Thus a Kevlar Lunavator would be able drop and/or lift 1/13 of its own mass each touchdown, or a 5 ton payload for a 65 ton tether.

The Moravec Lunavator would be 1160 km long, with its center in a 2.78 hour lunar orbit at 580 km altitude. The ends of the tether would touch down six times per orbit. The touchdown and liftoff acceleration of the tips with respect to the lunar surface would be 0.28 gees. Adding in the surface gravity of the Moon of 0.16 gees, the total acceleration on the payload would be 0.44 gees.

It should be emphasized that in a properly designed Lunavator, the relative velocity between the payload and the surface of the Moon at the time of landing is zero. To understand this, it helps to imagine the Lunavator tether as one spoke of a large imaginary bicycle wheel rotating along the lunar surface. The Moon has its own slow rotation, of course, but proper design of the Lunavator orbital and spin dynamics can compensate for that, reducing the relative velocity at touchdown to zero.

By using cable reels and small thrusters on a grapple structure for attaching the payload to the tip of the tether, the time for depositing the payload on the surface and picking up a new payload can be increased to many minutes. The payload would be "flown" in early, before the arrival of the tether by using a combination of rockets and lunar gravity while the grapple reels let out cable. After the payload was on the ground and while the tether was still descending, the grapple reels would reel in the excess cable. A well designed reeling system would not abruptly relax all tension in the cable as the payload touched the lunar surface, but would maintain most of the payload weight by cable tension so as to minimize transients in the main tether. After the nominal touchdown time had passed, the grapple structure could remain on the surface for an additional time by merely releasing cable as the main tether starts to pull away. After the payload transfer has been safely completed, the rate of unreeling of cable would be decreased, and the grapple structure, with the new payload attached, would be lifted from the surface.

Carroll Earth Tether Transport Node

In a NASA Contract Report[5] dated March 1991, Carroll carried out a detailed design of a rotating tether transport node facility that is capable of adding or subtracting a velocity increment ΔV to a payload. One ΔV increment on attachment to the tether, and another ΔV increment upon release. The report focused primarily on a 290 km barely-spinning, single-arm tether sling extending from a massive central facility in low Earth orbit. The facility would be able to capture objects at velocities 1.2 km/s less than orbital velocity, in trajectories with apogees as low as 130 km. It can then either retrieve them, release them into orbits similar to the facility orbit, or boost them into orbits with perigees above 600 km and velocities 1.1 km/s above circular orbit velocity. To prevent facility orbit decay, momentum balance would be obtained from return traffic and/or high specific impulse electric propulsion between captures.

Carroll also briefly looked at facilities in Moon and Mars orbits, including one with a 900 km barely-spinning tether sling in low lunar orbit, which picked up payloads from the lunar surface. This was essentially a slower-spinning, one-armed version of the two-armed Moravec Lunavator. These Mars and Moon slings would use similar hardware except that the tethers would be moderately longer and thinner, due to the smaller gravity gradients around those bodies.

Carroll's LEO tether transport node facility would be at an orbital altitude over 400 km, which is high enough to keep drag low, while allowing capture and release of payloads near 130 km. This is low enough for sub-orbital payload pickups without excessive heating of the tether material.

The facility was designed to handle 5 ton payloads. The tether was assumed to be made of Spectra 1000 which has a density of 0.97 g/cc and a design tensile strength of 2 GPa. The 290 km tether has a total mass of 4,700 kg, and the reel has a mass of 265 kg, making a replacement tether mass equal to the mass it can handle, so backup tethers can be handled as a single payload unit. The tether taper ratio is 1.35 (diameter taper ratio of 1.16), which is accomplished by changing the number of 20 micron fibers in the braided cable. The very tip, which has to enter the upper atmosphere, is protected by a winding of teflon tape around the last 30 km, which increased the effective diameter.

During rendezvous with the payload, the tip of the barely-spinning tether experiences a 0.33 gee centrifugal acceleration. Hence, the capture maneuver will resemble a flying trapeze maneuver more than it does a traditional docking maneuver. Payload capture and release would cause large and sudden changes in equilibrium tether tension and length. Carroll shows that the acceleration and the capture transients can be handled by judicious reeling and unreeling of the cable prior to and after docking. This typically requires reeling 1.7 km of tether in or out during the 46 seconds it takes an extension wave to make a round trip on the 290 km tether. Putting separate cable reels and rocket trusters on the grapple structure would help increase docking time and decrease docking accelerations and transients.

Carroll assumes the tether is a single cable with a diameter of 5.5 mm at the central facility. A single hit by micrometeorites or space debris will cause tether failure. He estimates the tether lifetime as one month of full exposure, and plans to limit the exposure by reeling in the tether when it is not needed. The total deployment time for the 290 km tether is 9.5 hours.

Since Carroll designed the facility to handle single 5 ton payloads, the facility will change orbital parameters after capturing or releasing the payloads. To keep the altitude shift and resulting drag acceptable after capture of a payload from a sub-orbital trajectory, Carroll had to assume that the central facility mass would be at least thirty times the design payload, or 150 tons to handle 5 ton payloads. The whole tether system mass, including power supplies, reels, winches, and backup tethers, would be expected to be only 10% of this required mass, or 15 tons. If the facility were part of a complete tether transport system where incoming payloads were always matched with outgoing payloads (even though some of the incoming payloads were just ballast loads of lunar dirt), then the facility mass could be significantly less than 150 tons, perhaps as low as 30 tons.

In 1988, a group at the California Space Institute carried out a study[6] of a low Earth orbit to low Moon orbit transportation system that used multiple rotating tethers in elliptical Earth orbits. Using a sling in a similar configuration, Carroll has suggested[7] a two tether system that would have a LEO sling at an orbital altitude of 400 km, orbital period of 1.5 hours, and a tether length of 290 km. It would pick up sub-orbital payloads and place them into an elliptical holding orbit with a perigee of about 700 km, period of 3 hours (twice that of the LEO sling).

Above the payload orbit, in an elliptical earth orbit (EEO) would be a second sling. This EEO sling would have a perigee of about 800 km, orbital period of 6 hours (4 times that of the LEO sling), tether length of 100 km, and a $\triangle$V capability of 0.9 km/s. The EEO sling would capture the payload from its holding orbit, and an orbit later, at an altitude of about 900 km, inject it into an escape trajectory from the Earth. To maintain co-planarity of the two facility orbits, they would have to be either polar or equatorial.

LEO to Lunar Surface Transport System

This paper proposes to combine the three elegant concepts of Moravec, Carroll, and Calspace to produce a tether transport system that can move payloads from LEO to the lunar surface without requiring the use of propellant (except for movement of payloads between the surface of the Earth and LEO).

As shown in Figure 1, there would be two Earth tethers, and one lunar tether. The lower Earth tether facility would be placed in a circular 400 km orbit and the other in a highly elliptical orbit with a 4:1 period resonance. Payloads would be picked up from a 150 km earth altitude by the lower tether facility and tossed into an elliptical orbit with an orbital period twice the lower facility and half the upper facility. There the payloads would be picked up by the higher tether facility and tossed toward the Moon. At the Moon, the 5-ton payloads would be retrieved by a rotating 100 ton facility with two 580 km tether arms and deposited on the surface of the Moon.

It is essential for this concept that equal amounts of mass flow in both directions, so that a tether picks up as much mass as it releases. First, this means the Earth tether facility masses can be almost an order of magnitude less than the mass estimates in the Carroll studies, which assumed the 5 ton payloads would be added or subtracted without exchanging a compensating mass. With equal mass flow, the Earth tether transport facilities can mass as low as 30 tons. Second, with equal mass flow, the system would be self-powered. Bags of lunar dirt moving down the tether system into the Earth gravity well would be the "fuel" needed to move payloads from LEO to the surface of the Moon.

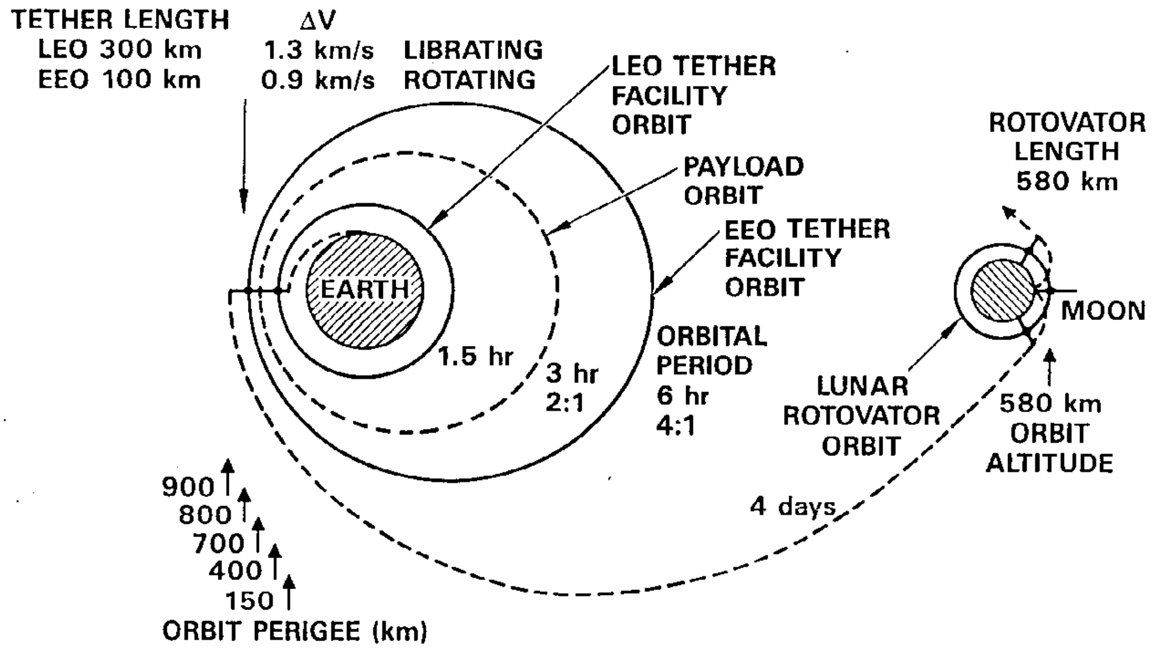

Fig. 1 - LEO-Lunar Surface Tether Transport System

Trajectory Analysis

No trajectory analysis has been done to match the Earth escape trajectory with a lunar capture trajectory. Therefore it is not known how much on-board propellant will be needed to adjust the transfer trajectory to accomplish a reasonable rendezvous with the lunar rotovator.

Lunar to LEO Energy Gain

The transfer of lunar dirt from the surface of the Moon to LEO or the Earth's surface results in a net gain of energy. This energy can be used to maintain the rotation and orbital energies of the tethers in the LEO-to-Lunar surface transportation system, despite inevitable energy losses.

A body of mass m on the surface of the Moon has a gravitational potential energy given by:

$$U_m(R_m) = -GmM_m/R_m = -2.8 \text{ MJ/kg} \quad , \qquad (6)$$

where M_m=7.4x10^{22} kg is the mass of the Moon, and R_m=1.7 Mm is the radius of the Moon.

If we wish to measure the energy in the rest frame of the Earth, we must put in two corrections. First, the mass m is also in the gravity field of the Earth, although out at the separation distance D of the Earth and Moon, so it has an additional negative gravitational potential energy due to the Earth, given by:

$$U_e(D) = -GmM_e/D = -1.0 \text{ MJ/kg} \quad , \qquad (7)$$

where D=384 Mm is the average distance of the Moon from the Earth, and M_e=6x10^{24} km is the mass of the Earth.

This negative potential energy is, of course, half-compensated by its positive kinetic energy $K_e(D)$ due to the orbital motion of the Moon at velocity v about the Earth at the same distance.

$$K_e(D) = mv^2/2 = +GmM_e/2D = +0.5 \text{ MJ/kg} \quad . \qquad (8)$$

Thus, the total energy W_m of a mass m on the surface of the Moon is given by the sum of these three energies, or:

$$W_m = U_m(R_m)+U_e(D)+K_e(D) = -3.3 \text{ MJ/kg} \quad . \qquad (9)$$

The gravitational potential energy $U_e(R_e)$ of the mass resting on the surface of the Earth is:

$$U_e(R_e) = -GmM_e/R_e = -63 \text{ MJ/kg} \quad , \qquad (10)$$

where R_e=6.4 Mm is the radius of the Earth. So moving a kilogram of lunar dirt (or anything) from the surface of the Moon to the surface of the Earth results in a net energy gain of:

$$W_n(R_e) = W_m-U_e(R_e) = +60 \text{ MJ/kg} \quad . \qquad (11)$$

If, instead, we only return the mass to low Earth orbit, at some altitude h, then the net energy gain is halved,

$$W_n(R_e+h)=W_m-U_e(R_e+h)+K_e(R_e+h)= +27 \text{ MJ/kg} \quad , \qquad (12)$$

since the kinetic energy $K_e(R_e+h)$ of the mass in orbit is half the gravitational potential energy $U_e(R_e+h)$ at the orbital altitude R_e+h.

If we had used rockets to do the transfer of that kilogram of mass, then we would have had to expend a lot of energy to move it from the lunar surface to LEO. We are using tethers, however, so instead, the excess energy from moving that mass from the lunar surface to LEO can be transferred to the rotational energy or the orbital energy of the tethers. This excess energy can be used to transfer more men and equipment to the lunar surface, as well as providing make-up energy to replace that lost by air drag, reel friction, and stretching of the tethers.

Feasibility and Credibility

As Carroll points out in his recent contract report, it is one thing to convince engineers that a concept is technically feasible, but it is another to convince them it is credible. A good part of Carroll's report discusses one critical problem area, a credible method of making a grapple structure which can assure high probability capture of the payload during the time-limited encounter of the grapple and payload. It is hoped that his arguments are persuasive.

Another major problem area that Carroll does not address is the high failure rate of single strand tethers in the debris environment of space. He does mention the possibility of weaving the tether in the form of a flat strap rather than a round string, but the improvement in lifetime is not large.

If the area of the tether were divided up into many threads (say six) that were separated by a number of centimeters (or perhaps even by meters), then the cutting of one thread would not result in catastrophic failure of the tether, but merely would degrade the strength of the tether until the thread could be replaced or repaired. The degraded strength could easily be accommodated by changes in the maximum allowed tension parameter in the tether reel control program. The simplest way to implement this would be to have six separate tether deployment systems working in tandem, with the six threads connected to a harness on the grapple structure that keeps the threads separated by a considerable distance.

If the six threads had properly designed cross-connections at periodic intervals, then at the cost of some amount of increased mass, the cross-connections would be able to provide a bridge across the broken portion of the thread. Whether the cross-connections would be "floating" when not being used to bridge gaps, or would help provide partial support for the load, would depend upon the exact design. The question here is how one expands the six-thread, cross-connected tether as it comes off the reel until the six threads have wide separation, and how one maintains that separation along the whole length of the tether despite the high longitudinal tensions in the threads that would lead one to expect radial collapse of the expanded structure.

The design of a practical multistrand tether would be a good term project or thesis topic for aerospace or physics students. A sufficiently novel design that results in high tether reliability at low excess mass might even be worth patenting.

Conclusion

This paper combines two elegant rotating tether concepts proposed by Joe Carroll and Hans Moravec into a proposal for tether transport system for moving masses between LEO and the lunar surface, without the expenditure of energy or reaction mass. The proposal needs a lot of study before it can be said to be even technically feasible. It does offer, however, a remarkably simple and relatively inexpensive way to not only explore the Moon, but build and support a permanent, manned facility there.

Acknowledgements

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References

[1] Paul A. Penzo and Paul W. Ammann, Tethers In Space Handbook - Second Edition, NASA Office of Space Flight, NASA Headquarters, Washington, DC 20546. [See the many references in the 33 page bibliography.]

[2] Hans Moravec, "A Non-Synchronous Orbital Skyhook," Journal of the Astronautical Sciences, Vol. 25, No. 4, Oct-Dec 1977, pp. 307-322.

[3] Hans Moravec, "Free Space Skyhooks", unpublished notes dated November 1978. [Obtain from author, Robotics Institute, Carnegie-Mellon University, Pittsburgh, PA 15213-3890.]

[4] Hans Moravec, "Non-Synchronous Orbital Skyhooks for the Moon and Mars with Conventional Materials", (unpublished paper, 1978). [Obtain from author, Robotics Institute, Carnegie-Mellon University, Pittsburgh, PA 15213-3890.]

[5] Joseph A. Carroll, Preliminary Design of a 1 km/sec Tether Transport Facility, March 1991, Final Report on NASA Contract NASW-4461, NASA Headquarters, Washington, DC 205465 with Tether Applications, 2603 Crosshaven Lane, San Diego, CA 92139.

[6] Martin O. Stern, Advanced Propulsion for LEO-Moon Transport, NASA CR-172084, June 1988. Progress Report on NASA Grant NAG 9-186, NASA/JSC, Houston, Texas with California Space Institute, UCSD, La Jolla, CA 92093.

[7] Joseph A. Carroll (private communication).