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Analysis and optimization of a network of orbital stations for momentum exchange transfers

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Abstract

A network of momentum-exchange space stations in Earth orbit can drastically reduce the consumption of propellant by other space systems. This work models and studies the orbital dynamics of a network of stations which can perform capture and release payload operations up to a limit relative velocity, thereby imparting a ΔV that allows them to reach the next station propellantlessly. As long as the mass of the stations is comparably larger than that of the payloads, the ascending transport operations are supported by the orbital energy and momentum of the stations. The network can restore its momentum by descending payloads (e.g. at the end of their usable life), thus behaving as an accumulator for orbital energy. A model incorporating the payload transfer operations, an iterative orbital propagator and a targeting scheme is capable of reproducing the functioning of the network, thus obtaining useful data on the degradation inflicted to the stations among other operational information. A network design procedure is proposed based on the maximum allowable relative velocity between payloads and stations. With applicable safety factors and design margins, the scheme can produce networks that improve the distribution of the degradation imposed on each station of the network upon mission execution, spreading the induced perturbations more evenly. Lastly, a scheme to optimize the capture/release schedule is established to minimize the perturbation to the orbital parameters of the stations for a given mission profile. Results measure the performance of a network under two example mission profiles. For the proposed case study, the optimizer algorithm successfully finds the appropriate timing of operations in order to fulfill the relative velocity constraint and attain an 8% improvement in the selected cost function.

Keywords: Space transportation, Momentum exchange, Mission analysis, Optimization

1. Introduction

The exploitation of Moon and near-Earth asteroid resources in the near future requires an efficient space transportation system, capable of raising and lowering payloads in near-Earth orbit on a regular schedule. Likewise, space missions to higher orbits can be performed by raising payloads in lower orbits, and the elimination of space debris is typically needs some form of modification of their orbit at end of life. To raise (lower) an object's orbit, its mechanical energy must be increased (decresed). The current technology used for these tasks are rockets that consume propellant to create thrust essentially parallel (antiparallel) to the velocity vector of the object, thereby boosting (dissipating) its orbital energy. Propellant accounts for an important fraction of the mass of a spacecraft and consequently the cost of the mission, and its depletion sets a duration limit to the mission.

Orbital energy storage and exchange systems, able to trade energy and momentum with ascending/descending payloads, can make this process more efficient in the presence of regular traffic, as the energy of downward-faring spacecraft can be used to economically increase that of upward-faring ones. Ideally, if traffic were perfectly balanced, no propellant would be needed, save for small station keeping and trajectory correction maneuvers. Moreover, part of the necessary station orbital corrections could be mitigated (or altogether avoided) by optimizing the payload traffic schedule, so that stations do not accumulate secular perturbations to the extent possible. Low Earth orbit (LEO) and Geostationary Earth orbit (GEO) satellites would benefit from this scheme, which would enable cheap orbit raising and the "recycling" of their orbital energy at their end of life, limiting the generation of additional orbital debris. As the applications for space technology and satellites keep growing the need for efficient orbit changing operations will increase. Additionally, a well-maintained network of stations could also serve other uses, acting e.g. as storage outposts for cargo and propellant for beyond-Earth missions, as safe havens for manned missions, as scientific/Earth Observation/telecommunications satellites, and as payload refueling/repair stations.

The concept of orbital energy/momentum exchange between two objects in space has been studied over the last decades, mainly around different specific technologies, which would enable a propellantless space transportation system. Most notable among these are (spinning) space tethers. Some of the first examples of this idea were proposed by H. Moravec in 1977 [1], whereby a long rotating tether (skyhook) attached to a ballast mass in a circular equatorial orbit could be used to "catch" payloads with the other end and transport them to a different orbit. The working principle is based on momentum conservation, meaning that the momentum provided or taken by the tether and the payload would need to be balanced out. Later work by J.A. Carroll [2] elaborated on further applications for space tethers, including maneuvers such as tether-mediated rendezvous, lunar orbiting tether facilities and tether-based aerobraking ideas. Other applications propose systems of two tethers specifically meant for Earth-Moon transportation [3, 4] and a two-stage tether system to raise payloads from low Earth orbit to Geostationary orbits [5]. Major concerns with these proposals are the dynamics of the flexible tethers, and the means for their spin-up/spin-down to match the required tip velocities. Lastly, in a different category falls the noteworthy concept of electrodynamic tethers, which can interact with the background plasma and magnetic field to generate forces, see e.g. [6] and references therein, for example to cause the active deorbiting of space debris [7].

The present work explores the orbital dynamics, design, and optimization of a network of momentum-exchange stations to handle a known traffic of payloads. The focus is placed on the system-level analysis of performance, rather than on the details of the physical implementation of the stations, and indeed we remain agnostic as to the specific technology used, which could be space tethers, spinning-wheel structures, electromagnetic accelerators, or a yet-unidentified scheme. Similarly, we do not discuss the possible capture-release mechanisms and the involved technical complexities. As such, the formulation and conclusions of this work are meant to be general and applicable regardless of the technologies used in the stations. The only technology-related characteristic relevant to our study is the maximum relative velocity that payloads rendevousing with or departing from a station may have with respect to its center of mass; this aspect is related to the limits of the available guidance, navigation and control systems, the attachment/release mechanisms used, and, in the case of rotating tethers/structures, their angular velocity. Also, it is noted that as a payload attaches from a station, the relative mechanical energy must be stored in another form, e.g. in the rotational energy of the payload-station assembly or in electrical energy (batteries), or dissipated as heat. Conversely, an energy input is needed to eject the payload with the required relative mechanical energy upon detachment.

The problem to be solved is threefold. First, tackling the coupled mission planning of multiple simultaneous payloads. This is related with the targeting problem of a payload, which must take into account any momentum exchange of other payloads with the target station (and its recoil) during its flight. Second, defining the mass properties and spatial structure of such network of stations so that it features a minimum number of stations, lower transit times, optimal availability, and maximal robustness. Third, optimizing the plan or schedule for a given set of upfaring and downfaring payloads, compensating their effect on the stations so as to minimize the net induced perturbation on the orbital parameters of the network.

To answer these points, a model to design payload transfers between stations and to analyze the operation and performance of the network in terms of the deviation from its nominal elements is presented. The analysis is based on the momentum conservation law that applies to each interaction between payload and station, modeled as point particles.

The rest of the paper is structured as follows. Section 2 introduces the model and its assumptions with a brief overview of the implemented algorithms. Section 3 describes a network design procedure that can be used to ensure a balanced Δv distribution for the transfers among stations and proposes an example that illustrates the operation the network. Finally, section 4 presents the mission profile optimization using a genetic algorithm. Conclusions are gathered in section 5.

2. Network model

We consider a network of N_s identical orbital stations s characterized by their masses m_s and their initial orbital elements. In the cases analyzed in this work, all networks begin in circular coplanar orbits of different radii, and they are labeled 1 through N_s from lower to higher altitude. We are interested in raising some payloads and lowering others, for a total of N_p payloads. To take advantage of the network, payloads p of known masses m_p are meant to arrive at station 1 or station N, where the first capture event takes place. From there, they are transferred propellantlessly to the other end of the network, following a series of ejection and capture events at the intermediate stations. After ejection from the last station in their journey, the payloads are assumed to reach their final destination using their onboard propulsion system as needed. We will refer to each individual payload jump between stations as an atomic operation, and to the set of all operations of all payloads as the mission profile of the network. The mission profile is characterized by the initial and final payload orbits connecting them to the network, and the set of payload times of flight t_f and their waiting times at the stations t_w.

The reason why intermediate stations are necessary is the constraint on the maximum relative speed v' that a payload may have with respect to a station center of mass upon arriving or departing from it, where

$$\boldsymbol{v}' = \boldsymbol{v}_p - \boldsymbol{v}_s. \tag{1}$$

The relative speed limits depend on the specific implementation of the capture/release mechanisms at the station, and for simplicity in this work they are assumed equal for all stations and labeled $v'_{\max}$, so the constraint reads $v'_p < v'_{\max}$ at every ejection/capture event.

The model assumes an impulsive interaction between payloads and stations. In a capture event, momentum conservation prescribes that

$$(m_s + m_p)\boldsymbol{v}_{s+p}(t^+) = m_s\boldsymbol{v}_s(t^-) + m_p\boldsymbol{v}_p(t^-), \tag{2}$$

where t^+ and t^- indicate the instants right after and right before the event, and $\boldsymbol{v}_{s+p}$ is the velocity of the temporary station-payload assembly. The velocity vector change experienced by the payload is

$$\Delta\boldsymbol{v}_p = \boldsymbol{v}_{s+p}(t^+) - \boldsymbol{v}_p(t^-) = -\frac{m_s}{m_s + m_p}\boldsymbol{v}'(t^-), \tag{3}$$

and the recoil of the station is

$$\Delta\boldsymbol{v}_s = \boldsymbol{v}_{s+p}(t^+) - \boldsymbol{v}_s(t^-) = -\frac{m_p}{m_s}\Delta\boldsymbol{v}_p. \tag{4}$$

In the limit $m_p/m_s \ll 1$, the station recoil becomes negligible and $\Delta\boldsymbol{v}_p \simeq -\boldsymbol{v}'_p(t^-)$. However, this approximation is no longer valid for $m_p/m_s \sim 1$, and to preserve generality, the model does not assume small payload masses. Analogous relations exist for a ejection event, mutatis mutandi.

The ballistic motion of each object i (payload, station, or assembly) within our model follows the equation of motion of the two-body problem, given by

$$\frac{\mathrm{d}^2\boldsymbol{r}_i}{\mathrm{d}t^2} = -\frac{\mu}{r_i^3}\boldsymbol{r}_i, \tag{5}$$

with μ the orbital parameter of the attracting body ($\mu = 3.986 \cdot 10^5$ km^3/s^2 for Earth). For cleanness of analysis, perturbations are not included in this work, although their effect must be taken into account to explore the long-term evolution of the network.

The simulation of a given mission profile requires routines for the propagation of coasting trajectories and the targeting of the payloads. The propagation of all the objects within the network is performed with a simple Cowell orbital propagator, in which the dynamics (5) are implemented and solved for $\boldsymbol{r}_i$ and $\boldsymbol{v}_i$ numerically. The payload targeting in the ideal two-body problem reduces to Lambert's problem between the initial position at ejection time and the position of the station at capture time. The algorithm used to solve this problem is based on [8], which exploits a global variable formulation of the problem to reduce it to the root finding of a nonlinear function in a fast and robust manner.

When the flight of two or more payloads departing/arriving at a given station overlaps in time, coupling of their trajectory computations will occur due to station recoil, and the targeting scheme must take this effect into account. Coupling happens when the information required to perform an operation depends on other operations that take place at the same time. For example, if payload p_1 departs to station s_1, and payload p_2 is ejected by s_1 an instant later, s_1 will drift from its original orbit, and the targeting of p_1 needs to be amended. Situations far more complicated can arise as the number of flying payloads and operations increases. To circumvent this issue we introduce an iterative procedure:

1. The solver first runs a dummy iteration in which coupling is ignored. The end-of-flight positions of each payload transfer will not match the arrival stations due to recoils.
2. Then, the targeting process is iterated, using the position of the stations at arrival time from the last run as the target position for all operations.
3. The process is repeated until the position errors at arrival are smaller than a chosen tolerance.

For most of the cases studied in this paper, the solver was able to converge in 2 to 5 iterations to machine precision.

The main output of the simulation is the complete log of positions and velocities for all the objects (payloads and stations). From these results, first, it is possible to first check the relative velocity constraints are satisfied for the given mission profile.

Second, the simulation data allow computing the degradation of the network after the mission completion, defined in terms of the alteration of the stations orbital parameters with respect to their nominal values. In the present work, we use the evolution of the semimajor axis a_s and the eccentricity e_s of each station orbit to define a metric Q of this degradation:

$$Q = \Sigma_a + w\Sigma_e, \tag{6}$$

where

$$\Sigma_a(t) = \sum_{s=1}^{N_s} \frac{|a_s(t) - a_s(0)|}{a_s(0)}, \tag{7}$$

$$\Sigma_e(t) = \sum_{s=1}^{N_s} \frac{|e_s(t)a_s(t) - e_s(0)a_s(0)|}{a_s(0)}, \tag{8}$$

and w is a chosen weight to regulate the relative importance of orbital energy (through a_s) and orbit circularity (through e_s).

A good network design ensures that there is an ample range of flight times t_f and relative configurations among the stations in which transfers are possible without surpassing the maximum relative velocity v'_{max}. This problem is explored in section 3. By varying the used flight and waiting times t_f and t_w, the mission profile of a given set of upfaring and downfaring payloads can be optimized to cause a minimal perturbation of the network. This problem is explored in section 4.

3. Network design and mission analysis

To illustrate the main principles of operation, a first example is presented, where we transport a single payload in ascending way (from the lowest station of a network to the highest) and another in descending way (from the highest station to the lowest station). We set the following specifications:

- The lowest station of the network is in a circular equatorial orbit at $a = 10000$ km.
- The network has 5 stations.
- The payload to station mass ratio is $m_p/m_s = 1\%$
- The payload/station interface can handle a relative velocity of up to $v'_{\mathrm{max}} = 60$ m/s, for both attachment and detachment manoeuvres.

This last constraint is rather arbitrary, and in reality an accurate value of v'_{max} would require a detailed description of the specific attachment/detachment system used.

A naive procedure to design the network of stations would be to equispace the stations based on their orbital altitude. In practice, however, this would lead to uneven distribution of the station degradation and relative velocities of the payloads traveling between them. Therefore, the network of stations is defined using a simple analytical approach, based on balancing the v' of each capture/ejection event for ideal Hohmann transfers among the stations, which is proportional to the Δv. Starting from an initial radius a_1 for station 1, the radii of the other stations

a_i $(i = 2, \ldots, N_s)$ can be computed by requiring that the Δv of the departure event in a Hohmann arc from station $i-1$ to station i be

$$\Delta v \equiv \sqrt{\frac{2\mu}{a_{i-1}} - \frac{2\mu}{a_{i-1}+a_i}} - \sqrt{\frac{\mu}{a_{i-1}}} = \frac{m_s f}{m_s + m_p} v'_{\max},$$

where equation (3) has been used and $f < 1$ is a chosen safety factor.

To provide insight on this spacing method, if it is used to design a network from outer LEO ($a = 8300km$) to GEO altitude with $m_p/m_s = 0.01$ and $f = 0.5$, 66 stations in total are required.

In the case study we use a reduced network following the previously listed requirements. Table 1 shows the altitudes of the resulting network generated using this scheme and $f = 0.5$.

Station number	a_0 [km]
1	10 000km
2	10 190km
3	10 386km
4	10 588km
5	10 795km

Table 1: Initial semimajor axis a_0 of the case study network. All stations have coplanar circular equatorial orbits and $m_s = 10^4$ kg

In order to test the network in the proposed case study, a mission has to be defined. As a first approach we need a steadfast way of estimating the flight times t_f and waiting times t_w in an analytical way so that they can later serve as an initial guess for optimization.

With the condition that the relative phase angles $\Delta\theta_0$ between stations at ejection time and capture time have to enable near-Hohmann transfers (180 deg), these times can be computed. The necessary assumption to do this a priori is to neglect variation in stations orbital parameters during the mission. This is only done as a means to estimate this times for the initial condition and will inevitably result in arcs that are not perfect Hohmann transfers on the actual simulation of the mission. For the time of flight t_f and the waiting-time dependent initial relative station phase angle $\Delta\theta_0(t_w)$ for the payload raising from station i to station $i+1$ we have:

$$t_f = \pi\sqrt{\frac{(a_i + a_{i+1})^3}{8\mu}} \quad (9)$$

$$\Delta\theta_0(t_w) = \theta_{i+1}(t_f) - \theta_i(t_w) = \pi - \sqrt{\frac{\mu}{a_{i+1}^3}} t_f \quad (10)$$

Figure 1 depicts the mission profile, i.e. the time history of payload transfers among the stations (which are numbered from lowest to highest as in table 1). The evolution of the performance functions Σ_a and Σ_e of the network with each consecutive event is depicted in figure 2. The accumulated perturbations in the semimajor axes of the stations at the end of the mission are small in this example, although this is so thanks to the balancing of the upgoing and downgoing payload mass: indeed, the perturbation accumulated in Σ_a increases in the first half of the mission, before the two payloads cross. At this point in time, station 3 has a semimajor axis of $a_3 = 10388.35km$. Then, the value of Σ_a decreases in the second half of the mission, as the subsequent payload transfers tend to correct the perturbation induced by the previous ones. This balancing effect is a consequence of the approximate conservation of mechanical energy that exists in the problem, and illustrates the capability of a network of stations to "store" it, spending it to raise payloads and restoring it upon payload deorbiting. Observe however that mechanical energy is not exactly conserved as each interaction event is inelastic, and involves either the supression or addition of mechanical energy into the system into/from another forms of energy.

The error in eccentricity Σ_e, however, does not compensate with the up- and down-going payloads. The accumulated eccentricity of each station depends on the anomaly at which the impulsive events take place. Notwithstanding this, and as further elaborated in section 4, it is possible to configure the optimizer in order to decrease the overall Σ_a and Σ_e for a given set of up- and down-going payloads.

Lastly, table 2 shows the relative velocities of each impulsive event, where payload 1 is the ascending one and payload 2 the descending one. This table reflects the main shortcoming of the analytical estimation of the mission profile. Some events are far exceeding the limit relative velocity.

There are several reasons why the relative velocity is affected:

- The variation of the semimajor axis of the stations during the mission (as a consequence of payload operations) is introducing small errors in the computation of the time of flight in equa-

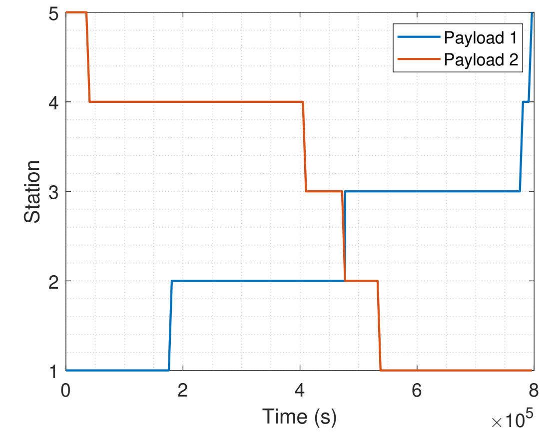

Figure 1: Payload launch sequence for the case study mission

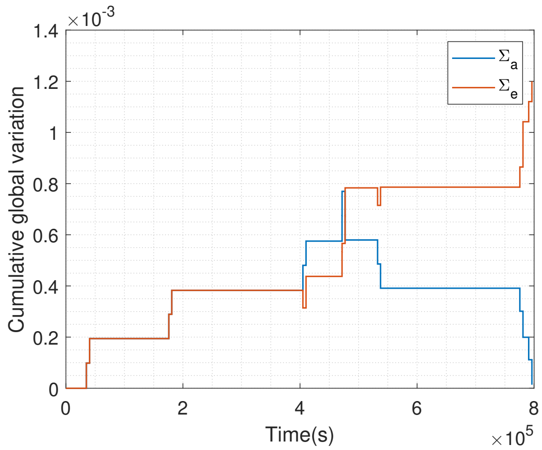

Figure 2: Cumulative global variation parameters Σ_a and Σ_e for the case study mission

$\boldsymbol{v'}$ [km/s]	Operation	Payload 1	Payload 2
Station 1	Capture	-	0.0302
	Ejection	0.0300	-
Station 2	Capture	0.0296	0.0591
	Ejection	0.0594	0.0297
Station 3	Capture	0.0538	0.0576
	Ejection	0.1043	0.0558
Station 4	Capture	0.0976	0.0297
	Ejection	0.0577	0.0549
Station 5	Capture	0.0571	-
	Ejection	-	0.0299

Table 2: Relative velocity report of the case study mission operations.

tion 9.

- The small error in the semimajor axis also affects the angular rate of the station, which accumulates over the many revolutions necessary to achieve the desired 180º arc.
- The change in the station eccentricity increases the relative velocity by making transfers non parallel. Regardless of the energy gap between the stations, this eccentricity perturbation produces relative velocities that scale with the product of orbital velocity and the tangent of the launch angle. At these altitudes, orbital velocities are above 6 km/s, requiring only a 1º misalignment to produce on their own over 100 m/s relative velocities.

Out of these three sources, the first one is minimal. The third source is hard to control and limits the weight that can be carried by the payloads being exchanged. The second one can be solved by proper timing of the launches, which will be our objective in the mission design.

4. Mission design and optimization

For a fixed network design and a set of payloads to raise/lower, it is possible to find the optimal operation timings to minimize the impact on the network configuration at the end of the mission. That is, the mission profile that inflicts the minimal degradation of the network, measured by the cost function Q from equation (6) with $w = 1$. Other cost functions were tested, reaching similar optimized results.

In practice, a large number of payloads and stations is expected, and consequently a large list of time parameters t_f and t_w to optimize. These parameters are constrained to be non-negative and to add up to a maximum mission time T, while the resulting payload transfers must not exceed v'_{max}.

The boundaries for these optimization variables are defined differently for each one. Waiting time is only constrained to be non-negative, i.e. payloads can only be launched from a station i to the next one once they are already in station i. The optimization space allows for solutions where the order of launches for payload 1 and payload 2 differs from the original estimated case of the initial condition. The time of flight is constrained also by a maximum value to allow for small corrections from the estimated case but preventing the solver from finding multiple revolution cases. The maximum mission time T is set to be a multiple of the largest synodic period found in the original network, to ensure that at least two launch windows exist for every operation in the solution space. The relative velocity requirement is not prescribed as a hard constraint. Instead, the cost function is artificially augmented with the ratio $2v'_{\text{c}}/v'_{\text{max}}$ if the requirement is not fulfilled, where v'_{c} is the most critical relative velocity found in the individual that violates the constraint. This method helps the solver to converge to solutions where the constraint is fulfilled in a smoother manner.

Our choice of optimizer is a genetic algorithm, in which the vector of all event times constitutes our set of "genes", and generations of different vectors are allowed to compete, reproduce, and evolve according to their fitness, based on the cost function Q. Individual vectors that do not comply with the constraints are eliminated. Crossover among successful individual vectors in each generation and random mutations are used to explore the optimization space and search for the minimum. The approach is versatile and less prone to stalling than the other techniques that were tested, although it requires a higher number of evaluations of the cost function.

To illustrate the optimization process, we consider the example of last section with 5 stations and 2 payloads, where the network is designed to allow for comparable v' in all impulsive events. Taking those near-Hohmann timings as the initial guess for the optimization process, after 13 generations and 326 cost function calls, a mission profile solution is found. This solution is depicted in figures 3 and 4. As it can be observed, the mission profile remains close to the initial condition, despite the solver constraints allowing for full reconfiguration of the launches.

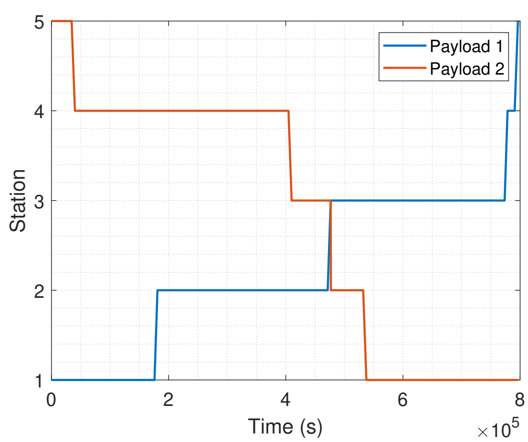

Figure 3: Payload launch sequence for the optimized mission

Table 3 reports the cost function of the initial guess (i.e. the case in the previous section) and the final, optimized case. We note that, with a weight of one, since the cost in semimajor axis is two orders of magnitude lower than the cost in eccentricity, the solver prioritizes optimization of the latter. In fact, the optimized case has a higher semimajor axis cost. This may not be desirable, in which case a different weight can be used. For the reasons disclosed in section 3,

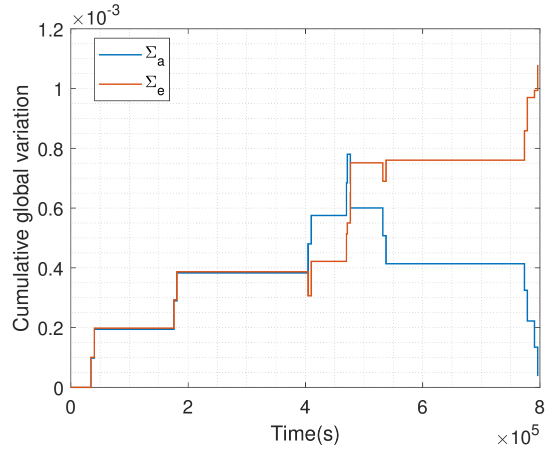

Figure 4: Cumulative global variation parameters Σ_a and Σ_e for the optimized mission

the cost in eccentricity is affecting the relative velocities to a higher extent. For this reason, and the fact that the semimajor axis cost is low enough not to be an issue, the current weighting of the cost function is deemed appropriate.

Case	$\Sigma_a \times 10^3$	$\Sigma_e \times 10^3$	$Q \times 10^3$ $(w = 1)$
Initial	0.0138	1.2001	1.2139
Optimized	0.0376	1.0789	1.1165

Table 3: Cost function breakdown for the case study

However, we do not see a dramatic reduction of the cost function (around an 8% for this case study). For this mission, the overall degradation is not that high to make the analytical estimator produce very costly missions as initial conditions. On the other hand, the optimizer is key to reduce the relative velocity enough to stay within bounds, as it is shown in table 4. Thus, the optimizer succeeds in generating valid missions if only by a small margin.

v' [km/s]	Operation	Payload 1	Payload 2
Station 1	Capture	-	0.0309
	Ejection	0.0300	-
Station 2	Capture	0.0296	0.0599
	Ejection	0.0506	0.0320
Station 3	Capture	0.0465	0.0505
	Ejection	0.0538	0.0423
Station 4	Capture	0.0415	0.0312
	Ejection	0.0577	0.0481
Station 5	Capture	0.0567	-
	Ejection	-	0.0331

Table 4: Relative velocity report of the mission operations for the optimized mission design

For higher payload masses, the optimizer will play a bigger role in reducing the cost function. However, the tight margins on the relative velocity make the design of the network for this missions more challenging. Improvements on the technological limit of $v'_{\max}$ allow for significant enhancements in the performance and applicability of the energy storage network.

5. Conclusions

A network of relay stations for propelantless payload transportation has been proposed and analyzed theoretically. The sustainability of this network relies on the two-way operation of the network, that allows energy equivalent transfer to take place minimizing the cost for the stations orbital energy while complying with maximum relative velocity requirements.

A model was introduced and used to study the degradation of the network with different payload transfer operations. To isolate this degradation from other perturbation sources, the model is developed under an ideal two body problem assumption. Thus, the only effect changing the stations orbit is the payload attachment/detachment. The network model integrates an algorithm capable to propagate, perform payload impulsive transfers, targeting using a Lambert algorithm and solve payload coupling in an iterative procedure.

A method for the design of the network was developed based on the maximum allowed relative velocity and ideal Hohmann transfers, so that the degradation is evenly split between the stations.

Finally, an optimization procedure for a mission profile involving several payloads was developed using a genetic algorithm, which proved effective on finding the patterns of operation times that best fit certain performance figures of merit. Most importantly, this allows the mission to fulfill the relative velocity constraint and attain a slight improvement in said figures of merit at the same time.

These findings prove that the usage of the network for self sustained operation is viable, with minimal maintenance if the balance between upfaring and downfaring payloads is kept. To this end, it is necessary to plan beforehand the launch sequence of the payloads to optimize the time scheduling using the genetic algorithm. Additionally, the network could be used for deorbiting of space debris, positively contributing to its own sustainability by increasing its orbital energy.

This work has not considered the physical realization of the stations and the interface mechanisms used for attachment/release of payloads, which is a major technical challenge. To further develop the project, these aspects need to be studied. The attachment/acceleration/release mechanism is of special relevance here since it determines the limit in relative velocity. Improvements in this area can reduce the number of stations required to cover an area of space and enable larger payload to station mass ratios. Other aspects includes the structural design, the station-keeping and the stability of the stations and payloads.

Additionally, different optimizations techniques can be employed and contrasted with the genetic algorithm approach. The latter can also be refined by doing an in depth study of the effect of different crossover and mutation functions. In particular, custom enhancements that ensure that multiple launch windows are explored could provide additional reduction of the cost function.

Future analysis that is not focused on the degradation caused by the operations solely can expand the network design considerations accounting for perturbations in the model. This introduces a more realistic approach to the simulations at the expense of a more noisy read of station degradation due to payload attachment/detachments. With the addition of the moon as a third body, the application of the network for Earth-Moon transport can also be studied. In this scenario more types orbits need to be introduced, that may also employ other cost functions to drive their performance. All of this future work requires the generalization of the targeting strategy with a shooting method that does not rely on an ideal two body problem scenario. The approach here might be introducing the targeting as part of the iteration in the payload coupling solver.

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