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10th China Trajectory Optimization Competition: Problem description and summary of the results

Xuxing Huang, Bin Yang, Pan Sun, Shuang Li (✉), and Hongwei Yang

College of Astronautics, Nanjing University of Aeronautics and Astronautics, Nanjing 210016, China

ABSTRACT

From March 20, 2019 to April 30, 2019, the 10th China Trajectory Optimization Competition (CTOC10) was jointly held by the Chinese Society of Theoretical and Applied Mechanics and Nanjing University of Aeronautics and Astronautics. The CTOC10 focused on trajectory optimization for Jovian exploration. The team from Harbin Institute of Technology won the first prize. In this paper, first, the history of the CTOC is presented. Subsequently, the mission of the CTOC10 is introduced, and an account of the final rankings of the competition is given. Finally, trajectory optimization methods are discussed, and suggestions for practical missions are provided.

KEYWORDS

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mission design
trajectory optimization
Jovian exploration

Review

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1 Introduction

Spacecraft (S/C) trajectories are designed and optimized on the basis of dynamic coupling, multiple constraints, consumption, as well as the mission scale and resources. Currently, trajectory design focuses on both the mission planning and the trajectory optimization while considering multiple factors. Existing optimization methods cannot provide a global optimal solution as some mission factors are difficult to optimize using mathematical methods [1].

The China Trajectory Optimization Competition (CTOC) series was established by Tsinghua University and the Chinese Society of Theoretical and Applied Mechanics in 2009 [1]. Inspired by the Global Trajectory Optimization Competition (GTOC) [2,3], CTOC focuses on the conceptualization and development of future space missions by improving the trajectory design and optimizing the capability of Chinese institutional affiliates through an exchange of novel space mission theories and techniques. It also promotes the development of related fields [1,3].

To ensure a scientific and fair competition environment, the champion of the current competition automatically acquires the right to host the next competition. Under this regulation, the CTOC has been successfully held ten times by several universities and institutes [1]. With the expansion of its influence, the CTOC has attracted international participants in recent years. Some basic information about the CTOC series, including holding years, mission descriptions, and previous champions, is presented in Table 1.

The 10th CTOC (CTOC10) was sponsored by the Chinese Society of Theoretical and Applied Mechanics and held by Nanjing University of Aeronautics and Astronautics [4,5]. This competition lasted for one and a half months, from March 20, 2019 to April 30, 2019, and 62 teams (including 8 international teams) contended for the first prize. Unlike the previous competitions, from CTOC6 to CTOC9, CTOC10 focused on a specific problem so that the participants could better gather their resources [1]. The CTOC10's challenge made it easy to submit a feasible solution, thus raising the enthusiasm of the participants, but a good result required a complicated optimization. The mission background of the CTOC10 concentrated on the exploration of the Jovian magnetic field and Galilean moons with a combined S/C. In this paper, a brief introduction to the problem is presented.

✉ lishuang@nuaa.edu.cn

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Table 1 History of CTOCs [1]

No.	Year	Mission topic	Champion
1	2009	Asteroid sample return	Institute of Optics and Electronics, Chinese Academy of Sciences
2	2010	Exploring Mars and multiple asteroids	Tsinghua University (TU)
3	2011	Exploring multiple planets and asteroids	Center for Space Science and Applied Research, Chinese Academy of Sciences (CSSAR)
4	2012	Exploring multiple asteroids	National University of Defense Technology (NUDT)
5	2013	Exploring two asteroids	Xi'an Satellite Control Center (XSCC)
6A	2014	Asteroid sample return	CSSAR
6B	2014	Heliocentric escape	NUDT
7A	2015	Exploring an irregular asteroid	CSSAR
7B	2015	Formation reconstitution	XSCC
8A	2016	Debris removing	Beijing Institute of Technology
8B	2016	Constellation design	TU
9A	2017	GEO monitoring	Nanjing University of Aeronautics and Astronautics
9B	2017	Constellation design	CSSAR

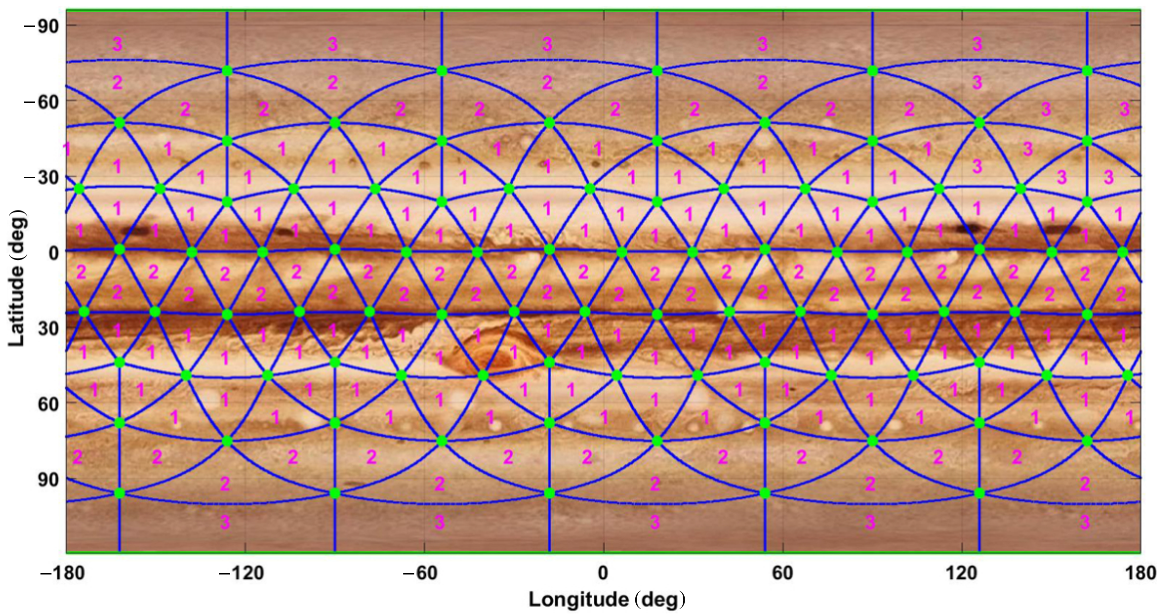

Fig. 1 Division of the Jovian magnetic field.

Then, the competition results and solutions are discussed.

2 Problem description

The Jovian system is the largest planetary moon system in the solar system. With the strongest magnetic field in the solar system and important Galilean moons, the Jovian system has a great scientific value for detection [6]. CTOC10 focused on the designing and optimizing the trajectory for exploring the Jovian magnetic field and the Galilean moons using a combined S/C within a specific time duration. In this section, the problem of CTOC10 is stated first. Then, the evaluation criteria and constraints are introduced.

2.1 Problem statement

2.1.1 Mission requirement

In this mission, a combined S/C, consisting of a main S/C and several probes, is provided to execute the exploration mission. The main S/C measures the Jovian magnetic field. The probes, which are released by the main S/C when it performs a fly-by, observe the Galilean moons.

As shown in Fig. 1, the Jovian magnetic field is divided into 180 triangular areas that are mapped on the Jovian surface. The main S/C needs to perform sampling for every triangular area to gain scores. There are extra scores if the subtasks are completed as requested. The main objective of the mission is to maximize the scores under specific conditions. The requirements of the main task and subtasks are as follows.

2.1.2 Main task

The main task is to achieve full-coverage measurement of the Jovian magnetic field, which requires the S/C to perform at least two and up to six samplings for all 180 areas within three years. The score of each sampling is calculated according to the basic score of every area shown in Fig. 1 and the sampling strategies. To ensure the timeliness of the sampling data, the interval between adjacent samplings for the same area is constrained as follows:

$$\begin{cases} t_{k2\mathrm{s}} - t_{k1\mathrm{s}} \leqslant 45 \text{ days} \\ t_{k3\mathrm{s}} - t_{k2\mathrm{e}} > 365.25 \text{ days} \\ t_{k4\mathrm{s}} - t_{k3\mathrm{s}} \leqslant 45 \text{ days} \\ t_{k5\mathrm{s}} - t_{k4\mathrm{e}} > 365.25 \text{ days} \\ t_{k6\mathrm{s}} - t_{k5\mathrm{s}} \leqslant 45 \text{ days} \end{cases} \tag{1}$$

where $t_{kj\mathrm{s}}$ and $t_{kj\mathrm{e}}$ represent the starting and ending moments of the jth sampling for area k (1–180). The calculation of the sampling score is presented in Section 2.2.1.

2.1.3 Subtask 1—fast coverage measurement

Subtask 1 requests a fast measurement of the magnetic field to avoid the disturbances due to Jovian radiation and the long-term evolution of the magnetic field. The main S/C is requested to perform at least two samplings for every triangular area within 300 days since the mission begins. The calculation of the extra score is included in Section 2.2.2.

2.1.4 Subtask 2—secular measurement

Subtask 2 requires a long time span of measurement to study the secular evolution of the magnetic field. An extra score can be obtained when the main S/C finishes at least four samplings for every triangular area. The calculation of the extra score is described in Section 2.2.2.

2.1.5 Subtask 3—Galilean moons observation

Subtask 3 aims to explore the Galilean moons with several probes. The main S/C can release a probe when performing a fly-by of the Galilean moons with an inbound hyperbolic excess velocity of less than 4 km/s. Only one probe can be released to each Galilean moon. The scores of each Galilean moon are provided in Section 2.2.2.

2.2 Scores and criteria

2.2.1 Sampling score calculation

In the Jovian magnetic field sampling mission, the evaluation criterion of every sampling consists of the basic score of the triangular area, which represents the sampling difficulty, and a sampling coefficient representing the sampling quality. The sampling score of certain area k is calculated as follows:

$$w_k = \varepsilon_j \cdot s_k \tag{2}$$

where s_k represents the basic score of area k and ε_j is a coefficient based on different sampling strategies. The basic scores for the 180 triangular areas are shown in Fig. 1. The nodes of every area are provided in the CTOC10 problem statement, which can be obtained on the Wechat official account (gh_108a7386647c). The sampling strategy is evaluated considering the Jovicentric distance and the sampling time, as presented in Table 2.

During each sampling, the projection of the main S/C's position on the Jovian surface must be inside the triangular area to measure the magnetic field of the corresponding triangular pyramid. The sampling schematic is shown in Fig. 2.

Furthermore, with a certain sampling strategy, the sampling value coefficient is acquired by satisfying the

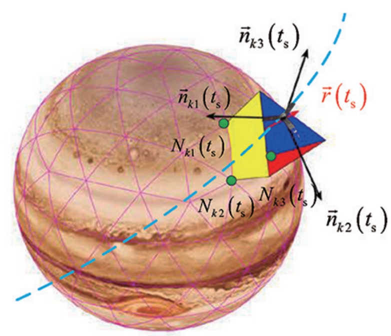

Fig. 2 Sampling schematic.

Table 2 Constraints and coefficients of sampling strategies

Sampling strategy	Jovicentric distance range	Required sampling duration (s)	Processing duration (s)	Sampling value coefficient ε
A	$1.05R_\mathrm{J} \leqslant r < 2R_\mathrm{J}$	30	300	1
B	$2R_\mathrm{J} \leqslant r < 4R_\mathrm{J}$	60	600	0.8
C	$4R_\mathrm{J} \leqslant r < 7R_\mathrm{J}$	120	1200	0.5

constraints given in Table 2. For each sampling strategy, the required durations are 30, 60, and 120 s, respectively. After each sampling, a processing duration which lasts 300, 600, and 1200 s for strategies A, B, and C, respectively, is required. Meanwhile, during each sampling, the Jovicentric distance of the main S/C must be maintained in a specific range, as provided in Table 2.

2.2.2 Evaluation criteria

The primary objective is to maximize the sum of the accumulated score as expressed in Eq. (3), which is equal to the weighted sum of the main task score W_0 and the three subtask scores W_1, W_2, W_3:

$$\mathrm{Obj}_1 = \frac{W_0}{6} + \frac{W_1}{2} + \frac{W_2}{2} + W_3 \tag{3}$$

The main task score W_0 is accumulated with the individual sampling scores as follows:

$$W_0 = \sum_{k=1}^{180}\sum_{j=1}^{l} w_{kj}, \quad l = 2,3,4,5,6 \tag{4}$$

where w_{kj} represents the score of the jth sampling for triangular area k.

W_1 is the score of subtask 1 (fast coverage measurement), which is calculated as follows:

$$W_1 = \max\left(0, 1 - \frac{\Delta T_{m1}}{300 \times 86400}\right) \times \sum_{k=1}^{180}\sum_{j=1}^{2} w_{kj} \tag{5}$$

$$\Delta T_{m1} = t_{m1\mathrm{e}} - t_0 \tag{6}$$

where ΔT_{m1} (s) represents the time span of the first full-cover measurement, which is the difference between the final moment of the last subtask 1 and the initial time of the mission. If the time span of subtask 1 is beyond 300 days, the extra score of subtask 1 is 0.

W_2 is the score of subtask 2 (secular measurement), which is obtained when the main S/C completes at least four samplings for every triangular area. The extra score W_2 is calculated as follows:

$$W_2 = \frac{\sum_{k=1}^{180}\left[(t_{k4\mathrm{s}} - t_{k3\mathrm{e}})(w_{k3} + w_{k4})\right]}{2 \times 365.25 \times 86400 + \Delta T_{m2}} \tag{7}$$

where ΔT_{m2} (s) represents the time span of the main S/C to perform the 3rd and 4th sampling of all areas, which is given as follows:

$$\begin{cases} \Delta T_{m2} = t_{4\max} - t_{3\min} \\ t_{4\max} = \max(t_{k4\mathrm{e}}), \quad k = 1,2,\cdots,180 \\ t_{3\min} = \min(t_{k3\mathrm{s}}), \quad k = 1,2,\cdots,180 \end{cases} \tag{8}$$

where $t_{4\max}$ is the maximum ending time of the 4th sampling, and $t_{3\min}$ is the minimum starting time of the 3rd sampling towards all 180 areas.

W_3 denotes the score of subtask 3 (Galilean moons observation), which is calculated as follows:

$$W_3 = \sum_{j=1}^{n} w_{\mathrm{G}j} \tag{9}$$

where n represents the number of probes to release and $w_{\mathrm{G}j}$ represents the exploration score of the jth probe. The exploration scores of the Galilean moons are presented in Table 3.

Table 3 Exploration scores of Galilean moons

Galilean moons	Io	Europa	Ganymede	Callisto
Score w_{G}	65	75	70	60

The secondary objective is to minimize the whole mission time, which is solved as follows:

$$\mathrm{Obj}_2 = \Delta T_{\mathrm{Mission}} = t_{\mathrm{e}} - t_0 \tag{10}$$

The secondary performance indexes take effect only if the primary performance indexes of the two results are equal.

2.3 Conditions and constraints

2.3.1 Dynamics

The motion of the combined S/C is considered under the dynamic model of Jupiter two-body problem with the Jovian J_2 term of non-spherical perturbation effect. The position and velocity of the S/C are propagated with numerical integration. The Jovicentric distance of the S/C must not be smaller than $1.05R_{\mathrm{J}}$ during the whole mission, where R_{J} is the Jovian radius. The specific values of the above parameters are provided on the Wechat official account.

The S/C adopts an impulse thruster with a specific impulse of 400 s to execute orbital maneuvers, which is simplified into instantaneous change of velocity as velocity increment (ΔV). The magnitude and direction of the ΔV are chosen arbitrarily. Remarkably, no maneuver is allowed during sampling.

As an efficient way to adjust the trajectory and reduce fuel consumption, the fly-by of Galilean moons is available. The fly-by trajectory is simplified by the patched conics method, and the time span of fly-by is omitted. The fly-by distance between the S/C and the

Galilean moon in Jovicentric frame must be smaller than 1 km. Meanwhile, the S/C's periapsis altitude in Galilean-moon-centric frame cannot be smaller than 50 km.

2.3.2 Initial states

For the combined S/C, the initial velocity magnitude is 4 km/s, the initial Jovicentric distance is $675R_{\mathrm{J}}$, and other initial orbital parameters can be chosen arbitrarily. The initial mass of the combined S/C is 2500 kg; the dry mass of the main S/C is 1100 kg, whereas the probe's mass is 200 kg. Three schemes are available according to the number of probes:

(1) 0 probe + 1400 kg available mass ($m_{\mathrm{fuel}} + m_{\mathrm{pen}}$)

(2) 1 probe + 1200 kg available mass ($m_{\mathrm{fuel}} + m_{\mathrm{pen}}$)

(3) 2 probes + 1000 kg available mass ($m_{\mathrm{fuel}} + m_{\mathrm{pen}}$)

where m_{fuel} and m_{pen} are the mass of the available fuel and the required radiation protection, respectively. The process of releasing a probe is simplified into an instantaneous mass reduction of the combined S/C at the end of the fly-by.

2.3.3 Radiation protection

Part of the available mass is transformed into the protection to avoid the damage from the Jovian radiation. The required mass for the radiation protective structure accumulates with the number of times of close approach to Jupiter. The penalty of available mass (kg) for each close approach is calculated as follows:

$$m_{\mathrm{pen}} = \begin{cases} 7 \times \left[\dfrac{1.05R_{\mathrm{J}}}{a(1-e)}\right]^2 \left(1 + \dfrac{R_{\mathrm{J}}}{R_{\mathrm{J}} + 2ae}\right) \dfrac{(1+\eta)}{4}\dfrac{(1+|\cos i|)}{2}, & e \in [0,1) \\ 7 \times \left(\dfrac{1.05R_{\mathrm{J}}}{p/2}\right)^2 \dfrac{(1+\eta)}{4}\dfrac{(1+|\cos i|)}{2}, & e = 1 \\ 7 \times \left[\dfrac{1.05R_{\mathrm{J}}}{a(1-e)}\right]^2 \dfrac{(1+\eta)}{4}\dfrac{(1+|\cos i|)}{2}, & e \in (1,\infty) \end{cases} \tag{11}$$

$$\eta = \begin{cases} \mathrm{sgn}\left(2 + 17|\cos i| - \dfrac{a(1-e)}{R_{\mathrm{J}}}\right), & e \neq 1 \\ \mathrm{sgn}\left(2 + 17|\cos i| - \dfrac{p}{2R_{\mathrm{J}}}\right), & e = 1 \end{cases} \tag{12}$$

where a, e, and i are the semi-major axis, eccentricity, and inclination of the orbit, respectively, and p is the semi-latus rectum of the parabola, $p = a(1-e^2)$.

2.3.4 Time constraints

The mission epoch range is [62502, 63962] (modified Julian date (MJD)). The time span of the whole mission is no longer than three years.

3 Competition results

After 42 days of competition, 18 effective final results were submitted before the deadline. Remarkably, this was the first time that an international team submitted an effective result to the CTOC. The team from Harbin

Table 4 CTOC10 competition results

Rank	Institutional affiliations	Obj_1	Obj_2
1	Harbin Institute of Technology (HIT)	357.81	94,592,916.02
2	NUDT, Yazhong Luo (Team L)	354.50	94,620,203.18
3	NUDT, Hongbo Zhang (Team Z)	332.14	94,553,331.00
4	XSCC	330.44	89,870,207.39
5	Beijing Aerospace Control Center (BACC)	310.20	94,423,265.18
6	Northwestern Polytechnical University (NPU), Binfeng Pan (Team P)	300.88	91,260,013.00
7	Jena University, Germany (JU)	293.72	94,505,114.86
8	Beijing Institute of Remote Sensing Information (BIRSI)	273.18	94,052,365.00
9	National Space Science Center (NSSC)	269.20	94,587,092.01
10	Technology and Engineering Center for Space Utilization, Chinese Academy of Sciences (CSU)	262.50	92,297,209.28
11	China Academy of Space Technology (CAST)	236.23	94,498,219.86
12	TU	222.52	94,508,046.00
13	NPU, Minghu Tan (Team T)	172.91	15,529,275.00
14	Astrocontrol Sci & Tech Co., Ltd. (AST Co., Ltd.)	147.80	94,577,353.00
15	Xi'an Jiaotong University (XJTU)	124.50	20,047,197.62
16	China Academy of Launch Vehicle Technology (CALT)	115.58	92,163,523.37
17	Sun Yat-sen University (SYSU)	110.90	91,589,549.00
18	Information Engineering University (IEU)	46.57	86,376,846.05

Table 5 Scores of every task

Affiliations	Main	Subtask 1	Subtask 2	Subtask 3
HIT	1523.90	186.81	20.83	0.00
NUDT, Team L	1551.00	180.62	11.17	0.00
NUDT, Team Z	1516.50	156.80	1.99	0.00
XSCC	1544.00	135.42	10.79	0.00
BACC	1438.60	136.56	4.30	0.00
NPU, Team P	1209.90	182.86	15.61	0.00
JU	1439.90	93.93	13.55	0.00
BIRSI	1101.30	161.53	17.72	0.00
NSSC	1180.20	137.62	7.38	0.00
CSU	705.00	0.00	0.00	145.00
CAST	1319.10	31.12	1.64	0.00
TU	1192.70	33.04	14.44	0.00
NPU, Team T	471.00	188.81	0.00	0.00
AST Co., Ltd.	886.80	0.00	0.00	0.00
XJTU	444.70	100.76	0.00	0.00
CALT	685.80	0.00	2.56	0.00
SYSU	664.40	0.00	0.33	0.00
IEU	279.40	0.00	0.00	0.00

Institute of Technology won the competition and obtained the right to host the next CTOC [1]. The final ranking and their objectives are listed in Table 4. The scores of every task are listed in Table 5. Further improvements have been made after the competition. Obj_1 was improved to 359.8 by NUDT (Team L).

4 Discussion

4.1 Analysis of mission design difficulty

According to the mission description, the main task requires repetitive sampling of the Jovian magnetic field, which demands high-inclination sampling around Jupiter. Subtask 1 requests a quick full cover of the field. Thus, quick insertion and a short orbital period for the sampling orbit are demanded. Subtask 2 involves a long time period between the 3rd and the 4th full cover sampling, and subtask 3 asks for a low inclination of the transfer orbit to satisfy the inbound hyperbolic excess velocity constraint.

Therefore, the three mission design difficulties are summarized by the participants as follows:

1) The scheme of the combined S/C, transfer strategy, and configuration of the sampling trajectory are the decision variables that are considered in the top-level strategy design process [1]. Furthermore, although these variables directly influence the final result, they cannot be optimized with a computer algorithm, which increases the optimization difficulty of the mission.

2) The available mass of the combined S/C is limited, which restricts the orbital maneuvers for transfer and adjustment, the mass for Jovian radiation protection, and the number of probes for Galilean moon exploration.

3) The sampling sequence of Jovian magnetic fields of the 180 triangular areas is difficult to optimize. As there is a processing duration constraint, the sampling of a certain area has an influence on the samplings of the neighboring areas, which is decided by the sampling trajectory. This optimization problem is a travel salesman problem (TSP) with a massive data volume.

4.2 Optimization process

As this mission involves some decision variables that are difficult to optimize, the conventional optimization methodology for previous CTOCs, which consists of a global search and a local optimization, is insufficient. Therefore, differing from the conventional processes, another process that artificially designs these variables is added and performed by the participants. In this paper, this extra process is called the mission design process, and the flow chart of the optimization process of this mission can be generalized as shown in Fig. 3. In the mission design process, the sampling and transfer strategies are designed manually. Then, the transfer and sampling trajectories are optimized in the global search process, which is similar to the conventional methodology. Finally, the maneuvers, radiation protection, and sampling sequence are optimized in the local optimization process, and the complete trajectory of the combined S/C is obtained.

In the mission design process, the scheme of the combined S/C, transfer strategy, and configuration of the sampling trajectory are artificially designed. These variables are decided mainly on the basis of the participants' experiments and the early analysis of the mission. Then, in the global search and local optimization process, the optimal trajectory is obtained with common optimization methods and algorithms. Therefore, this mission design process is the foundation of trajectory optimization.

For this mission, considering the main task of the mission, the first variable to design is the configuration of the sampling trajectory. The participants highlight the requirement of a small semi-major axis a, which represents a small orbital period, a low orbital periapsis r_{p}, and a high inclination i for the combined S/C with acceptable radiation protection mass. The quasi

Table 6 Sampling trajectory and sampling distribution

Affiliations	a (R_J)	T (day)	$r_p(R_J)$	i (°)	Total	A	B	C	M_{pen} (kg)
HIT	8.01	2.80	1.44	90	1080	848	191	41	352.23
NUDT, Team L	8.55	3.09	1.24	90	1080	881	193	6	408.97
NUDT, Team Z	9.72	3.74	1.38	76	1080	818	226	36	348.52
XSCC	8.51	3.09	1.40	90	1080	856	208	16	329.01
BACC	9.60	3.68	1.13	94	1042	639	268	81	463.16
NPU, Team P	7.45	2.51	2.00	90	1080	0	926	154	0
JU	9.77	3.77	1.25	79	1044	768	222	54	408.57
BIRSI	7.08	2.33	2.00	90	1080	0	589	391	0
NSSC	7.30	2.44	2.05	90	1032	0	975	57	0
CSU	8.08	2.84	1.08	76	590	360	32	198	147.15
CAST	8.98	3.32	1.30	90	1062	561	193	308	362.16
TU	10.34	4.11	1.05	88	925	538	200	187	454.66
NPU, Team T	5.71	1.68	1.05	100	360	187	130	3	92.70
AST Co., Ltd.	14.64	6.92	3.06	72	799	0	681	118	35.45
XJTU	8.19	2.89	1.08	85	360	220	45	95	74.16
CALT	10.62	4.37	4.34	77	840	0	138	702	32.97
SYSU	16.54	8.31	3.90	90	720	0	288	432	0
IEU	12.81	5.66	4.00	90	360	0	14	346	0

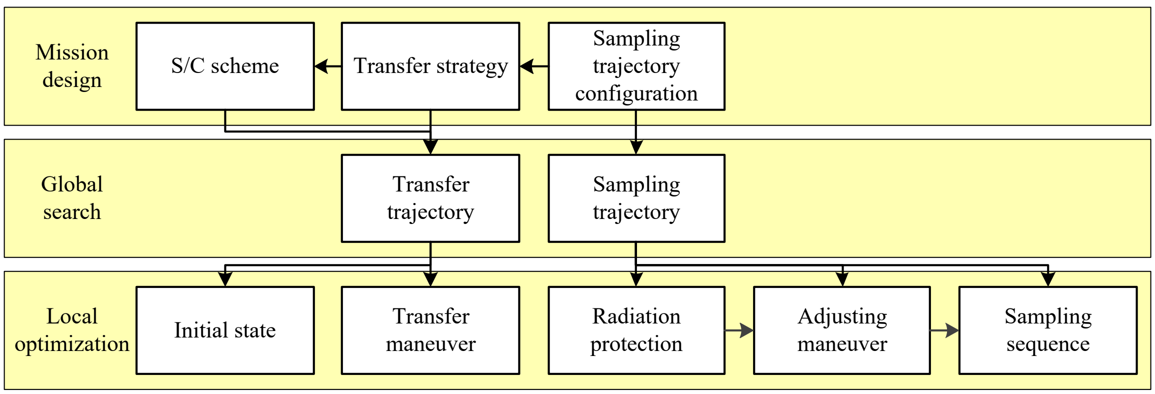

Fig. 3 Flow chart of optimization.

repeated-ground-track orbit is applied to guarantee a repetitive sampling effect. The radiation protection mass is then estimated. The configurations of the sampling trajectories and achieved sampling times are presented in Table 6. As can be observed, the top-score teams apply a sampling trajectory with lower orbital periapsis and a shorter period, completing all the possible samplings. In the end, this sampling trajectory provides these teams with a better rank. Therefore, this decision variable has a direct influence on the final solution. Besides, there is no apparent convergent trend of the top sampling trajectory configurations, which makes it difficult to optimize this variable using an optimization algorithm.

Then, the participants indicate that the transfer trajectory decides the scheme of the S/C. The second step in the mission design process is to decide the transfer strategy. According to the mission, subtask 1 demands high-inclination sampling in a short time, whereas subtask 3 involves low-inclination orbit insertion with long time transfer. It is difficult to achieve both subtasks with limited fuel. Therefore, the main purpose of the transfer strategy design is to construct the transfer trajectory that connects the sampling trajectory and to achieve either subtask 1 or subtask 3. Following the transfer strategy, the scheme and initial state of the combined S/C are obtained. The characteristics of the transfer strategy and obtained trajectory are listed in Table 7. It can be found from Table 7 that most of the teams choose scheme 1 as the combined S/C and apply large orbit maneuvers and finite fly-bys to construct the transfer trajectory, which indicates that the score of subtask 1 is greater than that of subtask 3. Similarly, the design of the transfer strategy is difficult to optimize using an optimization method. It requires a substantial amount of analysis of the potential

Table 7 Transfer trajectory

Affiliations	i (°)	ΔV (km/s)	Gravity assist	Scheme
HIT	93	2.05	3	1
NUDT, Team L	90	1.93	3	1
NUDT, Team Z	76	1.96	—	1
XSCC	80	2.19	4–3	1
BACC	94	1.73	—	1
NPU, Team P	90	3.06	—	1
JU	63	1.93	4–3-3	1
BIRSI	90	3.22	—	1
NSSC	90	3.17	—	1
CSU	0	2.01	Multiple	3
CAST	90	2.03	—	1
TU	88	1.60	—	1
NPU, Team T	100	2.83	—	1
AST Co., Ltd.	0	3.03	Multiple	1
XJTU	66	2.00	4–3-3-3	1
CALT	72	2.72	Multiple	1
SYSU	90	2.06	—	1
IEU	90	3.16	1	1

score of the subtask and needs to be decided manually.

In this mission design process, the decision variables that cannot be optimized using an optimization method are artificially designed. Then, the global search and local optimization processes can be carried out based on the conventional methodology.

4.3 Transfer trajectory optimization

The second difficulty focuses on the employment of the available mass of the combined S/C. As the radiation protection mass during sampling can be evaluated in the mission design process, the rest of the available mass is mainly employed for the transfer trajectory. The transfer trajectory is related to subtask 1 and subtask 3, which construct two different types of trajectory. The ΔV consumptions and fly-by strategies for the transfer trajectories are included in Table 7.

Considering subtask 1, the transfer trajectory requires to insert the main S/C in the targeted sampling trajectory using the minimum time of flight (TOF). In this case, Galilean moon fly-by, as indicated in Table 7, is still practicable to further reduce the fuel for the Jovian capture. The transfer trajectory optimization problem is then transformed into a time-optimal trajectory optimization problem. This is different from previous competitions where a fuel-optimal trajectory is always desired. Besides, the minimum TOF transfer trajectory allows the main S/C to complete all six samplings for every triangular area (1080 samplings in total). However, heuristic optimization methods, such as the differential evolution (DE), genetic algorithm (GA), and ant colony optimization (ACO), are employed by the top-scoring teams to obtain the time-optimal transfer trajectory and maximize the score of subtask 1, as presented in Table 7. Thus, this demonstrates the effectiveness of heuristic methods for solving the optimization problem. For example, the HIT team applied a GA to optimize the TOF and propulsion consumption (ΔV) [7]. The transfer trajectory submitted by the HIT team is shown in Fig. 4. The initial state of this high-inclination trajectory is indicated in Table 7. With two impulses and a Ganymede fly-by, the main S/C spends 111.890 days transferring to the sampling trajectory. This type of transfer trajectory helped the top-scoring teams, including the HIT team, to complete all the 1080 samplings and maximize the main task and subtask scores listed in Table 7.

The team from the Technology and Engineering Center for Space Utilization, Chinese Academy of Sciences (CSU, CAS) adopts subtask 3 and constructs the transfer trajectory. The transfer trajectory of the CSU team is exhibited in Fig. 5. In total, 147 impulses and 60 fly-bys are executed to raise the inclination from 0° to 76° during the transfer. Owing to the time consumption for the multiple fly-bys using the Galilean moons, the TOF

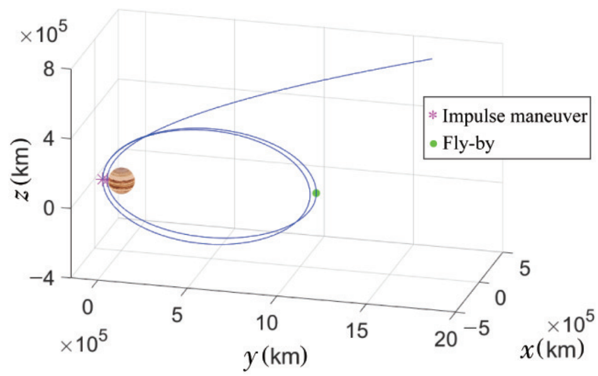

Fig. 4 Transfer trajectory applied by the HIT team with two impulses and one fly-by (TOF = 111.890 days) [7].

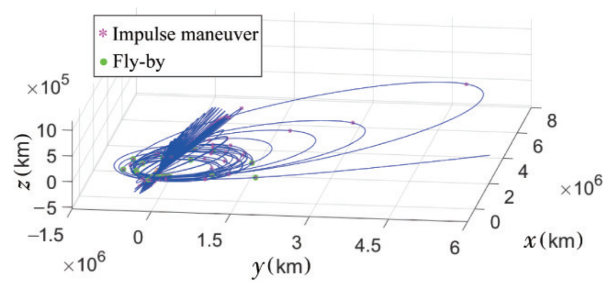

Fig. 5 Transfer trajectory applied by the CSU team with 147 impulses and 60 fly-bys (TOF = 924.743 days).

of the transfer trajectory is approximately 924.743 days. Remarkably, to search the solution space sufficiently, the CSU employs a V_∞ constricted transfer method instead of the conventional Lambert method to optimize the multiple fly-by sequence. This method can clearly increase the optimization efficiency. Then, a backflip method is employed to increase the orbital inclination and to connect the transfer trajectory with the sampling trajectory. However, although the obtained multiple-fly-by transfer trajectory efficiently reduces the fuel consumption and completes subtask 3, the time consumption for the transfer is excessive. As indicated in Table 6, the CSU team could not complete all the 1080 samplings as the top-score teams did, which limits the score of the main task. Furthermore, after the competition, Team L of NUDT provided an analytical method for estimating the TOF for the resonance fly-by. This geometric method calculates the TOF of an equatorial trajectory to a polar trajectory considering the variation in velocity. Team L of NUDT stated that it takes at least 400 days to finish raising the inclination, and hence, the fifth and sixth samplings are impractical. Therefore, Team L of NUDT abandoned subtask 3 and concentrated on subtask 1.

4.4 Sampling sequence optimization

The sampling sequence is optimized in the local optimization process. The sampling sequence optimization is different from that of the previous CTOCs, in which the orbital maneuver is the target to be optimized. The sampling sequence is determined by the sampling trajectory, which is mainly constructed using a quasi repeated-ground-track orbit. However, owing to the J_2 term of non-spherical gravity perturbation, the argument of the periapsis drifts over time. Taking the sampling trajectory employed by the HIT team as an example, the argument of the periapsis drifts over 180° during the sampling, as shown in Fig. 6 [7]. The cyan lines represent the sampling trajectory and the purple lines represent the first and last trajectories of each two full-convergence samplings. As the periapsis evolves, it is unavailable to hold a stable sampling behavior to generate the sequence.

Some teams apply extra orbital maneuvers for slightly adjusting the sampling trajectory and the sampling sequence. Meanwhile, the time duration constraints for sampling and data processing affect the feasibility of the sequence. This optimization becomes a mixed-integer

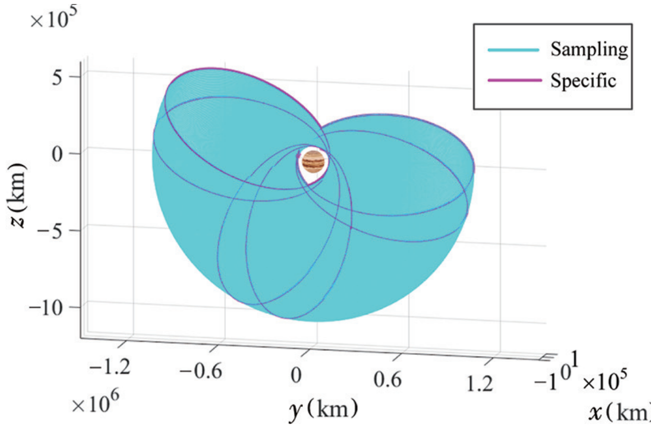

Fig. 6 Sampling trajectory of HIT team.

programming problem with more than 1000 samplings. To optimize the sequence, some of the teams perform a simple strategy by sequentially managing the sequence according to the time. However, this sequential management neglects the optimality of the subtasks. The top-score teams apply optimization methods to optimize the trajectory maneuver and sampling sequence. In their methods, the sampling sequence is optimized with operations such as verification and removal. The corresponding methods are detailed in the reference papers. Then, both the sampling sequence and orbital maneuver are optimized using a heuristic optimization algorithm, such as DE, GA, and ACO. The extra orbital maneuver consumptions are listed in Table 8. According to Table 6, the top-score teams complete over 800 samplings with strategy A, which results in maximized scores for subtask 1 and subtask 2, as presented in Table 7. To realize these solutions, the extra ΔV consumptions from Table 8 are acceptable. Therefore, heuristic algorithms such as DE, GA, and ACO are promising technologies for the trajectory optimization problem, which can be described as a mixed-integer programming problem.

4.5 Practical mission suggestions

The main purpose of this competition is to study the mission and the corresponding trajectory design for sampling the Jovian magnetic field and cycling around the Galilean moons with a combined S/C. According to the submitted solutions, some suggestions for a practical Jovian exploration mission are summarized as follows:

1) The Jovian full-cover exploration mission, including the magnetic field exploration, requires a high orbital inclination around Jupiter. In this case, the efficiency of the common Galilean moons multiple fly-by trajectories

Table 8 Extra consumptions

Affiliations	Maneuvers (times)	ΔV (m/s)
HIT	5	71.60
NUDT, Team L	3	53.00
NUDT, Team Z	2	1.28
XSCC	2	0.01
BACC	1	75.00
NPU, Team P	0	0
JU	254	12.63
BIRSI	0	0
NSSC	0	0
CSU	0	0
CAST	0	0
TU	0	0
NPU, Team T	0	0
AST Co., Ltd.	0	0
XJTU	0	0
CALT	0	0
SYSU	0	0
IEU	0	0

for Jovian insertion and increase in inclination is insufficient for a lifetime-limited S/C. A large orbital maneuver consumption ΔV for Jovian capture is necessary. Besides, the capture trajectory can still contain one or two fly-bys to further reduce the fuel consumption, and the efficient moons for fly-by are Ganymede and Callisto.

2) The mission of a full-cover Jovian exploration with a S/C and cycling around the Galilean moons with a probe is contradictory. The constraints of the orbital inclination and the transfer time restrict the release and gravity capture of the probe. Therefore, the appropriate way for Galilean moons exploration comprises fly-by measurement with the S/C and roving exploration with a lander.

3) Considering the time durations for sampling and data processing, a lifetime-limited S/C can still achieve a full cover of the Jovian magnetic field, which is divided into 180 triangular areas, in one year. A higher frequency of sampling for the Jovian magnetic field measurement is feasible according to the submitted solutions. In this case, sufficient consideration of the sampling efficiency, Jovian radiation, and feasible fuel is indispensable for designing the sampling strategy and optimizing the corresponding trajectory.

5 Conclusions

CTOC10 concentrated on optimizing the exploration trajectory of the Jovian magnetic field and the Galilean moons. The purpose of the competition was to attract more submissions and to rank the submitted solutions according to the skills of the participants. Furthermore, the challenge had some difficult-to-optimize decision variables, highlighting the experiences and analyses of the participants with respect to the space mission. According to the submitted solutions, the mission design rests on decision variables that may not be optimized using mathematical algorithms. For the global and local optimizations, heuristic algorithms show promise for sequence and trajectory maneuver optimization. Furthermore, in a practical mission, a few Galilean moon fly-bys and large orbital maneuvers are necessary for Jovian full-cover exploration. The sampling efficiency, Jovian radiation, and a feasible fuel should be sufficiently considered during the mission design.

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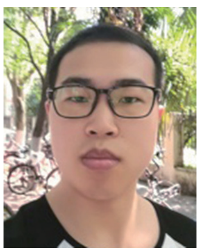
Xuxing Huang received his B.S. degree in space science and technology from the Harbin Institute of Technology, China, in 2012. He is currently pursuing his Ph.D. degree in flight vehicle design at Nanjing University of Aeronautics and Astronautics. He won the champion of the 9th China Trajectory Optimization Competition. He is hosting the Postgraduate Research & Practice Innovation Program of Jiangsu Province. His research interests include the trajectory design and optimization and the secular evolution analysis under multiple perturbations.



Bin Yang received his B.S. degree in detection guidance and control technology from the Department of Astronautics Control at Nanjing University of Aeronautics and Astronautics, China, in 2016. He is currently pursuing his M.S. degree in flight vehicle design at Nanjing University of Aeronautics and Astronautics. He has received the winning prize at the 8th China Space Orbit Design Contest. His research interests include interplanetary mission design and analysis, and low-thrust trajectory optimization. E-mail: binyang@nuaa.edu.cn.

Pan Sun received her B.S. degree in flight vehicle design and engineering from Nanjing University of Aeronautics and Astronautics, China, in 2018. Currently, she is pursuing her Ph.D. degree in spacecraft design at College of Astronautics, Nanjing University of Aeronautics and Astronautics. She is hosting the Postgraduate Research & Practice Innovation Program of Jiangsu Province. Her research interests include interplanetary mission design and analysis, quantification of uncertainty and space debris passive deorbiting. E-mail: sunpan@nuaa.edu.cn.

Shuang Li received his B.S.E, M.S.E, and Ph.D. degrees from the Department of Aerospace Engineering at Harbin Institute of Technology, China, in 2001, 2003, and 2007, respectively. Since 2007, he has been with the College of Astronautics, Nanjing University of Aeronautics and Astronautics, China, where he is a full professor now. He was also a visiting scholar at the Department of Mechanical and Aerospace Engineering, University of Strathclyde in 2012–2013. He is the author of over 100 articles in reputable journals and conference proceedings. His research interests include spacecraft dynamics and control, deep space exploration, spacecraft autonomous guidance navigation and control, and astrodynamics. He has undertaken and is conducting up to 40 projects sponsored from the Chinese government and the aerospace enterprises in the fields above. E-mail: lishuang@nuaa.edu.cn.

Hongwei Yang received his B.S. degree from the Department of Engineering Mechanics at Shandong University, China, in 2012 and Ph.D. degree from the School of Aerospace Engineering at Tsinghua University, China, in 2017. Since 2017, he has been with the College of Astronautics, Nanjing University of Aeronautics and Astronautics, China, where he is an associate professor now. He is also a recipient of the Young Elite Scientists Sponsorship Program by China Association for Science and Technology (CAST). His current research interests include astrodynamics, spacecraft guidance and control. E-mail: hongwei.yang@nuaa.edu.cn.