Multi-Objective Optimisation of NRHO-LLO Orbit Transfer via Surrogate-Assisted Evolutionary Algorithms

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Abstract

The near rectilinear halo orbit (NRHO) families around the Earth-Moon Lagrange 2 point offer favourable features for cislunar missions such as advantages in transfer and polar visibility. Multidisciplinary system design optimisation (MSDO) has been conducted for the NRHO to the low lunar orbit (LLO) transfer by means of evolutionary algorithm in the present study. The methodology consists of two steps; (1) perform multi-objective design optimisation (MDO) for transfer orbits simultaneously minimising total ΔV and time of flight by coupling an orbit propagator using a highly parallel GPU (graphics processing unit) into evolutionary algorithms; (2) perform MSDO considering the orbit, eclipse and visibility effects as well as subsystem mass using the surrogate models trained in the preceding MDO step. A Pareto optimal front indicative of a counteracting trend has resulted from the MSDO study. Presence of multiple families of feasible trajectories with different attributes has been suggested by post analysis.

Keywords: Lunar transfer, Evolutionary optimisation, Surrogate modelling

Introduction

Cislunar missions draw increasing attention for scientific exploration and in-situ resource utilisation of lunar environments. According to the global exploration roadmap [1], the current concept study focusses on a subset of the halo families specified as Near Rectilinear Halo Orbits (NRHOs) of the Earth-Moon system, in which the Gateway is to be positioned [2]. The present study is undertaken to develop and verify a new mission design approach utilised for a lunar surface observation mission starting from the Gateway in cislunar orbits.

Multidisciplinary system design optimisation (MSDO) is a design methodology that aims to identify a set of design solutions that perform optimally with respect to multiple objectives in various disciplines, while adhering to constraints imposed upon the system [3]. MSDO is achieved by incorporating design evaluation into optimisation algorithms and a state-of-the-art approach based on a surrogate-assisted evolutionary algorithms (SAEA) [4]. In traditional SAEA, surrogate models are built by relying on many results from high-fidelity analysis to enable accurate prediction of the system behaviour, entailing considerable computational time due to the number and cost of simulations inherently required in the population-based approach.

The new design approach presented in this paper is to conduct SAEA-based MSDO for the NRHO-LLO transfer problem and examine its efficacy and optimal design solutions. The methodology consists of two steps by performing; (1) MDO for transfer orbits to minimise total ΔV and time of flight simultaneously via evolutionary algorithms incorporating an orbit propagator using a highly parallel GPU (graphics processing unit) and build surrogate models; (2) MSDO considering the orbit and a subsystem (*e.g.*, eclipse for power balance, visibility for telecommunications) by using prediction from the surrogate models.

Problem Definition

Mission Scenario

In this study, a transfer mission from the Gateway located in the Earth-Moon L2 southern NRHO to a polar LLO is analysed. The L2 NRHO belongs to the halo orbit family of the Earth-Moon system around the Lagrange point 2. A typical NRHO has a perilune altitude of approximately 4,000 km, well inside the Moon's sphere of influence, while the apolune altitude is approximately 80,000 km and outside the sphere of influence.

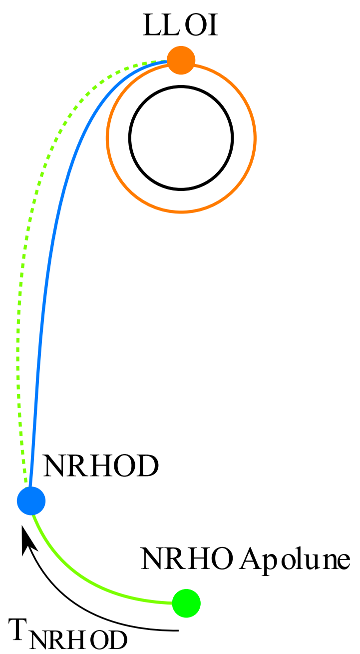


Fig. 1: NRHO−LLO transfer

The orbital transfer scenario is depicted in Fig. 1. The transfer from NRHO to LLO is characterised by two distinct manoeuvres, NRHO departure (NRHOD) and LLO insertion (LLOI), which are to be performed by chemical propulsion and thus assumed to be impulsive. LLOI is performed at the instant where the spacecraft reaches a specific Lunar altitude, while NRHOD is performed at a specific time duration after the spacecraft and Gateway have passed the apolune of the NRHO.

Upon LLOI, the spacecraft starts its observation mission by obtaining images of the lunar surface with an optical camera. A lower mission LLO altitude enables higher image resolution, whereas, a higher LLO altitude is associated with lower ΔV, thus resulting in a trade-off. The final LLO altitude must be determined by considering both orbital and optical subsystems, therefore a MSDO approach is employed to identify a set of Pareto-optimal design solutions.

MSDO System and Subsystem Modelling

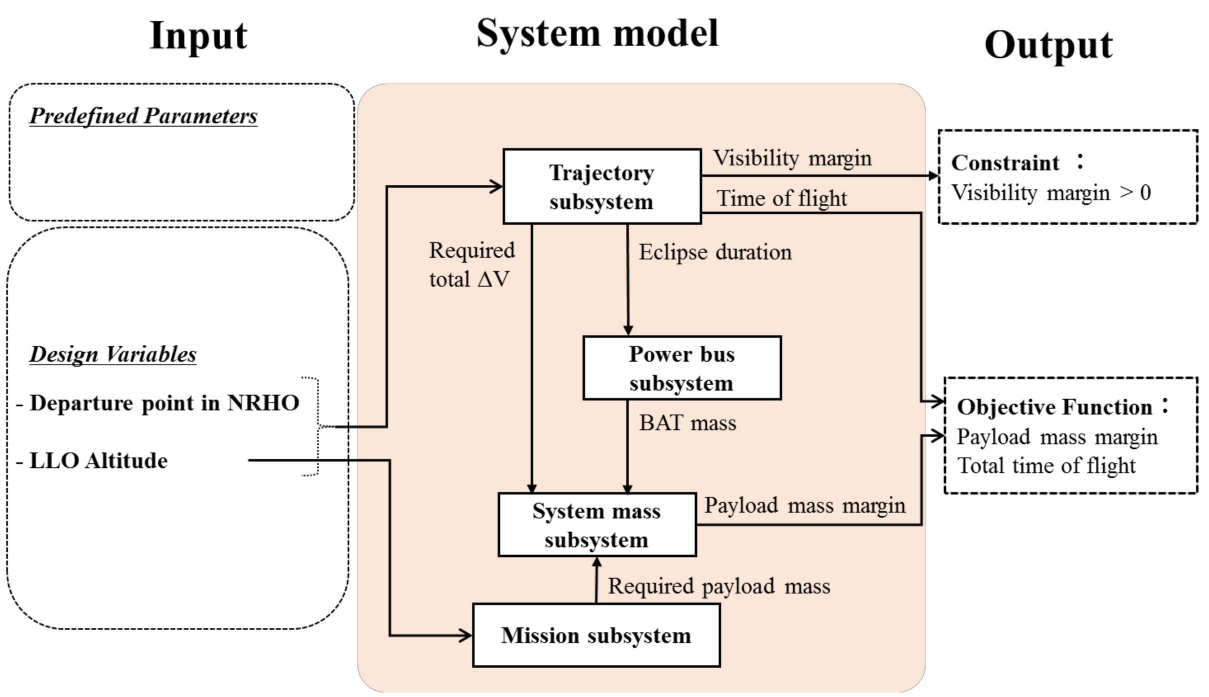


Fig. 2: MSDO system block diagram

The MSDO design problem is formulated for a system that consists of several subsystems. Each subsystem represents partial design problems (*e.g.*, the trajectory subsystem outputs key orbital states that are utilised by other subsystems as system output) and is therefore subject to interactions between subsystems. Fig. 2 depicts the block diagram of the system configuration for the spacecraft. Table 1 shows the definition of each subsystem and the input and output variables. Tables 2 and 3 define the system decision variables and the system output variables, *i.e.*, objectives and constraints, respectively.

Table 1: Definition of subsystems

Subsystem	Processing and modelling	Input	Output
Trajectory	Generate orbital transfer trajectory from NRHOD to LLOI by surrogate model trained by MDO. Visibility margin is calculated by comparing minimum distance from Moon's centre to link line at LLOI and Moon's radius. Eclipse duration is calculated based on orbital period of LLO and umbra area of the Moon.	NRHOD point LLO altitude	Required ΔV Time of flight Eclipse duration Visibility margin
Power bus	Calculate secondary battery mass according to eclipse duration and power density of the battery cell.	Eclipse duration	Battery mass
Mission	Calculate mission payload mass according to observation requirement. Mission mass is estimated with diameter of aperture. Diameter is calculated as below based on the following equation in Ref. [5]. $D = \lambda H / GSD$ where *GSD*: ground sample distance *H*: Altitude, *D*: Diameter, λ: Wavelength	LLO altitude	Payload mass
System mass	Calculate payload mass margin according to required mass of each subsystem. ΔV is translated into propulsion mass via specific impulse.	Required ΔV Battery mass Payload mass	Mass margin

Table 2: Definition of system decision variables

Parameter	Definition
ALT_{LLOI}	Altitude of LLO
T_{NRHOD}	Time of NRHOD past the apolune of NRHO

Table 3: Definition of system output variables

Parameter	Category	Definition
M_{margin}	Objective	Payload mass margin
TOF	Objective	Required total transfer time (time of flight)
VIS_{LLOI}	Inequality constraint	Visibility margin at LLOI point
distance	Inequality constraint	Propagation position gap at NRHOD (Internal constraint in trajectory subsystem)

Optimisation

MDO for transfer trajectories aiming to minimise total ΔV (ΔV_{total}) and *TOF* has been performed first so as to build surrogate model to be used for the trajectory subsystem in the MSDO. The decision variables for the MDO characterise the LLOI initial state and manoeuvre, as shown in Table 4. The LLO altitude and NRHOD point have been varied from 50 to 1000 km and -3.5 to 3.5 days, respectively, resulting in a total of 188 possible mission scenarios. An independent MDO has been performed for each scenario, yielding 1776 individuals over 35 generations, or until a feasible transfer trajectory has been generated. A distance constraint has been imposed, so that trajectories are deemed feasible if they approach within 50 km of the NRHOD point. The results are used to train surrogate models for the 4 decision variables and ΔV_{total}. The data points from MDO (black dots) are presented in Fig. 3, along with surrogate prediction.

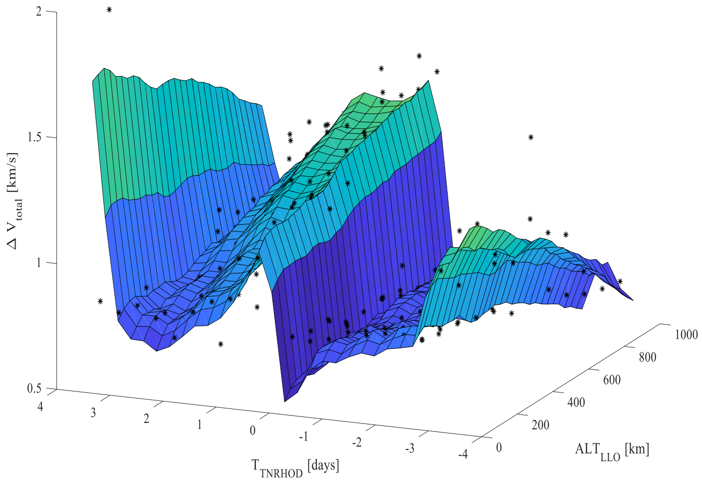


Fig. 3: MDO data points and surrogate prediction for ΔV_{total}

Table 4: Definition of decision variables for transfer trajectory MDO

Parameter	Definition
Ω	Right ascension of the ascending node of LLOI point
θ	Argument of latitude of LLOI point
T_{trans}	Total transfer time from NRHOD to LLOI
ΔV_{LLOI}	Magnitude of the LLOI Delta-V

MSDO has then been conducted, using the surrogate models from MDO for the prediction of the trajectory subsystem, aiming to maximise M_{margin} and minimise *TOF* simultaneously while maintaining a positive visibility constraint. The MSDO process yielded 888 individuals evolved over 20 generations, with the identical decision variable ranges to those used in the MDO.

Numerical Approaches

Simulation

The circular-restricted three-body problem (CRTBP) is employed to model the spacecraft dynamics throughout the transfer. In CRTBP, the spacecraft is assumed to be a point mass under gravitational influence of two massive bodies which rotate in circular orbits about a barycentre. The CRTBP describes the spacecrafts orbital motion in the Earth-Moon fixed rotating frame using a set of equations of motion, which have been extensively utilised. Ref. [6] provides the equations of motion and further detail, as well as the nominal NRHO orbit that has been used.

The trajectories have been calculated during the MDO and MSDO processes by concurrently performing simulations on a GPU, a class of hardware which enables highly parallel computing. The CRTBP equations of motion have been solved using a Runge-Kutta 4 fixed timestep integrator, which, along with the MSDO subsystems, has been coded in C++ using the CUDA parallel computing platform [7]. The spacecraft trajectory is solved by back-propagation, beginning from LLOI toward NRHOD, propagated for the specified time of flight, from which the required ΔV_{NRHOD} is calculated so as to match the Gateway's velocity at the NRHOD point.

Optimisation Algorithms

MDO and MSDO are performed in a population-based approach based on the evolutionary algorithms, in particular, elitist nondominated sorting genetic algorithm, where the candidate solutions in the population pool evolve over generations [8]. Offspring are created by applying recombination operators to the decision variable values of the parents. A simulated binary crossover and polynomial mutation are used as recombination operators at a given probability (0.85 and 0.15, respectively) with a specified distribution index (10 and 20, respectively).

Surrogate modelling is employed to estimate the objective and constraint values of the candidate solutions in an inexpensive manner, imitating the behaviour of the solutions from CRTBP-based MDO with metamodels represented by appropriate mathematical functions. Multiple surrogate models including the quadratic response surface model, radial basis function network, artificial neural network models, and kriging model [9], have been trained, based on the results from CRTBP-based MDO, and the models with minimum prediction errors have been adopted.

Results

Fig. 4 displays the results from the MSDO, indicative of the trade-off between the payload mass margin and the total time of flight, where no individual has been deemed infeasible with respect to the visibility constraint. The Pareto front comprises 3 local optimal frontiers, one of which features a plateau at a payload mass margin of approximately 28.3 kg.

Table 5 shows the total-effect indices for the influence of the decision variables on the performance parameters from the sensitivity analysis performed using surrogate models. The sensitivity indices indicate that all decision variables are highly sensitive to the time of NRHO departure, as compared to the altitude at lunar orbit insertion.

Table 5: Sensitivity indices of MDO results

Parameter	ALT_{LLOI}	T_{NRHOD}
Ω	0.02844	0.98320
θ	0.13791	0.98312
T_{trans}	0.02552	0.98548
ΔV_{LLOI}	0.26063	0.85649
ΔV_{total}	0.21284	0.99439

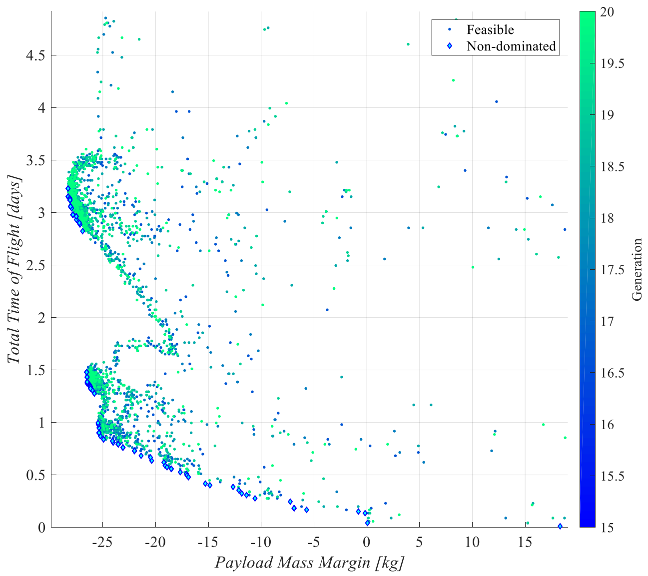
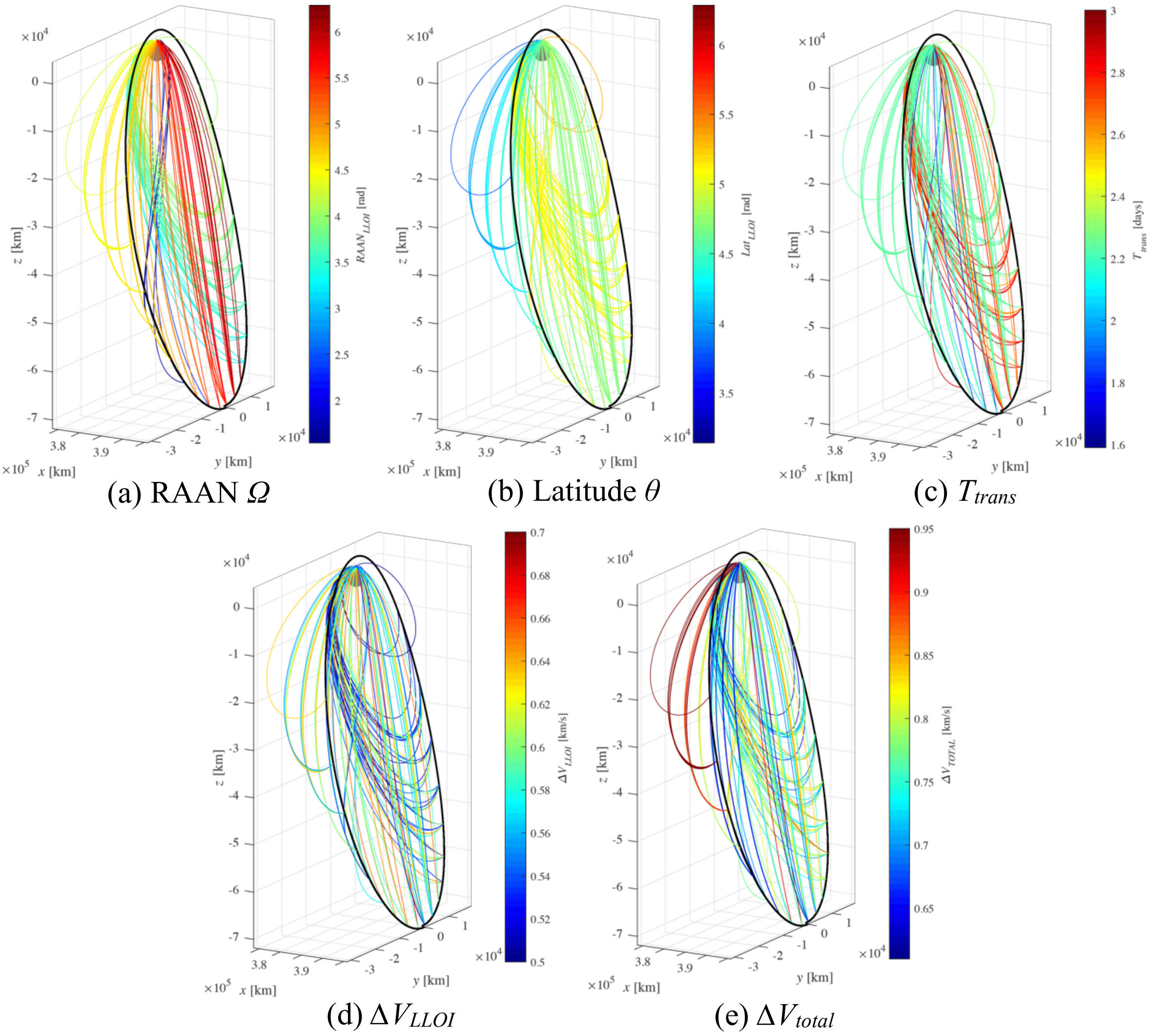


Fig. 4: MSDO results and Pareto optimal front

Discussions

Fig. 5 displays the all feasible trajectories that have been identified in the MDO study with respect to various attributes indicated by the colour variations. It must be noted that the trajectories presented here have been obtained by applying gradient-based optimisation to the solutions from MDO, which was conducted using an evolutionary algorithm hence heuristic approach, in order to further minimise the distance gap at NRHO departure to be within 1 km (from 50 km originally in MDO). This has been achieved by coupling the CRTBP solver into the local search method based on the *fmincon* function in MATLAB.



(a) RAAN Ω (b) Latitude θ (c) T_{trans}
(d) ΔV_{LLOI} (e) ΔV_{total}

Fig. 5: Feasible transfer trajectories from MDO (converged with *fmincon*)

The trajectories are commonly characterised by smooth colour variations indicative of smooth variations of the attributes of interest on the whole. However, it is noticeable that there are groups of trajectories featuring distinctly different characteristics from the other trajectories, such as those indicated by red and blue lines in Fig. 5 (a), for instance, which correspond to particularly high and low RAAN values, respectively. Differing trends can be found for the other attributes for such trajectories, as seen in Figs. 5 (b)-(d).

This observation suggests the existence of multiple groups of feasible trajectories for NRHO-LLO transfer featuring different characteristics, *e.g.*, high ΔV and low *TOF*, low ΔV and high *TOF* etc. Such trajectory groups are assumed to represent multiple trajectory families comprising clusters of local optima (Fig. 4) that correspond to the NRHOD condition considered. This renders a population-based approach particularly valuable for MSDO in order to identify all trajectory families owing to its global search capability in the entire design space.

It is also noteworthy that some attributes differ considerably from the original values (presented in Figs. 3 and 4) for certain trajectories as a result of gradient-based convergence via *fmincon*, which is inherently sensitive to the initial points for search (due to MDO, *i.e.*, population-based approach). This further underpins the potential presence of multiple feasible trajectories for a given set of the decision variables values (Table 4), subject to the initial search conditions.

It is deduced that surrogate modelling was performed, based upon the entire set of trajectory families. It is reasonable to assume that this has subsequently resulted in high sensitivity of the performance and attributes to the NRHO departure time due to the existence of multiple feasible trajectories for the same T_{NRHOD} values. The presence of multiple local frontiers in the MSDO results (Fig. 4) may well be attributed to the fact that the MSDO was conducted by employing the surrogate models that have been trained, based on multiple trajectory families.

Conclusions

An optimisation study using evolutionary algorithms has been conducted for the Lunar orbital transfer of a spacecraft for an observation-based mission consisting of trajectory, power, mass and observation subsystems. MSDO considering these subsystems has been performed to minimise total transfer time while maximising the payload mass margin.

The trajectory subsystem has been represented by surrogate models developed from a separate MDO study on the NRHO-LLO transfer problem aiming to minimise the total ΔV and transfer time. The spacecraft dynamics has been modelled using the equations of motion from CRTBP, with the propagation performed in a highly-parallel manner on GPU. The MSDO study resulted in a Pareto optimal front with a plateau at a maximum payload mass margin, indicative of trade-off characteristics between transfer time and payload margin. The rather complex Pareto front consisted of 3 local optimum frontiers, which is attributed to multiple trajectory families that have been employed to build the surrogate models in a mixed fashion.

Overall, this study has demonstrated the potential of the surrogate-based approach for global multidisciplinary design optimisation problems for complex spacecraft missions. On the other hand, it has revealed the potential presence of multiple feasible trajectories for orbit transfer, which would represent a challenge for conventional approaches that rely on local, gradient-based methods. It necessitates large-scale, global search of the design space based on population-based methods. It will also require an effective approach possibly employing machine learning algorithms that allows for categorisation of the trajectory families and thus construction of surrogate models for each trajectory family in a separate manner.

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