TEAM GERMANY SUPPORTS

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#INVOLVING EVERYONE

Deployment and Maintenance of Nanosatellite Tetrahedral Formation Flying Using Aerodynamic Forces

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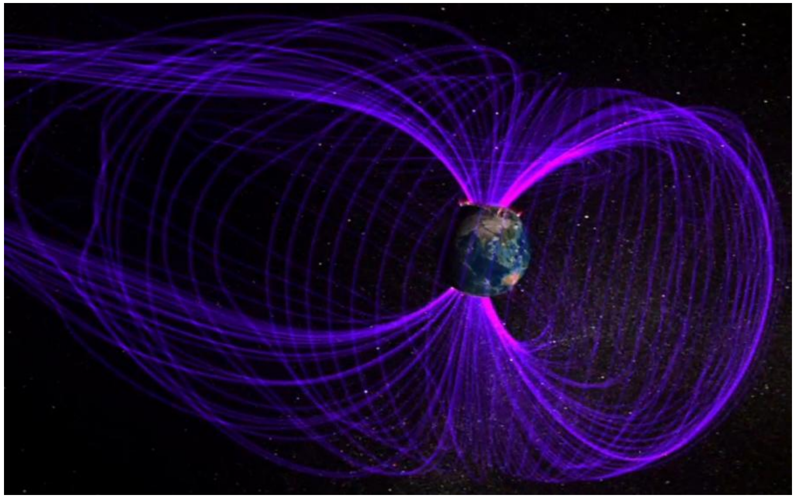
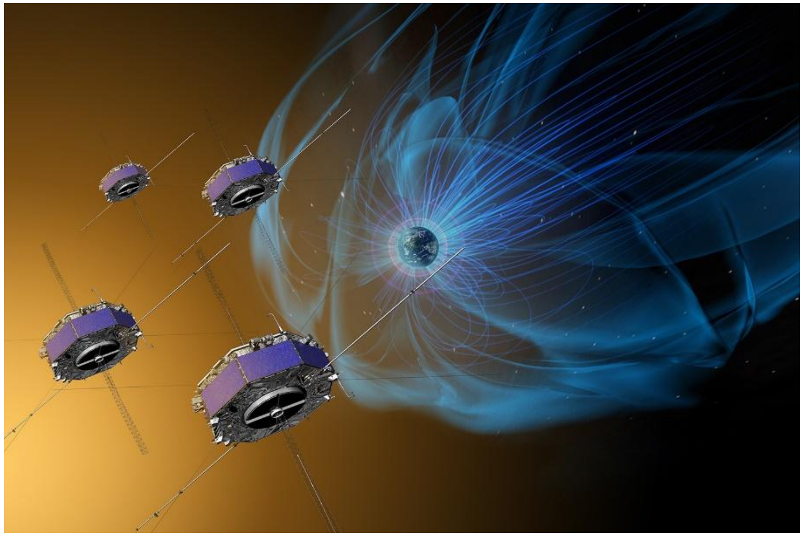
Motivation

- For an experimental study of the spatial distribution of the Earth magnetosphere parameters it is necessary to conduct simultaneous measurements at several points
- At least four satellites are required to carry out spatial measurements
- In the ideal case the satellites should fly so that they are always at the vertices of the regular tetrahedron
- To construct and maintain such a configuration the relative motion control must be applied
- For the Low-Earth Orbits the control can be performed using aerodynamic forces



MMS Mission – tetrahedral formation flying



Methods for Relative Motion Control in LEO

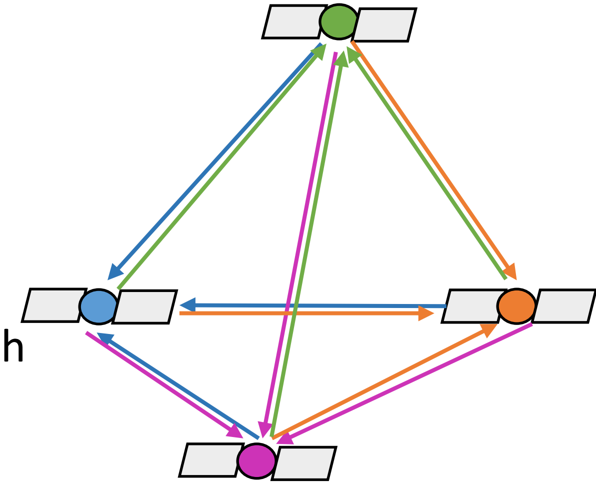
Thrusters	
Advantages	Disadvantages
Full controllability	Fuel consumption limitation
Maintenance of orbit	Expensive

Aerodynamics	
Advantages	Disadvantages
Inexpensively	Limitations on control source
No need for engines	Special form of the satellite
Not creating ionized cloud (Important for the study of the magnetosphere)	Active attitude system

Problem Statement

- The launch of four 3U CubeSats in LEO is considered
- Each satellite has information about relative motion of all other satellites
- The control is performed using aerodynamic forces (each satellite is equipped by an attitude control system)
- It is necessary to develop a decentralized control algorithm for tetrahedral configuration construction

The scheme of the launch as for PlanetLabs CubeSats

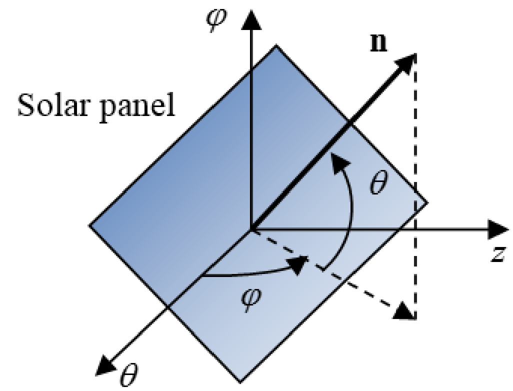


Decentralized control approach: each satellite decides how to control independently of others

Aerodynamic Force Model

Relative motion equation model:

$$\begin{cases} \ddot{x} + 2\omega\dot{z} = f_x, \\ \ddot{y} + \omega^2 y = f_y, \\ \ddot{z} - 2\omega\dot{x} - 3\omega^2 z = f_z, \end{cases}$$



The aerodynamic force model with lift component:

$$\vec{f}_i = -\frac{1}{m}\rho V^2 S\left\{(1-\varepsilon)(\vec{e}_V,\vec{n}_i)\vec{e}_V + 2\varepsilon(\vec{e}_V,\vec{n}_i)^2\vec{n}_i + (1-\varepsilon)\frac{\upsilon}{V}(\vec{e}_V,\vec{n}_i)\vec{n}_i\right\},$$

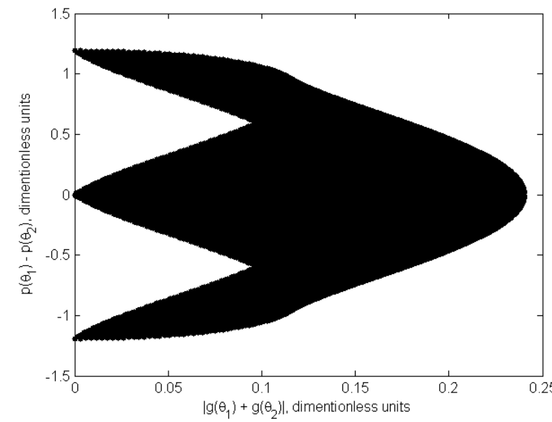
In the orbital reference frame:

$$\vec{f}_i = \frac{1}{m}\rho V^2 S\begin{bmatrix} -2\varepsilon(\sin\theta_i)^3 + \eta(\varepsilon-1)(\sin\theta_i)^2 + (\varepsilon-1)\sin\theta_i \\ -\cos\theta_i\sin\theta_i(\eta - \varepsilon\eta + 2\varepsilon\sin\theta_i)\cos\varphi_i \\ -\cos\theta_i\sin\theta_i(\eta - \varepsilon\eta + 2\varepsilon\sin\theta_i)\sin\varphi_i \end{bmatrix}$$

$$p(\theta_i) = -2\varepsilon(\sin\theta_i)^3 + \eta(\varepsilon-1)(\sin\theta_i)^2 + (\varepsilon-1)\sin\theta_i$$

$$g(\theta_i) = -\cos\theta_i\sin\theta_i(\eta - \varepsilon\eta + 2\varepsilon\sin\theta_i)$$

Acceptable control region



LQR-based Control Algorithm

- Motion equations

$$\dot{\mathbf{x}} = \mathrm{A}\mathbf{x} + \mathrm{B}\mathbf{u},$$

Cost function

$$J = \int_{\tau}^{\infty} (\mathbf{e}^T \mathrm{Q}\mathbf{e} + \mathbf{u}^T \mathrm{R}\mathbf{u})dt,$$

Feedback control is

$$\mathbf{u} = -\mathrm{R}^{-1}\mathrm{B}^T \mathrm{P}\mathbf{e}, \quad \text{where } \mathbf{e} = \mathbf{x} - \mathbf{x}_d,$$

matrix P is the solution of Riccati equation

$$\mathrm{Q} - \mathrm{PBR}^{-1}\mathrm{B}^T\mathrm{P} + \mathrm{PA} + \mathrm{A}^T\mathrm{P} = 0.$$

- In the case of four satellites for each satellite the mean deviation vector is

$$\bar{\mathbf{e}}_i = \sum_{j=1}^{3} \mathbf{e}_{ij} / 3, \quad \bar{\mathbf{u}}_i = -R^{-1}B^T P \bar{\mathbf{e}}_i$$

- Taking into account the force constraints the decentralized control is

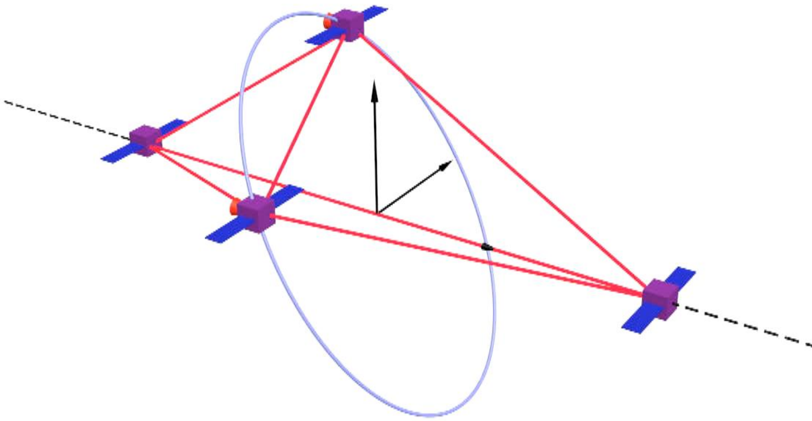
$$\mathbf{u}_i = \begin{cases} -\mathbf{u}_{\max}^x, \text{if } \bar{u}_i^x > u_{\max}^x, \\ -\mathbf{u}_{\max}^{yz}, \text{if } 0 < \bar{u}_i^x < u_{\max}^x, \\ \qquad \text{and } \sqrt{\left(\bar{u}_i^y\right)^2 + \left(\bar{u}_i^z\right)^2} > u_{\max}^{yz}, \\ -\bar{\mathbf{u}}_i, \quad \text{if } 0 < \bar{u}_i^x < u_{\max}^x, \\ 0, \quad \text{if } \bar{u}_i^x < 0. \end{cases}$$

Reference Trajectories for Tetrahedral Configuration

- Two of the satellites are moving along the same circular orbit with a constant separation equal to 2D
- The other two satellites are moving along the circular relative trajectories

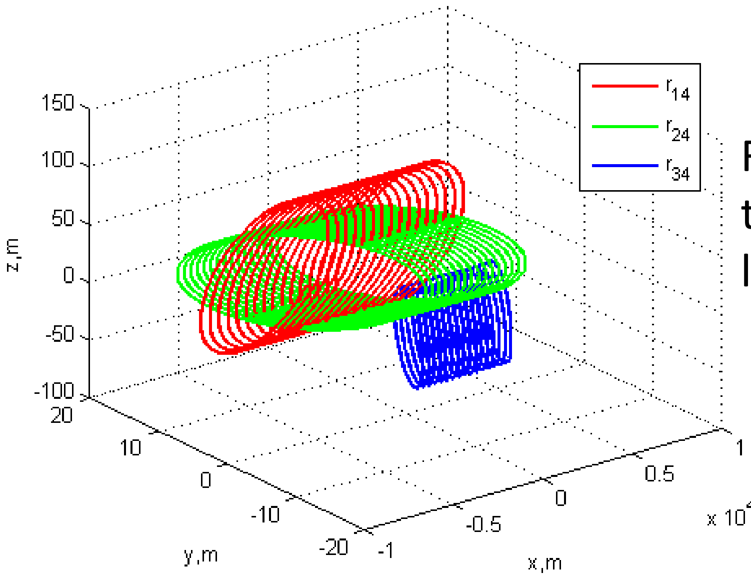
$$x_1 = 2A\cos(\omega t - \arccos(1/3)), \quad x_3 = D,$$
$$y_1 = A\sqrt{3}\sin(\omega t), \quad y_3 = 0,$$
$$z_1 = A\sin(\omega t - \arccos(1/3)), \quad z_3 = 0,$$

$$x_2 = 2A\cos(\omega t), \quad x_4 = -D,$$
$$y_2 = A\sqrt{3}\sin(\omega t + \arccos(1/3)), \quad y_4 = 0,$$
$$z_2 = A\sin(\omega t). \quad z_4 = 0.$$

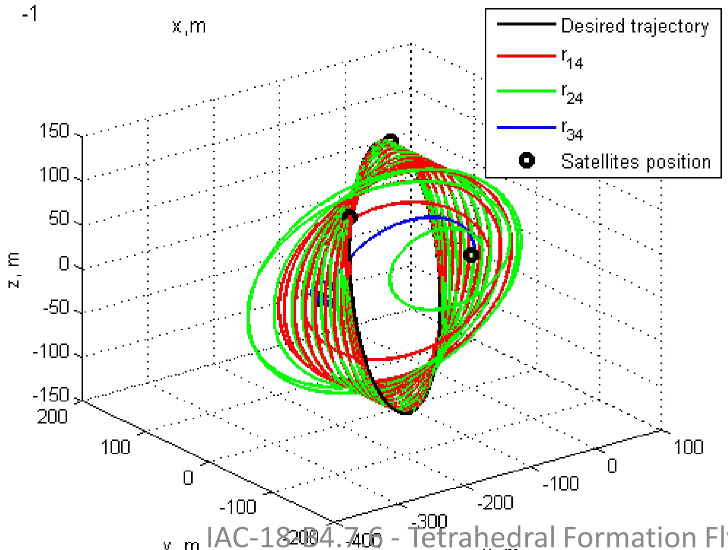


Y. Mashtakov, S. Shestakov Maintenance of the tetrahedral satellite configuration with single-input control // Preprints of Keldysh Institute for Applied Mathematics. 2016. № 95. 27 p.

Numerical Study



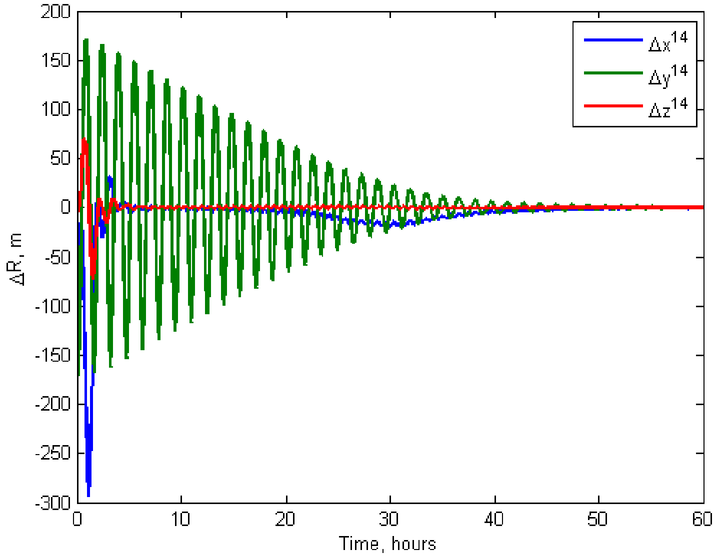
Free relative trajectories after the launch

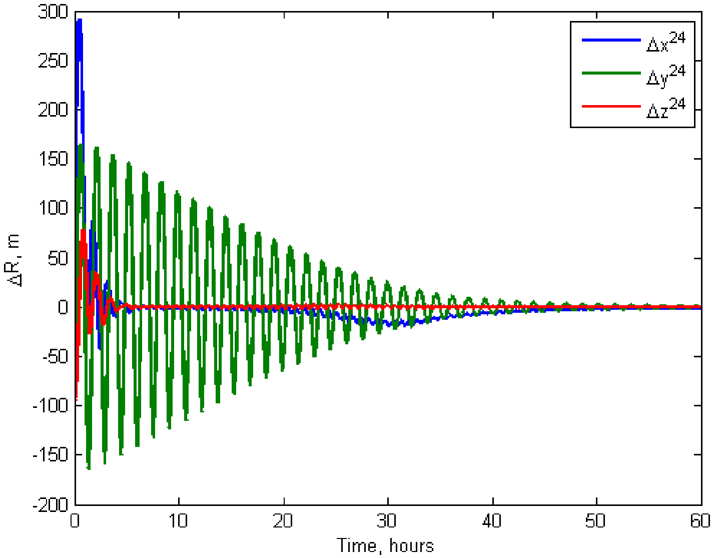


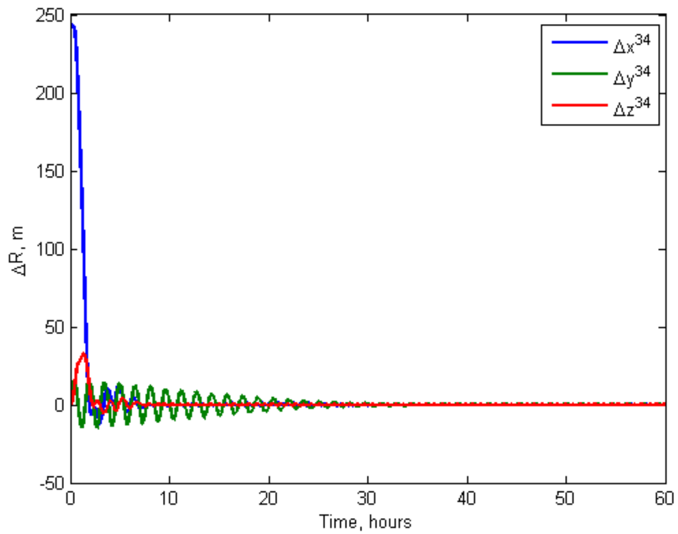
Controlled relative trajectories after the launch

Main parameters of the formation	
Number of satellites in the formation,	4
Time interval between control calculation,	150 s
Parameter of tetrahedron A	100 m
Parameter of tetrahedron D	115 m
Launch parameters	
Time interval between the launches,	10 s
Ejection velocity,	0.5 m/s
Ejection error deviation,	0.015 m/s
CubeSats parameters	
Mass of satellite,	3 kg
Difference between maximum and minimum value of the cross-sectional area,	0.02 m²
Aerodynamic drag coefficient,	2
LQR parameters	
Matrix	
Matrix R	diag ([1e-13; 1e-14; 1e-14])
Aerodynamic drag force parameters	
Constant atmosphere density,	kg/m³
Orbit altitude,	340 km
Airflow velocity,	7.69 km/s
Parameters and	0.1
Maximum of the control source,	m/s²

Relative Trajectories Deviations



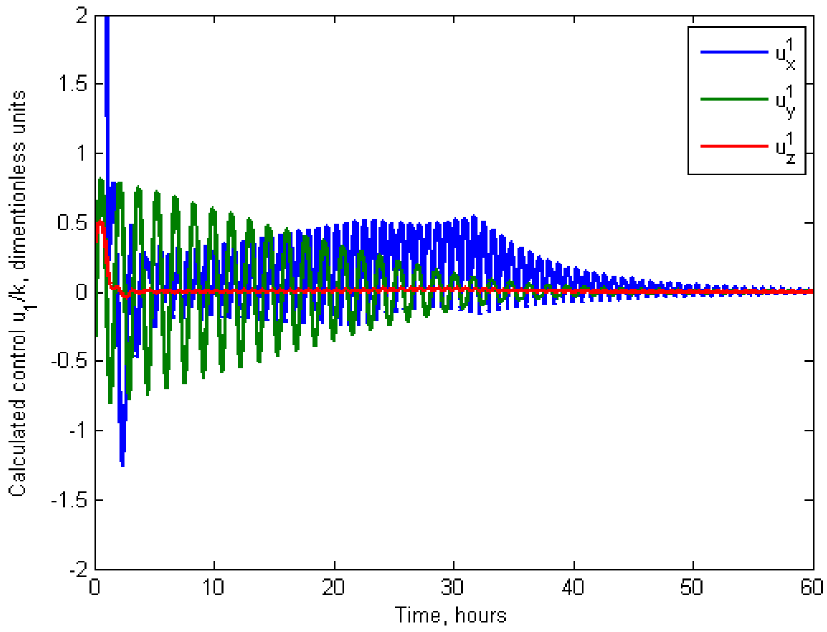




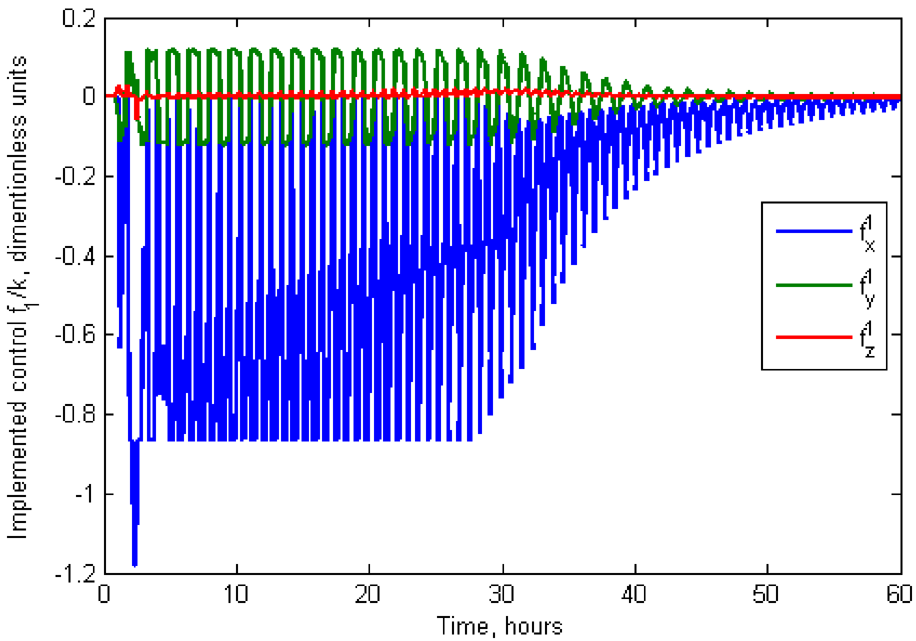
Calculated and Implemented Control

- Due to aerodynamic force restrictions and decentralized control strategy the calculated and implemented control vectors are different

Calculated control vector



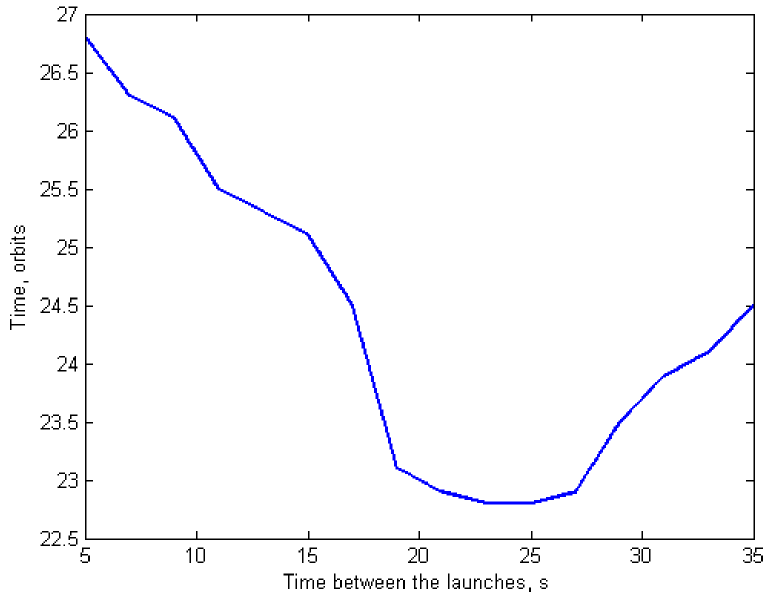
Implemented control vector



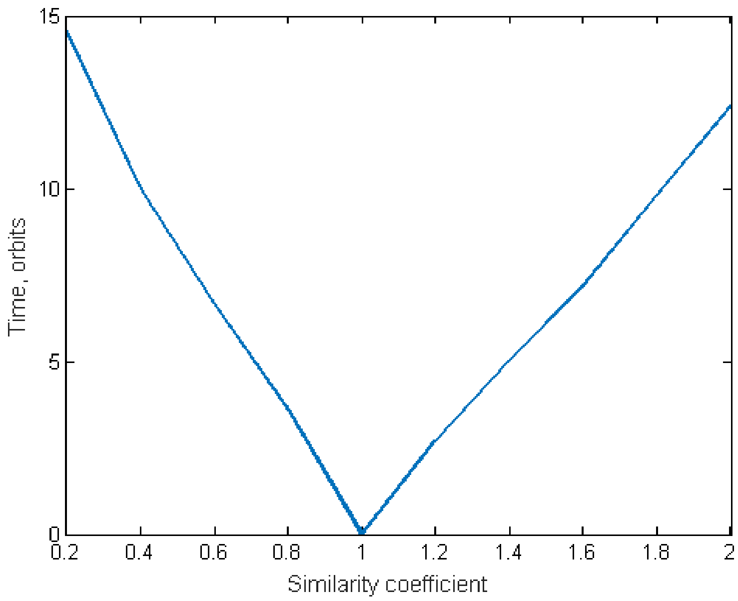
Construction and Resizing

- It is interesting to investigate the time that is needed to construct the tetrahedral formation flying depending on the launch conditions
- For magnetosphere measurements it is important to scale the size of the tetrahedron to investigate the magnetic effects at different scales

Tetrahedron construction on the time between the launches



Time for reconfiguration of the resizing of the tetrahedron



Conclusion

- The decentralized control scheme is proposed for the tetrahedral formation flying using the aerodynamic force with the lift component
- The proposed control scheme of the tetrahedral formation flying construction requires further investigation
- Active magnetic attitude control application should be studied in future work

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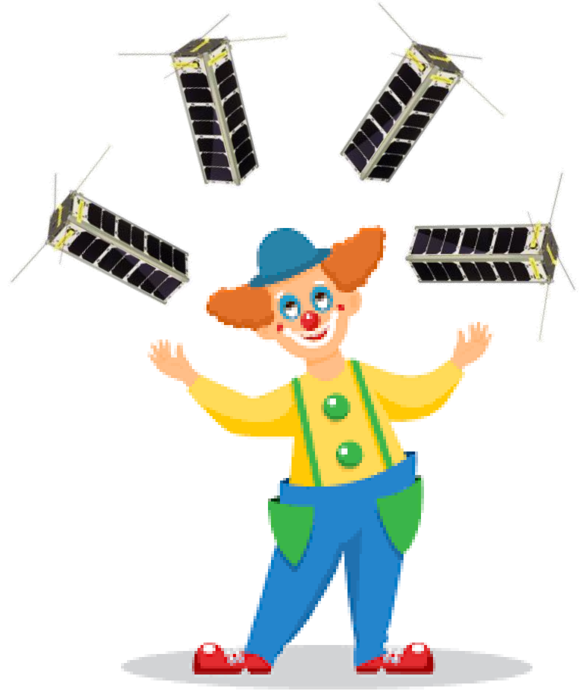
Thank you for attention!



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