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Optimal Peer-to-Peer On-Orbit Refueling Mission Planning with Complex Constraints

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Abstract**—**On-Orbit Refueling is of great significance in extending space crafts' lifetime. The problem of minimum-fuel, time-fixed, Peer-to-Peer On-Orbit Refueling mission planning is addressed here with the particular aim of assigning fuel-insufficient satellites to the fuel-sufficient satellites and optimizing each rendezvous trajectory. Constraints including perturbation, communication link, sun illumination, hold points for different rendezvous phases, and sensor switching are considered. A planning model has established as well as a two-level solution method. The upper level deals with target assignment based on fuel equilibrium criterion, while the lower level solves constrained trajectory optimization using special maneuver strategies. Simulations show that the developed method could effectively resolve the Peer-to-Peer On-Orbit Refueling mission planning problem and deal with complex constraints.

Keywords**—**Mission planning, orbital rendezvous, on-orbit refueling, space mission.

I. Introduction

SERVICING and refueling spacecraft in orbit periodically provides immense benefits for extending the useful lifetime of the spacecraft, reducing launching and insurance cost, and increasing the constellation's operational flexibility and robustness. Enabling technologies (e.g. automated rendezvous, capture, and fuel exchange, etc.) for servicing single spacecraft have already been demonstrated by successful experiments, such as Orbital Express [1]. Nowadays, more attention has been paid to multiple Servicing Spacecrafts (SScs) refueling multiple satellites. There are number of reported works devoted in On-Orbit Refueling (OOR) mission planning, i.e. developing optimal mission sequence and trajectories for SSc refueling multiple targets, aiming at improving the economic returns and fuel consumptions [2]-[5].

A system of multiple satellites can be served by a single servicing spacecraft in one by one pattern or by a distributed peer-to-peer (P2P) strategy, i.e. satellites exchange fuel amongst themselves in pairs, with the fuel-sufficient satellites providing fuel to the fuel-deficient satellites [6]. P2P strategy is a distributed and robust refueling pattern, which could offer protection against failures to some extent [7], [8]. Systematical studies have been performed on P2P OOR mission planning by Dutta and Tsiotras, formulating the problem by network flow model or bipartite graph. Multiple models and solving strategies have been formulated to address P2P refueling problems of variable scenarios, such as Asynchronous P2P, Egalitarian P2P, Cooperative P2P and Cooperative Egalitarian P2P scenarios [7]-[10]. Based on Dutta's work, Yu et al. solved P2P mission planning problem with time window constraint in [11].

Under the basis of the work above, the mission planning problem of P2P OOR is addressed in this paper with the particular aim of dealing with complex constraints. A two-level planning model is established as well as the solution method.

II. Problem Description

We consider a constellation with *2N* satellites distributed over low earth orbits. *N* of these *2N* satellites are fuel-sufficient, active and called SSc, while the others are fuel-deficient, passive and called Object Satellites (OS). One SSc can exchange fuel with only one OS. After a fuel exchange takes place between the active and the passive satellite, the active satellite returns to its original available orbital slots. A typical rendezvous process includes four major phases: phasing, far range rendezvous, close range, and mating. All these phases should be considered in rendezvous trajectory optimization. Furthermore, complex constraints on perturbation, ground station, sun illumination, hold points, and sensor switching should also be taken into account.

III. Analysis and Modeling

A. Design Variables

(1) Mission Assignment

Assuming there are *n* satellites, the former *n/2* satellites are SScs while the latter *n/2* ones are OSs. Let $x_i = j$, when OS j is assigned to SSc i , where $i \in [1, n/2]$ $j \in [n/2+1, n]$. The decision variable can be formulated as $X = \{x_1, x_2 ... x_s\}$.

(2) Time Distribution

A typical rendezvous process includes four major phases: phasing, far range rendezvous, close range, and mating (see Fig. 1). In this paper, perturbed Lambert Transfer is employed for AB segment, while the well-known Clohessy–Wiltshire equations are used for BC and CD segments. The decision variable for time distribution is given as: $T = (t_{A1}, t_{As}, t_{B1}, t_{Bt}, t_{C1}, t_{Cp}, t_{back1}, t_{back2}, \Delta v_{AB}, \Delta v_{BC}, \Delta v_{CD}, \Delta v_{back})$, where $t_{A1}, t_{As}, t_{B1}, t_{Bt}, t_{C1}, t_{Cp}$ represent the rendezvous maneuver time at each rendezvous phase, t_{back1}, t_{back2} denote the transfer

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maneuver time for SSc coming back (only phasing is considered when coming back), $\Delta v_{AB}, \Delta v_{BC}, \Delta v_{CD}$ describe the maneuver cost for each phase, while Δv_{back} gives the maneuver cost of SSc coming back.

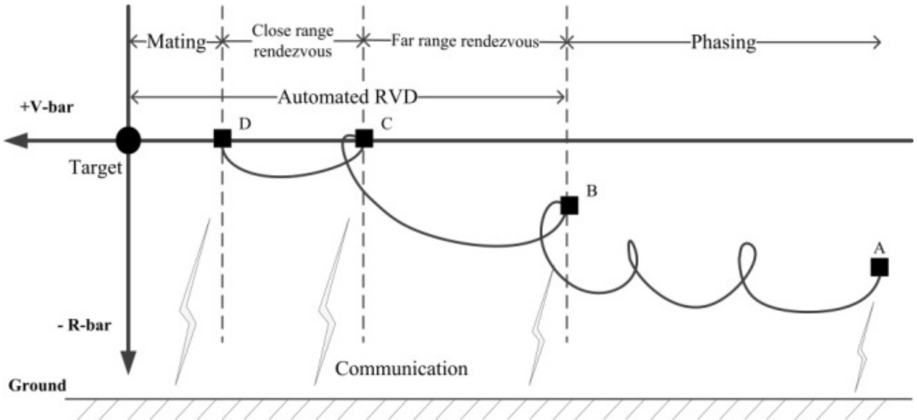

Fig. 1 Rendezvous process

B. Objective Function

(1) Maneuver cost index: The total velocity increment, which is directly proportional to the fuel consumption of maneuver, is expected to be as small as possible. Let $\Delta v_{ito}, \Delta v_{iback}$ represent the maneuver cost for servicing and return respectively, so we can get

$$J_1 = \min \sum_{i=1}^{n/2} (\Delta v_{ito} + \Delta v_{iback}) \tag{1}$$

(2) Fuel equilibrium index: The goal of the P2P refueling problem is thus to redistribute the fuel among all satellites such that after a set of fuel transactions the fuel stored among the satellites is equalized. Let $aveM$ denote the average fuel stored among all satellites in the constellation after transactions. Let M_i denote the fuel stored by the i th satellite after the whole mission. It is expected to redistribute the fuel as equal as possible.

$$J_2 = \min \sum_{i=1}^{n} \sqrt{(M_i - aveM)^2} \tag{2}$$

C. Constraints

- C_1: Communication Time Window. Generally, prior to the start of each rendezvous phase, communication between chaser and the ground should be established, and each maneuver should be performed within certain communication time window.
- C_2: Hold Point. If the chaser arrives at these points, some time will be spent for functional check-out and synchronization tasks. It is defined that the holding time is $\Delta t_H > t_{H\min}$, where $t_{H\min}$ gives the minimal time required for holding.
- C_3 : Sensor Switching. To obtain high navigation precision, different rendezvous phases require different navigation sensors. During station-keeping at the hold points, sufficient time Δt_{switch} should be reserved for sensor switching. A following orbital maneuver performed within Δt_{switch} is not permitted.
- C_4: Sun Illumination. The orbital sun angle β is the angle between the sunlight and the orbital plane. The smaller the $|\beta|$ is, the more solar energy the spacecraft will gather. $|\beta|$ partly represents the power ability of the spacecraft. During each rendezvous phase, it is required that $|\beta| \le \beta_{\max}$.
- C_5: One SSc can exchange fuel with one and only one OS.

D. Modeling

Summing up, the P2P OOR mission planning problem could be modeled as:

$$\begin{array}{ll} \text{find} & X, T \\ \text{optimize} & J_1, J_2 \\ \text{s.t.} & C_1 \cap C_2 \cap C_3 \cap C_4 \cap C_5 \end{array} \tag{3}$$

IV. Solution Method

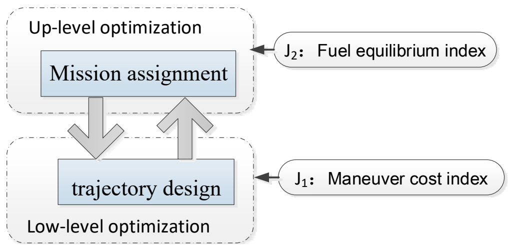

Fig. 2 Two-level optimization model

A two-level hybrid optimization strategy is proposed to solve the provided the P2P refueling problem (see Fig. 2). The up-level assigns fuel-deficient satellites to fuel-sufficient satellites in optimal pairs, while the low-level focuses on trajectory design. In the upper level, only fuel equilibrium index is

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considered. All possible pairs are enumerated to find the best one. In the lower level, the orbital rendezvous optimization method developed in [12] is employed for dealing with complex constraints.

The trajectory design process could be summarized as:

Step1. Preparation. Compute all available communication time windows.

Step2. AB segment design for phasing. Select the optimal time windows for each maneuver by using Simulated Algorithm. The orbital transfer is calculated by Lambert Transfer method with two-body propagation model.

Step3. AB segment modification for phasing. Based on the selected time windows, calculate the maneuver time. Taking the unperturbed solution calculated by step 2 as an initial guess, improve the transfer parameters by modifying the expected final state repeatedly with high precision propagator until the state error is within the tolerance.

Step4. BC segment design for far-range rendezvous. Repeat steps 2 and 3, and replace Lambert Transfer with Clohessy-Wiltshire equations.

Step5. CD segment design for close-range rendezvous. Repeat steps 2 and 3, and replace Lambert Transfer with Clohessy-Wiltshire equations.

Step6. Record all of the optimal results for each phase.

V. Simulations

A. Computation Condition

In this section, the proposed methods are applied to a practical P2P OOR mission. The Gregorian universal coordinated time (UTCG) for planning period is from 1 Feb 2020 00:00:00.000 to 10 Feb 2020 00:00:00.000. Denoting 1 Feb 2020 00:00:00.000 as the starting time, the initial orbital elements of the satellites (semimajor axis, eccentricity, inclination, argument of perigee, RAAN, true anomaly) are depicted in Table I. The ground station parameters are given in Table II.

TABLE I
Parameters for Satellites

Satellites	semimajor axis (km)	eccentricity	Inclination (°)	argument of perigee (°)	RAAN (°)	true anomaly (°)	Initial fuel (unit)
1	6914.27	0	42.5	0	98.6	220	88
2	6714.22	0	42.5	0	98.8	30	76
3	6856.33	0	42.0	0	99	60	100
4	7024.67	0	43	0	98.4	120	8
5	6755.44	0	42.8	0	98	0	12
6	6824.11	0	42.5	0	99	160	16

TABLE II
Parameters for Ground Stations

Ground station	Name	Latitude (°)	Longitude (°)	Altitude (m)
1	Gila_River	33.1133	-112.031	0
2	Islamabad	33.7182	73.0605	542.373
3	Kashimia	35.9531	140.666	0
4	Tokyo	35.7088	139.492	0

Taking satellite 1 as an example, the β angle variation with time is depicted in Fig. 3. It is defined that all missions should be completed before 4 Feb 2020 00:00:00.000, and the SScs could come back during 7 Feb 2020 00:00:00.000 to 10 Feb 2020 00:00:00.000.

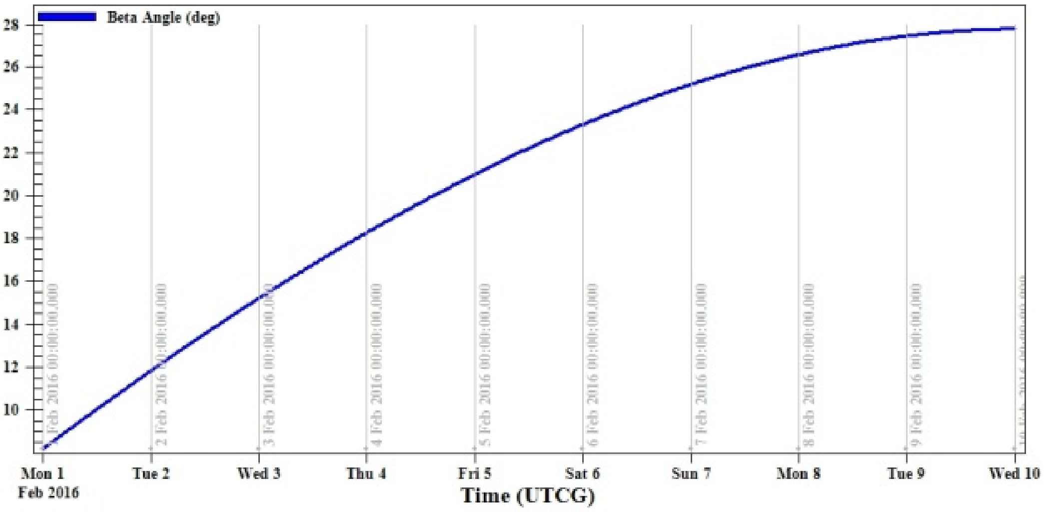

Fig 3 Beta angle variation with time

B. Results and Discussions

After mission planning, satellite 1 serves satellite 5, satellite 2 serves satellite 6, and satellite 3 serves satellite 4. The detailed parameters about the whole process are described in Tables III and IV.

TABLE III
SIMULATION RESULTS FOR REFUELING

P2P Pairs (SSc→target)		1→5	2→6	3→4
AB phasing	t_{A1} (s)	81196	98105	15800
	Ground station	2	2	2
	t_{As} (s)	99308	131358	43485
	Ground station	2	1	1
	$\lvert\Delta \boldsymbol{v}_{AB}\rvert$ (m/s)	750.081	525.759	544.808
BC far range rendezvous	t_{B1} (s)	99488	131538	43665
	Ground station	2	1	1
	t_{Bt} (s)	132062	165020	125329
	Ground station	1	3	1
	$\lvert\Delta \boldsymbol{v}_{BC}\rvert$ (m/s)	2.265	5.586	1.989
CD close range rendezvous	t_{C1} (s)	132242	165200	125509
	Ground station	1	3	1
	t_{Cp} (s)	159933	170652	154890
	Ground station	3	2	4
	$\lvert\Delta \boldsymbol{v}_{CD}\rvert$ (m/s)	5.925	3.514	2.909
Total	J_1 (m/s)	758.271	534.858	549.705

TABLE IV
SIMULATION RESULTS FOR SSCS COMING BACK

P2P Pairs (SSc ⟵ target)	1⟵5	2⟵6	3⟵4
t_{A1} (s)	687644	663889	619698
Ground station	4	1	2
t_{As} (s)	731764	691608	648242
Ground station	1	2	1
J_1 (m/s)	579.519	419.608	761.841

Simulations show that the method proposed in this paper could address P2P OOR mission planning problem effectively. The complex constraints could be satisfied by using some special orbital rendezvous method.

VI. CONCLUSION

OOR plays a significant role in lengthening satellites' lifetime. There are number of reported work devoted in OOR mission planning [2]-[12], i.e. developing optimal mission sequence and trajectories for SSc refueling multiple targets, aiming at improving the economic returns and fuel consumptions. The problem of minimum-fuel, time-fixed, Low Earth Orbit (LEO) P2P OOR mission planning is addressed here, and complex constraints on perturbation, ground station, sun illumination, hold points for different rendezvous phases, and sensor switching are taken into account. A two-level planning model is established as well as the solution method. The upper level deals with P2P target assignment based on fuel equilibrium criterion, while the lower level solves complex constrained trajectory optimization using special maneuver strategies. Simulations show that the developed method could effectively resolve the P2P OOR mission planning problem and deal with complex constraints.

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