Overview of control approaches and algorithms for distributed space systems

Danil Ivanov, Uliana Monakhova

Keldysh Institute for Applied Mathematics, Moscow, Russia

ОРДЕНА ЛЕНИНА
им.М.В.КЕЛДЫША
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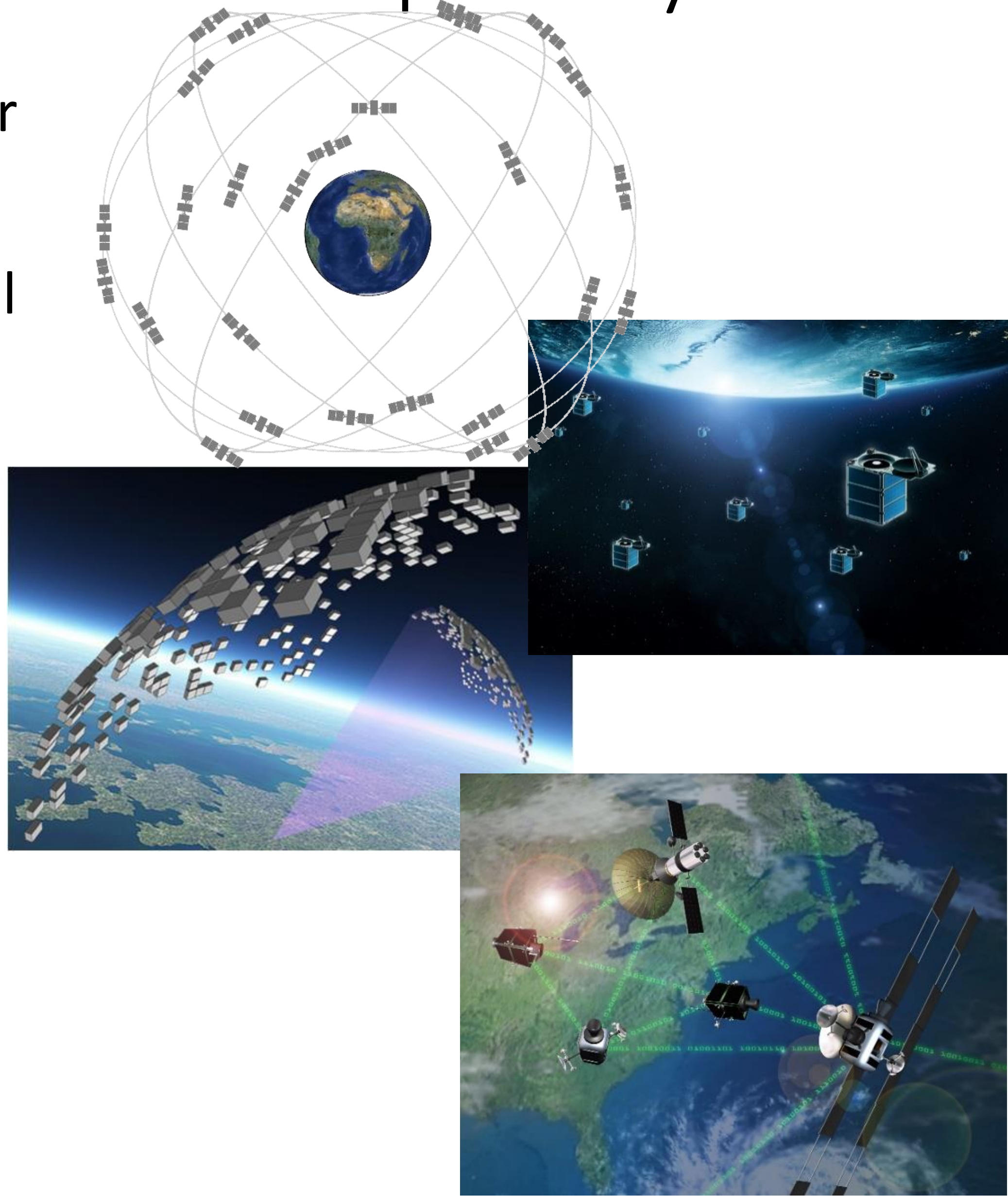
What is distributed system?

- A space system consisting of multiple space elements that can communicate, coordinate and interact in order to achieve a common goal.
  - Concurrency of elements
  - Tolerance for failure of individual systems
  - Scalability and flexibility in design and deployment of system

Definitions for distributed space systems

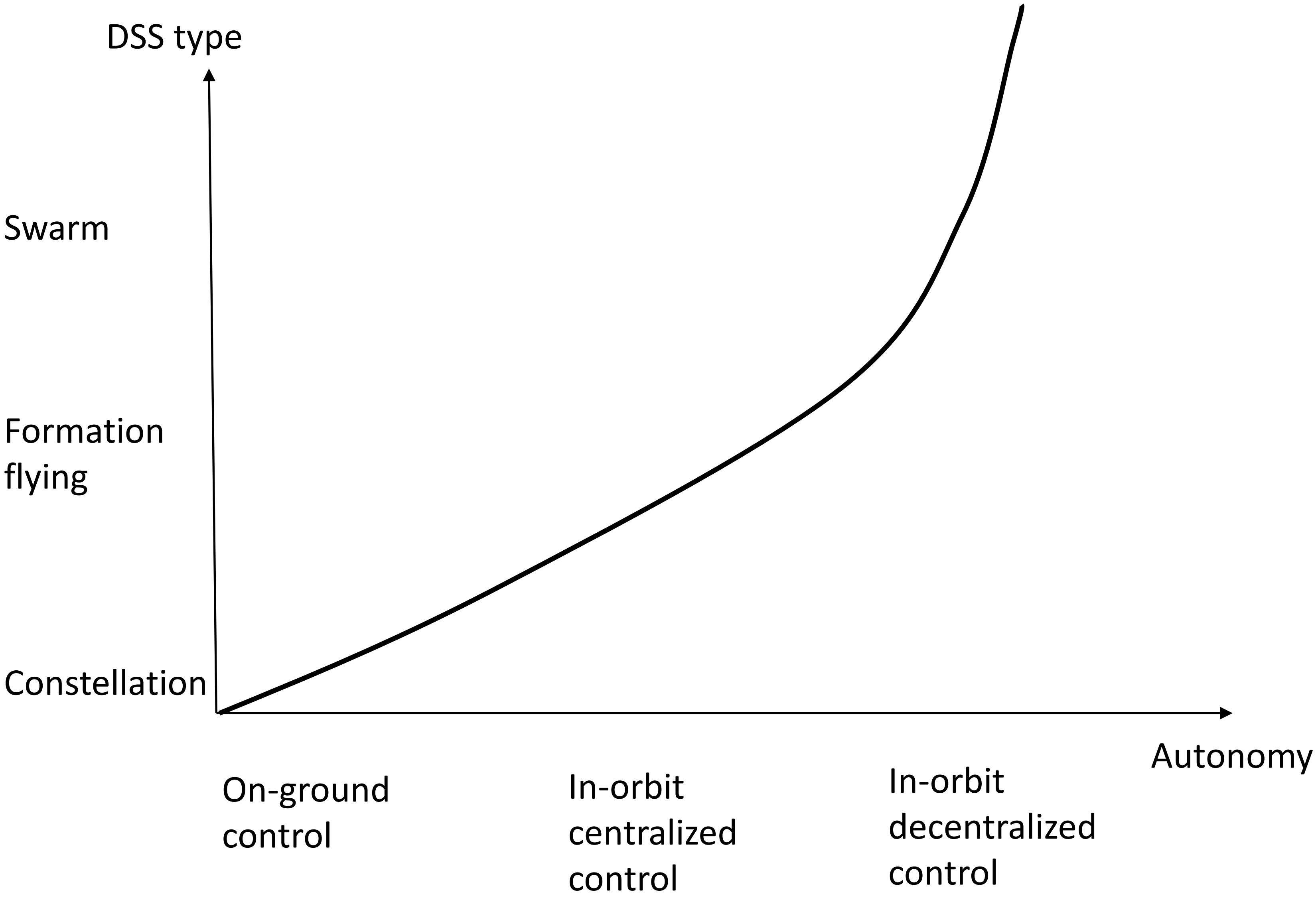
- Constellation: similar trajectories without control for relative position; coordination from a control center.
- Formation: closed-loop control on-board in order to preserve topology in the group and to control relative distances
- Cluster: distributed heterogeneous system of satellites to achieve in cooperation a joint objective.
- Swarm: a group of similar (homogenous) vehicles cooperating to achieve a joint goal without fixed positions; Each member determines and controls relative positions in relations to others.



Main parameters of distributed SS

- A number of satellites
- Degree of autonomy
- Communication links between satellites
- Relative trajectory types

Autonomy in relative control



Natural distributed systems

School of fishes

Flock of birds

Swarm of bees

Herd of animals

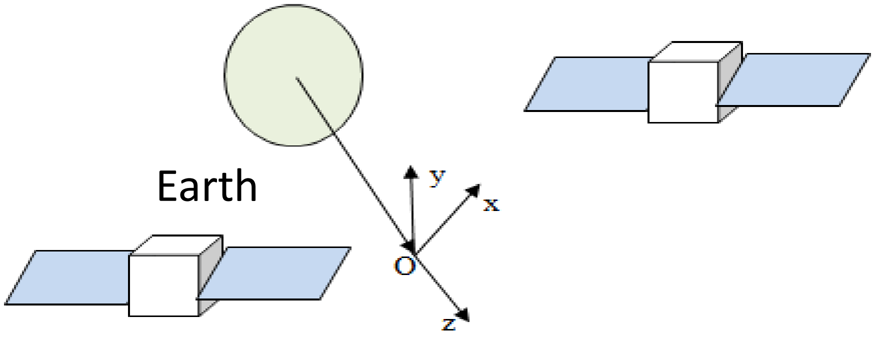
Satellite formation flying features

- A small number of satellites
- Centralized control:
  - Mother-daughter relationship: mother knows the best for her children and command them
  - Leader-follower relationship: leader moves everywhere it wants, the followers pursue it
- Communication with all the group members
- Motion along predefined trajectories

Equations of relative motion: linear model, near circular orbit

On the first stage of control algorithms investigation Hill-Clohessy-Wiltshire model is used:

$$\begin{cases} \ddot{x} + 2\omega\dot{z} = 0 \\ \ddot{y} + \omega^2 y = 0 \\ \ddot{z} - 2\omega\dot{x} - 3\omega^2 z = 0 \end{cases}$$



Scheme of motion

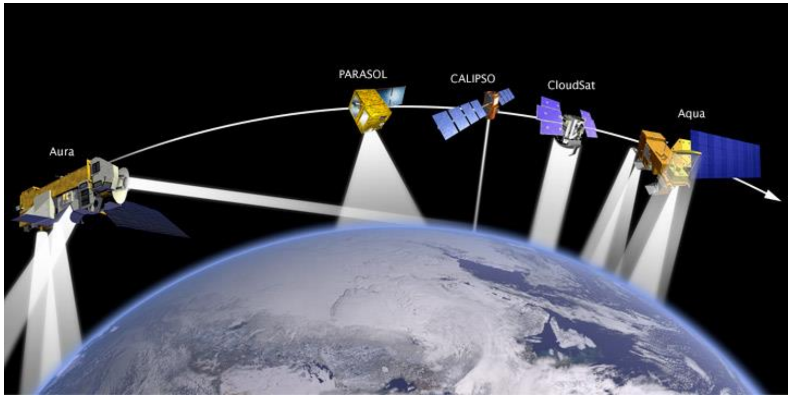
Solution is :

$$\begin{cases} x = -3C_1\omega t + 2C_2\cos\omega t - 2C_3\sin\omega t + C_4 \\ y = C_5\sin\omega t + C_6\cos\omega t \\ z = 2C_1 + C_2\sin\omega t + C_3\cos\omega t \end{cases}$$

$-3C_1\omega t$ - Relative drift

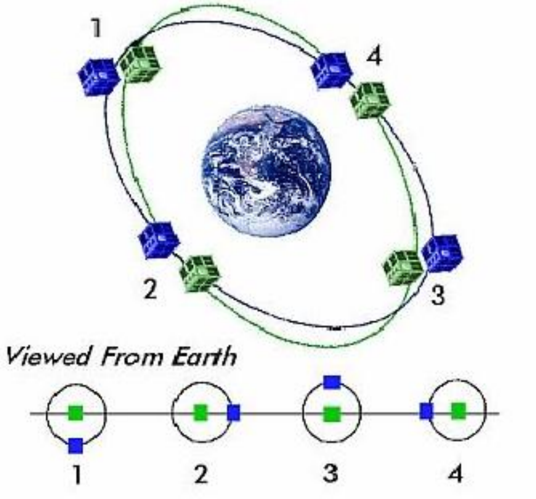
Formation flying specific relative trajectories

- Train formation
- Relative circular orbit
- Docking trajectories



A-train formation flying

KIKU-7 mission



CanSat4&5 mission

Satellite swarm features

- A large number of satellites
- Decentralized control
- Communication with limited number of group member
- Motion along occasional trajectories:
  - Random but bounded relative trajectories

Swarm control objectives

- Collision avoidance
  - When the relative distance d_{ij} is less then fixed threshold R_{av} the collision maneuver is performed
- Alignment
  - The satellites tent to align to its neighbors $R_{av} < d_{ij} < R_{al}$
- Attraction
  - Each satellite try to be closer to far members $R_{al} < d_{ij} < R_{att}$

Artificial potential control approach

- Collision avoidance

$$U_{ij}^{rep} = -C_{rep} e^{-\frac{d_{ij}}{R_{rep}}}$$

- Alignment

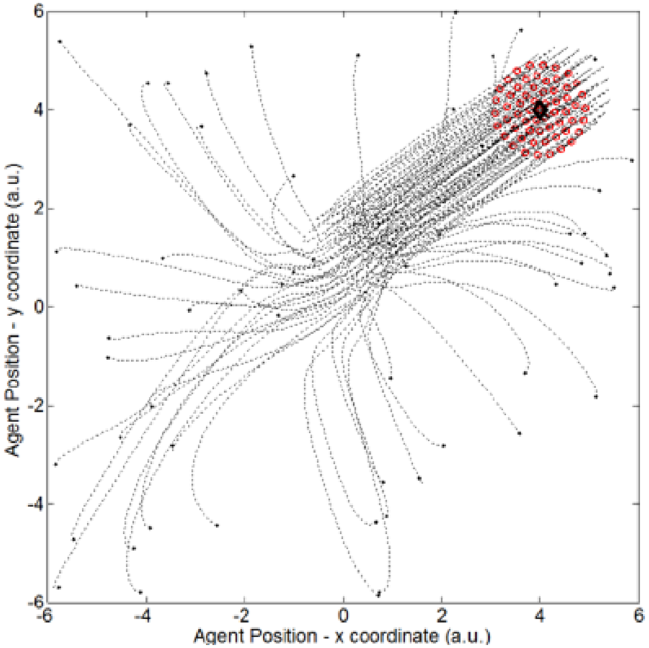
$$\mathbf{d}_i = \sum_{j,j\neq i} C_{al} \left(\mathbf{v}_{ij} \cdot \mathbf{r}_{ij}\right) e^{-\frac{d_{ij}}{R_{al}}} \mathbf{r}_{ij}$$

- Attraction

$$U_{ij}^{at} = -C_{at} e^{-\frac{d_{ij}}{R_{at}}}$$

Equations of motion

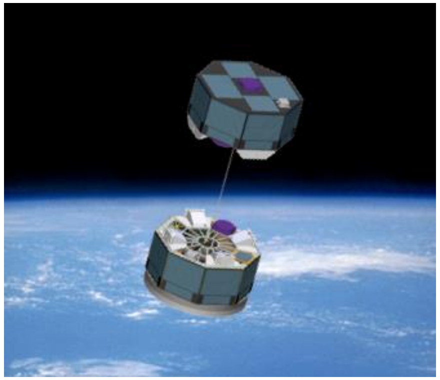
$$m_i \mathbf{r}_i = -\nabla_i U(\mathbf{r}_i) + \mathbf{d}_i$$

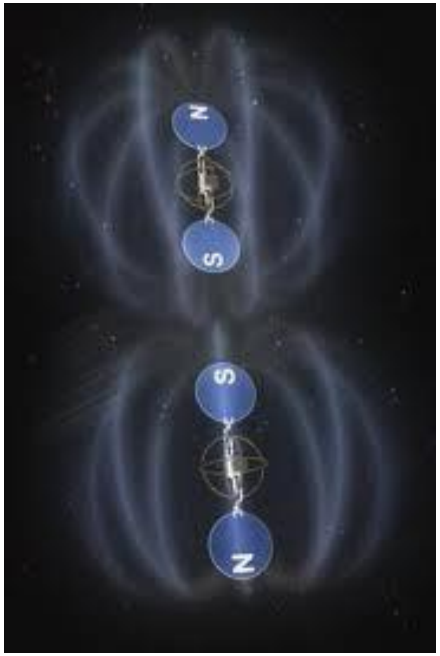


M. Sabatini, G. B. Palmerini and P. Gasbarri. Control Laws for Defective Swarming Systems// Advances in the Astronautical Sciences, Second IAA DyCoss'2014, V. 153. p. 132-153.

Fuelless FF Control Concepts

- Tethered systems
- Aerodynamic drag
- Electro-magnetic interaction
- Solar pressure
- Momentum exchange





Methods for controlling relative motion in a low-Earth orbit

Thrust engines	
Advantages	Disadvantages
Full controllability	Fuel consumption limitation
Maintenance of orbit	Expensive

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

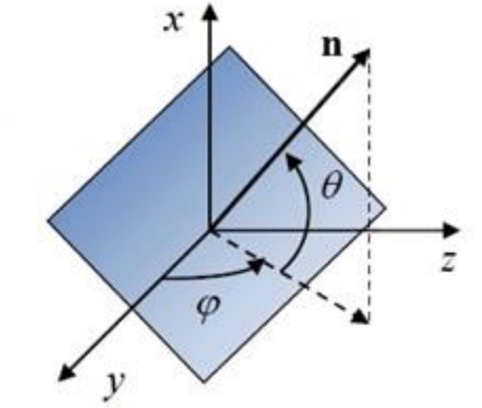
Model of aerodynamic force

Equations of relative motion with allowance for aerodynamic force:

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

The model of the force acting on one of the satellites:

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

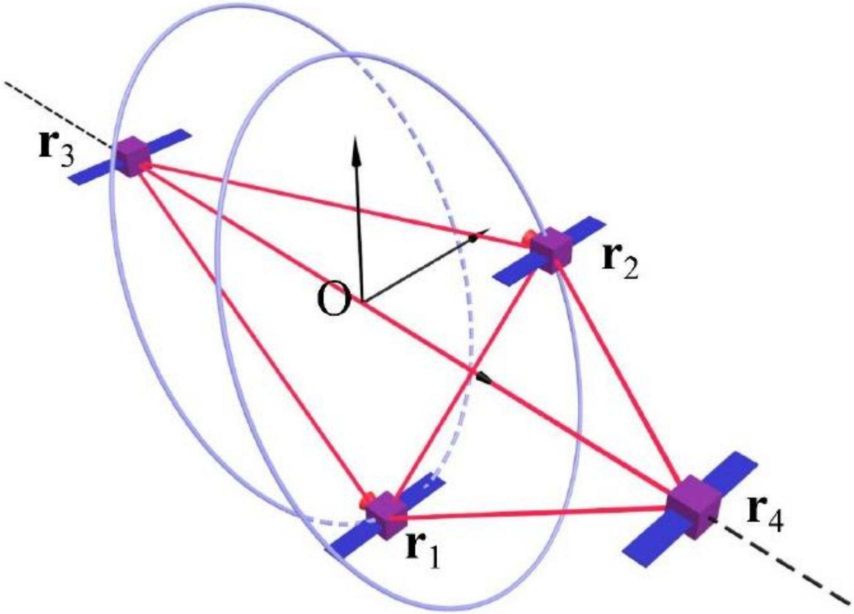


Reference trajectories

A tetrahedron with the best quality is achieved when the satellites move along the following reference orbits when considering a linear motion model for a low-Earth orbit:

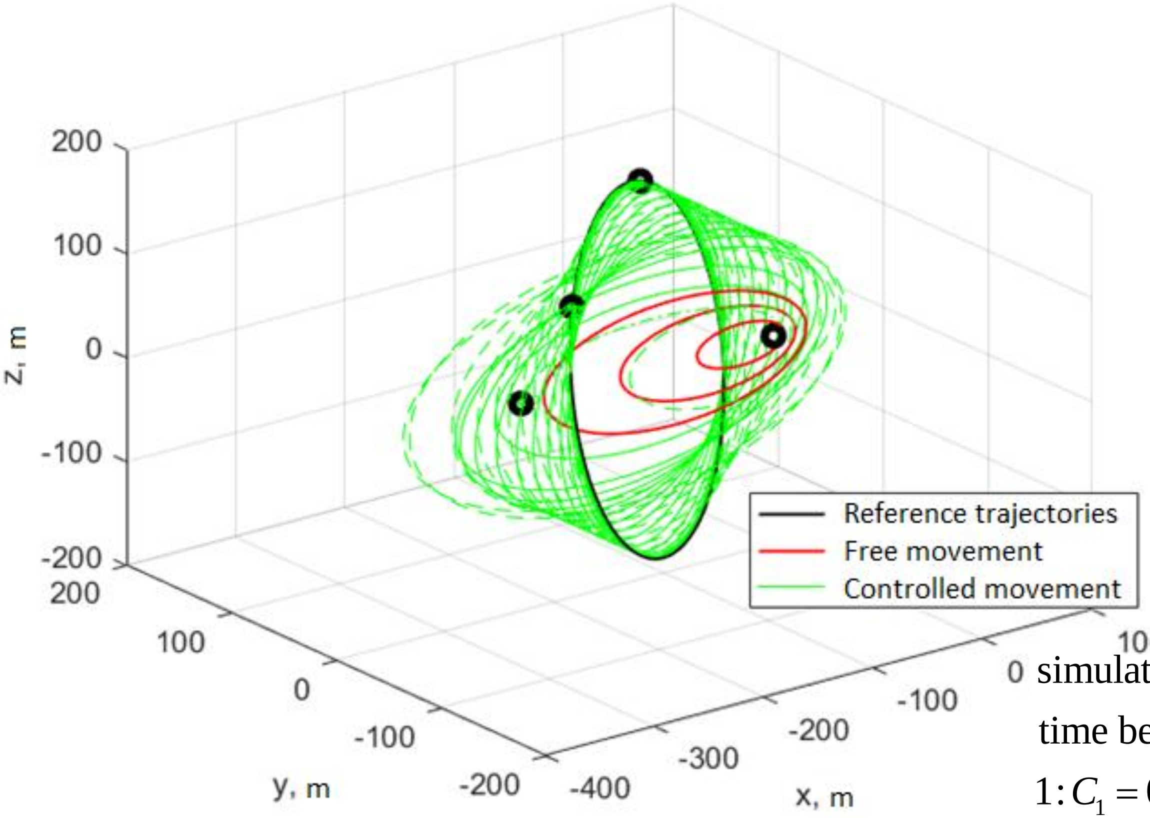
$$x_1 = 2A\cos(\omega t - \arccos(1/3)), \qquad x_3 = D,$$
$$y_1 = A\sqrt{3}\sin(\omega t), \qquad y_3 = 0,$$
$$z_1 = A\sin(\omega t - \arccos(1/3)), \qquad z_3 = 0,$$

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



- *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.*

Simulation:
Relative trajectories



simulation parameters:

time between launch $= 20\text{s}$

$1: C_1 = 0, C_2 = 0, C_3 = 325, C_4 = 0, C_5 = 250, C_6 = 0$

$2: C_1 = 0, C_2 = 0, C_3 = 200, C_4 = 0, C_5 = 100, C_6 = 0$

$3: C_1 = 0, C_2 = 0, C_3 = 215, C_4 = 0, C_5 = 115, C_6 = 0$

$4: C_1 = 0, C_2 = 0, C_3 = 225, C_4 = 0, C_5 = 145, C_6 = 0$

Swarm control rules

- Most distant satellite drift elimination

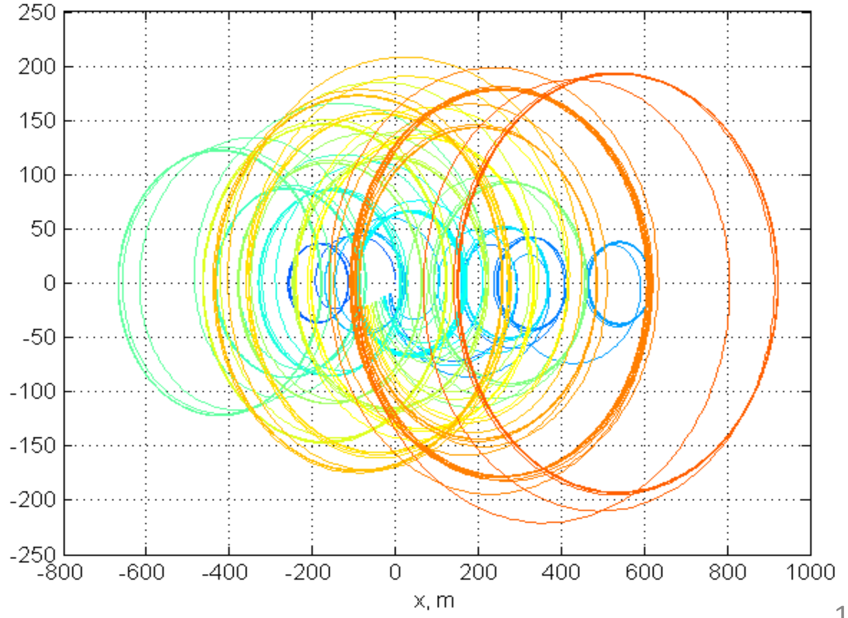
$$u_i^{\max R} = \frac{-\omega C_1^{iJ}}{\Delta T}, J = \arg\left(\max_j\left(R_{ij}\right)\right), j \in [1,\dots,N_{comm}], j \ne i, R_{ij} \le R_{comm}$$

- Maximum drift elimination

$$u_i^{\max C_1} = \frac{-\omega C_1^{iJ}}{\Delta T}, J = \arg\left(\max_j\left(C_{ij}\right)\right), j \in [1,\dots,N_{comm}], j \ne i, R_{ij} \le R_{comm}$$

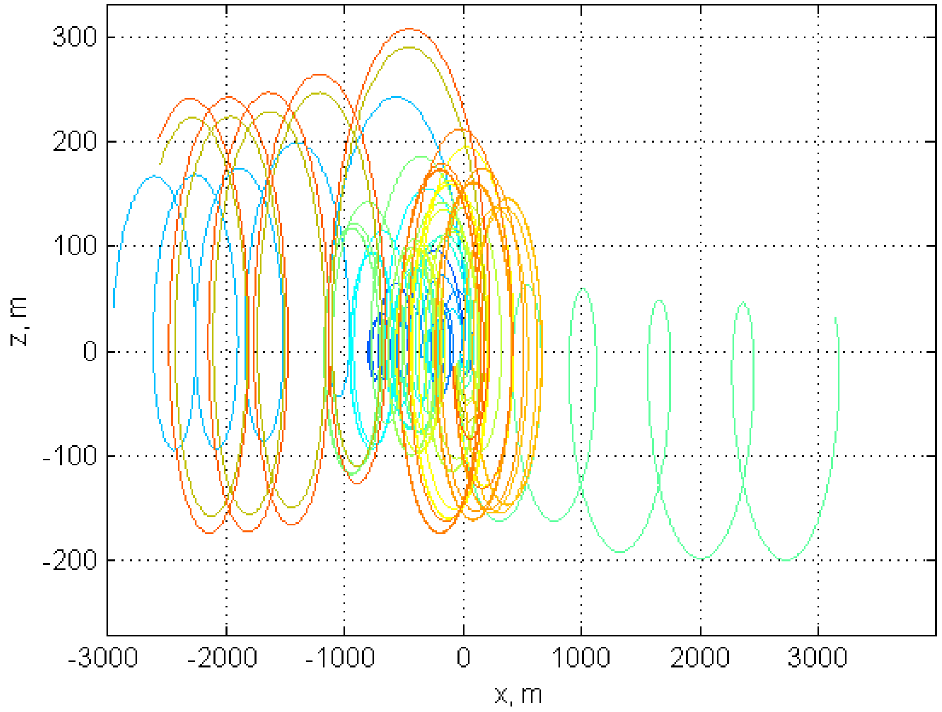
- Average drift elimination

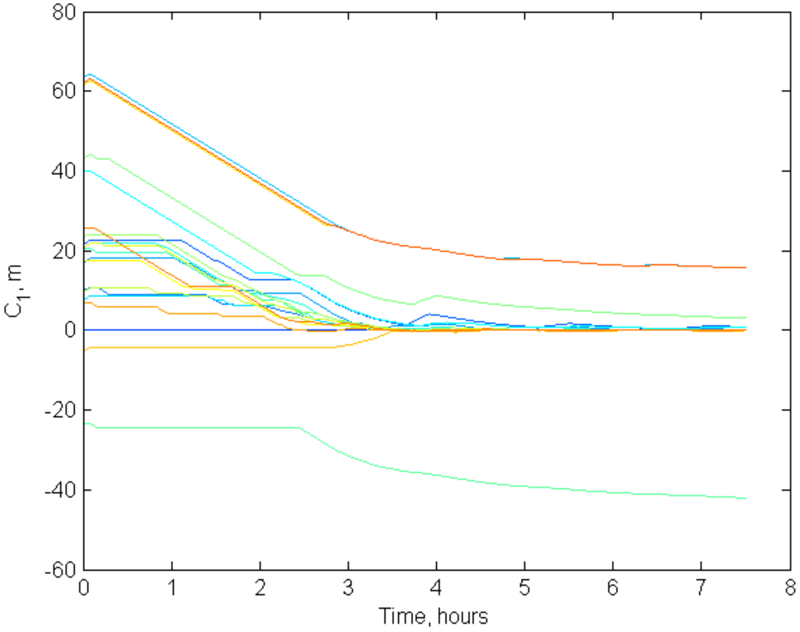
$$\bar{C}_1^i = \sum_{j=1}^{N_{comm}} C_1^{ij} / N_{comm} \,, \quad \bar{u}_i = \frac{-\omega \bar{C}_1^i}{\Delta T}$$



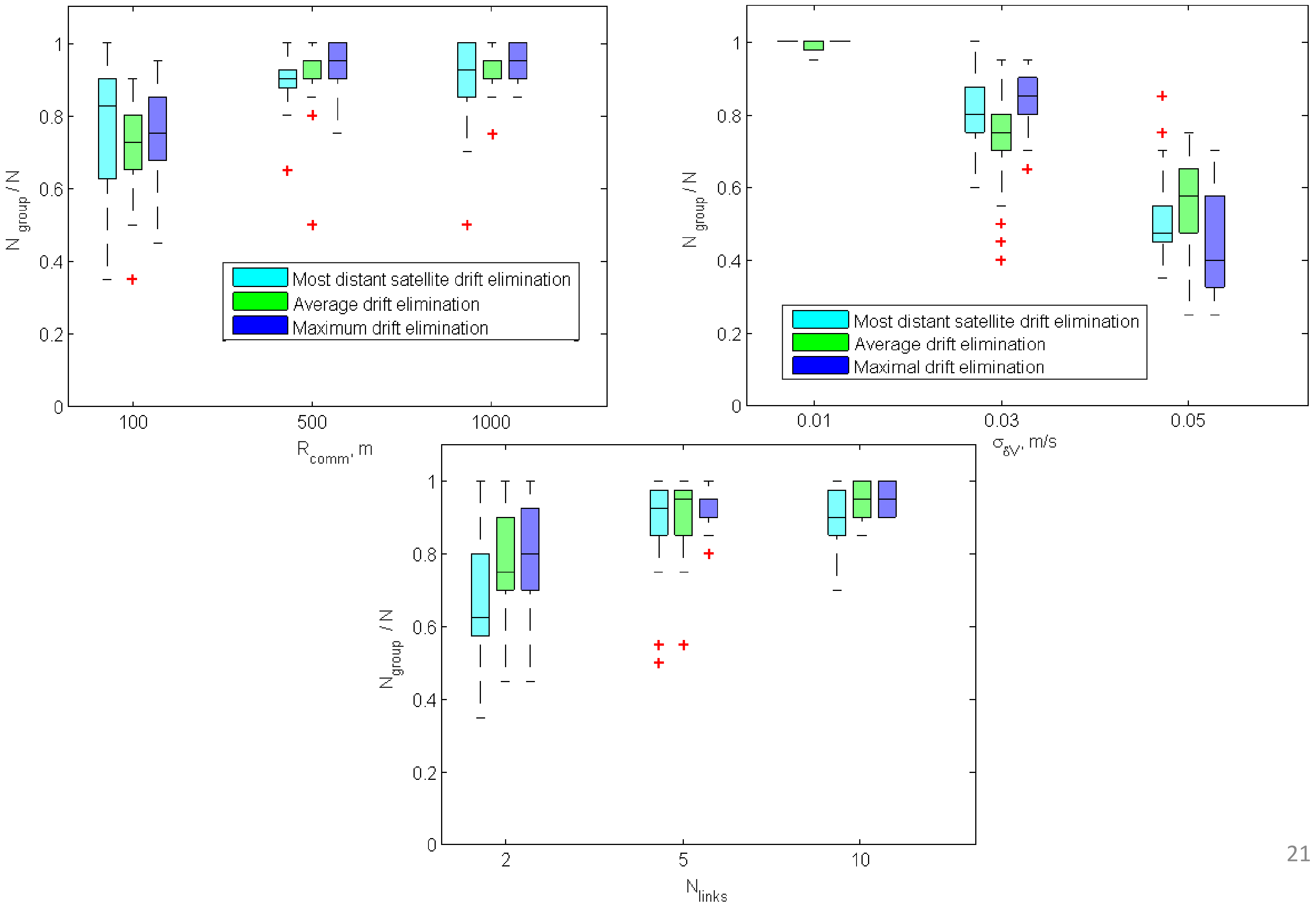
Separation of the swarm

Example of the relative motion trajectories in the case of separation of the swarm





Comparison of control rules



Conclusion

- The swarm of the satellites is a new paradigm in space systems
- The fuelless control approaches are fitting small satellite restrictions, they are smart but challenging
- We should allow for the distributed system to be autonomous and self-organizing

Thank you for your attention!