IEEE Access
Multidisciplinary ⋮ Rapid Review ⋮ Open Access Journal

Received March 2, 2020, accepted March 22, 2020, date of publication March 25, 2020, date of current version April 8, 2020.

Digital Object Identifier 10.1109/ACCESS.2020.2983307

Charged-Spacecraft Formation: Concept, Deployment and Coulomb-Force Control

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This work was supported by the National Natural Science Foundation of China under Grant 11772024 and Grant 11432001.

ABSTRACT Proximate spacecraft formation flying has many applications in high accurate earth observation and astronomy. In comparison to conventional or electronic thrust, Coulomb thrust has obvious advantages in close-formation control, such as fast throttling, nearly propellantless features and no thruster plume impingement. This paper presents the concept of charged-spacecraft formation and deployment, also investigates the Coulomb-force control for desired spacecraft formations. It is assumed that the charged chief spacecraft has several controllable charged spheres distributed around it and deputies are charged spheres. The deputies are deployed from the chief spacecraft to the desired formation orbits under the active charge control. In order to deploy these deputies subject to the constraints on the limited controllable charges, the transition trajectories are planned by using pseudo-spectral discretization method. Then a charge feedback controller is designed to track the transition trajectories and the desired formation. Numerical simulation results show that one or more deputies can be deployed by controlling the limited charge of the chief spacecraft.

INDEX TERMS Coulomb-force control, formation deployment, pseudo-spectral optimization, charged formation flying.

I. INTRODUCTION

Electrostatic force used for spacecraft control was first proposed by Cover *et al.* [1]. They considered the use of electrostatic force to inflate and maintain the shape of a large-scale space reflector. King *et al.* [2] first put forward the concept of Coulomb formation flying (CFF) that the Coulomb force generated from a chief spacecraft and the deputies is used to maintain or reconfigure the formation flying. Spacecraft cluster form, close proximity spacecraft formation flying for example, has obvious advantages compared with a single large spacecraft, whose weight is reduced and configuration is variable, and it can be deployed and repaired by multiple launching [3]. However, conventional chemical or electric propulsion systems are not suitable for the control of close proximity and high-precision formation flying due to their limited throttle-ability and thruster plume impingement [4]. Coulomb propulsion systems, different from the conventional, can overcome these problems and the force can be changed within few milliseconds. Besides, Coulomb propulsion system costs only several hundred milliwatts to generate inter-spacecraft forces with specific impulse value as high as 10^6 seconds [5]. Based on these advantages, Coulomb propulsion control can be applied to Coulomb tether Formation [6], which is similar to the concept of tethered satellites but it does not have tether cables to connect crafts. There are other potential applications in spacecraft flying formation including autonomous inspection and contactless removal of space debris [7], [8].

Basically, the research of Coulomb control for spacecraft is in the stage of primary theoretical and applied in foundational research. There are only a very few simulated or physical experiments of Coulomb control for spacecraft on the ground or in the space. Schaub *et al.* studied the Coulomb induced spacecraft attitude control and constrained Coulomb structure stabilization by building up one-dimensional testbed on the ground [9], [10]. As for space experiments, many space missions including SCATHA [11], ATS [12], and CLUSTER [13] have primarily verified the ability of active spacecraft potential control (ASPOC) [14], [15]. Although Coulomb control for spacecraft has many advantages as shown in theoretical and experimental researches, it cannot provide full controllability for spacecraft because Coulomb force is an internal force. Thus, the Coulomb formation should be supplemented with inertial thrust such as electric propulsion to realize full control over spacecraft. In addition, due to

The associate editor coordinating the review of this manuscript and approving it for publication was Chao-Yang Chen.

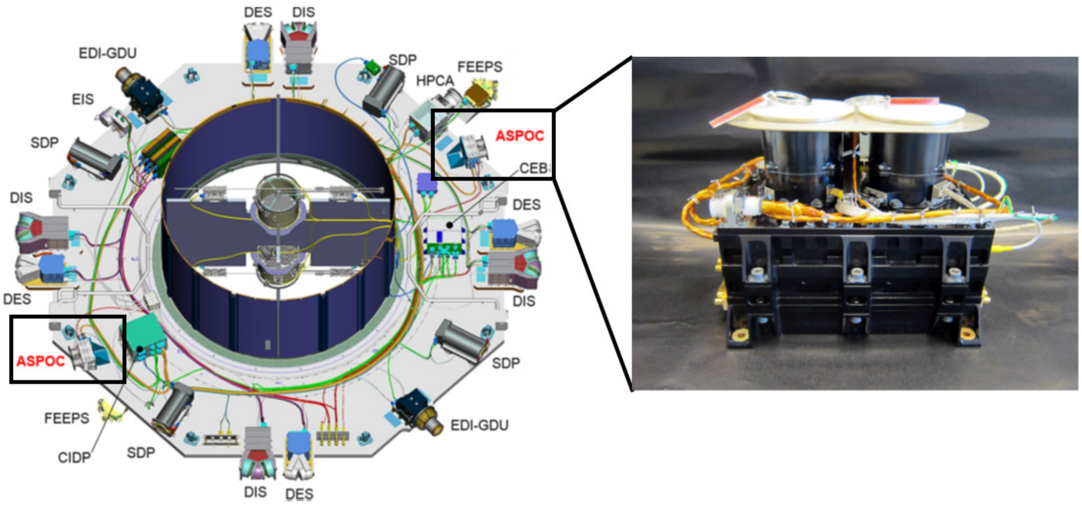


FIGURE 1. Accommodation of ASPOC on the payload deck of the spacecraft and its instrument photo [15].

shielding effect of free plasma particles in space, the actual electric field of charged spacecraft exponentially decays with the distance increases.

For Coulomb formation flying research, many static or dynamic configurations are usually proposed with respect to a circular reference orbit. Hogan and Schaub [16], [17] studied the equilibrium of Coulomb formation Equation in two cases of no gravitational forces and libration points of circular restricted three-body gravitational models [18], [19]. Schaub and [20] analyzed the stability of these equilibria and developed continuous feedback controllers to formation-keeping. Natarajan and Schaub [21] presented charge feedback controllers for static 2-craft and N-craft formation reconfigurations, respectively. Ref. [17] applied the pseudo-spectral method to optimize the Coulomb formation shape with hybrid control. Felicetti and Palmerini [22] presented and applied a Lyapunov based global control strategy to perform three-spacecraft formation acquisition and maintenance maneuvers. The researches above suggest no obvious difference between chief and deputy spacecraft. However, because of the incomplete controllability of the Coulomb control, it would be more suitable for those situations such as deputy craft deployment from a chief spacecraft, whose weight is far greater than deputies and has its own active control system for station and attitude keeping. Parker *et al.* [23] preliminarily investigated these applications and designed a simple feedback controller to deploy three deputy crafts from a chief with multiple charged spheres to specify final states.

Inspired by their work in spacecraft deployment using inter-spacecraft Coulomb forces, the concept of charged-spacecraft deployment is presented in this paper. The dynamics and control of one and multiple small deputies deployed from chief large spacecraft to the desired formation configuration at high Earth orbits (HEO) are discussed in this paper. First, the hardware feasibility study for Coulomb force control is introduced. Second, the concept of coulomb formation deployment, reconfiguration and station-keeping for charged spacecraft is discussed. Then, taking a case of Coulomb deployment, the dynamical equation for Coulomb formations is derived. The chief reference orbit is assumed to be circular in formation flying and the mass of the chief spacecraft is assumed up to several tons, far large than the weights of deputies (about tens of kilograms). Thus, the centroid of the chief can be regarded as the formation center of mass. To achieve our goal, an active charge feedback controller is designed to track the reference formation trajectory. In order to avoid the deputies becoming unable to converge to the desired formation trajectory under finite charge control bounds, the transition trajectories from the chief to the desired formation are planned using pseudo-spectral discretization method. Simulation results validate that one or more deputies can be deployed by controlling the limited charges on the chief. Moreover, the peak value of the charge control including the planning trajectory is greatly reduced compared to that without planning trajectory.

II. CONCEPT OF CHARGED-SPACECRAFT FORMATIONS AND DEPLOYMENT

This paper is aimed to make a discussion about some new applications of Coulomb forces such as deployment, reconfiguration and station-keeping for spacecraft. To achieve that goal, the hardware feasibility study for Coulomb force control is introduced firstly. Coulomb control for formation-flying is based on the technology of ASPOC. Fig. 1 shows the accommodation of ASPOC on the payload deck of the spacecraft and its instrument photo [15]. It is primarily designed to ensure the effective and complete measurement of the ambient plasma distribution functions. The spacecraft potential can be changed actively by adding an electrical current from the spacecraft into the plasma. ASPOC achieves this goal by releasing charge produced by indium ion emitters [15]. It has been successfully applied in the CLUSTER [13] and Double Star [15] missions. According to the results calculated in the Reference [2], the specific impulse value of Coulomb thrust

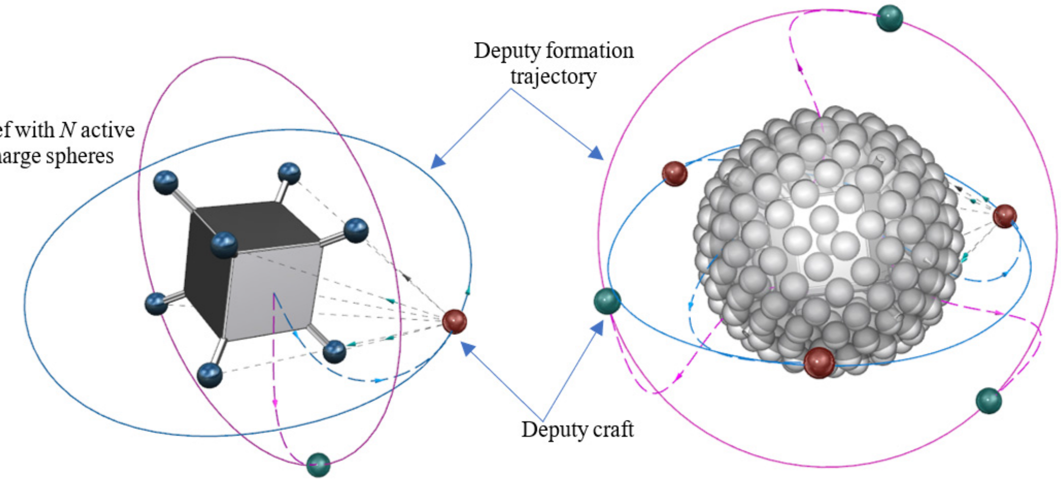


FIGURE 2. Using Coulomb force to deploy deputies from the chief spacecraft to the desired formation trajectories: (a) finite active charged spheres, (b) infinite active charged spheres (limited condition).

can range between $10^6 - 10^9$ s and the electric power less than 1 W, greater than conventional EP systems. In spite of these obvious advantages, Coulomb force is effective only for close formations within the distance of known as Debye length of charged spacecraft because of the interaction between the isolated charged spacecraft and the ambient plasma. For LEO plasma environment, the lowest Debye length is only 0.02 m, where the Coulomb formation is meaningless. But for GEO plasma environment, it is about 100-1400 m, which is appropriate for formation-flying using Coulomb forces.

To prevent the very small plasma Debye length at LEO, the study of Coulomb formation deployments is at HEO and the chief spacecraft is in a circular orbit. Different from the previous research [16], [17], [20]–[22], it is assumed that the mass of chief spacecraft is far larger than the deputy spacecraft and the weights of them are at different orders of magnitude. Besides, the chief spacecraft has its own propulsion control system and several controllable charged spheres used to actively control deputy craft as shown in Fig. 2. Every deputy is assumed to be a charged sphere and without their own propulsion system. When the number of active charges is finite as shown in Fig. 2 (a), the number of controllable deputies and their trajectories is highly restricted. If we increase the number of active charges to infinity in theory, they will form a continuous charged surface as shown in Fig. 2 (b) and gain maximum control benefits for deputies.

Deployment means that one or more deputies are simultaneously released from an initial position near the chief to one or more desired relative orbits in formation flying with an initial speed (see Fig. 2). The desired relative orbits can be natural only under the effect of gravity of the earth. In this case, only the small charge control can keep deputies on the desired orbits. Besides, it can also be unnatural relative orbit by applying larger active charge control. In order to avoid the deputies becoming unable to converge to the desired formation trajectory under limited Coulomb force, the transition trajectories from the initial position to the desired orbits should be programmed.

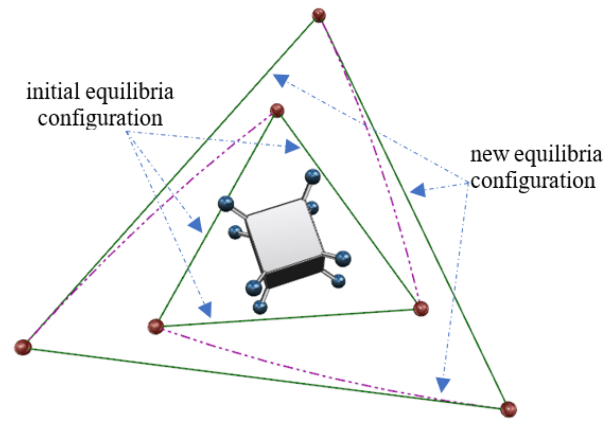


FIGURE 3. Appling Coulomb force for equilibria reconfigurations with three deputies.

In the mission of spacecraft formation, the configuration often should be changed for on-orbit serving, i.e., formation reconfigurations. The Coulomb force can also be exploited to reconfigure deputies' formation between two equilibria charged configuration as shown in Fig. 3.

During this reconfiguration, three charged deputy crafts form an initial equilibria configuration. Then under the active charge control of the chief spacecraft, the deputies are manipulated to form a new configuration along a planned transfer trajectory. Without the thrust system, the deputies can be designed to be smaller and more powerful. Analogously, Coulomb force can be applied for the active station-keeping.

III. CONTROLLED DEPLOYMENT FOR COULOMB FORMATIONS AND TRAJECTORY PLANNING

Commonly, the Clohessy-Wiltshire (CW) equation is used for Coulomb formation dynamics [6]. The rotating Hill orbit frame is defined to describe the relative motion of the deputies with respect to the chief. For the present discussion, the centroid of the chief can be regarded as the formation center of mass. Thus, the chief location can be set as the origin of coordinate system. Then Cartesian unit vector x is directed radially outward from the center of the Earth, vector z is normal to the orbit plane and positive in the direction of the angular momentum vector, and y is completed by the right-hand triad. Assuming that the chief has N controllable charged spheres, the CW equation of deputy with respect to the chief spacecraft can be formulated as [6]

$$\ddot{\boldsymbol{r}} = A\boldsymbol{r} + B\boldsymbol{v} + C\boldsymbol{u} \tag{1}$$

where $\boldsymbol{r} = \begin{bmatrix} x & y & z \end{bmatrix}^T$ is the position vector of deputy satellite in Hill frame. The matrix A and B are defined as

$$\begin{cases} A = \begin{bmatrix} 3\omega^2 & 0 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & -\omega^2 \end{bmatrix} \\ B = \begin{bmatrix} 0 & 2\omega & 0 \\ -2\omega & 0 & 0 \\ 0 & 0 & 0 \end{bmatrix} \end{cases} \tag{2}$$

$\boldsymbol{v} = \dot{\boldsymbol{r}}$ and the j - th column of the matrix C is given by

$$\boldsymbol{C}_i = \frac{k_c q \left(1 + \frac{r_i}{\lambda_d}\right)}{m r_i^3 e^{\frac{r_i}{\lambda_d}}} (\boldsymbol{r} - \boldsymbol{R}_i) \tag{3}$$

and the control variables $\boldsymbol{u}$ is a $N \times 1$ vector as

$$\boldsymbol{u} = \begin{bmatrix} q_1 & q_2 & \ldots & q_N \end{bmatrix}^T \tag{4}$$

$\boldsymbol{R}_i$ is the position vector of i-th charged sphere of the chief satellite. The constant orbital angular rate of the chief is $\omega = \sqrt{\mu}/r_c^3$, μ is the gravitational coefficient of the Earth, r_c is the geocentric radius of the chief. m is the deputy mass. $k_c = 8.99 \times 10^9$ $\mathrm{Nm^2/C^2}$ is the Coulomb's constant and λ_d is the Debye length. q is the deputy charge and q_i is the i-th charge of the chief.

In equation (1), the last item $C\boldsymbol{u}$ on the right represents the total Coulomb force, while equation (3) shows that C is the coefficient matrix related to the position vector $\boldsymbol{r}$ and $\boldsymbol{R}_i$. Thus, equation (1) is strongly nonlinear and it is a challenge to controllably manipulate deputies from an initial position near the chief to desired relative orbits in formation flying. Besides, if $||\boldsymbol{R}_i|| \ll ||\boldsymbol{r}||$, then we have $\boldsymbol{r} - \boldsymbol{R}_1 \approx \boldsymbol{r} - \boldsymbol{R}_2 \approx \ldots \approx \boldsymbol{r} - \boldsymbol{R}_N$ and $C_1 \approx C_2 \approx \ldots \approx C_N$. In this case, the total Coulomb force $C\boldsymbol{u}$ is

$$C\boldsymbol{u} \approx C_i(q_1 + q_2 + \cdots + q_N) \tag{5}$$

Eq. (5) means that if $||\boldsymbol{R}_i||$ is too short, the charge control force will fail, which will greatly affect the orbit accuracy. Therefore, $||\boldsymbol{R}_i||$ should be carefully selected for high-precision trajectory control. The detailed value of $||\boldsymbol{R}_i||$ will be numerically analyzed in Section IV.

Next, a control law for the simultaneous deployment of one and multiple deputies is studied. Considering the deputies with only simple structures and limited controllability, we assume the deputy charges are uncontrollable and constant. The deputy deployment is implemented by actively controlling the charge of the chief q_i. Firstly, the controllable deployment of one deputy is investigated. From a practical perspective, it is assumed that the position and velocity vector of deputy craft can be measured. There are many control laws that can be applied to track the desired trajectories. Here a simple feedback controller is presented to deploy the deputy from the initial position to the desired formation orbits. $\boldsymbol{f}_d$ denote as the right side of equation (1). Then it is a second-order system as

$$\ddot{\boldsymbol{r}} = \boldsymbol{f}_d \tag{6}$$

The desired formation orbit is denoted $\boldsymbol{r}_d(t)$ and it can be given by

$$\boldsymbol{r}_d(t) = \begin{bmatrix} x_{d0} + A_x \sin(\omega t + \alpha) \\ y_{d0} + A_y \cos(\omega t + \alpha) \\ z_{d0} + A_z \sin(\omega t + \beta) \end{bmatrix} \tag{7}$$

where $\boldsymbol{r}_{d0} = \begin{bmatrix} x_{d0} & y_{d0} & z_{d0} \end{bmatrix}^T$ is the center of the desired relative orbit. A_x, A_y and A_z are the amplitude of bounded relative motion of the deputy with respect to the chief along radial, in-track, and cross-track directions, respectively, while α and β are its phases. Eq. (7) constitute a parametric representation of the desired relative orbit. Then the tracking error is

$$\Delta\boldsymbol{r} = \boldsymbol{r}_d - \boldsymbol{r} \tag{8}$$

Deriving equation (8) with time twice and noticing the equation (6), we have

$$\Delta\ddot{\boldsymbol{r}} = \ddot{\boldsymbol{r}}_d - \boldsymbol{f}_d \tag{9}$$

Now a simple feedback control law is applied as

$$\boldsymbol{f}_d = K_p\Delta\boldsymbol{r} + K_d\Delta\dot{\boldsymbol{r}} + \ddot{\boldsymbol{r}}_d \tag{10}$$

where K_p and K_d are 3×3 diagonal gain matrices. Substituting equation (10) into equation (6), the second-order system of trajectory tracking error can be obtained as

$$\Delta\ddot{\boldsymbol{r}} + K_p\Delta\boldsymbol{r} + K_d\Delta\dot{\boldsymbol{r}} = 0, \tag{11}$$

and the real control law can be obtained by solving the following equation:

$$A\boldsymbol{r} + B\boldsymbol{v} + C\boldsymbol{u} = \boldsymbol{f}_d \tag{12}$$

Before the real control law solution is given, the relationship between its controllability and the number of chief charged spheres is briefly discussed. First, at least the rank of the matrix C is 3, then the deputy can be completely controlled, or $N \geq 3$. However, if $N = 3$, the three charged spheres form a plane, beyond which the rank of the matrix is $C < 3$ and results in the deputy cannot be controlled [23]. Thus, the number of the charged spheres N must be ≥ 4. Then the dimension of control variables N is greater than control freedom of equation (1) so the solution of $\boldsymbol{u}$ is not unique. Here the optimization criteria $J = \frac{1}{2}\boldsymbol{u}^T\boldsymbol{u}$ is employed then we obtain the minimum pseudo-inverse solution

$$\boldsymbol{u} = C^T \left(CC^T\right)^{-1} (\boldsymbol{f}_d - A\boldsymbol{r} + B\boldsymbol{v}) \tag{13}$$

For the deployment of multiple deputies, the similar controller can be designed. Assuming the number of deputies is M, then their equation can be formulated as

$$\ddot{X} = \begin{bmatrix} A & & \\ & \cdots & \\ & & A \end{bmatrix} X + \begin{bmatrix} B & & \\ & \cdots & \\ & & B \end{bmatrix} \dot{X} + \begin{bmatrix} C_1 \\ \cdots \\ C_M \end{bmatrix} U \quad (14)$$

where $X = \left[\boldsymbol{r}_1 \ \ldots \ \boldsymbol{r}_i \ \ldots \ \boldsymbol{r}_M \right]^T$, and $\boldsymbol{r}_i$ is the position vector of i-th deputy satellite. If tracking trajectory of i-th deputy is $\boldsymbol{r}_{di}$, then similar the above discussion, the dimension of control variables N must be greater than control freedom of equation (13): $N > 3 \times M$. And the solution of U is

$$U = \left[C_1 \ldots C_M \right] \left(\begin{bmatrix} C_1 \\ \cdots \\ C_M \end{bmatrix} \left[C_1 \ldots C_M \right] \right)^{-1} \times \left(F_d - \begin{bmatrix} A & & \\ & \cdots & \\ & & A \end{bmatrix} X + \begin{bmatrix} B & & \\ & \cdots & \\ & & B \end{bmatrix} \dot{X} \right) \quad (15)$$

where $F_d = K_p \Delta X + K_d \Delta \dot{X} + \ddot{X}_d$, $\Delta X = X - X_d$, and $X_d = \left[\boldsymbol{r}_{d1} \ldots \boldsymbol{r}_{di} \ldots \boldsymbol{r}_{dM} \right]^T$. Although the above close-loop feedback control law tracks the desired trajectories well, the control law may provide excessive control force/charges at initial time because the initial position is too far from the target trajectory. However, the control force generated by chief charges is limited. Thus, the transition trajectories from the chief to the desired formation trajectory are planned using pseudo-spectral method to avoid the deputies becoming unable to converge to the desired trajectory under limited control force.

To achieve this goal, the General Pseudospectral Optimization Software (GPOPS) [24], based on an hp-adaptive Pseudospectral method, is employed. Firstly, the transition trajectory planning problem should be reformulated as an optimal control problem that can be solved by pseudo-spectral method. Here takes the situation with one deputy for example, the state vector $\boldsymbol{x}$ is defined as $\boldsymbol{x} = \left[\boldsymbol{r} \quad \boldsymbol{v} \right]^T$. The optimum trajectory planning problem is that the deputy is released from its initial position given by $\boldsymbol{x}(t_0) = \boldsymbol{x}_0$ at the initial time t_0 to the terminal position given by $\boldsymbol{x}\left(t_f\right) = \boldsymbol{x}_f$ at free final time t_f, while minimizing control charges, or objective function

$$J = \int_{t_0}^{t_f} |\boldsymbol{u}| \, dt \quad (16)$$

Subject to the dynamical constraint

$$\dot{\boldsymbol{x}} = f(\boldsymbol{x}, \boldsymbol{u}) = \begin{bmatrix} \boldsymbol{v} \\ A\boldsymbol{r} + B\boldsymbol{v} + C\boldsymbol{u} \end{bmatrix} \quad (17)$$

where the control charges $\boldsymbol{u}$ is limited by the actual electric equipment. Denote the maximum charge q_{max}, then the control constriants are given by

$$-q_{max} \leq \boldsymbol{u} \leq q_{max} \quad (18)$$

Besides, the terminal state is constrained to the desired formation orbits, $\phi(\boldsymbol{x})$ by

$$\phi\left(\boldsymbol{x}_f\right) = \boldsymbol{x}_f - \left[\boldsymbol{r}_d\left(t_f\right) \ \boldsymbol{v}_d\left(t_f\right) \right]^T = \boldsymbol{0}. \quad (19)$$

TABLE 1. Simulation parameters used for deploy deputy spacecraft.

Parameter	Value	Units
$\boldsymbol{m}$	50	kg
$\boldsymbol{k_c}$	8.99×10^9	Nm^2/C^2
$\boldsymbol{q}$	-1.11235	μC
$\boldsymbol{\omega}$	7.2593×10^{-5}	rad/s
$\boldsymbol{\lambda_d}$	180	m
$\boldsymbol{q_i}$ ($\boldsymbol{i}$=1,…N)	≤1.12	μC
$\boldsymbol{l}$	5	m
$\boldsymbol{N}$	6	1

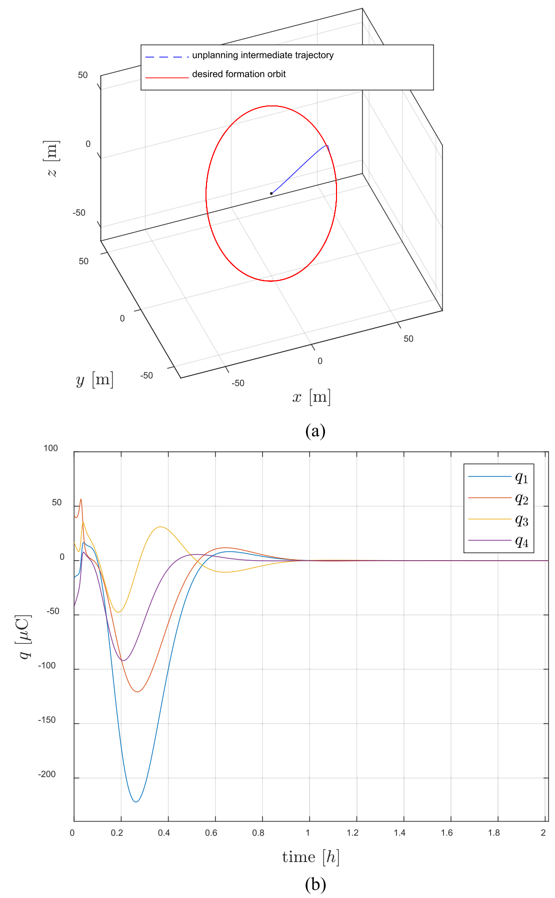


FIGURE 4. Deployment the deputy with unplanning transition trajectory: (a) trajectory form the initial position near the chief to the desired relative orbits, (b) the charged spheres voltage time histories.

IV. SIMULATION SCENARIOS FOR FORMATION DEPLOYMENT

In this section, the validity of control strategy and planning transition trajectory is illustrated in following two numerical simulation examples. Table 1 lists the simulation parameters and their constant values. All deputies' charges q are -1.11235 μC, each with a mass of 50 kg and all the controllable maximum charges of the chief spacecraft q_i ($i = 1, \ldots N$) are 1.11235 μC. The Debye length is assumed to

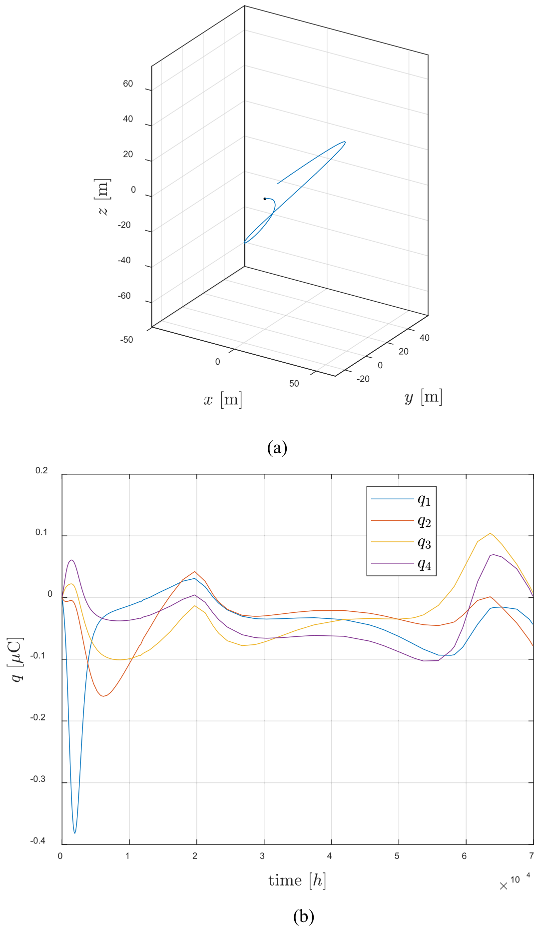


FIGURE 5. Planning trajectory and open-loop control: (a) transition trajectory, (b) optimal open-loop control charges results.

TABLE 2. Initial position of deputy and the coordinates of charged spheres.

Position vector	x(m)	y(m)	z(m)
Initial position $\boldsymbol{r}_0$	l	0	0
$\boldsymbol{R}_1$	l	$-\frac{1}{\sqrt{3}}l$	$-\frac{1}{\sqrt{6}}l$
$\boldsymbol{R}_2$	$-l$	$-\frac{1}{\sqrt{3}}l$	$-\frac{1}{\sqrt{6}}l$
$\boldsymbol{R}_3$	0	$-\frac{2}{\sqrt{3}}l$	$-\frac{1}{\sqrt{6}}l$
$\boldsymbol{R}_4$	0	0	$\frac{3}{\sqrt{6}}l$

be 180 m [4]. The chief orbit radius is 4.227×10^7 m and its orbital angular rate ω is 7.2593×10^{-5} rad/s. It should be noted that l in Table 1 means the distance between the charged spheres and the center of mass of the deputies, i.e. $\|\boldsymbol{R}_i\|$. For the acquired trajectories are bounded the space with $\|\boldsymbol{r}_i\| \leqslant 100$ m in this paper, our simulations show the charged spheres can obtain a good control ability for acquired trajectory (error < 0.01 m) only when $l \geqslant 2$ m. Besides, the actual attainable length of the boom is limited and thus, a practically reasonable length, $l = 5$ m, is selected for high-precision trajectory control.

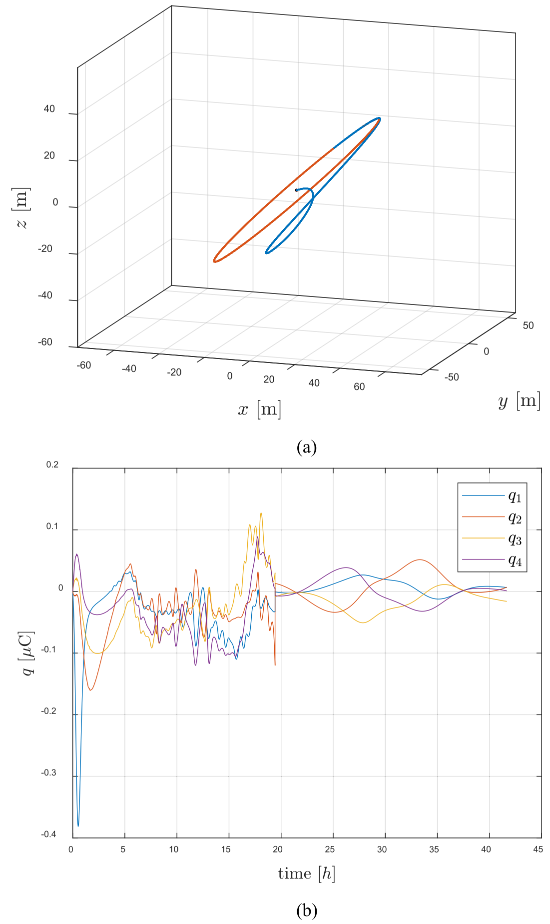


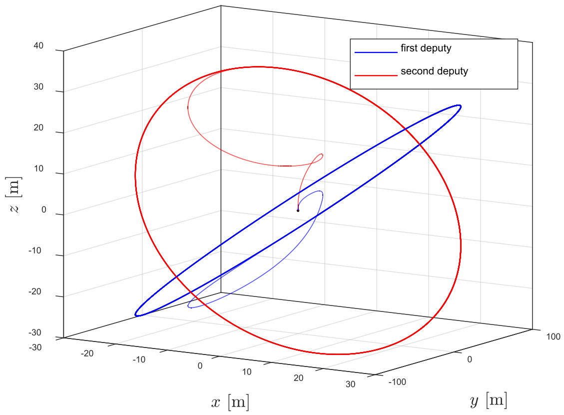
FIGURE 6. Deployment the deputy with planning transition trajectory with closed-loop control: (a) trajectory form the initial position near the chief to the desired relative orbits, (b) the charged spheres voltage time histories.

A. SCENARIO I: DEPLOYING ONE DEPUTY FLYING AROUND CHIEF

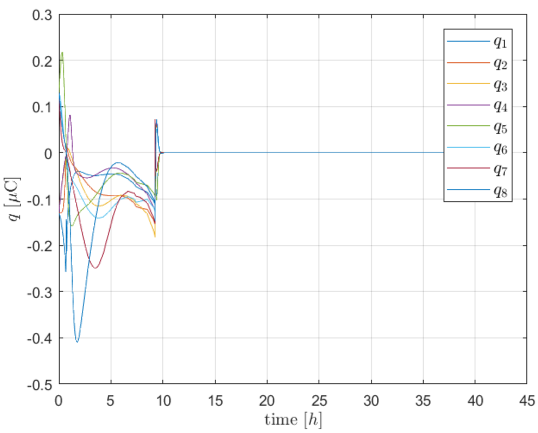
Firstly, the case of only a deputy deployment is considered, with 4 charged spheres, $N = 4$. Their coordinates are given in Table 2, where $l = 5$ m. Besides, the desired formation orbits are given by equation (7), which are the solution of CW equation if we set $x_{d0} = y_{d0} = z_{d0} = 0$, and the amplitude is $A_y = 2A_x = 2A_z = 60$ m. In this case, the desired formation orbits are natural and stable, which can be maintained almost without control.

The deployment trajectory is obtained as shown in the Fig. 4 (a). The dotted line is unplanned transition trajectory and solid line is the desired orbit. As expected, the deputy entries the desired orbit finally. Fig. 4 (b) shows the charged sphere voltage time histories.

However, it is shown that the controllable charges are greater than the given maximum ($q_i \leq 1.12$ μC) before its entries the desired orbit in Fig. 4 (b). Thus, the transition trajectory should be planned to satisfy constraint of the maximum charges using the trajectory planning strategy described in Section III. Fig. 5 shows the transition planning trajectory of the deputy and its open-loop control charged sphere



(a)



(b)

FIGURE 7. **Deployment of two deputies: (a) deployment trajectory to the desired formation orbits, (b) the charged spheres voltage.**

voltage time histories. Then tracking the transition trajectory and the desired orbits by using the control law (1), the close-loop trajectory and the corresponding control charges can be shown in Fig. 6. It is observed that the deputy takes more time to arrive at the desired orbits through the transition planning trajectory but the constraints can be satisfied.

B. SCENARIO II: DEPLOYING MULTIPLE DEPUTIES FLYING AROUND CHIEF

The simulation of subsection IV-A verifies the effectiveness of charge feedback controller. Now it is extended for applying more deputies deployment, where two cases of two and three deputies are simulated. In the first case, the number of deputies is $M = 2$. From the analysis of complete maneuverability of the deputy in Section III, the dimension of control variables N must be $N > M \times 3 = 6$. Besides, considering the symmetry of the multiple charge distribution of the chief, $N = 8$ is a better selection than $N = 7$. Similar to the subsection IV-A, their coordinates are local at the eight vertices of the cube with the length $l = 5$ m as shown in Fig. 2(a). The parameters of the initial positions and the desired orbits of two deployed deputies are given in Table 3 (the third deputy is included).

TABLE 3. **The initial positions and the desired orbits of two deputies.**

parameters	Initial positions	Center of desired orbits	Amplitude
First deputy	$[l, 0, 0]^T$	$[0,0,0]^T$	$A_{x1} = 30$ m $A_{y1} = 60$ m $A_{z1} = 30$ m
Second deputy	$[-l, 0, 0]^T$	$[0,0,0]^T$	$A_{x2} = 35$ m $A_{y2} = 70$ m $A_{z2} = 30$ m
Third deputy	$[-l, 0, 0]^T$	$[5, 5, 0]^T$	$A_{x2} = 40$ m $A_{y2} = 70$ m $A_{z2} = 30$ m

TABLE 4. **The coordinates of charged spheres.**

Position vector	x(m)	y(m)	z(m)
$\boldsymbol{R}_1$	0	l	0
$\boldsymbol{R}_2$, $\boldsymbol{R}_3$	$\pm\frac{\sqrt{3}}{2}l$	$-\frac{1}{2}l$	0
$\boldsymbol{R}_4$, $\boldsymbol{R}_5$	0	0	$\pm l$
$\boldsymbol{R}_6$, $\boldsymbol{R}_7$, $\boldsymbol{R}_8$, $\boldsymbol{R}_9$	$\pm\frac{\sqrt{15}}{5}l$	$-\frac{\sqrt{5}}{5}l$	$\pm\frac{\sqrt{5}}{5}l$
$\boldsymbol{R}_{10}$, $\boldsymbol{R}_{11}$	0	$\frac{2\sqrt{5}}{5}l$	$\pm\frac{\sqrt{5}}{5}l$

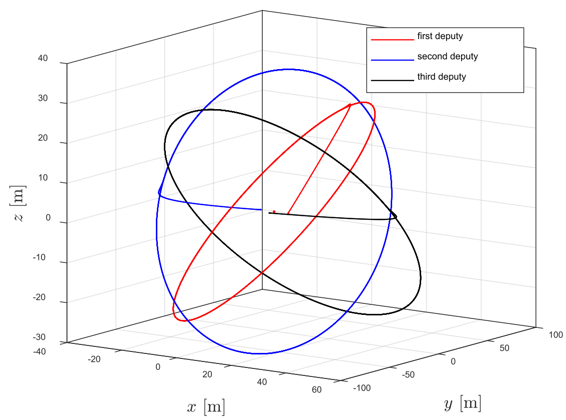


FIGURE 8. **Deployment trajectories of three deputies.**

Then the trajectories of these deputies are planned using pseudo-spectral method as shown in Fig. 7 (a) and the corresponding charged sphere voltage time histories are shown in Fig. 7 (b). From Fig. 7 it is known that two deputies can be successfully deployed into their own desired orbits under the constraint of limited controllable charges.

As mentioned in Section II, multiple deputies can be manipulated simultaneously to any desired formation configuration as long as there is enough controllable charged spheres in the chief. It can be imagined that the case of three deputies marks a significant threshold in the formation applications. Next, the case of three deputies, i.e. $M = 3$, is simulated to demonstrate chief's ability to actively control multi deputies. $N = 11 > M \times 3 = 9$ is determined for greater control. Tables 3 and 4 give the relative orbit parameters of three deputies and the position vectors of 11 charged spheres, respectively. As expected, Fig. 8 shows that the chief can actively control three deputies to entry the desired orbits and maintain the formations. The result demonstrates the powerful control ability of charged spacecraft to deploy multiple deputies and maintain their desired formations.

V. CONCLUSION

The concept of Coulomb formations deployment is presented in this paper. The controller is designed to actively release one deputy from initial positions near the chief to the desired formation orbits. The controller can also be extended to simultaneously release more deputies by adding more controllable charged spheres in the chief. The transition trajectories from the chief to the desired formation are planned using pseudo-spectral discretization method to satisfy the constraint that the controllable charge is limited in practice. Finally, the simulation results illustrate that one or more deputies can be deployed by controlling the limited charges of the chief. The peak value of the charge control with planning trajectory is greatly reduced compared with unplanned transition trajectories from the chief to the desired formation orbit. To verify the proposed Coulomb formation model, the test bed for charge control experiments would be carried out in the future work. Besides, the dynamics analysis and designed controller with planning transition trajectories in the more complicated dynamics model, such as the Sun-Earth-Moon ephemeris system, is another work to be done.

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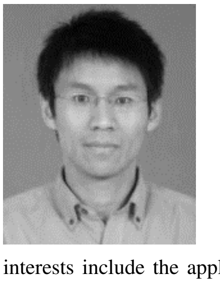

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