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Optimal scheduling of multispacecraft refueling based on cooperative maneuver

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Abstract

The scheduling of multispacecraft refueling based on cooperative maneuver in a circular orbit is studied in this paper. In the proposed scheme, both of the single service vehicle (SSV) and the target satellite (TS) perform the orbital transfer to complete the rendezvous at the service places. When a TS is refueled by the SSV, it returns to its original working slot to continue its normal function. In this way, the SSV refuels the TS one by one. A MINLP model for the mission is first built, then a two-level hybrid optimization approach is proposed for determining the strategy, and the optimal solution is successfully obtained by using an algorithm which is a combination of Multi-island Genetic Algorithm and Sequential Quadratic Programming. Results show the cooperative strategy can save around 27.31% in fuel, compared with the non-cooperative strategy in which only the SSV would maneuver in the example considered. Three conclusions can be drawn based on the numerical simulations for the evenly distributed constellations. Firstly, in the cooperative strategy one of the service positions is the initial location of the SSV, other service positions are also target slots, i.e. not all targets need to maneuver, and there may be more than one TS serviced in a given service position. Secondly, the efficiency gains for the cooperative strategy are higher for larger transferred fuel mass. Thirdly, the cooperative strategy is less efficient for targets with larger spacecraft mass.

Keywords: Cooperative maneuver; Refueling strategy; Multispacecraft; Multi-island Genetic Algorithm; Optimization

1. Introduction

Refueling is considered to be a very important and beneficial operation of On-orbit servicing (OOS). Many satellites end their mission just because they have run out of fuel. Refueling can extend the lifetime of satellites. The refueling ability can also bring change to the mission design of the satellites. If satellites have the ability to be refueled, they can be designed to execute new kinds of missions, such as long term earth observation on the extremely low-altitude, high-drag orbits. The Orbital Express mission successfully demonstrated the automated satellite servicing including automated propellant transfer (Heaton et al., 2008).

The current space industry emphasizes the importance of multi-satellite platforms, rather than a traditional monolithic spacecraft. For such systems, the problem of servicing is being addressed recently (Shen and Tsiotras, 2003; Dutta and Tsiotras, 2010). Serving multiple spacecraft is based on the multi-spacecraft rendezvous. The scheduling of the multiple rendezvous maneuvers is challenging, even for a constellation of satellites in a circular orbit, owing to the consideration of numerous orbital transfer problems. One main characteristic that distinguishes refueling from other OOS operations is that the mass of the service spacecraft

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Nomenclature

s_i	satellite with index i
ϕ_i	orbit slot with index i
p_j	service place with index j
q_j	index set of spacecraft refueled in p_j
yi	the index of service place which refuels s_i
m	number of service places
n	number of target spacecraft
Δmf_i	fuel transferred from service spacecraft to spacecraft s_i, kg
Δmf_i^e	the effective refueled fuel of s_i
ms_i	permanent structure mass of spacecraft s_i, kg
mf_i^-	initial fuel mass of s_i before the refueling mission, kg
mf_i^+	final fuel mass of s_i after the refueling mission, kg
c_0	the character constant of the rocket engine of the spacecraft
T_0	the total mission time for SSV, s
T_i	the total mission time for TS, s
$\mathbf{Y}_1$	variable sets, denotes the corresponding service place of each TS
$\mathbf{Y}_2$	variable sets, decides the transfer of the SSV between service places
sta_j	the time for the supplier to stay in p_j, Tr
sta_i'	the time for spacecraft s_i to stay in p_{yi}
T_i	allowed total time for spacecraft s_i to engaged in the mission
Δt_j	time period for supplier to transfer from p_{j-1} to p_j
$\Delta t_{i,1}'$	time period for spacecraft s_i to transfer from ϕ_i to p_{yi}
$\Delta t_{i,2}'$	time period for spacecraft s_i to return from p_{yi} to ϕ_i
Δv_j	normalized velocity cost for supplier to transfer from p_{j-1} to p_j
$\Delta v_{i,1}'$	normalized velocity cost for spacecraft s_i to transfer from ϕ_i to p_{yi}
$\Delta v_{i,2}'$	normalized velocity cost for spacecraft s_i to return from p_{yi} to ϕ_i
C_j	fuel cost of s_i in the whole mission
$C_{i,1}'$	fuel cost for spacecraft s_i to transfer from ϕ_i to p_{yi}
$C_{i,2}'$	fuel cost for spacecraft s_i to return from p_{yi} to ϕ_i
Tr	reference orbital period, s
Ttr_i	time period of fuel transfer for s_i, s
$\mathbf{X}_1$	denotes the number of the service places
$\mathbf{X}_2$	variable set, decides the transfer of the SSV between service places
$\mathbf{X}_3$	integer variable set, denotes the sets of TS which are serviced by the SSV in the each service place

and the target spacecraft will be significantly changed during the servicing process. According to the current research, multi-spacecraft refueling missions can be divided into two categories.

The first is the refueling missions in which the service spacecraft visits multiple fuel-deficient spacecraft one by one. The target spacecraft remain at their stations for the whole process. Shen (2003) studied the scheduling of servicing multiple satellites in a circular orbit and solved the problem in a two-step process: optimal time distribution and optimal sequence problem. Alfriend et al. (2006) formulated the geosynchronous satellites minimum cost (Δv) service problem as a traveling salesman problem and took plane changes into account. Xu and Feng (2011) proposed a scheme based on formation flying for the constellation refueling problem. Zhang et al. (2012, 2014) studied the multi-spacecraft refueling optimization considering the J_2 perturbation and time-window constrains.

In such missions, it is necessary to determine the service sequence and to optimize the rendezvous strategy. The problem contains integer and continuous variables, hence mission planning needs the development of Mixed Integer Nonlinear Programming (MINLP) models inherently. Hybrid Optimal Control (HOC) theory has also been applied to space mission planning (Ross and Souza, 2005; Conway et al., 2007; Chilan, 2009; Chilan and Conway, 2009). An approach using nested loops, including an outer-loop to optimize the sequence and an inner-loop to find the optimal trajectory for a given sequence, was developed for the mission planning formulated as HOC problems (Wall, 2007; Yu et al., 2014). Wall and Conway (2009) used genetic algorithm (GA) to solve the outer-loop and inner-loop problem, and it was proved to be efficient. Englander et al. (2012) used GA to solve the outer-loop and used a cooperative algorithm based on particle swarm optimization and differential evolution to solve the inner-loop problem.

The second category of missions uses the strategies based on Peer-to-Peer (P2P) maneuvers. In these kind of strategies, each satellite can play the role of the refueling/servicing spacecraft (Shen and Tsiotras, 2005; Dutta and Tsiotras, 2009). Systematical studies have been performed on P2P and mixed refueling strategies (Dutta and Tsiotras, 2006), and it has been shown that a mixed refueling strategy consumes less fuel than a strategy with only one service satellite for a large number of satellites and for short refueling periods (Tsiotras and de Nailly, 2005). Several models and corresponding algorithms have been