TOWARDS A TETHER BASED FREIGHT DELIVERY INFRASTRUCTURE BETWEEN EARTH AND MOON

Interim Report

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ME525: Aero-Mechanical Group Project

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Abstract

The aim of the project is to construct a mission architecture for the bi-directional transportation of 1000kg of freight between the Earth and the Moon utilising Motorised Momentum Exchange Tethers (MMETs). This report will outline the research conducted thus far; focusing on transportation methods from Earth to Low Earth Orbit (LEO), Moon based tether system to the lunar surface, and the technical aspects of MMETs that will be necessary to calculate the specification required for their design. The future steps of the project will then be discussed which will form the building blocks of the mission architecture as a whole.

Contents

1 Nomenclature

A – cross sectional of tether, m^2

L – tether length from CoM to payload

M_M, M_P – motor and payload mass, kg

r_c – circular orbit radius at payload release, m

r_M, r_P – radius of motor and payload, m

r_{Ti}, r_{To} – inner and outer radius of tether tube, m

μ – gravitational parameter of body being orbited

ρ – density of tether, kg/m^3

σ – tensile strength of tether, N/m^2

τ – motor torque, Nm

$\ddot{\psi}$ – angular acceleration of tether, rad/s^2

$\dot{\psi}$ – angular velocity of tether, rad/s

ψ – angular displacement of tether, rad

2 Introduction

Momentum Exchange Tethers (MET) enable the orbital transfer of two bodies by allowing the transfer of momentum and hence energy between the two bodies [1]. This concept will form the basis for this project which aims to construct a mission architecture for the bi-directional transportation of 1000kg freight between the Earth and the Moon. The future of space exploration is reliant on the development of technologies which reduce its economic and environmental impact. Currently conventional rocketry requires that 70-80% of the total mass be used solely for propellant. The aforementioned mission would allow for a large a reduction in propellant required by utilising the principle of momentum exchange.

The mission will consist of 3 main transportation stages;

- Earth's surface to the LEO based tether, eMMET
- The eMMET to the Moon based tether, lMMET
- The lMMET to the lunar surface

Various transportation methods used for these stages will be compared along with a comparison of the system as a whole to conventional rocketry.

In this report a comprehensive literature review is presented which outlines the nature of possible MET configurations that could be used for this mission. It then proceeds to discuss the possible methods of transferring the payload from the Earth to the eMMET and from the lMMET to the lunar surface.

The future structure of the project and work thus far are then discussed, outlining key design stages and the final aims.

3 Literature Review

3.1 Fundamental Principles of Momentum Exchange Tethers

There is a large variety of momentum exchange tethers that can be considered to raise or lower the orbit of an orbiting body. These are symmetric or asymmetric tethers of which would be either hanging, swinging or spinning as discussed by Ziegler and Cartmell [2]. An asymmetric tether would typically consist of one tether connecting two non-equal masses. This means that the centre of mass (CoM) of the system would be bias towards the larger mass. These masses, for our purposes, would be the main body of the tether system (the larger mass) and the payload (the smaller mass). This means that when the payload is released that the CoM changes location. This dynamical change of the system can impact the orbital parameters. A symmetrical tether for the purposes of this mission would be one consisting of two tether lengths connecting three masses. The set up would be a central mass, which would be the main body of the system, with two smaller and equal masses connected at each side by tethers of equal length.

A symmetrical tether orbiting the Earth will naturally ‘hang’, aligned along the Earth’s gravity gradient. This is known as Gravity Gradient Stabilisation (GGS) [1]. The CoM of the tether is orbiting the Earth at a specific angular velocity, as the two payload masses are connected they orbit with the same angular velocity. However, their tangential velocities are different, the upper payload has a higher tangential velocity which is greater than the velocity required for its orbit, and the lower payload has a velocity which is lower and insufficient for its current orbit. This means that the two payloads are effectively pulling on the CoM. If the payloads were to be released, then the upper payload would move into a raised elliptical orbit with the release point being the perigee, and the lower payload would move into a lower orbit with the release point being the apogee. If the payloads are released at the same time, then the CoM will remain on its orbit as the change in forces maintain the equilibrium. However, due to the change in mass of the system there may be long term orbital effects on the CoM due to perturbations which would need to be corrected [2].

A symmetrical hanging tether as discussed above can raise and lower the orbits of its payloads due to the difference in tangential velocity. This velocity difference can be increased by adding angular velocity to the tether about its CoM. This can be done by either swinging or spinning the tether using a motor located at the CoM. The payloads in this case should still be released simultaneously and when the tether is aligned along the gravity gradient. The greatest amount of velocity change would be achieved when the tether is spinning in prograde and in its orbital plane about the Earth. If the angular velocity of the tether is sufficient the tangential velocity of the payload will be at escape velocity which would allow interplanetary transfers.

The fundamental principle behind such a tether system is combining the orbital energy of the system with additional rotational energy which results in a tangential velocity at the tips that is great enough to propel the payload to the moon.

The tether used for this mission will be a symmetrical MMET. The motor will be located at the CoM and will accelerate the tether to a specific angular velocity. The torque applied will need to be great enough to overcome the gravitational forces acting on it. A key component of the MMET is a counter rotating inertial stator that will allow the system to spin. This will consist of structures shorter than the tethers with large masses at the ends. This can be seen in *Figure 1* [2].

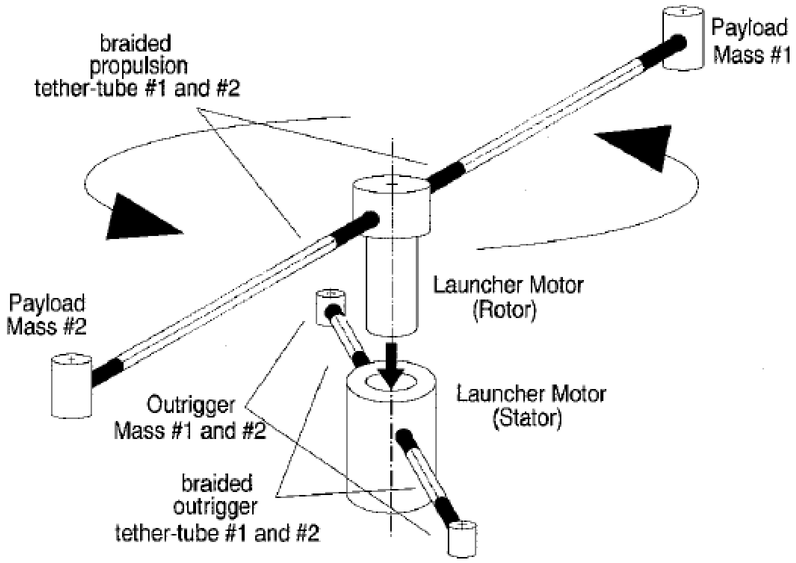

Figure 1: Conceptual MMET as suggested by Cartmell and Ziegler [2]

The tether lengths must be equal to ensure that the symmetry and hence equilibrium of the system is conserved. If the two tether lines were released by separate mechanical components, i.e. two separate reeling spools controlled by an electrical control system then there is potential for an error to occur. It would therefore be preferred that there was an additional mechanical system interlinking the two tether lengths to ensure that, even in the case of a technical error, the tether lengths are always equal. This could be implemented by releasing the tether lengths from reels powered by one central shaft connected via a gearing system.

The strength of the tether is of critical importance as the system is desired to be reusable and be able to operate continuously. Not only is the tensile strength of the tether important but also its durability. For the Earth-Moon tether system to be cost effective it will have to operate without crewed maintenance for a reasonable time period. This means that the tether will have to withstand orbital strikes from debris in the Earth's orbit. There are millions of pieces of debris within the Earth's orbit that range from large trackable objects to tiny particles such as flecks of paint. Due to the high velocities of these particle even a small fleck of paint has the ability to damage a spacecraft [3], meaning that it there is a high potential for damage to the tether lengths. While the tethers are very thin they are still extremely long which creates a large area for a strike to take place. The solution to this is to build in redundancies in the form of multiple strands within the tether. A tether such as this has been developed by Tethers

Unlimited™ called The Hoytether™ [4]. The tether consists of multiple lines in a tubular structure. There are two types of line within the structure; primary lines and secondary lines. The primary lines of the structure carry the tensile stress when the tether is first deployed and undamaged. However, if the tether is struck by a piece of debris which severs the primary lines then the secondary lines support the forces within the tether. This can be seen in *Figure 2* [4].

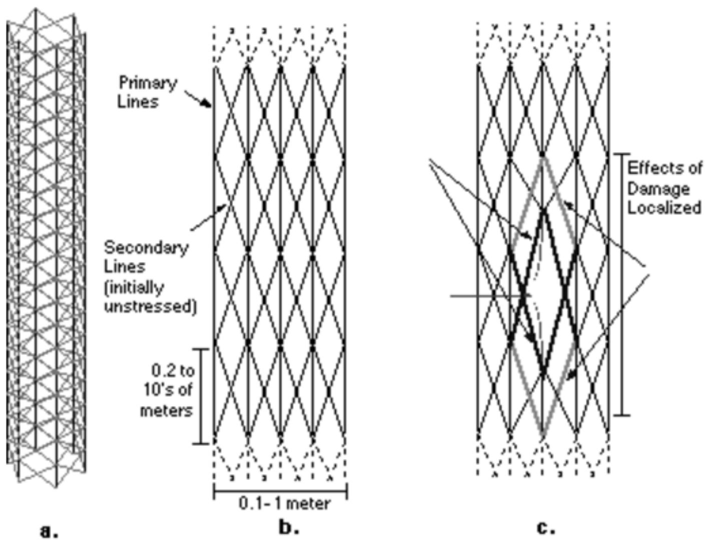

Figure 2: The Hoytether™ structure [4]

To design the MMET it is necessary to calculate the torque that would be required to accelerate it to a specific angular velocity, in addition to the stress this would exhibit on the tether lengths. This was carried out by Ziegler and Cartmell for a model constrained by the following assumptions [2]:

- The Earth and Moon's gravitational fields are spherical
- The environmental perturbations are negligible
- The tethers motion is coplanar with its orbital plane (This allows a 2D analysis to be conducted)
- The tethers act as rigid structures (This means that the payload ends of the tether must have initial thrust to avoid the motor reeling them in or be released slowly as the MMET begins spinning)
- The cross sectional area of the tether is constant
- The payloads are released when the tether is aligned along the gravity gradient

- The payloads will go into an elliptical orbit with the release point being the pericenter of the upper payload and the apocenter of the lower payload

These assumptions may not describe fully the motion of the tether in three dimensions but allow the conception of an initial design. Equation 1 is the equation of motion of the tether and can be numerically integrated to obtain the motor torque required to achieve a specific angular velocity, $\dot{\psi}$, for the chosen tether parameters.

$$\left\{\frac{M_M r_M^2}{2} + M_P(2L^2 + r_P^2) + \frac{\rho AL\left[4L^2+3\left(r_{To}^2+r_{Ti}^2\right)\right]}{6}\right\}\ddot{\psi} + \frac{\mu M_P r_c L\sin\psi}{\left(r_c^2+L^2-2r_c L\cos\psi\right)^{\frac{3}{2}}} - \frac{\mu M_P r_c L\sin\psi}{\left(r_c^2+L^2+2r_c L\cos\psi\right)^{\frac{3}{2}}} -$$

$$\mu\rho A\tan\left(\frac{\psi}{2}\right)\frac{r_c+L^2-r_c L(1-\cos\psi)+(L-r_c)\sqrt{r_c^2+L^2+2r_c L\cos\psi}}{r_c+L^2+2r_c L\cos\psi+(L+r_c\cos\psi)\sqrt{r_c^2+L^2+2r_c L\cos\psi}} +$$

$$\mu\rho A\cot\left(\frac{\psi}{2}\right)\frac{r_c+L^2-r_c L(1+\cos\psi)+(L-r_c)\sqrt{r_c^2+L^2-2r_c L\cos\psi}}{r_c+L^2-2r_c L\cos\psi+(L-r_c\cos\psi)\sqrt{r_c^2+L^2-2r_c L\cos\psi}} = \tau \qquad (1)$$

An expression relating the tensile stress in the tether and its angular velocity is also derived and allows the maximum possible angular velocity to be calculated.

$$\dot{\psi} = \sqrt{\frac{\sigma A}{L\left(M_P+\frac{\rho AL}{2}\right)}} \qquad (2)$$

To reduce the angular velocity and hence the stress on the tether lengths the use of staged tethers from LEO to a higher altitude orbit was proposed by Cartmell, McInnes and McKenzie [5]. This however, added a layer of complexity to the management and timing of the operation which was undesirable.

The velocity of the payload required for it to switch to a lunar transfer orbit, upon release, will be calculated using the principle of Keplerian orbital mechanics and a Hohmann transfer.

Even assuming the tether system works correctly, and the payloads are released on their intended trajectories, there may still be a need for corrections and/or safety manoeuvres due to the complex and often unpredictable nature of space travel. A small delta v produced by conventional rocketry must be built into the payload to allow for this, however this would be negligible when compared to a typical fully rocket powered Earth to Moon Transfer.

3.2 Methods of freight delivery from surface of Earth to LEO

3.2.1 Conventional Rocketry

The lower atmosphere of Earth, consisting of troposphere and stratosphere, poses a great challenge for reaching space, especially using conventional rocketry. Through this layer; the launch vehicle has to overcome the greatest aerodynamic drag, gravitational pull from the Earth and initial mass of the vehicle itself, hence, it is the most fuel-intensive 20-40km of space travel. This has major environmental implications due to the large amount of fuel expended within the lower atmosphere. This fuel consumption leads to large mass allowances for fuel and subsequently higher costs per kg and a lower payload capacity. An alternative mode of space travel is proposed by High Altitude Balloon (HAB) technology, discussed in the next section.

3.2.2 HAB technology

HAB technology involves a payload mass being lifted, by a large scientific balloon, to a typical stratospheric altitude range of 18-37km before bursting. This method of transportation takes advantage of the lower atmospheric properties by using a lighter-than-air gas for the balloon, typically helium, to generate positive lift/buoyancy force. In the context of this project, however, the payload is required to reach a much higher altitude, above 160km, than the capabilities of a HAB (37km maximum), which restricts the use of HAB technology on its own. A solution to this limitation is the integration of HAB technology with conventional rocketry, in order to attain a greater altitude. This concept is known as ‘Rockoon’ (rocket-balloon).

3.2.3 Integration of High Altitude Balloon with Conventional Rocketry

The Rockoon concept was initially developed by Cmdr. Lee Lewis, Cmdr. G. Halvorson, S.F. Singer, and J. A. Van Allen dates back to 1949, at the time of Aerobee firing cruise of U.S.S. Norton Sound [6]. As of recent usage, the current development of NASA’s Low Density Supersonic Decelerator (LDSD) and Zero2Infinity’s Bloostar project provides useful insight into the future of balloon-assisted launch.

On June 28th 2014, NASA’s LDSD project conducted its’ first test flight of a balloon-assisted test vehicle launch. A 34 million cubic feet scientific balloon, [7] noted as the largest available, was filled with helium to hoist a 7000lb (around 3200kg) test vehicle to an altitude of 120000 feet (37km) above the surface of the Earth. The test vehicle was then released and the solid-rocket powered motors, on the test vehicle, were ignited to propel it to an altitude of 180000 feet (54.9km). The project manager of the LDSD, Mark Adler, noted, on a question-and-answer site called Quora [8], that the largest scientific balloon is actually capable of lifting 8000lb (roughly 3600kg) for a single ascent but attempting to increase the balloon size, for payload gain, would consequent in scaling issues. Adler [8] also mentioned that for a LEO, the payload capacity would be a maximum of around 200lb (90kg) out of the 8000lb budget.

Zero2Infinity, a Spanish-based company, has plans to take a payload (satellite in their case) to LEO using a multi-stage launch vehicle called Bloostar [9], as opposed to NASA's LDSDs' single-stage test vehicle.

Figure 3: Flight cycle of Bloostar [9]

As illustrated by *Figure 3*, the initial flight, similar to that of NASA's LDSD project, involves the Bloostar being hoisted to stratospheric altitude of around 20-40km, after which it disintegrates from the balloon and the vehicles' liquid-fuelled engines are fired. In comparison to LDSDs' 34 million cubic feet balloon, Bloostar uses a 3.2 million cubic feet balloon to lift a slightly greater payload mass of near 100kg.

As a result of the findings from LDSD [7] and Bloostar [9] projects, this section details an investigation into how a single ascent of a 100kg by a balloon-assisted launch scales against a single ascent of conventional rocketry for the same payload size, both to LEO.

The cost of crude helium to non-Government users, as per 2016 U.S. Geological Survey [10], is at $ 3.75 per cubic meter. It has to be noted that since the helium requires room to expand along the ascension, the volume of helium required at launch doesn't equal the volume of the balloon. Hence, the volume of helium required was found using Equation 3:

$$V = \frac{M}{\rho_a - \rho_h} \tag{3}$$

where, V = Volume of helium required; M = Total mass of uninflated balloon and payload; ρ_a= density of air; ρ_h= density of helium. Using known data for a similar balloon, 30 million cubic feet, used by Red Bull [11], a volume of 4767.2 m^3 is required and hence, this culminates in a cost of around $18,000 for helium alone, over the single ascent.

The cheapest payload delivery to LEO using conventional rocketry is around $ 5000 per kilogram (Falcon 9.0) [12]. Hence, sending a payload mass of 100kg would cost around $ 500,000.

Lastly and most importantly, for the initiation of the mission, the requirement of payload delivery to a specific point in LEO for the eMMET to capture. This is not a problem in conventional rocketry because of modern and sophisticated targeting technologies. A balloon, on the other hand, is very susceptible to winds which makes steering, to a desired region in space, an issue. Also, the initial trajectory of the rocket, launched from the balloon, is not easily adjustable. As wind speeds and direction change with different altitudes, Red Bull's Stratos Balloon [11] used the strategy of gaining or losing altitude to attain regions of favourable wind conditions as a means of steering. This is very weather reliant and hence, does not function as a technical solution to the problem. Bloostar [9], on the other hand, uses a balloon gondola which is capable of directing the launch vehicle to a desired azimuthal direction. This is a reliable solution for launch vehicle attitude control but does not influence the direction of the balloon itself.

3.3 Transfer of Payload: IMMET to Lunar Surface

3.3.1 Powered Descent

A large number of issues arise when travel beyond LEO is considered, in this case to the Moon. Obviously the infrastructure does not exist on the Moon to accommodate spaceplanes or any similar technology therefore the fuel requirements increase greatly and so too does the weight allowance for said fuel. Since a powered descent is currently required to touch down on the lunar surface, fuel demands mean profitability of any such private excursion to the Moon would be minimal. The current rate to transport 1kg of cargo privately from the surface of the Earth to the lunar surface is a minimum of $1.2 million with additional costs incurred depending on specific requirements for the payload such as communication, power and thermal control needs. These prices are quoted from Astrobotics, the leading competitor in the private sector, who works in partnership and as a sub-contractor of NASA. From a Payload User Guide produced by Astrobotics [13] the company has given data and a mission architecture for its first planned mission. In this it gives the dry mass of the lunar lander as 222kg with 35kg of this being the payload allowance. Also given is the wet mass of the lander i.e. the mass of the lander plus cargo and fuel which totals 700kg. Thus only 5% of the mass which leaves Earth actually consists of useful payload whilst over 68% consists of fuel required to transport it. Reducing the mass of fuel required for this mission would greatly reduce the cost per kilogram of payload and, in turn, increase the profitability of such enterprises. If profitability were to increase in such a manner, it could be postulated that a ‘domino effect’ would occur in that more privately held companies may be inclined to invest in the space industry. This could lead to accelerated advancements in this field along with space travel to the Moon becoming commonplace.

3.3.2 Lunar Tether

Whilst all currently practical methods of transporting cargo from a lunar orbit to the lunar surface are based on a powered descent there is promising work ongoing in the field of lunar based tethers. In 1978 Moravec [14] put forth the idea of a non-synchronous tether, or ‘Lunar Skyhook’ as he named it, which could provide a minimal propellant transfer of payload from lunar orbit to the lunar surface. He proposed a large central facility with two tether arms both having length equal to the orbit distance of the aforementioned facility. It was to rotate in prograde with its orbit direction with the velocity at the tip of each tether equal to the orbital velocity of the central facility thereby allowing the velocity relative to the surface of the Moon to be zero at the point where the tether tip ‘grazes’ the lunar surface. The best way to visualise this is to imagine the tether as the spokes of a bicycle wheel rolling around the surface of the Moon. Moravec also concluded that if the arms had equal length then an arm length of 1/6 the Moon’s diameter would allow the mass of the tether system to be minimised. This would allow each of the arms to contact the surface at a rate of 3 per orbit which could, in theory, allow 6 payload transfers, at different locations, per orbit. An illustration of this process can be seen in *Figure 4*:

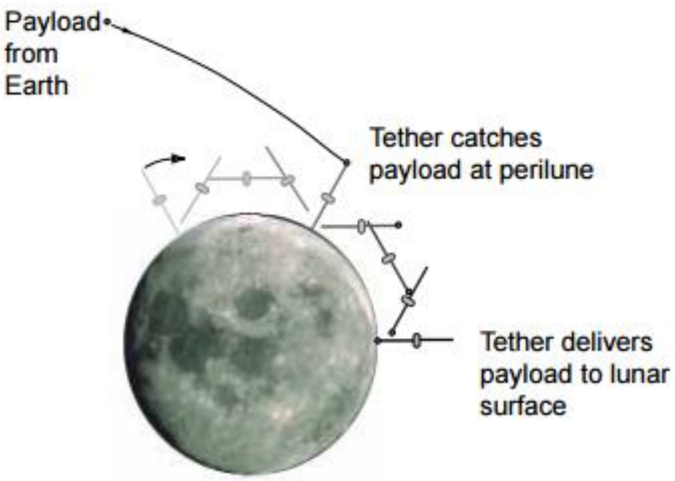

Figure 4 - Illustration of Moravec's Lunar Tether [15]

In reality a tether which literally touched the lunar surface would be likely very impractical due to the uneven nature of the Moon’s surface. Additionally, this would not allow a very large margin for error, which, given the scale of the tether system and the accuracy of timing required could result in operational failure of the tether. In reality the tether would possibly extend to a distance of perhaps 50-100m from the surface and then release the payload which could either be caught by an appropriate system such as a safety net, or the payload could even be equipped with a small rocket booster and orientation system to lower itself to the surface.

This release of a payload, if not symmetrical, would produce instability in the orbit of the tether system which, while it is correctable, is not an entirely desirable impact on such as system. Therefore, it would be preferable if each arm of the tether was loaded and unloaded simultaneously. As an example, when the payload is released to the lunar surface a payload of equal mass would be released on an Earth Transfer Trajectory and be caught at the eMMET. These catch and release operations would continue in tandem and, ideally, indefinitely as long as required.

Another Lunavator design was put forth by Hoyt [15] who theorised a single arm tether capable of accelerating payload. This idea addressed a key issue with Moravecs 'Skyhook' tether in that it could not be accelerated or decelerated meaning the payload was required to match the velocity of the tether system which would require a substantial burn of rocket fuel to achieve. Hoyt proposed to make the tether do the work, so to speak, using only electricity generated from solar energy. The tether system was composed of one single long tether with a counter balance mass (CBM) at one end with a central facility located between the CBM and the tether tip which was capable of 'climbing' the tether in either direction. Initially the facility would be located close to the centre of the tether, hence the centre of mass would be located between it and the CBM around which the system would rotate until the payload was captured at perilune. At this point the facility would utilise captured solar energy, or an alternative power source, to move 'up' the tether towards the CBM allowing the centre of mass to remain at the same altitude and thereby prevent any destabilisation of the system's orbit. Additionally, since the distance from the payload to the centre of mass increases and the facility mass moves closer to the CBM then by the conservation of angular momentum the angular velocity of the payload will increase to match the required speed for zero relative velocity with the lunar surface [15]. This process is outlined below in *Figure 5:*

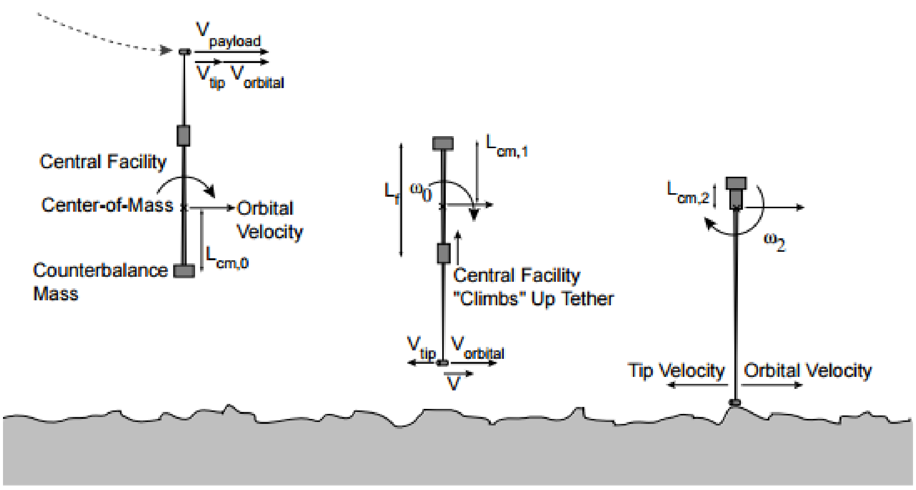

Figure 5 - Hoyt's Lunavator tether process [15]

It would be hoped that a Lunavator paired with an LEO based tether could essentially create an interplanetary ‘highway’ of sorts allowing the constant transportation of freight from the Earth to the Moon allowing the Moon to serve as an outpost and staging point for excursions further afield, for example, to Mars and beyond.

3.3.3 Comparison of Methods

It is difficult to practically compare a standard powered descent with any Lunavator method since the latter only exists in theory. It is however possible to carry out a theoretical comparison based on sensible assumptions and preliminary available data. Firstly, and most importantly, the potential economic costs of each method must be considered since profitability ultimately drives the future of any industry. The main difference between the methods is that a powered descent will require a much larger delta v in order to successfully land on the lunar surface and will obviously require a larger amount of propellant. The actual costs for the propellant are minimal compared to overall project costs however in conventional rocketry the propellant can account for 70-80% of the overall wet mass meaning space and energy is being expended to launch propellant for use throughout the descent. If the Lunavator was used for descent some propellant would still be required for course corrections and possibly emergency manoeuvres, however, the delta v would be very small by comparison. Of course there would be large capital costs to set up and develop the Lunavator system, for which conventional rocketry would be required. However, this initial outlay would be the main component of the overall costs and therefore it would be expected that for frequent, high volume traffic between the Earth and the Moon this method would lead to large transport cost reductions since the Lunavator process would be continuous and non-propellant intensive. It could transport much larger quantities of smaller payloads as opposed to the larger more infrequent payloads which would be transported by conventional rocketry. In this way more mass could be transported for a lower cost since operational costs would be minimal by eliminating the requirements to send large quantities of propellant along with payloads.

It could be argued that the technology required to successfully implement a Lunavator system does not yet exist, specifically with regards to the material science required to create a tether system on this scale, whilst the technology for conventional rocketry already exists. It would possibly be more useful, with regards to the near future, to focus entirely on advancing current rocket technology, however, advancements are slow in these areas and focus mainly on ionic propulsion technology. In the long run it is pertinent that we utilise our closest cosmic neighbour as an outpost, and indeed, a means of practice for more ambitious endeavours. To achieve this a Lunavator, as part of a tether system set up between the Earth and the Moon is the most efficient means of transporting freight due to its minimal reliance on propellant and its bi-directional nature. Moreover, the fact that most of the costs are capital set up costs mean the operations would not be dependent on economic factors such as budgetary constraints, as in the case of NASA. Once the system was set up it would be neither profitable nor practical to shut down fully.

As a final point, the Lunavator method would be favourable both environmentally and politically since it would reduce the use of fossil fuels and reduce wastage of non-reusable parts such as rocket engine boosters. Of course this method would not entirely replace conventional rocketry since any further excursions would requires rocketry to set up an appropriate system so advancing technology in both fields would be equally pertinent.

4 Project Plan

The project will use the findings from the literature review to select the means of transportation for each stage. This will involve mathematical analysis of the dynamics of the tether, resulting in values of its angular velocity which would be required for the payload trajectory. The results of the analysis will be used in conjunction with materials, both available and in development, to design the tethers and the infrastructure that will need to be in place to support their function. A costing analysis will be run in conjunction with the mission construction to ascertain the economic requirements it would entail. The project structure can be broken down into the following parts:

- Earth to eMMET transfer method (Cost and resources)
- lMMET to lunar surface transfer method (Cost and resources)
- Mathematical analysis of payload trajectory along with initial capture and release timings

- Optimal launch/landing sites and launch windows
- Construction of MMETs to specifications that allow calculated results to be obtained. This will include, among others, the power of the motor, solar panels needed to power it and strength of the tether its self.
- Theoretical frequency of payload transfers required to ensure economic feasibility
- Summation of costs and comparison with conventional rocket technology
- Possible safety concerns; orbital collisions and structure failure
- Mechanisms required in the event of failure to capture or launch payload i.e. small delta v propellant stored on payload
- Assessment of how the catch and release system design will impact on payload mass

Finally, the mission architecture will be assessed to determine how sustainable the concept would be and when it would be realistically possible to implement such a system.

5 Conclusion

A comprehensive and applicable knowledge, in line with the aims of the project, was achieved through a literature review. This will be crucial moving forward as it will influence any decisions made with regard to the selection of transportation methods, along with the overall design and modelling of the tether mission architecture. A preliminary mission overview for the remainder of the project duration was presented in the form of a project plan. This plan outlines how the theoretical knowledge of tether systems, in conjunction with existing space exploration technology, would be utilised to construct a realistic Earth-Moon transportation system. This will lead to the assessment of the sustainability of the system and how recently it could be potentially implemented.

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