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SPACECRAFT FORMATION FLYING AND RECONFIGURATION WITH ELECTROSTATIC FORCES

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Abstract

Natural charging due to ambient plasma and the photoelectric effect can produce Coulomb forces of 10-1000 mN, which could disturb the configuration of spacecraft in formations close enough that Debye shielding is negligible. The magnitude of these disruptive inter-satellite Coulomb forces is comparable to typical ion thrusters proposed for spacecraft formation flying. Rather than fighting them, it would be wise to make use of these effects. In this work, a novel hybrid propulsion system is developed by combining Coulomb forces and standard electric thrusters for formation flying of the order of tens of meters in Geostationary Earth Orbit (GEO). This novel approach will provide fuel-efficient propulsion, which will also minimize potentially damaging exhaust plumes, reduce mass, and eliminate an important class of disturbances. In this work, Artificial Potential Field (APF) method is used for path planning and Sliding Mode Control (SMC) is used for designing a robust controller. The performance of the proposed hybrid propulsion system is demonstrated using an example of four spacecraft forming a tetrahedron formation.

Key words: Coulomb force, Formation flying, Artificial potential field

INTRODUCTION

In GEO and other high Earth orbits, spacecraft surface charging due to interaction with the plasma environment poses a major challenge. Garett [1] reviewed the field of spacecraft surface charging in 1981. Walker [6] explored the formation-flying concept in early 1980's. In recent years, there has been much interest in close-proximity (10-50m) spacecraft formation flying. The spacecraft formation-flying concept exploiting the inter-spacecraft electrostatic force can be found in [2], [3]. A detailed analysis of the concept of Coulomb Spacecraft Formations (CSF) can be found in [4].

Formation flying requires an efficient path planner for collision-free navigation. The APF method introduced by Khatib [5] is a well known approach for terrestrial robot path planning. Similar to this technique, Izzo and Pettazzi [6] have developed a technique for satellite path planning that exploits a behaviour-based approach to achieve an autonomous and distributed control of identical spacecraft over their relative geometry. Also it is proved that sliding mode control for satellite formation control is an effective way of implementing distributed architectures.

In this work, a novel hybrid propulsion system is developed by combining Coulomb forces and standard electric thrusters for formation flying of the order of tens of meters in GEO. Following its initial investigation of hybrid propulsion using Coulomb forces, this work move on to implementing a navigation and reconfiguration algorithm based on an artificial potential-field method and sliding mode control for path planning and formation control of satellite swarms. The simulation results demonstrate that this novel approach will provide fuel-efficient propulsion and will have all the benefits associated with the robust path planner using APF method and SMC method.

HYBRID PROPULSION USING COULOMB AND ELECTRIC FORCES

The objective of designing a Coulomb-actuated spacecraft is to provide maximum acceleration for limited electrical power. The goal of this work is to develop a suite of spacecraft architecture concepts that take advantage of the proposed hybrid actuation scheme; artificial potential field and sliding mode control of spacecraft steering. Some of the critical questions to be answered involve power, charge management, sensing, and actuation strategies.

Figure 1 illustrates the force experienced by a satellite in a formation of three satellites using Artiificial Potential Field (APF) method. It is desired that the Swarm Agent 2 (SA2) move towards the final target position. Initially, SA1 exerts a repulsive force, and the target exerts an attractive force on SA 1. Then it moves to a new location in the direction of the resultant force. At this position, SA3 exerts a repulsive force and target exerts an attractive force on SA2 and it moves towards the next intermittent location. Here the target exerts the attractive force and SA2 finally moves towards its target position, thereby achieving the desired configuration. In this approach the steering direction of a particular spacecraft undergoing reconfiguration within the spacecraft swarm is determined by assuming that the other members of the constellation (obstacles) assert repulsive forces on the spacecraft and the goal (desired terminal state) asserts attractive force. Consequently, the spacecraft experiences a generalized force equal to the negative of the total potential gradient that drives the spacecraft towards the goal or the desired terminal state. In this way the APF provides a constantly active navigation, offering a collision free trajectory for the each of the individual satellites that form part of a constellation or formation.

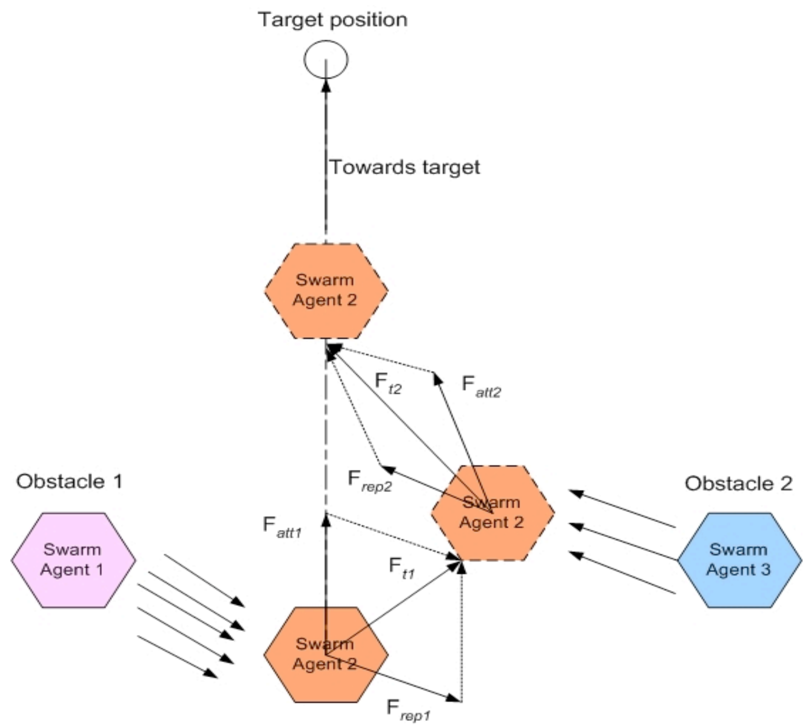

Figure 1. Schematic diagram of path planning using APF method

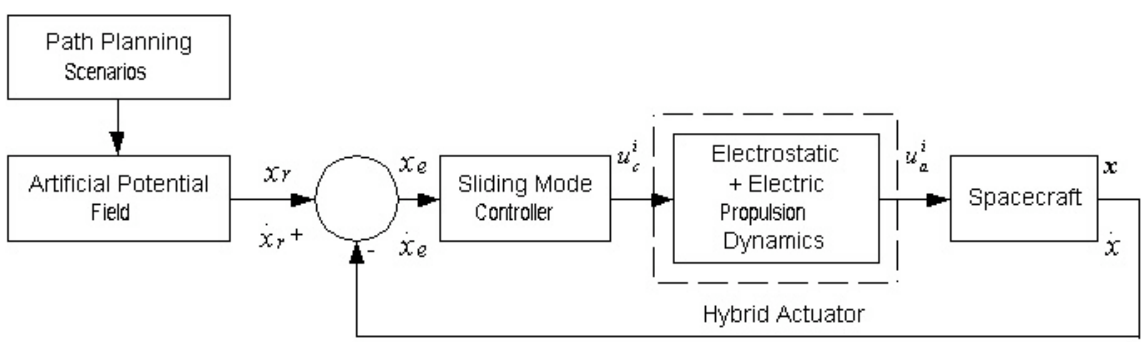

Figure 2. Schematic diagram of swarm path planning and control with hybrid actuator

The schematic diagram of the proposed navigation and control architecture is shown in Figure 2. The path-planning module is capable of avoiding obstacles and provides a goal-oriented navigation in an optimal time period. This approach has less computational load as compared to deliberative techniques that carry out extensive map building from raw sensory data. The command force from the sliding mode controller is the input to the hybrid actuator. Of interest is how well these APF-SMC based control forces can be implemented with electrostatic thrusting and what forces components must be provided with electric thrusting. The torque or force required for thrusting is generated by means of hybrid propulsion using the conventional electric thrusters (e.g., Snecma PPS 1350 EP thruster, Field Emission Electric Propulsion, micro-Pulsed-Plasma Thrusters) and inter-spacecraft electrostatic forces developed due to natural charging of spacecraft in space plasma environment. The proposed strategy will have all the benefits associated with the APF method along with the added advantage of utilizing Coulomb force.

Let u_a^i denote the actual force available from the hybrid thrusters to i^{th} spacecraft for changing its manoeuvre. Due to the actuator dynamics, u_a^i will differ in magnitude from the commanded thrust u_c^i. In this work, first the charge product is determined from the commanded force u_c^i and is then used to determine the actual electrostatic force that acts on each spacecraft in the swarm. Note that this actual electrostatic force will generally not be equal to the commanded force and cannot change the formation cluster momentum. This is performed using electric propulsion and its magnitude is equal to the difference between the commanded force and electrostatic force.

Consider the non-linear inertial equation of motion of the spacecraft represented by

$$M_i(x^i)\ddot{x}^i + f_i(x^i, \dot{x}^i) = u^i, 1 \le i \le N \qquad (1)$$

where $x^i \in R^n$ is the position vector of agent i, $M_i \in R^{n \times n}$ is the mass or inertia matrix and is assumed to be non-singular, N is the number of agents in the swarm, $u^i \in R^n$ represents the control inputs and $f_i(x^i, \dot{x}^i) \in R^n$ is the centripetal, Corriolos, gravitational effects and additive disturbances. In APF method, corresponding to Equation (1), the motion of individual spacecraft is governed by the equation [7]

$$\dot{x}^i = \sum_{j=1, j \ne i}^{N} g(x^i - x^j), i = 1, \ldots, N \qquad (2)$$

where, $g(.) \in \Psi$ is an odd function which represents the sum of the function of attraction and repulsion between the agents i.e., $\boldsymbol{g}(.) = \boldsymbol{g_a}(.) + \boldsymbol{g_r}(.)$ and Ψ is the set of all attraction/repulsion functions. The function $\boldsymbol{g_a} : \boldsymbol{R}^+ \to \boldsymbol{R}^+$ represents (the magnitude of) the attraction term, where as $\boldsymbol{g_r} : \boldsymbol{R}^+ \to \boldsymbol{R}^+$ represents (the magnitude of) the repulsion term. Again $\boldsymbol{g}(.)$ can be represented by

$$g(y) = -y\left[g_a(\|y\|) - g_r(\|y\|)\right]$$

where $y \in R^n$ is arbitrary and $\|y\| = \sqrt{y^T y}$ is the Euclidean norm. For formation control, we consider the case in which the attraction/repulsion functions $g(.)$ are pair dependent i.e. ,

$$\dot{x}_i = \sum_{j=1, j \ne i}^{N} g_{ij}\left(x_i - x_j\right) i = 1, \ldots, N$$

where $g_{ij}(.) \in \Psi$ for all pairs (i, j) and $g_{ij}(x_i - x_j) = g_{ji}(x_j - x_i)$. For formation control the attraction and repulsion functions and therefore the equilibrium distance δ_{ij} for different pairs of individuals can be different. The desired formation can be uniquely specified with respect to rotation and translation by the formation constraints

$\left\|x_i - x_j\right\| = d_{ij}$ for all $(i, j), j \neq i$. The idea is to chose each of the attraction/repulsion functions $g_{ij}(.)$ such that $\delta_{ij} = d_{ij}$ for every pair of individuals (i, j). The generalized Lyapunov function $J(x) = \sum_{i=1}^{N-1} \sum_{j=i+1}^{N} \left[J_a\left(\left\|x_i - x_j\right\|\right) - J_r\left(\left\|x_i - x_j\right\|\right)\right]$ then have its minimum at the desired formation and once the formation is achieved $\dot{x}_i = 0$ for all i. Here J_a and J_r represents the attractive and repulsive potentials.

The n-dimensional sliding manifold for i^{th} spacecraft is given by

$$s^i = \dot{x}^i + \nabla_{x^i} J(x) = 0, i = 1, \ldots, N \tag{3}$$

The sliding mode controller is given by

$$u^i = -u_o^i(x) sign(s^i) + f_i^k(x^i, \dot{x}^i) \tag{4}$$

where, $sign(s^i) = \left[sign(s_1^i) \quad \ldots \quad sign(s_N^i)\right]^T$. The gain of control input is chosen as

$$u_o^i > \frac{1}{\underline{M}_i}\left(\overline{M}_i \bar{f}_i + \bar{J} + \varepsilon^i\right),$$

for some $\varepsilon^i > 0$, it is guaranteed that $s^{iT} \dot{s}^i < -\varepsilon^i \left\|s^i\right\|$. Here $\underline{M}_i$ and $\overline{M}_i$ are the known lower bound and upper bounds of the inertia matrix respectively. In the above controller only the known part $f_i^k(x^i, \dot{x}^i)$ of the spacecraft dynamics is considered.

Consider a formation of N spacecraft in GEO, having charge products $p = (N(N-1)/2)$, the charge products can be perfectly implemented into individual real spacecraft charges. For the i^{th} spacecraft, consider all possible pairs of charge product due to the remaining $N-1$ spacecraft as $Q_{ij} = q_i q_j$, $j = 1, \ldots, N, i \neq j$. Then the commanded force acting on i^{th} spacecraft is:

$$u_c^i = \sum_{j=1, i \neq j}^{N} (k_c Q_{ij} / x_{ij}^{\ 2}) x_{ij} \exp(-x_{ij} / \lambda_d) \tag{5}$$

where $k_c = (4\pi \varepsilon_0)^{-1} = 8.99 \times 10^9$ Nm^2/C^2 is a constant of proportionality that depends on the permittivity of free space, x_{ij} is the spacecraft separation and λ_d is the Debye length. At present, the control forces in (4) makes no consideration for what forces are implementable with Coulomb thrusting and which are not. Then using least-square inverse, the charge product $\tilde{Q}$ for i^{th} spacecraft can be computed from equation (5). The charge product thus derived is then used for computing the actual thrust developed by Coulomb charging of i^{th} spacecraft as:

$$u_{CSF}^i = [\mathbf{A}_i][\tilde{Q}] \tag{6}$$

where,

$$[\mathbf{A}_i] = [(k_c / x_{i1}^{\ 2}) x_{i1} \exp(x_{i1} / \lambda_d) \ldots (k_c / x_{iN}^{\ 2}) x_{iN} \exp(x_{iN} / \lambda_d)]$$

$$[\tilde{Q}] = [q_i q_j \quad \ldots \quad q_i q_N]^T.$$

Note that this actual Coulomb force will generally not be equal to the commanded force. These formation internal forces cannot change the cluster momentum. Such force components are produced by the Electric Propulsion (EP) system by computing:

$$u_{EP}^{i} = u_{c}^{i} - u_{CSF}^{i} .$$

In other words, the actual thrust acting on i^{th} spacecraft is:

$$u_{a}^{i} = u_{CSF}^{i} + u_{EP}^{i} . \tag{7}$$

From (7), it is seen that the electric thrusters is used only for compensating the difference between the commanded force u_{c}^{i} and that generated by electrostatic forces u_{CSF}^{i}. A detailed derivation can be found in [8].

SIMULATION STUDY

Table 1. Coulomb Spacecraft Formation Simulation Parameters

Simulation parameter	Value/Units
Spacecraft individual mass M	150 kg
Lower bound on mass $\underline{M}$	$0.5M$
Upper bound on mass $\overline{M}$	$1.5M$
Spacecraft radius η (assumed spherical)	0.5 m
Debye length (GEO)	200 m
Snecma EP peak thrust	88,000 μN
Snecma EP specific impulse	1650 sec
Charge saturation limit	2 μC
Number of spacecrafts N	4
Initial separation	5 km
Final inter spacecraft formation separation d	50m
Manoeuvre time	24 hrs
Peak magnitude of differential disturbance in GEO	2 μN

The simulation results for tetrahedron formation show that the concept of propellant-less propulsion using electrostatic forces could be successfully used for spacecraft formation flying applications and are capable of generating 10-1000 micro-Newton thrust. This helps to reduce the thrust required from the electric or ion thrusters on-board the spacecraft. The results in this paper also show that the autonomous navigation and reconfiguration using artificial potential field is suitable for spacecraft formation flying. Moreover, the use of sliding mode control makes the overall system highly robust to differential perturbations acting on the spacecrafts. This methodology can be easily extended to any number of spacecraft swarms.

CONCLUSIONS

A novel hybrid propulsion system using electrostatic forces and electric propulsion was developed for geostationary spacecraft formation flying. A tetrahedron formation was used to demonstrate the hybrid propulsion technique along with a path planning logic based on artificial potential field method. The robust controller was designed using sliding mode control. The simulation results prove that this new concept is feasible for formation flying in geostationary orbits. The feasibility of the proposed hybrid propulsion for various other formation scenarios and spacecraft swarm aggregation has been successfully studied in parallel [8].

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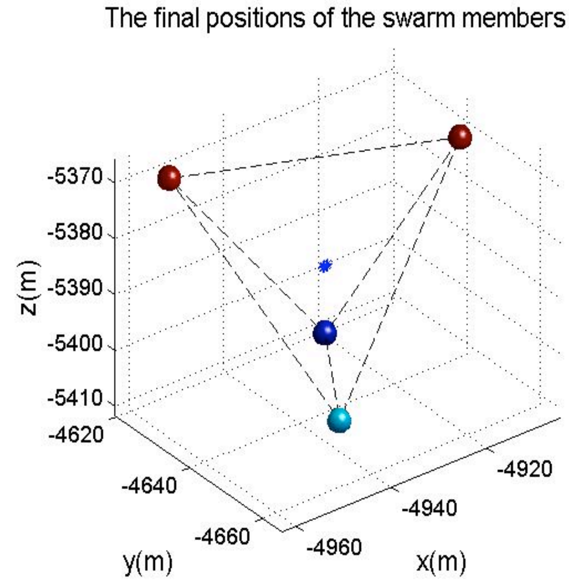
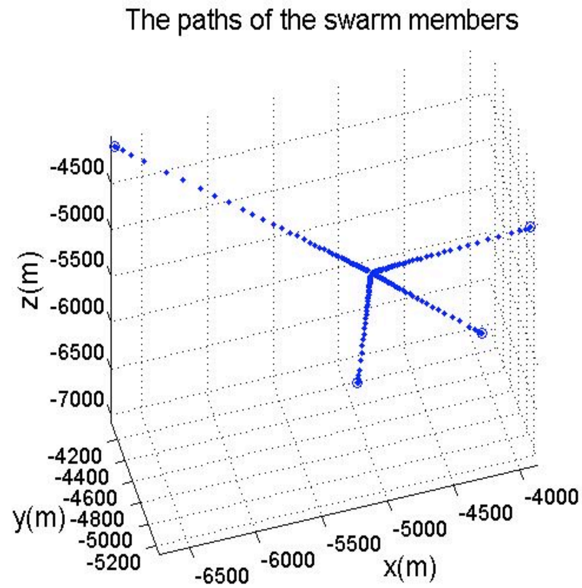


(a)



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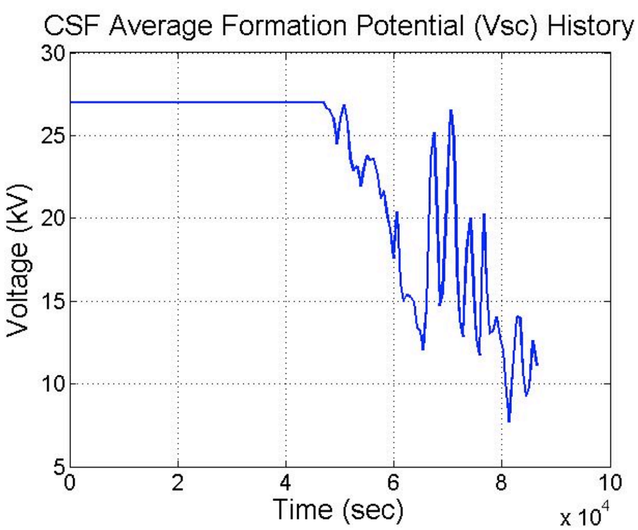

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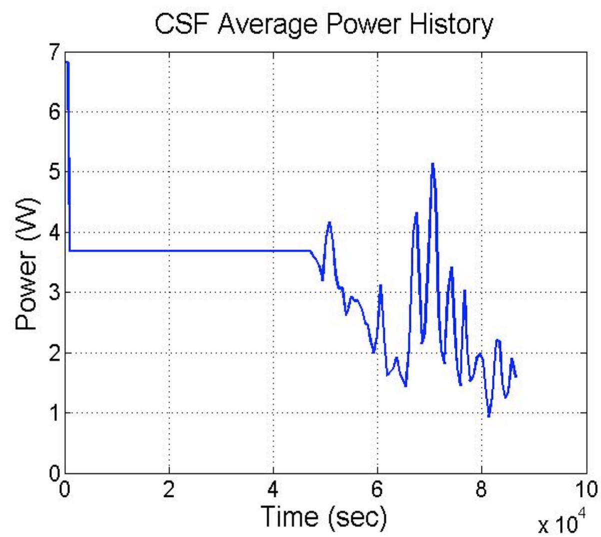

(d)

Figure 3. Simulation plots for tetrahedron formation using SMC and maximum initial separation of 5 km: Path planning (a)-(b), and hybrid propulsion parameters (c)-(d).

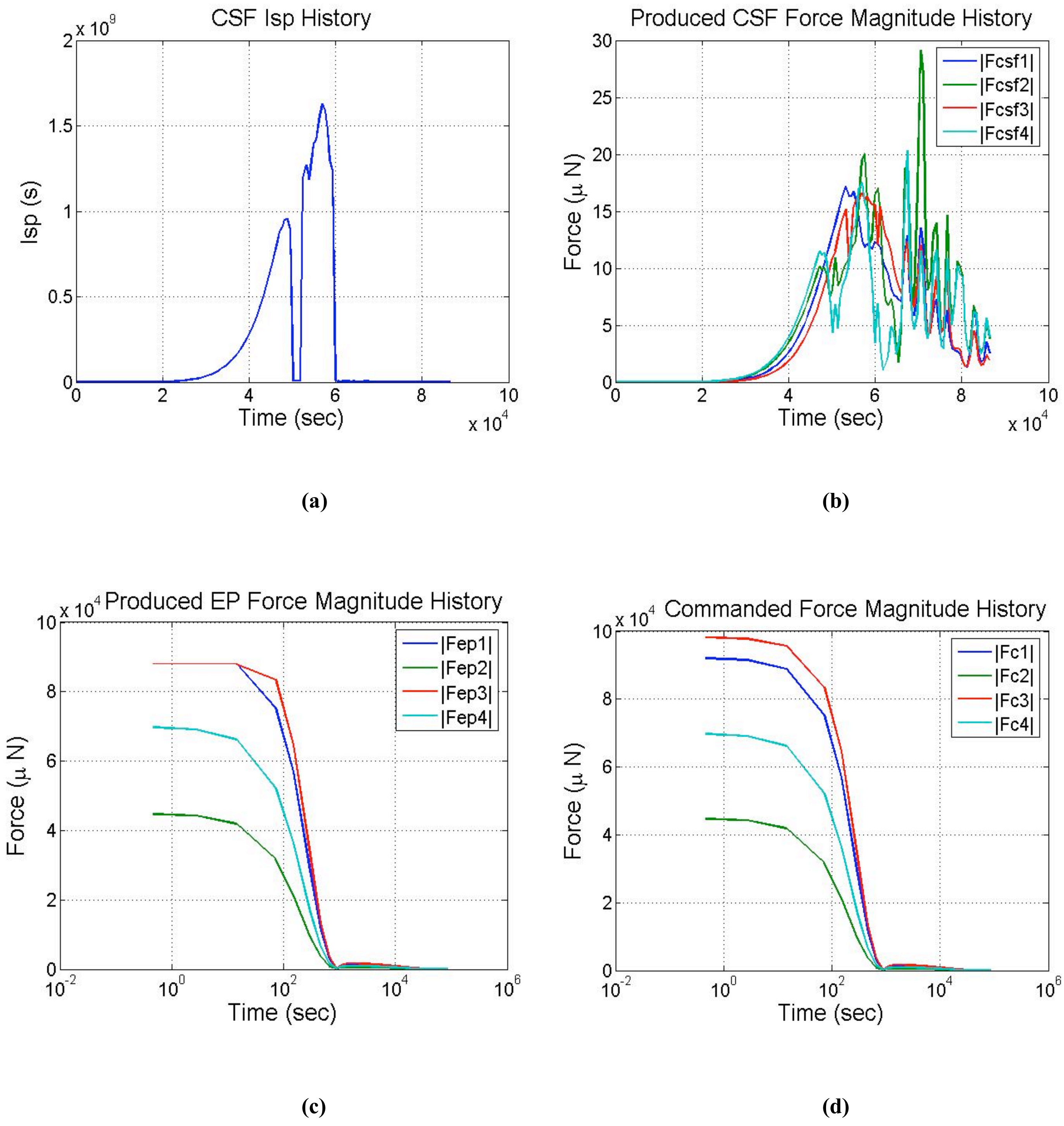

Figure 4. Simulation plots for tetrahedron formation using SMC and maximum initial separation of 5 km: Hybrid actuator parameters (a)-(d).