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Incremental planning of multi-gravity assist trajectories ☆

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ABSTRACT

The paper presents a novel algorithm for the automatic planning and scheduling of multi-gravity assist trajectories (MGA). The algorithm translates the design of a MGA transfer into a planning and scheduling process in which each planetary encounter is seen as a scheduled task. All possible transfers form a directional graph that is incrementally built and explored simultaneously forward from the departure planet to the arrival one and backward from the arrival planet to the departure one. Nodes in the graph (or tree) represent tasks (or planetary encounters). Backward and forward generated transfers are then matched during the construction of the tree to improve both convergence and exploration. It can be shown, in fact, that the multi-directional exploration of the tree allows for better quality solutions for the same computational cost. Unlike branch and prune algorithms that use a set of deterministic branching and pruning heuristics, the algorithm proposed in this paper progressively builds a probabilistic model over all the possible tasks that form a complete trajectory. No branch is pruned but the probability of selecting one particular task increases as the algorithm progresses in the search for a solution. The effectiveness of the algorithm is demonstrated on the design optimization of the trajectory of Marco Polo, JUICE and MESSENGER missions.

1. Introduction

A gravity assist manoeuvre takes advantage of the gravity field of celestial bodies to change the velocity of a spacecraft without the use of any propulsion system. The use of an optimal sequence of gravity assist manoeuvres enables the access to high ΔV targets in the Solar System, like Jupiter or Mercury. The optimality of a sequence of gravity assist maneuvers rests on the optimal selection of the celestial bodies (generically called *swing-by planets* in this paper) and of the encounter time with each of them.

Selecting the optimal sequence of swing-by planets and encounter dates is a complex mixed-integer nonlinear programming problem that will be called the Multi-Gravity Assist Problems (MGAP) in the remainder of this paper.

Deterministic algorithms for the solution of the MGAP are those that solve a problem in a systematic manner returning the same result every time they are applied to the solution of the same instance of the problem. Some deterministic algorithms for the solution of the MGAP are

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based on simplified models and an enumerative search like PAMSIT (Preliminary Analysis of Multiple Swing-bys Interplanetary Trajectories) [1], or a two-level approach in which the problem is split into two sub-problems: one finds a set of candidate optimal sequences of planetary encounters from an analysis of Tisserand's graph, or from simple energetic considerations [2], the other finds, for each sequence, the optimal set of encounter dates with a branch and prune type of procedure.

In the last decade, bio-inspired algorithms, such as Particle Swarms, Genetic Algorithms or Ant Colony, have become an appealing alternative to find solutions to the MGAP. Bio-inspired techniques for the solution of the MGAP can be found in [3,5,6]. In [3] the authors proposed a Hybrid Branch & Prune and Evolutionary process that could automatically generate sequence and optimal multi-gravity assist transfer with Deep Space Manoeuvres (DSM's) in a single loop. In [5] and [6] the authors proposed to divide the problem in two loops: the outer loop and the inner loop. The outer loop generates the planet sequence by the use of the Hidden Genes Genetic Algorithm (HGGA) that is passed to the inner loop to compute the optimal time sequence with a Monotonic Basic Hopping algorithm (MBH). In [4] the MGAP is translated into a planning and scheduling problem, and then the solution is incrementally built with a modified Ant Colony Optimization strategy.

The bio-inspired heuristic presented in this paper takes inspiration from the behaviour of a simple amoeboid organism, the *Physarum polycephalum*, that is endowed by nature with simple heuristics that can solve complex discrete decision making problems. For example, it was shown that the *P. polycephalum* is able to find the shortest path through a maze [9], recreate the Japan rail network, reproduce the designed highway network among several Mexican cities [7], solve multi-source problems with a simple geometry [8,9], mazes [10] and transport network problems [11].

The algorithm presented in this paper is applied to three different instances of real MGA problems. First, it is applied to an Earth–Near Earth Asteroid transfer type (MARCO POLO mission) [12], and then to an Earth–Jupiter transfer type (JUICE mission) [13,14]. Finally, it is applied to an Earth–Mercury transfer type (MESSENGER mission) [15,16].

The paper is organized as follows. First, a description of the proposed algorithm is given in Section 2. Then, the introduction of the trajectory model is addressed in Section 3. The performances of the algorithm through of different case studies are assessed in Section 4, and some final remarks conclude the paper.

2. Multi-directional discrete decision making

The optimization algorithm proposed in this paper takes inspiration from the biology of the *P. polycephalum*, a large single-celled amoeboid organism that in its plasmodium state extends a net of veins looking for food. The flux inside this net of veins is incremented or decremented depending on the relative position of the food with respect to the centre of the Physarum. The longest is the path connecting the centre with the source of food, the smallest is the flux.

Table 1
Setting parameters for the modified Physarum solver.

m	Linear dilation coefficient, see Eq. (6)
ρ	Evaporation coefficient, see Eq. (3)
GF	Growth factor, see Eq. (5)
N_{agents}	Number of virtual agents
p_{ram}	Probability of ramification
λ	Weight on ramification, see Eq. (8)

The optimization algorithm inspired to the Physarum biology works like a branch and prune algorithm in which the decision to branch or prune a vein is made probabilistically rather than deterministically. To be more specific, branches are never really pruned but the probability of selecting them falls to almost zero. The mechanism is analogous to the most commonly known Ant Colony Optimization algorithm although with the distinctive novelty that the exploration of the tree of decisions proceeds in multiple directions. In analogy with A* type of path planning or with dynamic programming algorithms, when the search proceeds forward from the source to the sink, the backward branches work as the heuristic function and vice versa when the search proceeds backward. The algorithm has already been extensively tested on a variety of known Travelling Salesman and Vehicle Routing problems with good results [20,21].

In order to be amenable to a solution with the Physarum solver, the MGAP is modelled using a tree-like topology. Starting from the Earth, that represents the root node, each following planet for fly-by is a children. The graph can be grown incrementally by the algorithm with time, where each precedent child becomes the parent of the following children up until the target planet is reached. The graph is built incrementally by Virtual Agents following the Physarum heuristic. Each arc connecting a parent to a child has an associated cost evaluated making use of the models in Section 3.

The Physarums mathematical model is composed of two main parts: (1) decision network exploration and (2) decision network growth in multiple directions. They are presented in this section along with a restart procedure that mitigates the risk of stagnation. The main parameters of the modified Physarum solver are summarized in Table 1. The complete pseudocode of the multidirectional incremental modified Physarum solver is provided in Algorithm 1.

Algorithm 1. Multidirectional incremental Physarum solver.

initialize m, ρ, GF, N_{agents}, p_{ram}, λ
for each generation **do**
  for each virtual agent in all directions (*DF* and *BF*) **do**
    if current node $\neq$ end node **then**
      if $\nu \in \mathcal{U}(0,1) \leq p_{ram}$ **then**
        using Eq. (8) create a new decision path, building missing links and nodes
      else
        move on existing graph using Eq. (4).
      end if
    end if