SPACECRAFT FORMATION FLYING AROUND DOUBLE CENTRAL BODIES

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Abstract: *Spacecraft formation flying around Single Central Body (SCB) has become more viable and valuable since the 20th century. This paper brings up a new idea—Spacecraft Formation Free-Flying (SFFF) under gravitational attractions of Multiple Central Bodies (MCB), and mainly describes SFFF under the gravitational attractions of "the Earth and the Moon" Double Central Bodies (SFFF of "E+M" DCB). Firstly, according to the basic theories of Two-Body problem, the common orbital design constrains of SFFF under the gravitational attractions of Single Central Body (SFFF of SCB), and by using Systems Tool Kit (STK) as an important analysis and design software, a preliminary orbital (or trajectory) design method is put forward for SFFF of "E+M"DCB; based on a typical example for SFFF of "E+M" DCB on an Earth-to-Moon transfer orbit which takes spacecrafts 116 hours to fly from about 200km near the Earth to about 200km near the Moon and with a 90° inclination relative to the moon's equator, the stability of SFFF of "E+M" DCB is clarified since there is almost no divergence on the baseline formed by the spacecrafts. And then, some characteristics of SFFF of "E+M" DCB are analyzed by adjusting the spacecrafts' kinematic state parameters. Finally, some possible applications of this new type of SFFF are predicted, including two new mission concepts. It is worth mentioning that the research of this paper can also be easily extended into interplanetary exploration and travel.*

Keywords: *Spacecraft Formation Free-Flying (SFFF), "the Earth and the Moon Double Central Bodies" ("E+M" DCB), preliminary orbital (trajectory) design, stability of baseline, Systems Tool Kit (STK)*

1. Introduction

As a new idea, Spacecraft Formation Free-Flying (SFFF) under the gravitational attractions of Multiple Central Bodies (MCB) is formed by N (≥2) spacecrafts free-flying in formation under the gravitational attractions of at least two celestials without or with only a little maneuver. Compared to SFFF around Single Central Body (SCB), it has three main differences [1-2]:

a) **Attracted by multiple central bodies.** Every spacecraft flies cross least one central bodies' Sphere of Influence (SOI), which makes it difficult to model their orbits;

b) **Obvious orbital changes.** Their osculating orbit roots change obviously. For instance, in Earth-to-Moon transfer, the spacecrafts' orbits with respect to the geocenter may be elliptical, while those with respect to the selenocenter must be hyperbolic;

c) **The variations of the spacecrafts' relative motions are aperiodic.** Usually, the relative motions for SFFF of SCB change periodically because the spacecrafts' absolute orbits are closed and periodic. However, the spacecrafts' absolute orbits in SFFF of MCB are unclosed and aperiodic, so the variations of their relative motions would also be aperiodic.

Due to the above differences, people may find it complicate to actually form SFFF of MCB. However, disregarding these complicities, it is imaginable that its spacecrafts will also be very cooperative when fulfilling a space mission, because essentially, it is a new type of formation flying. Therefore, just like the traditional formation flying, SFFF of MCB would also have the "three-high" benefits: high accuracy, high resolution and high reliability [3-5]. Moreover, because more celestials are involved, SFFF of MCB can be applied to some new fields such as simultaneous observation of multi-points in deep space and even on-orbit lifesaving for interplanetary travel.

This paper mainly describes SFFF of "E+M" DCB. It contains four sections: the method of preliminary orbital design (including an example of SFFF in Earth-to-Moon transfer), characteristic analysis of SFFF of "E+M" DCB, two new mission concepts and the general orbital design method of SFF of MCB.

It should be emphasized that Systems Tool Kit (STK) is often regarded as the most significant COTS in space mission analysis and design. Therefore, the relative analyses and designs in this paper are also based on STK [6-8].

2. The method of preliminary orbital design

This section focuses on the preliminary orbital design of SFFF of "E+M" DCB. For the spacecrafts, one of them is regarded as Reference Spacecraft (RS), and the others are called as Accompanying Spacecraft (AS).

For simplicity, the subscripts R and A are used to represent RS and AS in the following.

2.1 Orbital design of RS

Apparently, the issue this paper mainly describes is a Three-Body problem, so the appropriate way to figure out RS' orbit is using **Patched-conic Approximation (PCA)**, *i.e.,* **to break DCB into two regions, and consider only the gravitational attraction on the spacecrafts from one body in each region** [9]. By looking at the problem with respect to one attracting body at a time, the initial Three-Body problem has "degenerated" into double Two-Body problems.

However, because of "approximation", **PCA can only helps to find a rough orbit for RS; for the precise one, STK is very effective for searching it** [6].

Based on a typical example of Earth-to-Moon transfer, the following text aims at clarifying the stability of SFFF of "E+M" DCB.

Assume that the injection point of the Earth-to-Moon transfer orbit is 10 Jun 2013 19:29:06.21 UTCG. It takes RS 116 hours to transfer to the Moon at 15 Jun 2013 15:32:09 UTCG, and the orbit is with a 90° inclination relative the Moon's equator. At 14 JUN 2013 22:20:09.21, RS enters the Moon's SOI when its geocentric distance is 382708km.

The orbit is roughly figured out by PCA, and adjusted by STK. The corresponding orbital roots are with respect to the geocenter; besides, RS' position vector and velocity vector are based on J2000.0 Earth-Centered Inertial (ECI) Coordinate System. When using STK, the integration method is RKF7 (8), and the force model of Earth-to-Moon transfer is determined by the Earth gravitational model WGS84 with maximum degree and order 8. Meanwhile, the gravitational perturbations of the sun and the Moon should also be involved.

Figure 1 shows a 2D map projection, in which the yellow one is RS' track of sub-satellite point, and the moment is when RS approaches the Moon. It is clear that the motions of RS and the Moon are almost in the Earth equatorial plane.

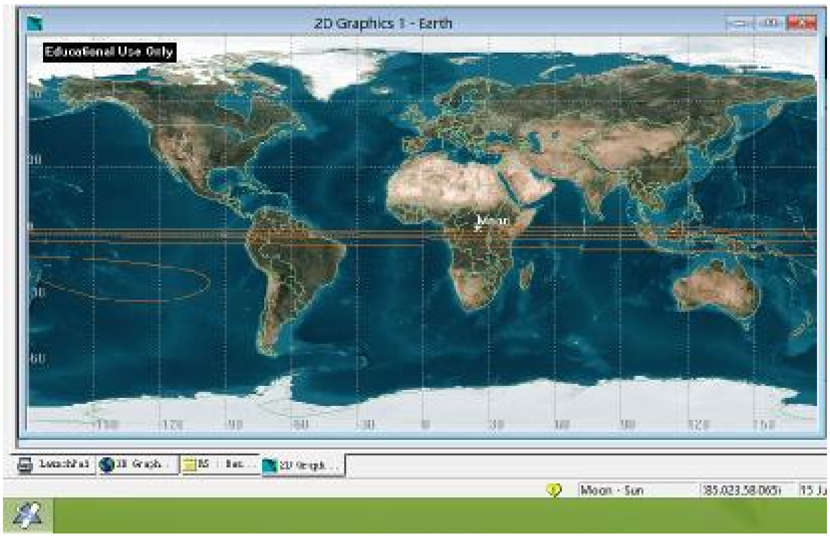

Fig. 1 The 2D map projection of RS' orbit

Figure 2 gives two 3D images which represent the movement when RS is near the Earth and near the Moon separately.

(a) Near the Earth **(b) Near the Moon**

Fig.2 The 3D images of RS' orbit (Inertial coordinate)

Figure 1 and 2 indicate that RS' orbit here is just a typical sample, because actually the orbit is not only near the Earth, but also near the Moon. Therefore, in the real transfer, the two celestials would provide more gravitational attractions, which lead the spacecraft's osculating orbit to change obviously.

It is convenient for orbital analysis and design by using spherical coordinate system to describe RS' kinematics states. In STK, the position vector is represented by right ascension a, declination d, and radius r, while the velocity vector is represented by elevation H, azimuth A and velocity v.

Table 1 shows the kinematic states of RS in the forms of osculating orbital roots, Cartesian coordinates, and Spherical coordinates. Based on the initial states of RS (when it is at the injection point), predict its position vector and velocity vector when it is about $20×10^4$, $30×10^4$ and $38×10^4$ km away from the Earth. In fact, its osculating orbital roots and spherical coordinates can be reported directly by STK.

Tab.1 The kinematic states of RS

r_R *	Osculating orbital roots					
	a_R(km)	e_R	i_R	w_R	Ω_R	f_R
0	206493.174	0.968175	$30°59'09''.18$	$185°11'57''.59$	$159°54'27''.27$	$359°53'04''.29$
20	199851.656	0.967231	$31°10'38''.04$	$185°20'22''.92$	$159°44'49''.38$	$165°18'00''.41$
30	199473.870	0.967915	$32°20'30''.36$	$185°22'07''.34$	$159°33'04''.70$	$171°47'53''.50$
38	198617.046	0.974842	$48°46'01''.22$	$184°28'54'''.81$	$160°06'40''.25$	$177°56'45''.20$
r_R	Cartesian coordinates					
	X_R	Y_R(km)	Z_R(km)	$\dot{X}_R$(km/s)	$\dot{Y}_R$(km/s)	$\dot{Z}_R$(km/s)
0	6318.870756	-1779.848397	-299.800557	2.285506	9.097749	-5.602427
20	-175470.286872	94403.272498	-16836.260600	-1.357406	0.380878	0.068106
30	-276360.953057	116414.787458	-7932.117235	-0.796204	0.118784	0.105661
38	-363196.566764	120030.918366	12191.665520	-0.240934	-0.034193	0.130205
r_R	Spherical coordinates					
	a_R	d_R	r_R(km)	H_R	A_R	v_R(km/s)
0	$344°16'08''.27$	$-2°36'53''.20$	6571.596	$-0°03'24''.50$	$120°53'10''.68$	10.926105
20	$151°43'10''.86$	$-4°49'47''.43$	199963.144	$75°17'30''.21$	$59°09'42''.70$	1.411474
30	$157°09'25''.70$	$-1°30'54''.64$	299984.496	$73°05'16''.05$	$57°41'23''.63$	0.811920
38	$161°42'42''.94$	$01°49'31''.94$	382708.277	$53°34'29''.142$	$41°15'30''.60$	0.275992

* unit: $×10^4$km, same with the first column of the following tables

0—the geocentric radius is 0km (injection point) at the orbit epoch 10 Jun 2013 19:29:06.21 UTCG

20—the geocentric radius is about $20×10^4$km at the orbit epoch 11 Jun 2013 19:14:06.21 UTCG

30—the geocentric radius is about $30×10^4$km at the orbit epoch 12 Jun 2013 22:08:06.21 UTCG

38—the geocentric radius is about $38×10^4$km(the moment of the Moon's SOI) at the orbit epoch 14 Jun 2013 22:20:06.21 UTCG

2.2 Reviews on the orbital design of SFFF of SCB

According to the basic Two-Body theories, in order to let spacecrafts free-flying in formation, among the five orbit element roots, that is the eccentricities e, inclinations

i, arguments of perigee w, right ascensions of ascending nodes (RAAN) Ω, and true anomaly f, at least one of these five should be slightly different , but the semi-axes a should be the same in order to avoid the divergence of SFFF configuration.

How to realize the equal semi-axes?

Equation 1 is the well-known **vis viva equation** (here, the Latin word "vis viva" means kinetic energy),

$$v^2 = m(\frac{2}{r} - \frac{1}{a}) \qquad (1)$$

where v is a spacecraft's velosity, m is a constant (which is the production of the gravitational constant G and the mass M of the central body), r is a spacecraft's distance from a central body, and a is semi-axis of a spacecraft's orbit.

According to Equation 1, in order to make $a_R = a_A$, let scalars $r_R = r_A$ and $v_R = v_A$ directly. But in order to let the other five orbital roots have slight differences, the position vectors of RS and AS should be a little different from each other.

Again, according to the Two-Body theories, six static volumes are necessary to determine a spacecraft's orbit. When the velocity vectors are fixed ($\dot{X}_R = \dot{X}_A$, $\dot{Y}_R = \dot{Y}_A$, $\dot{Z}_R = \dot{Z}_A$), and $r_R = r_A$, two static volumes about the direction of the position vector are still unconstrained.

How to change the direction of the position vector?

There are Two spherical constrains:

Assume that the length of the baseline between RS and AS is Δr, so

$$\sqrt{(X_A - X_R)^2 + (Y_A - Y_R)^2 + (Z_A - Z_R)^2} = \Delta r \qquad (2)$$

Besides,

$$\sqrt{X_A{}^2 + Y_A{}^2 + Z_A{}^2} = r_R \qquad (3)$$

Equation 2 determines a sphere centered on RS and with Δr as radius, and AS locates on it; Equation 3 determines a sphere centered on a central body and with r_R as radius, and AS also locates on it. Therefore, the simultaneous equation of Eq.2 and Eq.3 represents the overlap of the two spheres, whose shape is actually a ring, and AS is actually restricted on it. Otherwise SFFF cannot be formed

2.3 The orbital design of AS and its feasibility

When designing AS' orbits, the methods of designing SFFF of SCB, **which is based on the "same semi-axes" constraint**, is also adaptable to roughly figure out an AS's orbit, and the precise one should be found out by adjusting the orbital parameters slightly.
Assume that the osculating orbit epoch is when RS is about 20×10^4 km away from the Earth, and the positional vector difference of RS and AS is (-0.44, 1, 1) (unit: km).

Table.2 shows the kinematic states of RS and AS this moment and at injection point.

Tab. 2 The kinematic states of RS and AS

r_R	Osculation orbital roots					
	a_R(km) / [*] a_A(km)	e	i_R / i_A	w_R / w_A	Ω_R / Ω_A	f_R / f_A
0	206493.209 / 206492.746	0.968175	$30^\circ59'09''.12$ / $30^\circ59'03''.38$	$185^\circ11'57''.55$ / $185^\circ11'58''.47$	$159^\circ54'27''.29$ / $159^\circ54'267''.26$	$359^\circ53'02''.72$ / $359^\circ53'29''.43$
20	199850.884 / 199851.659	0.967231	$31^\circ10'37''.72$ / $31^\circ10'32''.30$	$185^\circ20'22''.87$ / $185^\circ20'23''.81$	$159^\circ44'49''.32$ / $159^\circ44'48''.34$	$165^\circ18'00''.31$ / $165^\circ17'59''.98$
r_R	Cartesian coordinates					
	X_R(km) / X_A(km)	Y_R(km) / Y_A(km)	Z_R(km) / Z_A(km)	$\dot{X}_R$(km/s) / $\dot{X}_A$(km/s)	$\dot{Y}_R$(km/s) / $\dot{Y}_A$(km/s)	$\dot{Z}_R$(km/s) / $\dot{Z}_A$(km/s)
0	6318.473982 / 6319.139577	-1781.510133 / -1779.207452	-298.781052 / -300.217627	2.287127 / 2.284889	9.097287 / 9.098008	-5.602478 / -5.602086
20	-175470.286872 / -175469.846832	94403.272498 / 94404.272498	-16836.260600 / -16835.260600	-1.357406	0.380878	0.068106
r_R	Spherical coordinates					
	a_R / a_A	d_R / d_R	r_R(km) / r_A(km)	H_R / H_A	A_R / A_A	v_R(km/s)
0	$344^\circ16'08''.27$ / $344^\circ16'29''.88$	$-2^\circ36'53''.38$ / $-2^\circ37'06''.13$	6571.592 / 6571.699	$-0^\circ03'25''.27$ / $-0^\circ03'12''.13$	$120^\circ53'10''.68$ / $120^\circ53'03''.86$	10.926108 / 10.926017
20	$151^\circ43'10''.64$ / $151^\circ43'09''.73$	$-4^\circ49'47''.46$ / $-4^\circ49'46''.39$	199962.758 / 199963.146	$75^\circ17'30''.00$ / $75^\circ17'29''.77$	$59^\circ09'43''.02$ / $59^\circ09'48''.37$	1.411474

[*] the data above and under "/" represent the motion states of RS and AS separately, similarly hereinafter

Let the length of the baseline between RS and AS at the osculating epoch be Δr_0, and at the rest of the time Δr. Because the positional vector difference of RS and AS is (-0.44, 1, 1) (km), in Tab.2, the Δr_0 is about 1.5 km.

Figure.3 shows the Δr with respect to Table.2. It is obvious that there is only a little divergence on the length of the baseline between RS and AS (Max. 1.48km, min. 0.34km, and mean 1km) during the whole transfer, although on the journey to the Moon, the range may be a little unstable.

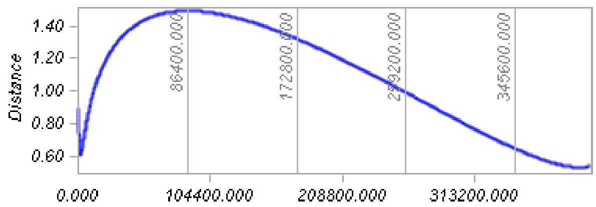

Fig.3 The length of baseline between RS and AS

3. Characteristics analysis for SFFF of "E+M" DCB

Fix the Δr_0 as 1.5 km, and let the moments when the RS is 20×10^4, 30×10^4 and 38×10^{4}km away from the Earth be the orbit epochs, so the equivalent angles $\Delta q = \Delta r_0 / r_R 180^\circ \times 3600'' / p$ are $1''.55$, $1''.03$ and $0''.81$ separately.

Table 3 gives the variation of Δr during the whole transfer by adjusting AS' position based on AS' orbital design constraints mentioned in section 2.3.

Tab.3 The variation of Δr

r_R	Δq		tendency	Max. (km)	Min. (km)	Mean(km)
20	a	$+1''.55$	↗	8.883	0.029	2.223
		$-1''.55$	↗	9.085	0.087	2.251
	d	$+1''.55$	↗	2.773	0.024	2.093
		$-1''.55$	↗↘	2.774	0.024	2.093
30	a	$+1''.03$	↗	6.150	0.057	1.514
		$-1''.03$	↗	5.909	0.073	1.503
	d	$+1''.03$	↗↘	1.928	0.092	1.418
		$-1''.03$	↗↘	1.939	0.092	1.426
38	a	$+0''.81$	↘↗	4.368	0.826	1.343
		$-0''.81$	↗	4.421	0.188	1.260
	d	$+0''.81$	↗↘	1.444	0.071	1.016
		$-0''.81$	↗↘	1.714	0.116	1.217

[*] If the length of the baseline is increasing, it is shown as↗, and decreasing as↘. Similarly, "increasing, and then decreasing" is shown as ↗↘.

Two laws can be drawn from Table.3:

1) **The moment of choosing osculating orbit is farther from the Earth, there will be less variations on Δr;**

2) **Relatively, changing the latitude between RS and AS will cause fewer variations on Δr than changing the longitude.**

According to theoretical analysis, the osculating epoch is farther from the Earth, the states of the osculating orbit are more similar to the actual, and there will also be fewer changes on Δr. Moreover, because the Moon moves near the celestial equator and the Earth-to-Moon transfer orbit is almost in the Earth equatorial plane, changing the latitude between RS and AS will cause fewer gravitational differences of the Moon, and also fewer variations on Δr.

In order to analyze the stability of the baseline, let AS-1, AS-2 and AS-3 fly with RS in formation freely. They all fly at the same osculating epoch when RS enters the

Moon's SOI; meanwhile, the corresponding Δr_0 between RS and the three AS are 1.5km, 15km and 150km separately, and each baseline is formed by changing the equivalent latitudes of the three AS (written as Δd) only. Table 4 shows the variations of Δr during the whole transfer.

Tab.4 The variations of Δr between RS and AS with Δr_0 formed by adjusting the equivalent latitudes of AS only

The spacecrafts	Δr_0 / Δd	tendency	Max.(km)	Min.(km)	Mean (km)
RS and AS-1	1.5km / $-0''.81$	↗↘	1.444	0.071	1.016
RS and AS-2	15km / $-8''.1$		17.466	4.769	12.203
RS and AS-3	150km / $-81''.0$		151.526	41.618	111.843

According to Table.4, when adjusting Δr_0, the variations are kept "increasing and decreasing (↗↘)", which indicates that both the Earth and the Moon are able to reduce Δr and the magnitude of the variations is increasing almost linear. This also proves that SFFF of "E+M" DCB is feasible in spacecraft formation flying design.

4. The applications of SFFF of "E+M" DCB

The research on SFFF of "E+M" DCB is of significant theoretical values for orbital mechanics, and it is a beneficial complement to the orbit mechanics of the current deep space detection and the theories of SFFF.

According to the introduction and the characteristics analysis in this paper, two new mission concepts can be put forward:

1) Forming a new type of space-based interferometer observation baseline

By SFFF around MCB, a new type of space-based interferometer observation baseline can be formed. Therefore, the simultaneous observation of interplanetary areas can also be realized. In addition, accurate dynamic data of environments in deep space such as celestials' gravitational and magnetic fields can also be obtained.

2) On- orbit lifesaving for manned interplanetary travel

This can be regarded as a new on-orbit service. For instance, two spacecrafts, one is manned, and the other is cargo, fly separately to the planet in formation, rather than f forming a combination traditionally. Therefore, there will be some back-up supplements near the target planet waiting for support the manned spacecraft or ensure the mission continue in case of emergency, rather than the common situation: all the supplements are destroyed or became unusable so that the mission has to be aborted. It is just like an idiom goes, "Do not put all the eggs in the same basket." Based on the benefits of SFFF of MCB , the flexibility and reliability can be enhanced in avoiding space disasters like the accident of Apollo 13 [4].

5. Summary

In conclusion, the general orbital (trajectory) design method of SFFF of MCB is as the following:

1) Figure out the osculating orbit of RS by PCA and STK;

2) Based on the "same semi-axes" constraint of Two-Body formation free-flying

design, let the position vectors of RS and AS have slightly differences in direction (but their radius from celestial should be the same);

3) Ensure that RS and AS are all moving towards the same target;

4) The gravitational attractions of the Earth and the Moon are able to reduce the Δr between RS and AS.

Therefore, the orbital design method of this paper is actually “numerical-analytical”.

The discussions and analyses in this paper are only based on a typical example of SFFF on an Earth-to-Moon transfer orbit, but it is convenient to prove the conclusions (or method) by the relative orbital theories. However, the research this paper has done is actually very rough, so the further work should be continuing characteristics analysis on the SFFF orbits of “E+M” DCB, in order to demonstrate the universality of the conclusions (or method).

This paper only discusses the orbit design about SFFF of MCD simply. Therefore, the following text is about the problems which still need to be solved or explored in the future:

- The example in this paper is a transfer from near one central body to near another one. Hence, what about the SFFF orbiting around Two Central Bodies? What about free-flying around Two Central Bodies once or more than once?
- The transfer this paper described is from the Earth (bigger celestial) to near the Moon (smaller celestial). What about the opposite situation?
- The Two Central Bodies in this paper are a Planet (the Earth) and its "natural satellite". What about the two (or more than two) Planets? It will deal with two SOI of these planets.

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