The 9th Global Trajectory Optimization Competition Workshop

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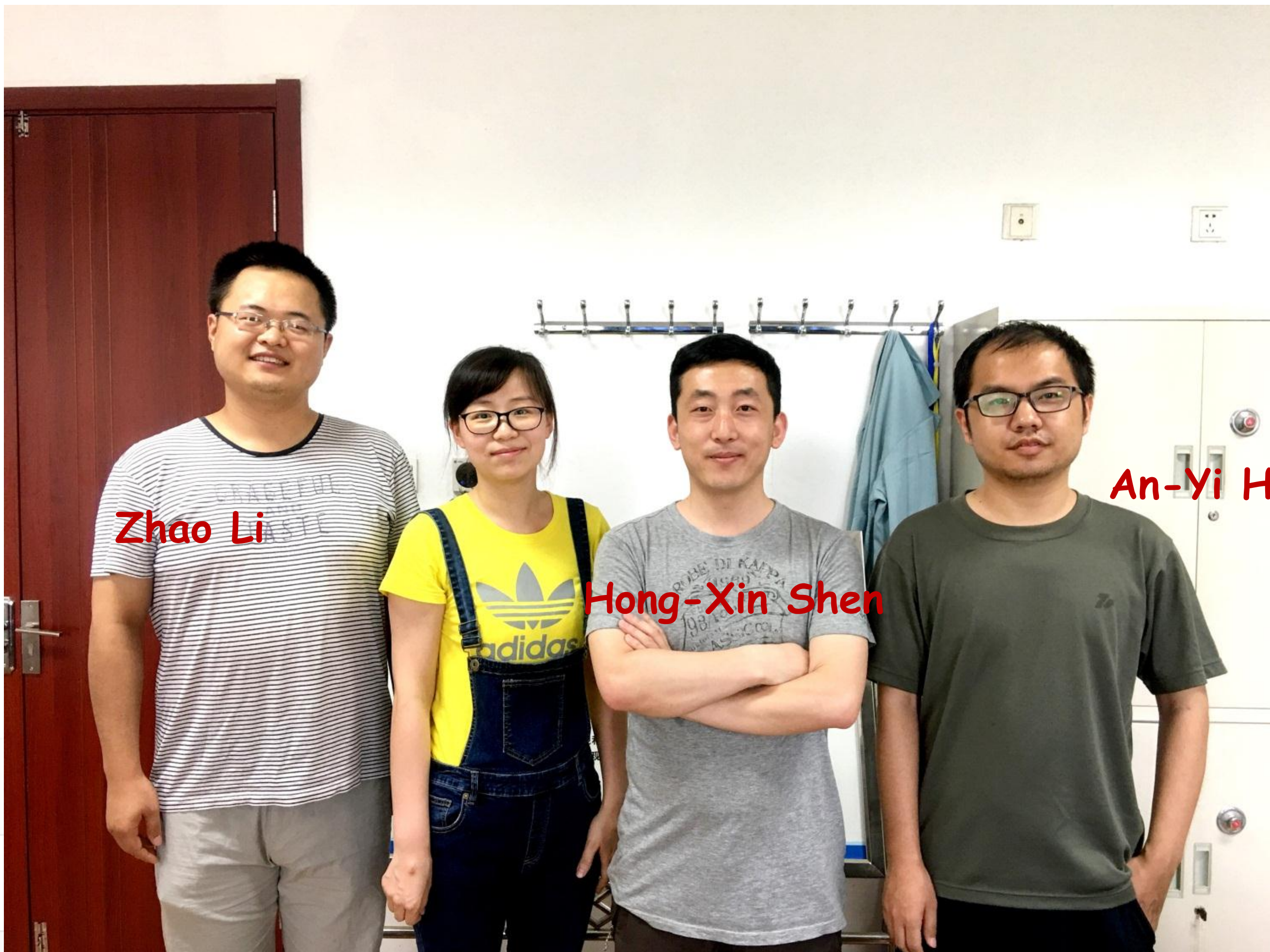
June 2017, Japan

The XSCC-ADL team

They are satellite control engineers~



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Strategy overview

- GTOC9 is in essence a dynamic TSP, but we only can solve classic TSP and very small-scale DTSP.
- The search of global optimum was divided into three basic stages.
  - 1. Debris sequence global search by solving a classic TSP-like problem/ACO algorithm
  - 2. Single mission sequence re-optimization/DE (POST-COMPETITION☹)
  - 3. Optimization of accurate impulsive transfers/ACOR, DE
- The second stage is to compensate partly the dynamic property neglected in the first stage.

DeltaV approximation

- DeltaV between a debris pair consists two terms: time-independent part and time-dependent part

$$\Delta V_1 = 0.5\left(V\sqrt{(\Delta a / a)^2 + \Delta e^2}\right) + 2V\sin(0.5\Delta i)$$

$$\Delta V_2 = 2V\sin(0.5\Delta\Omega(t))$$

- Because optimization often gives better result than the approximation above, and it seems difficult to get an accurate approximation in mathematical rigor, thus an experienced correction is used here.

$$\Delta V = 0.7(\Delta V_1 + \Delta V_2)$$

Time approximation

- In a single mission, it is greedy to choose the best rendezvous time t_2, in the given rendezvous time domain based on the last rendezvous time t_1, i.e., t_2 is determined in a range [t_1+5.5d, t_1+30d], where 0.5 day is reserved for a transfer.
- To determine the first rendezvous time of the next mission, the range of t_2 is arbitrarily extended to [t_1+40d, t_1+250d]
- The best rendezvous time is simply chosen to obtain a minimum Delta RAAN, that is

$$t_2 = \begin{cases} t(\Delta\Omega = 0), & \text{if } \Delta\Omega(t_{2\min})\Delta\Omega(t_{2\max}) < 0 \\ t\left(\min\left(\Delta\Omega(t_{2\min}), \Delta\Omega(t_{2\max})\right)\right), & \text{else} \end{cases}$$

ACO

- Objective function
  - min $J = cn + \alpha \sum_{i=1}^{n} \Delta m_i^2, \quad 50 \le c \le 55$
- Algorithm
  - First, each ant builds a solution according to the transition rule.
  - Subsequently, a local search procedure is employed to improve this solution. Then, pheromone is updated
  - the iterative process terminates when the total time reach the maximum value. Also, when dv of one leg or of a single mission violates a specific value (1500m/s, 5000m/s and more), a new mission is applied

Accurate optimization

- Three impulses are always assumed, sometimes the middle one tends to vanish.
- A coast arc is specified at the beginning, which may benefit long time transfer.
- 6 variables are used. Three variables are for the impulse time, and the other three are for the first impulse. Note that a lambert solver is used for the last stage.
- ACO in continuous domain and DE approach are employed to optimize multiple impulse trajectories. Generally three runs are performed using both ACO and DE, and the best solution are saved.

Solution submitted

- 12 launches
  - 16-10-12-11-11-9-12-9-9-10-6-8
- J=821
  - Initial mass:4871,3886,3864,4038,5768,4484, 5844,4834,4482,4826,3146,4245
- The body-to-body trajectories may still have room to be improved
- We never got missions less than 12 during competition. After competition, We try to decrease launches first by using a pseudo performance index.

Post-competition results

- Pseudo objective function

$$J = cn + \alpha \sum_{i=1}^{n} \Delta m_i^2 / \mathrm{k}$$

k=30. Pseudo J permits longer single mission easily sought!

- New approach: MINLP with DE
  - Only used for a single mission, variables include debris id and transfer times
  - DE only deal with continuous variables, but the first half continuous variables can be **sorted** in order to correspond to debris sequence, i.e., integer variables.

Post-competition results

- J=731

N	Debris id	Tstart	Tend	cost
15	16,57,118,50,113,20,79,25,84,27,83,121,117,97,38	114.29	454.16	85.4
14	74,76,110,53,29,58,3,52,28,73,64,10,107,61	485.51	684.47	76.9
15	75,67,18,33,102,68,34,88,45,82,41,7,94,70,112	715	1023.6	72.8
14	100,21,90,19,9,69,30,93,77,55,95,66,115,120	1089.80	1447.34	68.3
11	105,96,46,119,24,63,108,114,32,87,37	1477.45	1617	67.2
15	36,89,91,1,40,62,54,99,122,35,85,15,59,98,8	1647.27	1878.71	81.6
8	47,11,39,13,5,51,26,101	1915	2104.3	73.3
9	81,31,92,65,6,2,4,22,48	2322.67	2488.25	70.8
11	80,60,23,43,12,106,71,72,104,116,49	2518.25	2720.78	69.9
11	44,56,78,111,109,0,17,86,14,103,42	2758.51	2952	64.6

Post-competition results

- J=722

N	Debris id	Tstart	Tend	cost
16	50,15,22,38,95,57,118,23,117,79,55,113,25,27,84,83	5.58	340.39	85.8
11	66,28,72,76,29,51,90,74,53,64,58	370.39	504.81	65.7
18	7,70,63,85,47,88,34,37,2,104,11,75,18,122,26,0,108,44	537.19	922.85	89.7
9	97,111,107,61,49,42,56,12,8	1052.92	1238.59	61.9
12	106,68,100,93,30,69,9,77,33,65,19,21	1268.61	1429.19	67.0
12	82,41,3,87,45,105,86,46,119,24,114,32	1459.19	1604.95	68.7
13	36,89,35,40,62,54,1,112,99,121,67,20,116	1637.6	1893.84	77.9
8	101,78,43,103,71,13,60,39	1924	2051.89	64.9
12	31,115,96,81,110,92,4,6,10,91,73,48	2289.83	2553.58	71.8
12	102,120,80,16,59,94,98,5,109,52,14,17	2596.85	2842.59	69.1

Discussion

- PROS
  - 1. Traditional pruning techniques are avoided, and any human-picked work is not involved, computer gives the final solution
- CONS
  - 1. MILNP algorithm cannot suit large-scale problem (123 debris here), we are NOT sure of that a classic ACO in the first step can give a solution that is quite close to the global optimum
  - 2. Accurate optimization is very important for the performance index, due to the square penalty on the fuel consumption. Maybe indirect/direct combining optimizer is useful to guarantee the global optimum.
  - 3. The ACO procedure runs slowly without parallel computation

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