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Algorithms for Optimal Scheduling of Multiple Spacecraft Maneuvers

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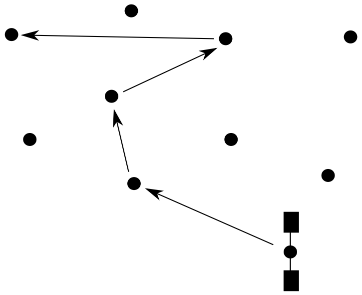
WSU Astronautics Research Laboratory (2014 –)

- Multi-rendezvous mission planning
- All-electric satellites
- Spacecraft attitude control
- CubeSat for science experiments and technology demonstration

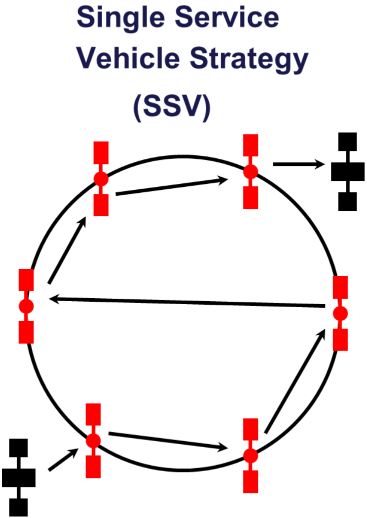
Presentation Overview

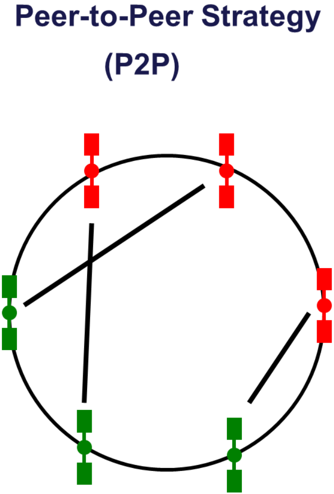
Active Debris Removal

- Recent studies have indicated that at least 5 objects need to be removed every year for stable on-orbit debris management
- Many debris removal techniques likely require multi-rendezvous mission planning



Servicing of Satellite Constellations

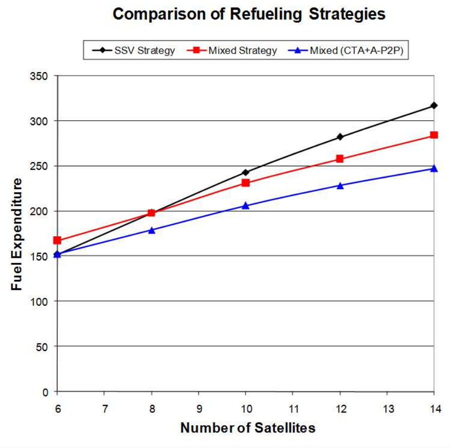




Mixed Servicing Strategy

- Mixed strategy outperforms the single service vehicle strategy with increasing number of satellites in the constellation

- Mixed strategy does even better with asynchronous maneuvers and optimal P2P trip times



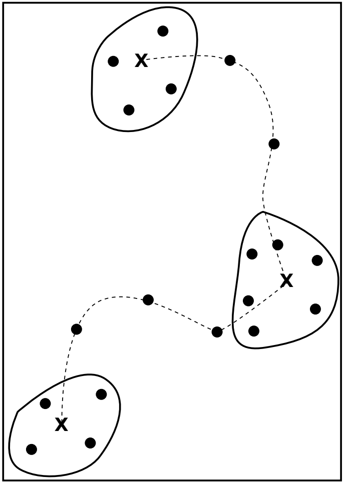
**Dutta and Tsiotras, "Asynchronous Optimal Mixed Peer-to-Peer Satellite Refueling Strategies," Journal of the Astronautical Sciences, Vol. 54 (3-4), Dec 2006, pp. 543-565.*

Challenges

- Continuous optimization: optimization over transfers
- Combinatorial aspects: target selection, optimization over sequences
- NP-hard: ~~polynomial time algorithm~~
- Researchers have used genetic algorithms, branch-and-bound methods, Greedy random adaptive search procedures

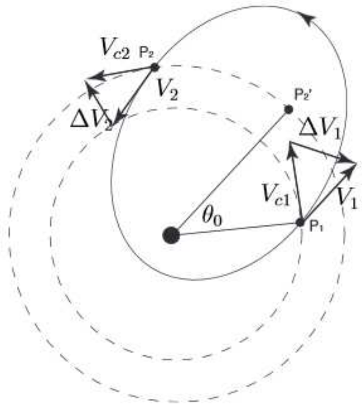
Greedy Random Adaptive Search Procedure

- Widely used in operations research community to solve k-assignment problem
- Multiple phases: construction of a basic feasible solution, local search, path relinking
- Known to yield good quality solutions



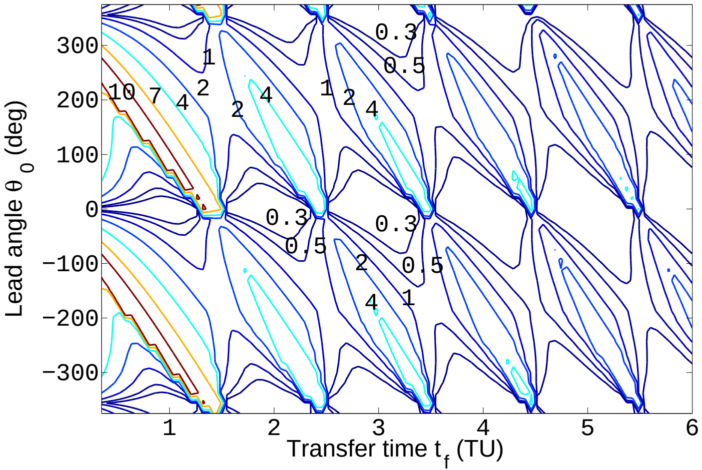
Presentation Overview

Two-Impulse Transfer

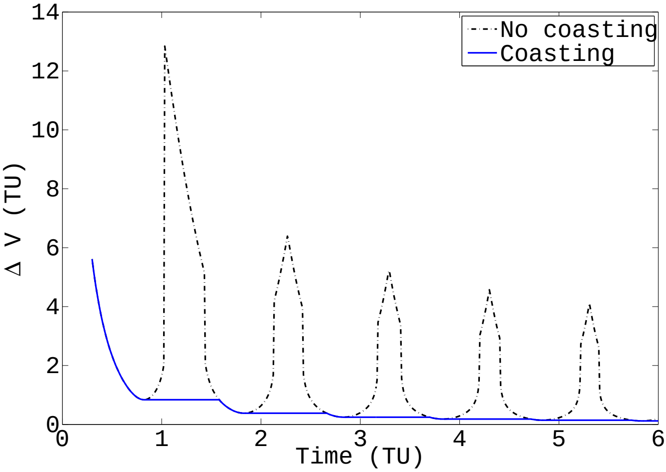


- Multi-revolution solutions to Lambert's Problem

Circular Orbit Rendezvous Cost (1 of 2)

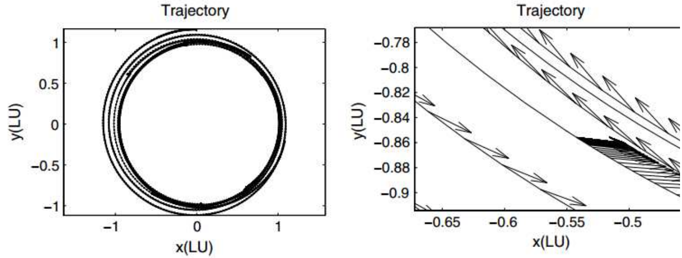


Circular Orbit Rendezvous Cost (2 of 2)



Low-Thrust Rendezvous

- Lower the propulsive cost of missions
- Enhance the flexibility of missions



Presentation Overview

Problem Statement

- Service vehicle needs to visit m out of n candidate targets $s_1, s_2, \ldots, s_n$
- Sequence $\sigma : \mathcal{J} \mapsto \mathcal{I}$, where $\mathcal{J} = \{1, 2, \ldots, m\}$ and $\mathcal{I} = \{1, 2, \ldots, n\}$
- ~~Time at which transfers take place: τ_i, where $i \in \mathcal{J}$~~, Time duration of the maneuvers: $t(\sigma(i), \sigma(j))$, where $i, j \in \mathcal{J}$, Maximum mission time T
- Objective is to minimize cost of a sequence

$$\min_{\sigma(\mathcal{I})} \mathcal{C}(\sigma(\mathcal{I}))$$

Basic Feasible Solution

- Set time duration for the transfers to be equal at the beginning

$$t(\sigma(i), \sigma(i+1)) = \frac{T}{m+1}, \text{ for all } i \in \mathcal{I}$$

- Cost is uniquely defined for each transfer (i, j), only a subset of these transfers are considered based on some user-defined value η

$$\mathcal{E}_0 = \mathcal{E} \backslash \{(i,j) : c\,(i,j) > \underline{c} + \eta(\bar{c} - \underline{c})\}$$

- The elements of $\sigma(\mathcal{J})$ are picked in m iterations, with the element k being picked in the k^{th} iteration

$$(k-1, k) \in \mathcal{E}_{k-1}$$

- Selection of a target will make irrelevant several transfers that are dropped from the set being considered

Local Search (1 of 2)

- Difference between two sequences:

$$\delta\left(\sigma_1, \sigma_2\right) = \{k : \sigma_1(k) \neq \sigma_2(k)\}$$

- Distance between two sequences is simply the cardinality of the difference between them:

$$d\left(\sigma_1, \sigma_2\right) = \left|\delta\left(\sigma_1, \sigma_2\right)\right|$$

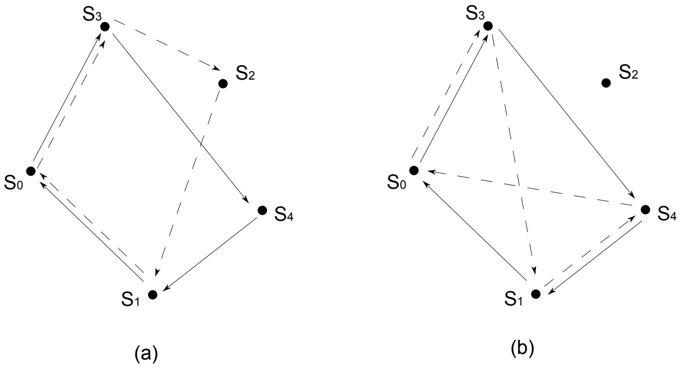
- Neighborhood of the sequence is given by all sequences that have distance less than or equal to k

Local Search (2 of 2)

- We consider $k \leq 2$

(a) $\{0, 3, 4, 1, 0\}$ and $\{0, 3, 2, 1, 0\}$

(b) $\{0, 3, 4, 1, 0\}$ and $\{0, 3, 1, 4, 0\}$

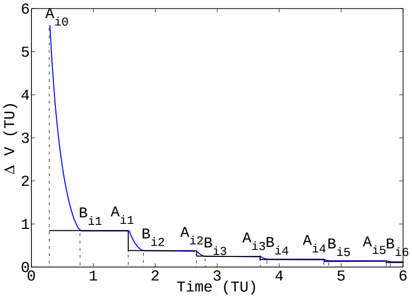


Numerical Example

- Visiting 5 satellites out of 8 in a circular orbit.

	Basic Feasible Solution	Cost (DU/TU)	Targets Not Visited
-	$s_0 \to s_5 \to s_2 \to s_7 \to s_3 \to s_8 \to s_0$	0.6730	s_1, s_4, s_6
1	$s_0 \to s_5 \to s_2 \to s_7 \to s_3 \to s_1 \to s_0$	0.6166	s_4, s_6, s_8
2	$s_0 \to s_5 \to s_1 \to s_7 \to s_3 \to s_2 \to s_0$	0.5820	s_4, s_6, s_8
3	$s_0 \to s_5 \to s_1 \to s_7 \to s_4 \to s_2 \to s_0$	0.0036	s_3, s_6, s_8
4	$s_0 \to s_5 \to s_1 \to s_6 \to s_4 \to s_2 \to s_0$	0.0025	s_3, s_7, s_8
5	$s_0 \to s_5 \to s_1 \to s_6 \to s_4 \to s_2 \to s_0$	0.0025	s_3, s_7, s_8

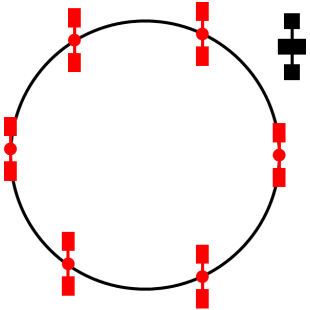
Optimal Transfer Time Allotments



- Binary Integer Programming Problem (Shen and Tsiotras, 2003)
- Iterative algorithm: avoid the solution of the binary integer programming problem (ASC, 2015)

Presentation Overview

Problem Statement



Given

- Fuel-deficient satellites
- Service spacecraft
- Satellite characteristics
- Maximum time for mission

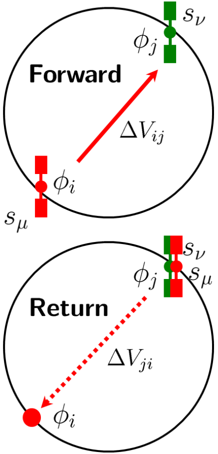
Allow

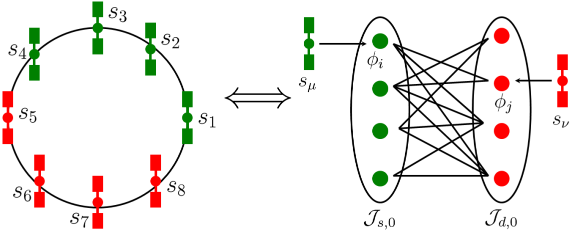
- Orbital transfers for delivery of fuel to fuel-deficient satellites

Goal

- Minimum fuel expenditure during the overall refueling mission
- All satellites must be fuel-sufficient at the end of refueling mission

P2P Maneuver and Constellation Graph





Constellation **Bipartite Graph**

Satellite roles (active/ passive) not known apriori!

Feasible P2P Maneuvers

- Active satellites have enough fuel to complete their forward trips
- Both satellites must be fuel-sufficient at the end of a P2P maneuver

NP-hard P2P Problem

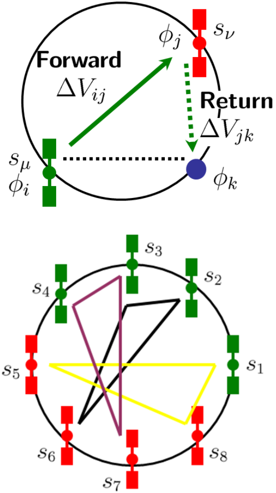


Figure: E-P2P Maneuver.

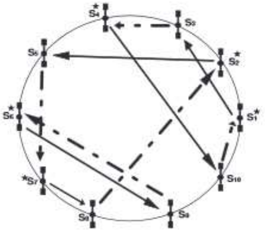
Assumption: All satellites are similar, perform similar functions and can interchange their orbital positions.

- 3-index assignment problem
- Good-quality solutions

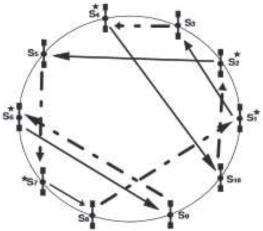
**Dutta and Tsiotras, "An Egalitarian Peer-to-Peer Satellite Refueling Strategy," Journal of Spacecraft and Rockets, Vol. 45 (3), 2008, pp. 608-618.*

**Coene, Spieksma, Dutta and Tsiotras, "On the Computational Complexity of P2P Refueling Strategies," INFOR: Information Systems and Operational Research, Vol. 50, No. 2, 2012, pp. 88-94.*

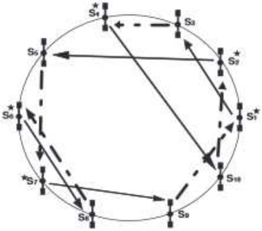
P2P Local Search



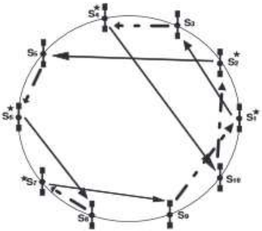
(a) Cost = 24.87



(b) Cost = 24.77



(c) Cost = 22.61



(d) Cost = 20.48

General P2P Strategy

C-P2P + E-P2P

Theorem

$$\mathcal{C}_{\mathrm{LB}} \leq \mathcal{C}_{\mathrm{CE}} \leq \min\{\mathcal{C}_{\mathrm{C}}, \mathcal{C}_{\mathrm{E}}\}$$

Lower Bound Computation

- Bipartite matching
- Solvable in polynomial time

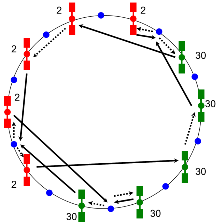


Figure: C-P2P Maneuver.

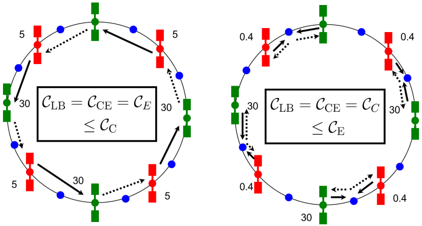
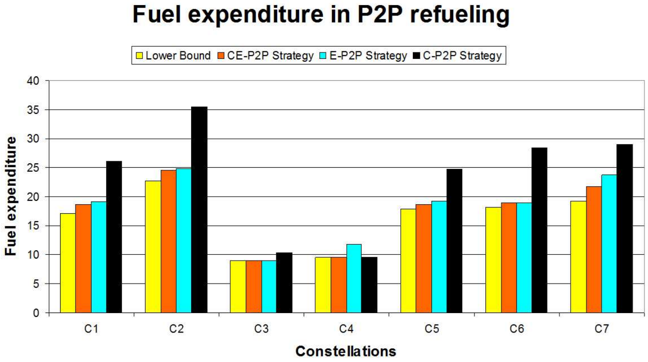


Figure: Global Minima (Cost = Lower Bound).

**Dutta and Tsiotras, "A Network Flow Formulation for Cooperative Peer-to-Peer Refueling Strategies," Journal of Guidance, Control and Dynamics, Vol. 33(5), 2010, pp. 1539-1549.*

Comparison of (Impulsive) P2P Strategies

Lower Bound $\leq$ CE-P2P $\leq$ C-P2P / E-P2P $\leq$ P2P



**Dutta, "Optimal Cooperative and Non-Cooperative Peer-to-Peer Maneuvers for Refueling Satellites in Circular Constellations," Ph.D. Dissertation, Georgia Institute of Technology, Atlanta GA USA, 2009.*

Presentation Overview

1. Motivation
2. Optimal Transfer for a Spacecraft
3. Maneuvers by a Single Servicing Spacecraft
4. Peer-to-Peer Maneuvers
5. **Concluding Remarks**

Concluding Remarks

- GRASP Methodology is useful for both types of multi-rendezvous maneuver planning problem
- Good-quality solutions for P2P servicing problem
- Preliminary framework developed for SSV case
- Straightforward to incorporate operational constraints like mandatory target visits and imposed roles on satellites
- GRASP methodology can incorporate low-thrust transfers and cooperative rendezvous maneuvers
- Future research focussed on extending the studies in a number of ways