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Satellite formation flying control approaches and algorithms

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Content

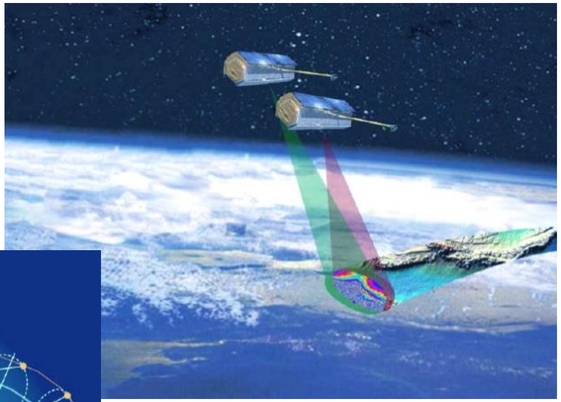
- Formation flying features
- Overview of control approaches
- Fuelless satellite formation flying control concepts
- Mission examples
- Laboratory simulations
- Conclusion

What is satellite formation flying?

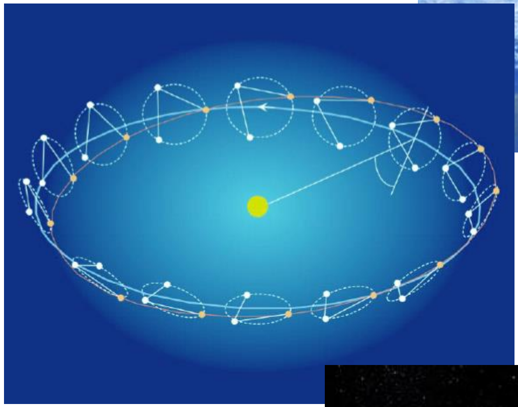
- It is space distributed system consisting of multiple elements flying in a short relative distances in orbit that can communicate, coordinate and interact in order to achieve a common goal
- Its main advantages:
  - Concurrency between the satellites
  - Tolerance for failure of individual systems
  - Scalability and flexibility in design and deployment of system

What is formation flying needed for?

- Earth remote sensing using interferometric measurements
- Gravitational waves measurements
- Building of the space stations in orbit
- Solar activity precise measuremets
- Space debris removal
- And so on…



TanDEM-X mission

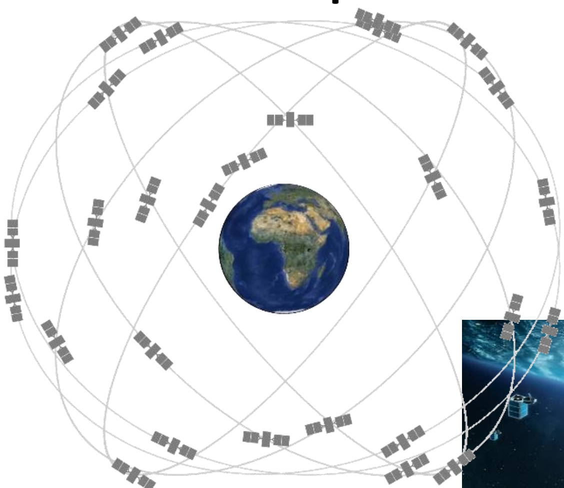


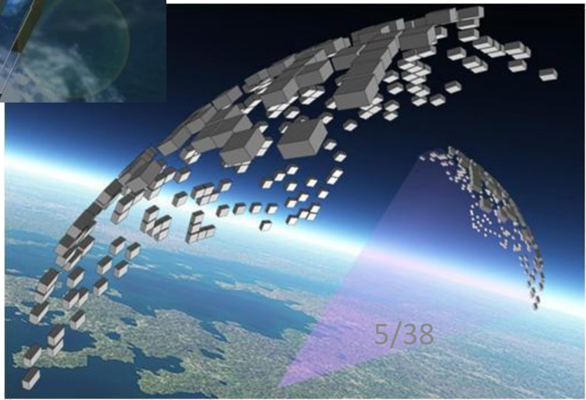
LISA mission

Grabbing the debris

Definitions for distributed space systems

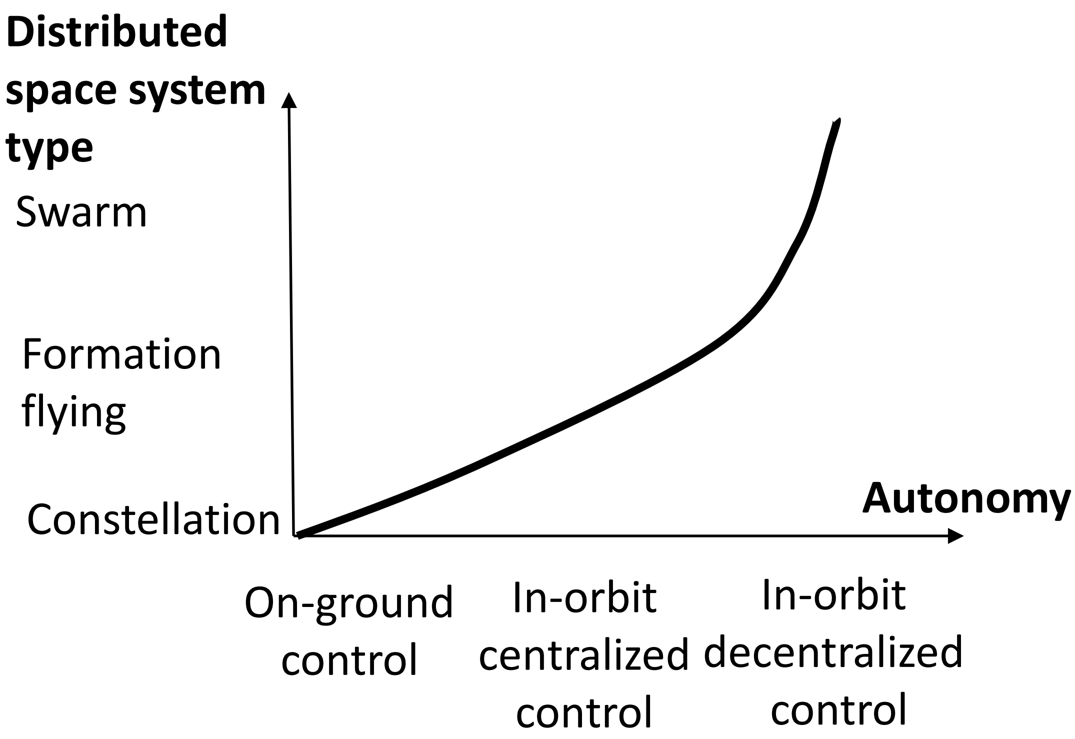
- **Constellation**: similar trajectories without control for relative position; coordination from a control center
- **Formation**: closed-loop control on-board in order to preserve topology in the group and to control relative distances
- **Swarm**: a group of similar vehicles cooperating to achieve 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
- A degree of autonomy
- Communication links between satellites
- Relative trajectory types

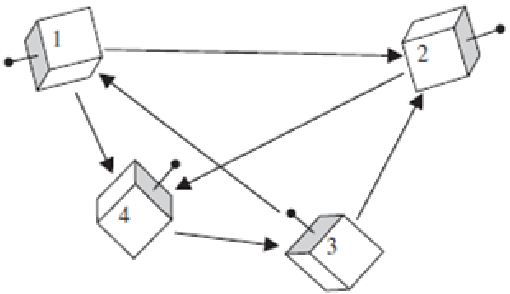


Autonomy in relative control

Communication between satellites

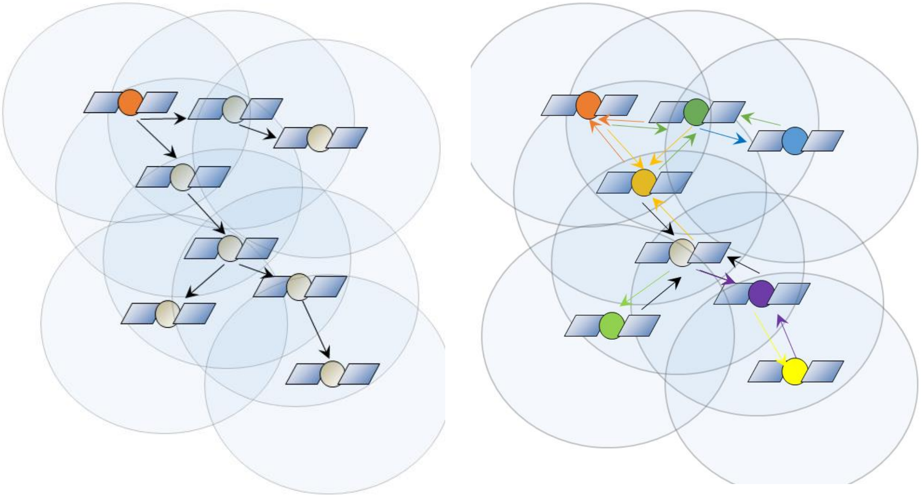
- The communication is information exchange or just measuring of relative pose
- There could be directed or mutual communication
- Each satellite has limited communication area
- If det(A)≠0, the formation is decentralized
- If det(A)=0, the formation is of leader-follower type, communication is cycled

$$A = \begin{bmatrix} 0 & 1 & 0 & 1 \\ 0 & 0 & 0 & 1 \\ 1 & 1 & 0 & 0 \\ 0 & 0 & 1 & 0 \end{bmatrix}$$



Centralized

Decentralized



Natural formation motions

School of fishes

Flock of birds

Swarm of bees

Herd of animals

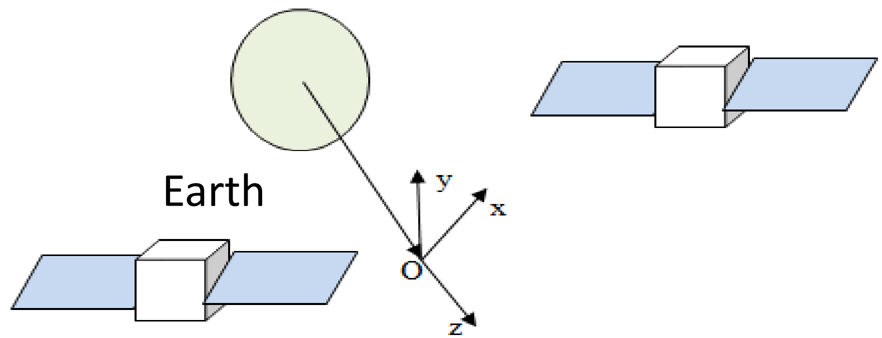
Satellite formation flying features

- 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 of the group members
- Motion along predefined trajectories

Equations of relative motion: linear model, near circular orbit

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

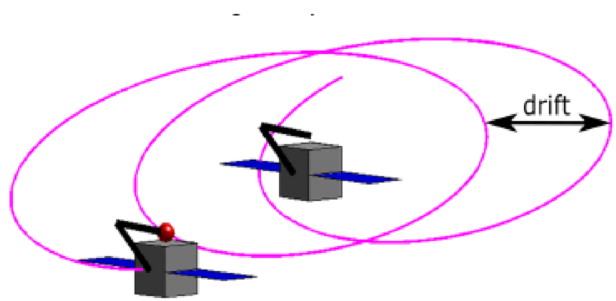
$$\begin{cases} \ddot{x} + 2\omega\dot{z} = 0 \\ \ddot{y} + \omega^2 y = 0 \\ \ddot{z} - 2\omega\dot{x} - 3\omega^2 z = 0 \end{cases}$$



Scheme of motion

Solution is :

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

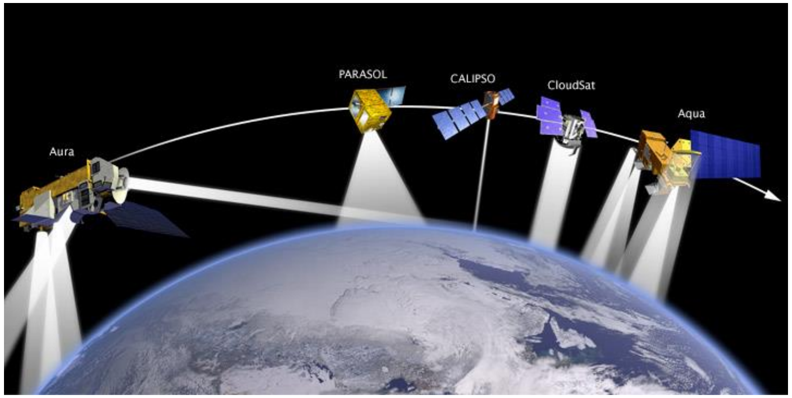


The relative drift

$-3C_1\omega t$ - Relative drift

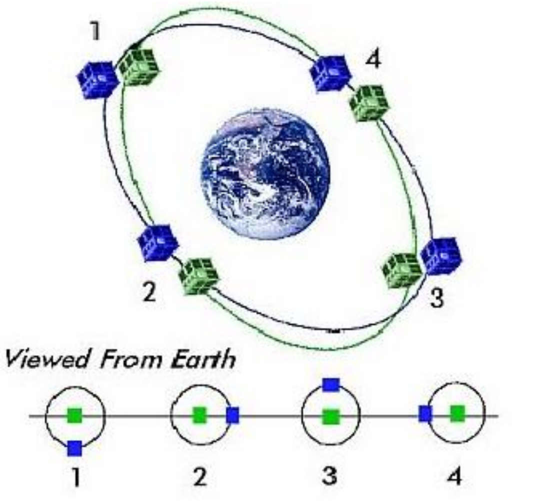
Formation flying specific relative trajectories

- Train formation
- Relative circular orbit
- Projected circular orbit
- Docking trajectories
- And so on



A-train formation flying

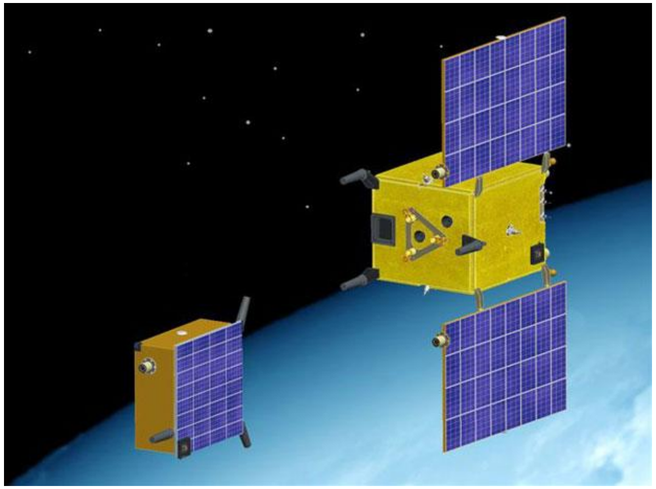
KIKU-7 mission



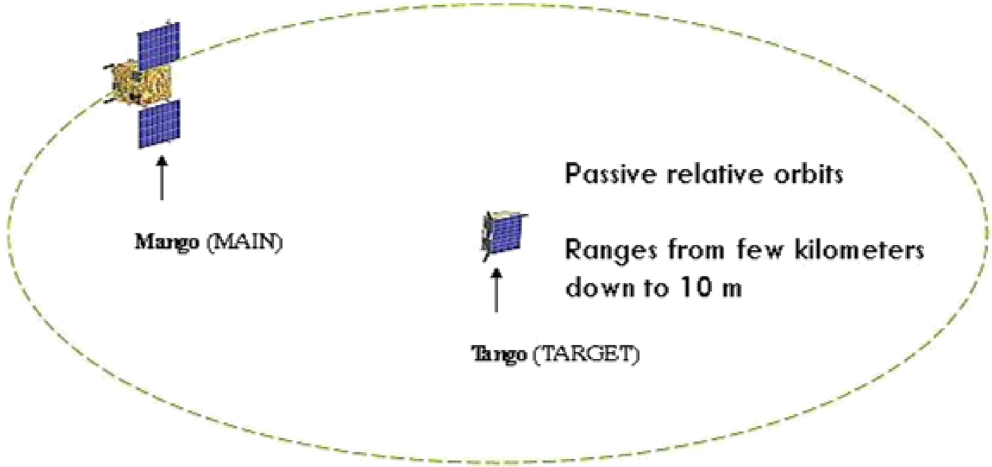
CanSat4&5 mission

Formation flying control actuations

- On-board propulsion system
  - Cold gas thrusters
  - Plasma thruster
- Fuelless alternative control concepts
  - Aerodynamic drag
  - Electromagnetic interaction
  - Solar pressure
  - ...



PRISMA mission



Tango propulsion system

An example: tetrahedron formation maintenance

Problem statement:

- Given four satellites on closed, possibly elliptical, orbits
- Need to obtain a reference orbit in order that the corresponding tetrahedron maintains over time
- Also provide a control algorithm using propulsion system for several satellites to neglect perturbations

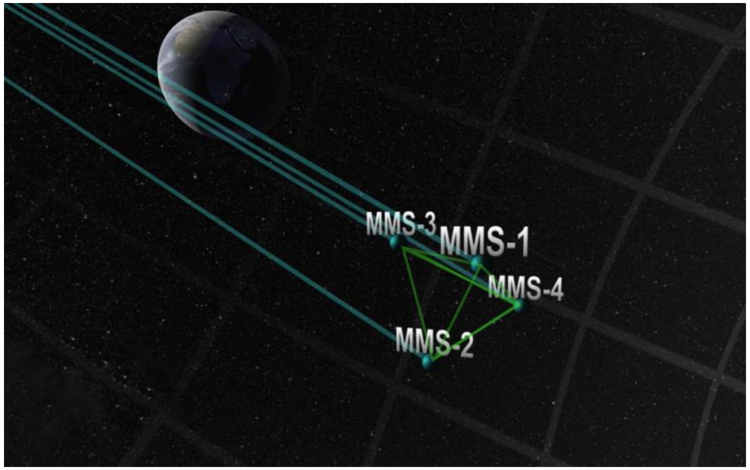
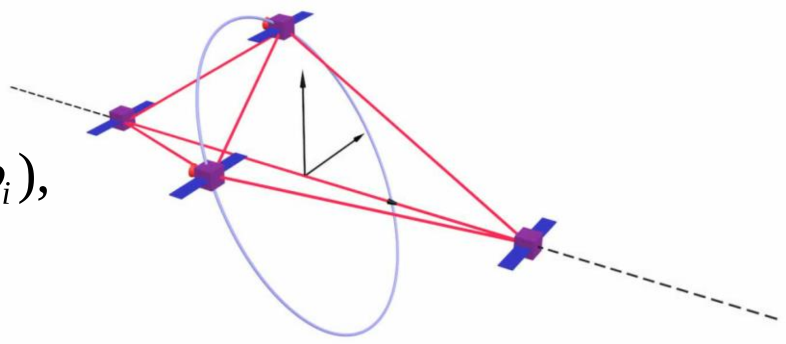


image from NASA, MMS mission

Reference orbit for circular orbits

- For reference orbit search we use linearized HCW model, closed orbits estimation

$$\ddot{x} - 2n\dot{y} - 3n^2 x = 0, \quad x_i = A_i \sin(nt + \varphi_i),$$
$$\ddot{y} + 2n\dot{x} = 0, \quad y_i = C_i + 2A_i \cos(nt + \varphi_i),$$
$$\ddot{z} + n^2 z = 0 \quad z_i = B_i \sin(nt + \psi_i)$$



- Introduce the *quality of the tetrahedron*

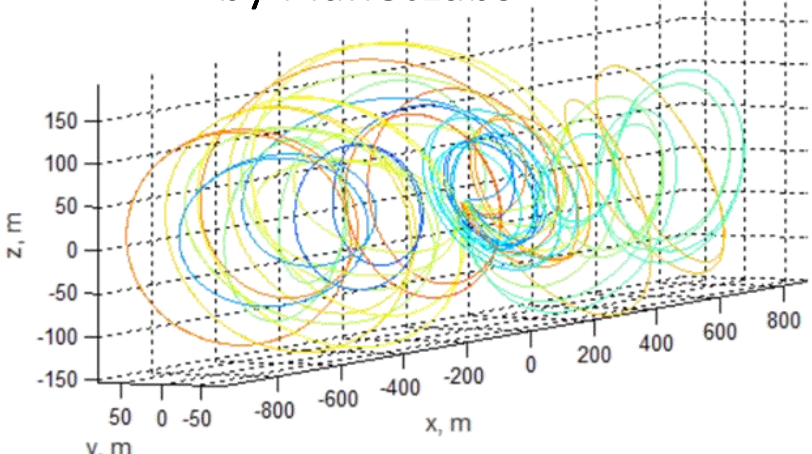
$$Q = 12\frac{(3|V|)^{2/3}}{r_{12}^2 + r_{13}^2 + r_{14}^2 + r_{23}^2 + r_{24}^2 + r_{34}^2} = 12\frac{(3|V|)^{2/3}}{L}$$

- Volume conservation is the conservation of the size
- Quality conservation is the conservation of the shape

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

Launch of 88 3U CubeSats developed by PlanetLabs



Example of relative trajectories

Artificial potential control approach

- Collision avoidance

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

- Alignment

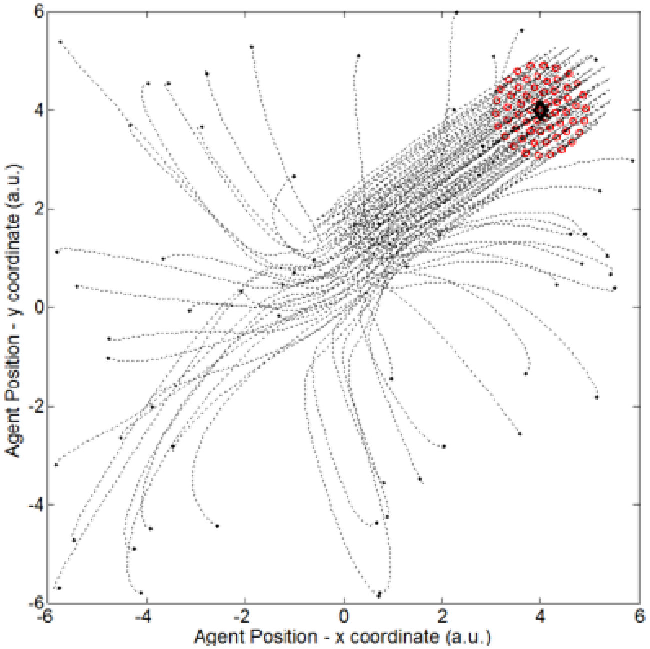
$$\mathbf{d}_i = \sum_{j, j \neq i} C_{al} \left(\mathbf{v}_{ij} \cdot \mathbf{r}_{ij} \right) e^{-\frac{d_{ij}}{R_{al}}} \mathbf{r}_{ij}$$

- Attraction

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

Equations of motion

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

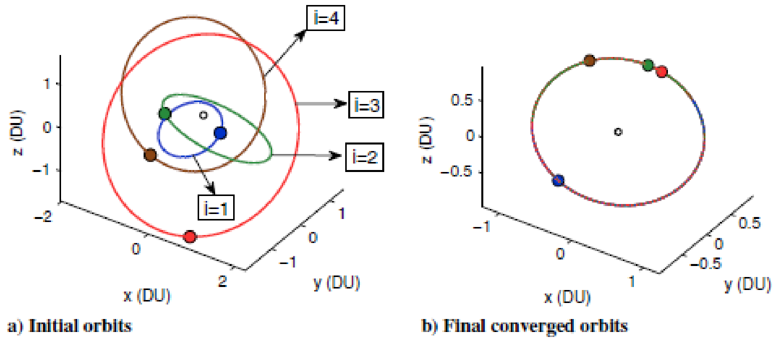


M. Sabatini, G. B. Palmerini and P. Gasbarri. Control Laws for Defective Swarming Systems// Advances in the Astronautical Sciences, Second IAA DyCoss'2014, V. 153. p. 132-153.

Swarm consensus control

- Convergence to a common orbital plane
  - The error function:

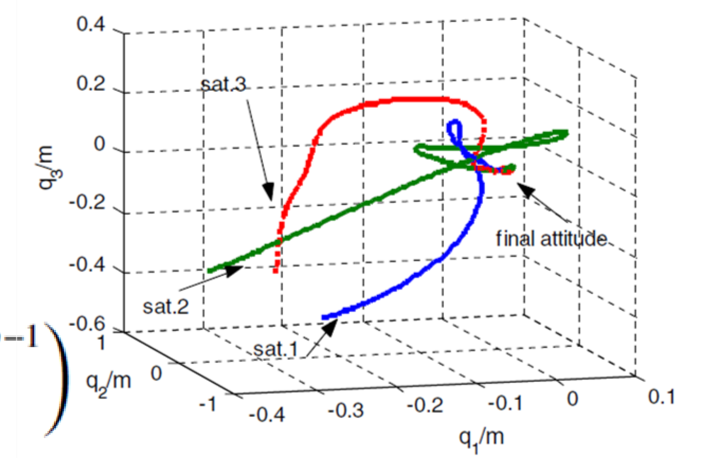
$$\xi_i = \sum_{j=1}^{n} a_{ij} (1 - \mathbf{n}_i^T \mathbf{n}_j)$$



Thakur D., Hernandez S., Akella M.R. Spacecraft swarm finite-thrust cooperative control for common orbit convergence // J. Guid. Control. Dyn. 2015. Vol. 38, № 3. P. 478–487.

- Attitude synchronization
  - Non-linear control law:

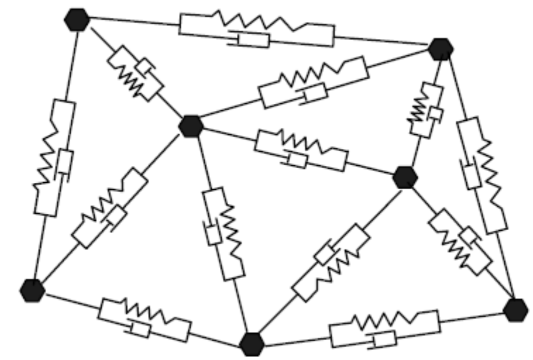
$$\boldsymbol{\tau}_i = \boldsymbol{\omega}_i^{\times} \boldsymbol{J}_i \boldsymbol{\omega}_i + \boldsymbol{J}_i \Bigg(-\boldsymbol{Q}_i^{-1} \dot{\boldsymbol{Q}}_i \boldsymbol{\omega}_i - \boldsymbol{Q}_i^{-1} k_1 \times \left\{ (\boldsymbol{Q}_i \boldsymbol{\omega}_i)^p + k_2^p \left[\sum_{j \in N_i} a_{ij} (\boldsymbol{q}_i - \boldsymbol{q}_j) + b_i (\boldsymbol{q}_i - \boldsymbol{q}_d) \right] \right\}^{2/p-1} \Bigg)$$



Zhou J., Hu Q., Friswell M.I. Decentralized Finite Time Attitude Synchronization Control of Satellite Formation Flying // J. Guid. Control. Dyn. 2013. Vol. 36, № 1. P. 185–195.

Virtual structure control approach

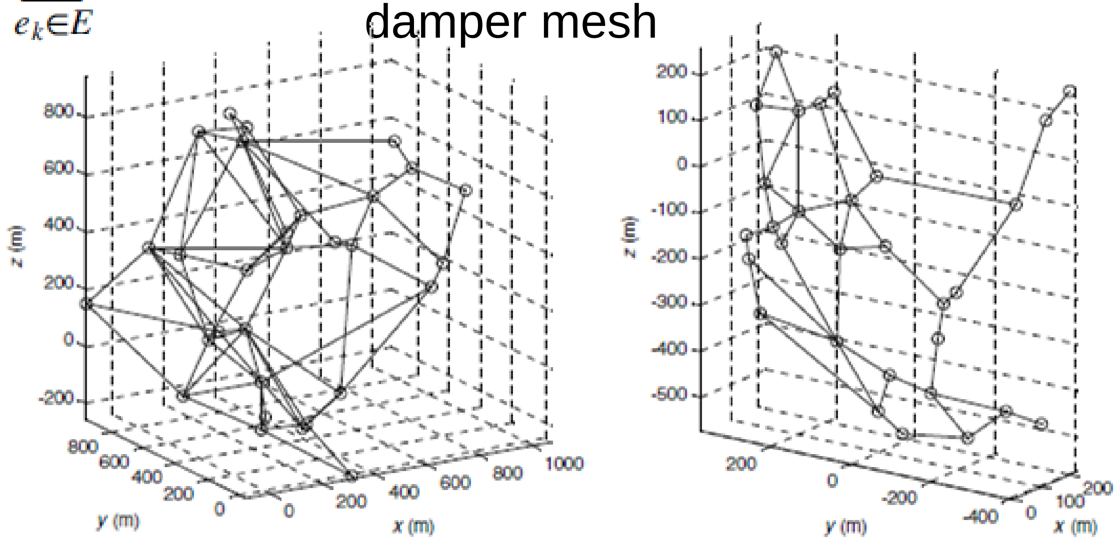
- Imitation the satellite system by a solid structure model
- Control law



$$\boldsymbol{u}_i = -\sum_{e_k \in E} k_s d_{ik}(\boldsymbol{p}_k - \boldsymbol{p}_k^d) - \sum_{e_k \in E} k_d d_{ik} \dot{\boldsymbol{p}}_k$$

Point masses connected by a spring-damper mesh

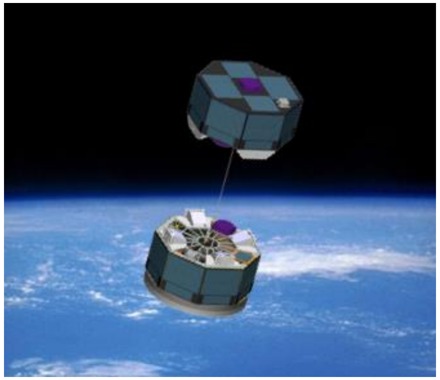
Chen Q. et al. Virtual Spring-Damper Mesh-Based Formation Control for Spacecraft Swarms in Potential Fields // J. Guid. Control. Dyn. 2015. Vol. 38, № 3. P. 539–546.

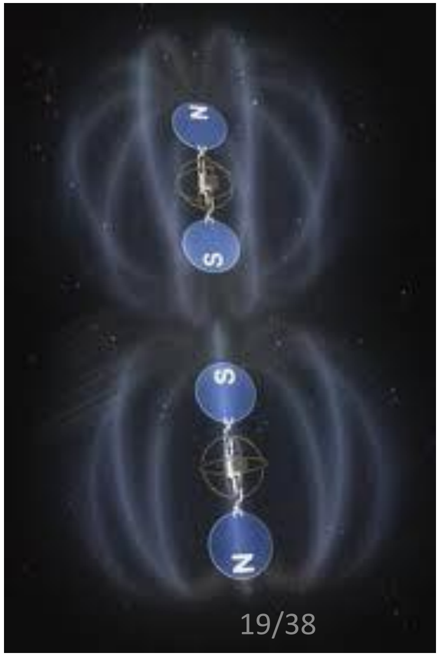


a) Initial time ($t = 0$ s) b) Steady state ($t = 8000$ s)

Fuelless FF Control Concepts

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

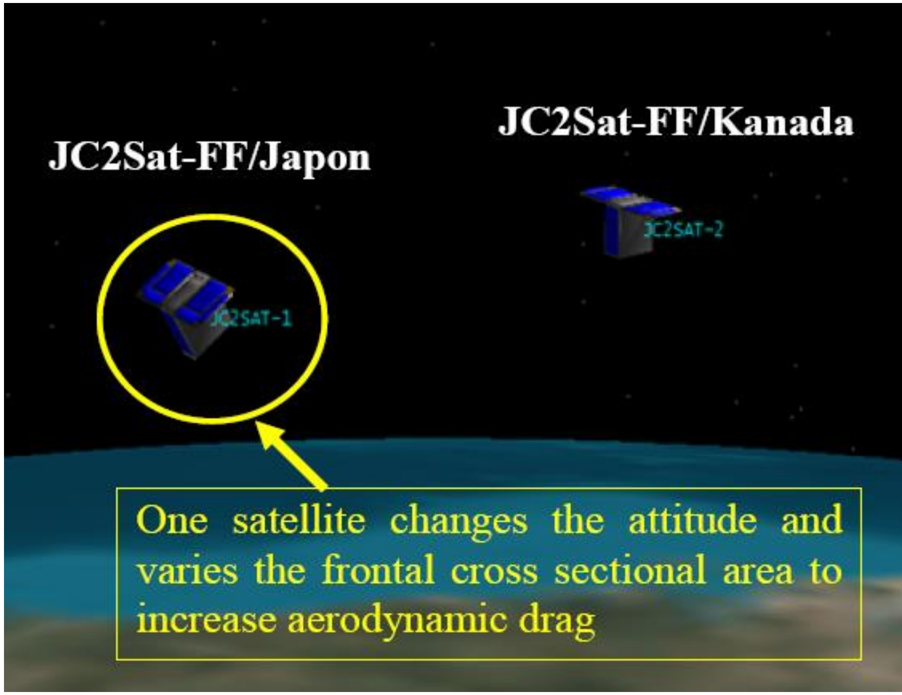




Aerodynamic drug based control

- Features:
  - *Low Earth Orbit*
  - *Satellites with variable cross section area*

- Shortcomings:
  - *Short lifetime*
  - *Reaction wheel saturation during attitude control*



JC2Sat Mission

LQR-based control algorithm

- Aerodynamic force

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

$$\mathbf{n} = (\cos\alpha\cos\beta; \sin\beta; \sin\alpha\cos\beta).$$

- Linear-quadratic regulator

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

Minimising cost function

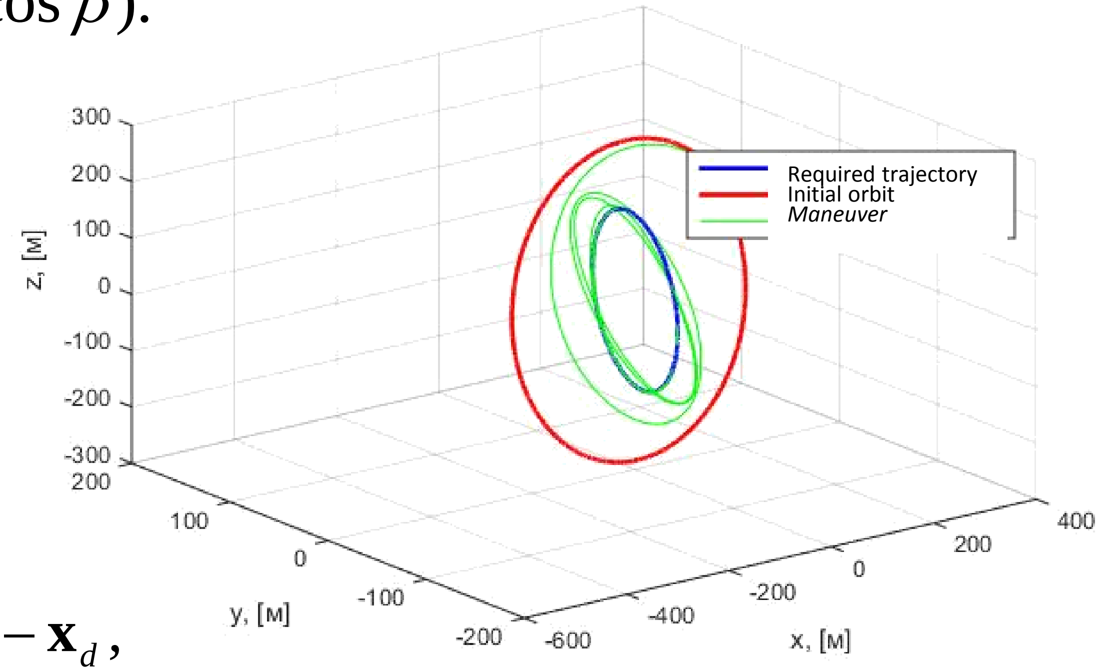
$$J = \int_\tau^\infty (\mathbf{e}^T \mathrm{Q}\mathbf{e} + \mathbf{u}^T \mathrm{R}\mathbf{u})dt,$$

Feedback control is

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

matrix P is the solution of Riccati equation

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

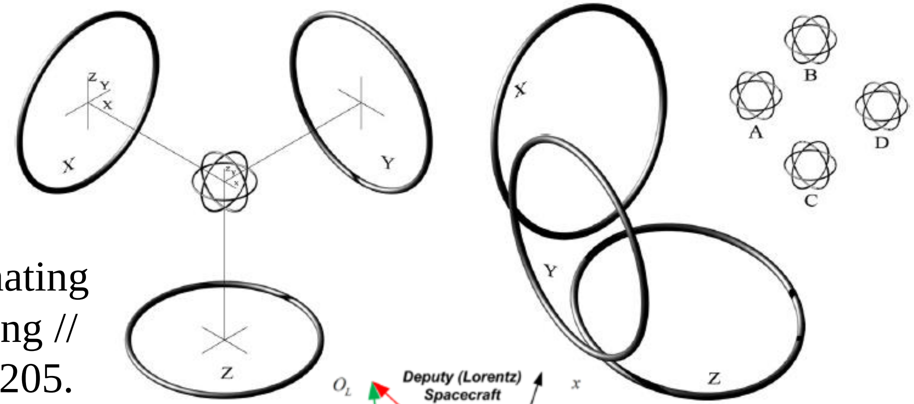


Relative trajectories during the maneuver

Electro-magnetic interaction based control

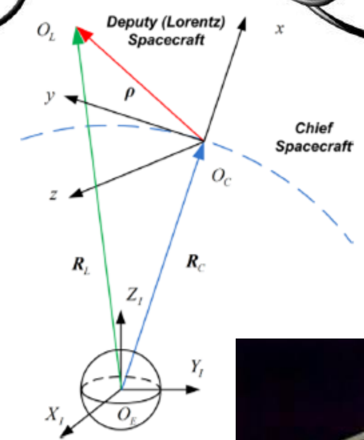
- Magnetic interaction

Youngquist R.C., Nurge M.A., Starr S.O. Alternating magnetic field forces for satellite formation flying // Acta Astronaut. Elsevier, 2013. Vol. 84. P. 197–205.



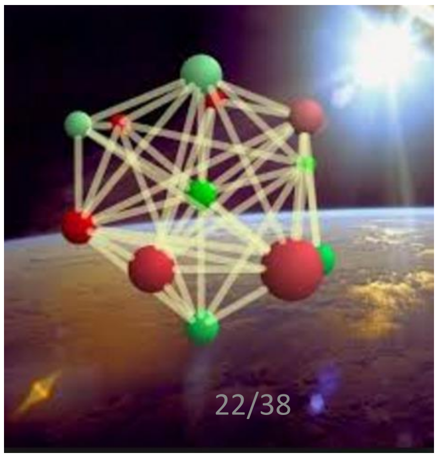
- Lorenz force of charged satellite

Peck M.A. et al. Spacecrat Formation Flying Using Lorentz Forces // J. Br. Interplanet. Soc. 2007. Vol. 60. P. 263–267.



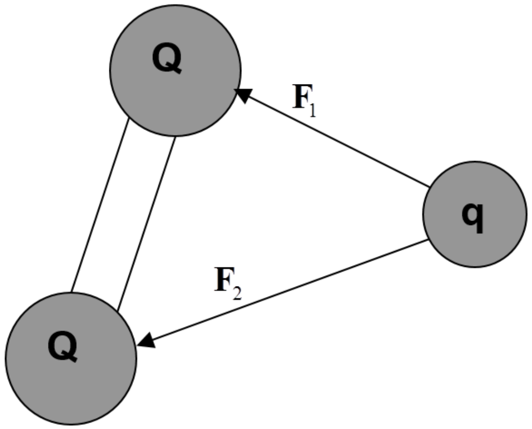
- Coulomb force interaction

Schaub H. et al. Challenges and Prospects of Coulomb Spacecraft Formation Control of the Astronautical Sciences // J. Astronaut. Sci. 2004. Vol. 52. P. 169–193.

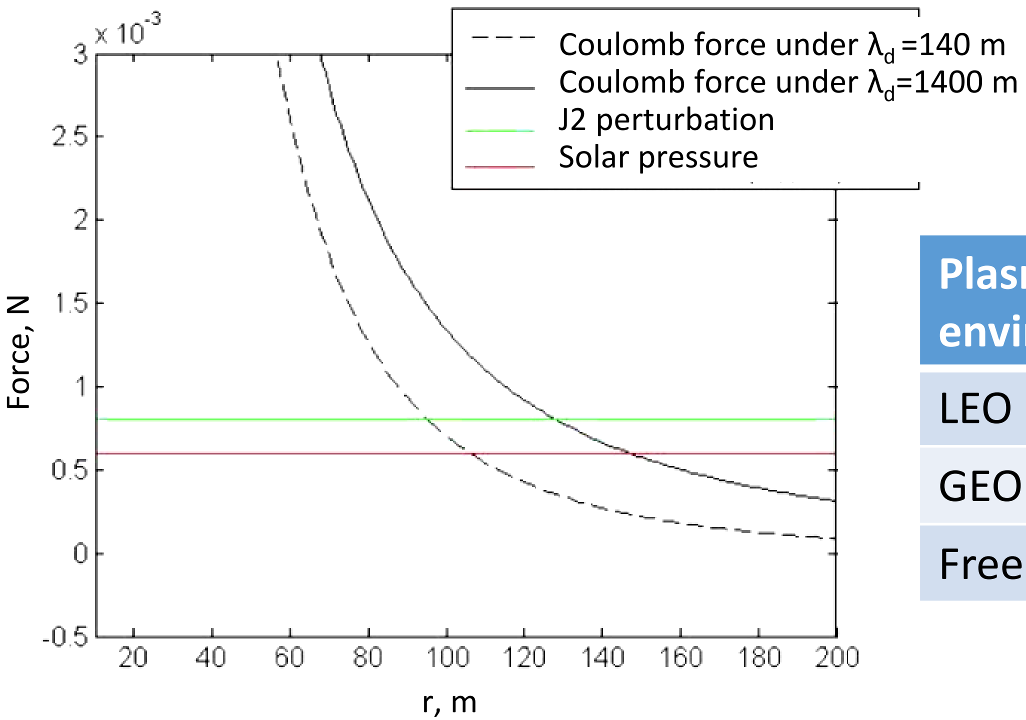


Coulomb force based control algorithm

- Features:
  - *The charging device is required*
  - *Small relative distances*
  - *Charges are eliminating by plasma*



$$f_{12} = k_c \frac{r_{12}}{r_{12}^3} q_1 q_2 e^{-\frac{r_{12}}{\lambda_d}}$$



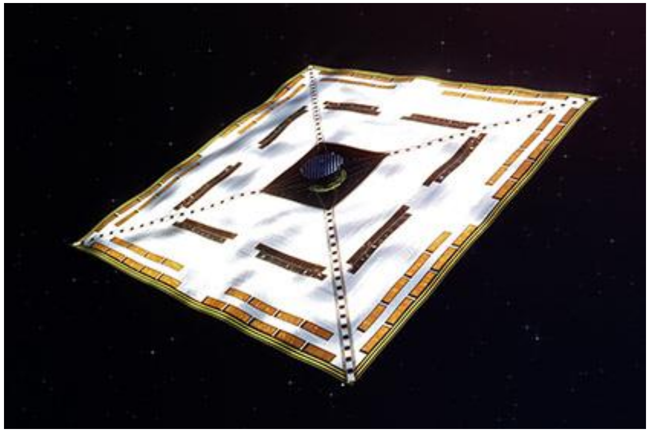
Plasma environment	$\lambda_{d\ min}$, m	$\lambda_{d\ max}$, m
LEO	0.02	0.4
GEO	142	1496
Free space	7.4	24

Solar radiation pressure based control

- Solar sail with fixed orientation

Smirnov G.V., Ovchinnikov M.Y., Guerman A.D. Use of solar radiation pressure to maintain a spatial satellite formation // Acta Astronaut. 2007. Vol. 61, № 7-8. P. 724–728.

- Solar sail with variable reflection

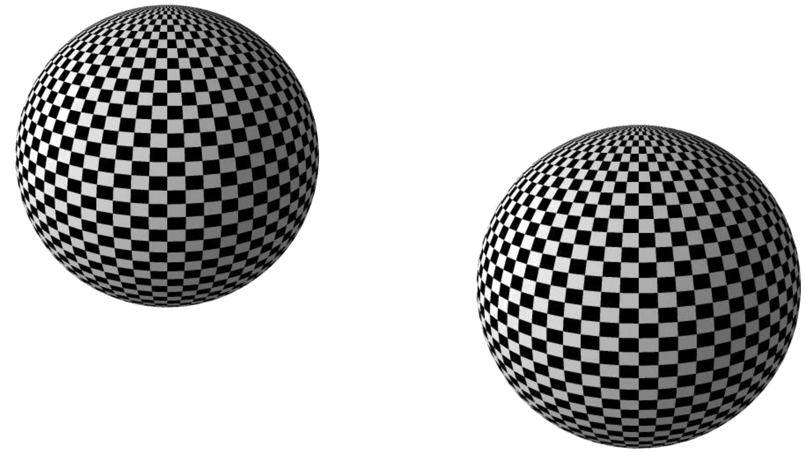


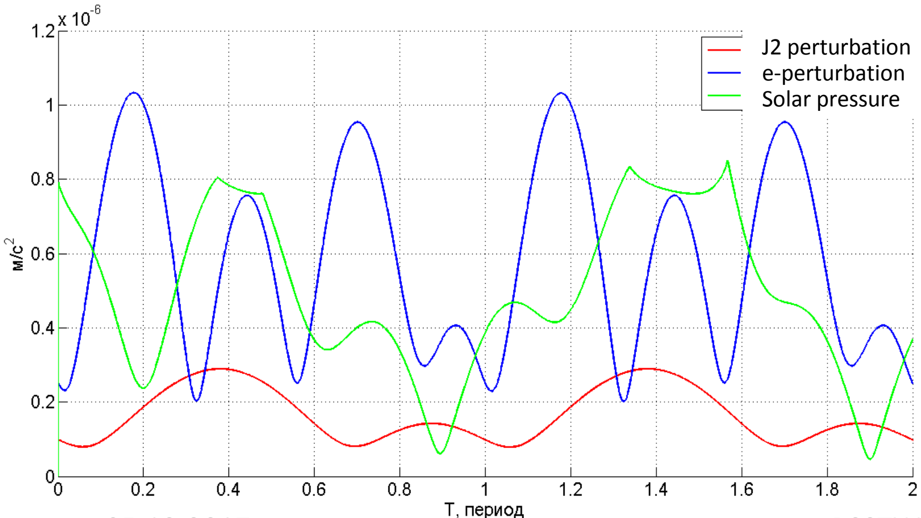
Mori O. et al. First Solar Power Sail Demonstration by IKAROS // Trans. Japan Soc. Aeronaut. Sp. Sci. Aerosp. Technol. Japan. 2010. Vol. 8, № ists27. P. To_4_25 – To_4_31.

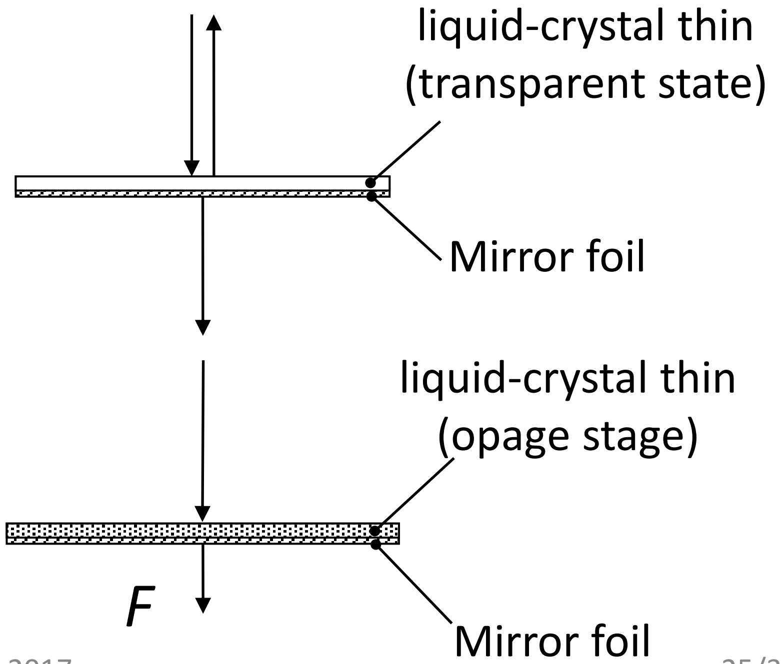
Solar radiation pressure based control

We consider:

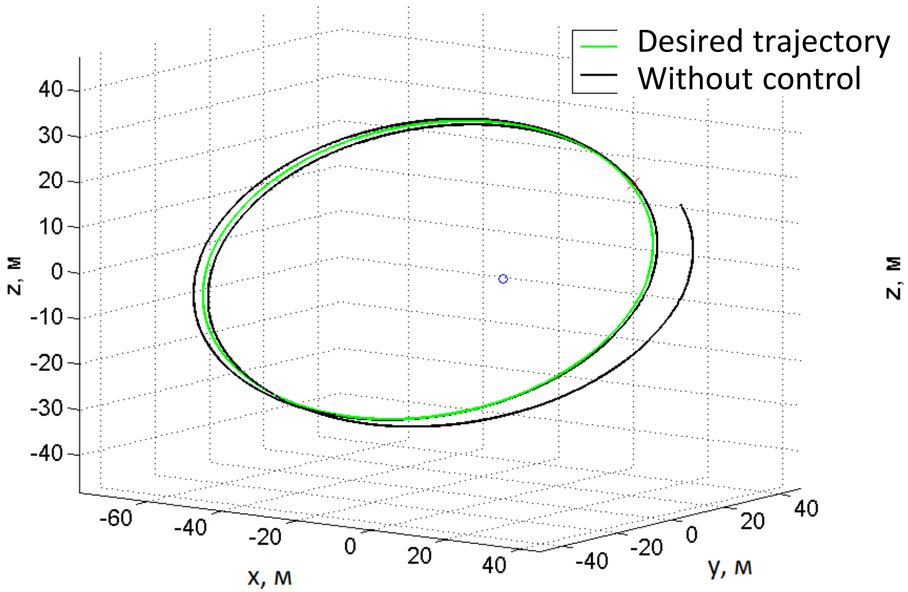
- *Spherical satellites*
- *Variable reflection on “pixel” surface*
- *Nearcircular orbits*



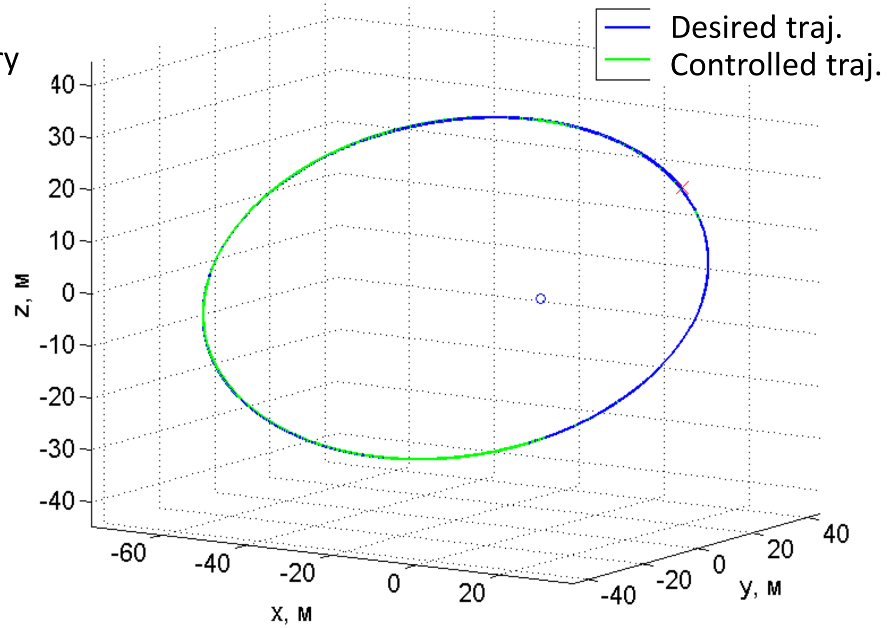




Numerical example of the SPR control



Relative trajectories without control



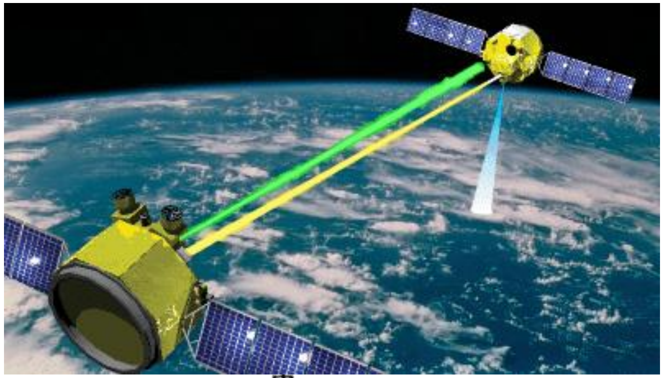
Relative trajectories with control

The momentum exchange-based control

- The momentum from lasers for repulsive force

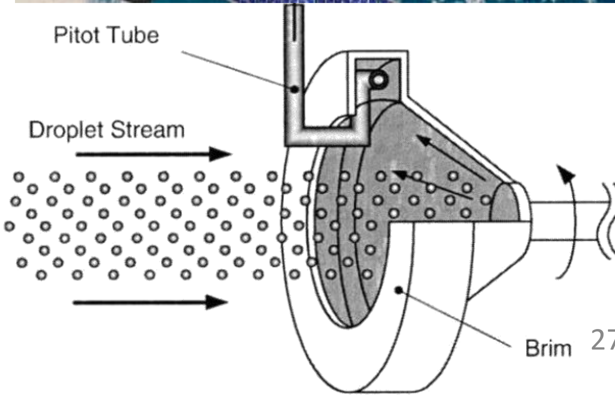
Y. K. Bae. A contamination-free ultrahigh precision formation flying method for micro-, nano-, and pico-satellites with nanometer accuracy. In Space Technology and Applications International Forum-Staif 2006, volume 813, pages 1213–1223, 2006.

- Continuous stream of mass travelling between the satellites



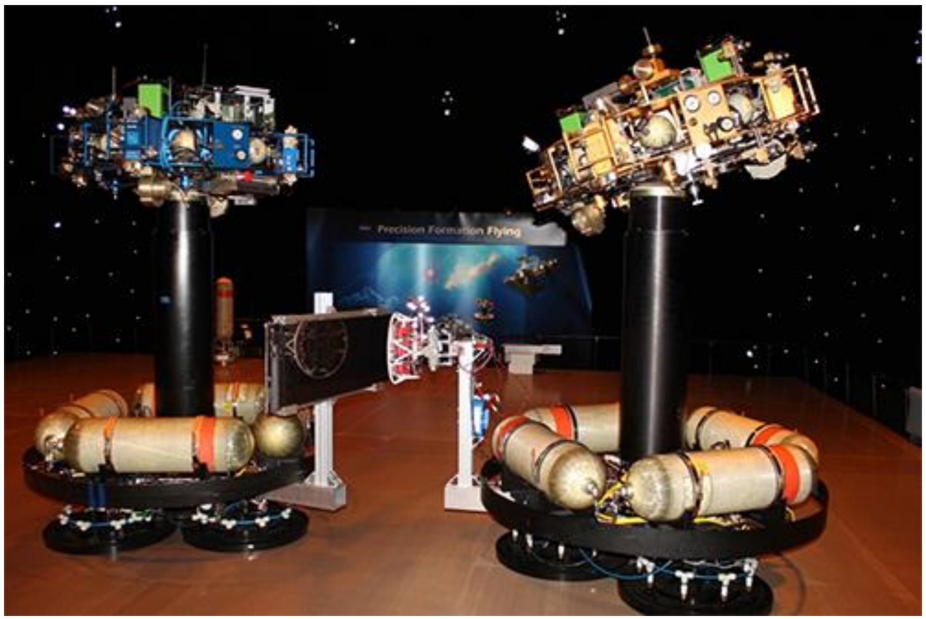
S. G. Tragesser. Static formations using momentum exchange between satellites. Journal of guidance, control, and dynamics, 32(4):1277 – 1286, 2009.

- Liquid droplet streams exchange

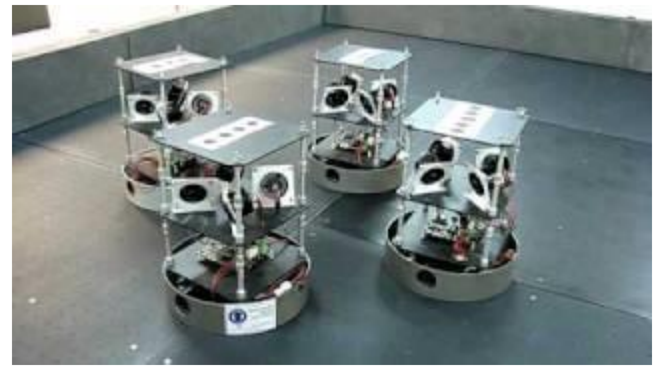


T. Joslyn and A. Ketsdever. Constant momentum exchange between microspacecraft using liquid droplet thrusters. In 46th joint Propulsion Conference, volume 6966, pages 25–28, 2010.

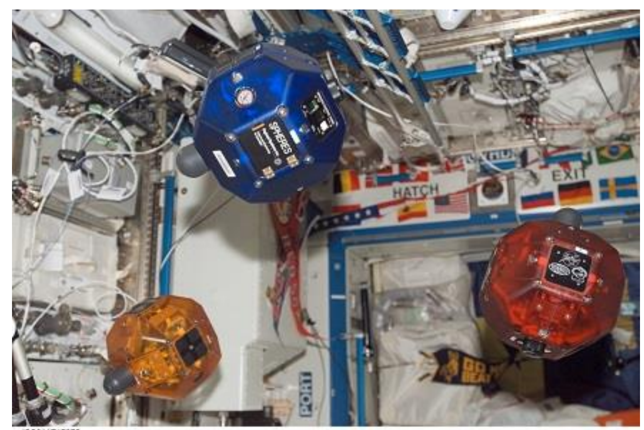
Laboratory facilities for formation flying control algorithms testing



The Formation Control Testbed at the JPL

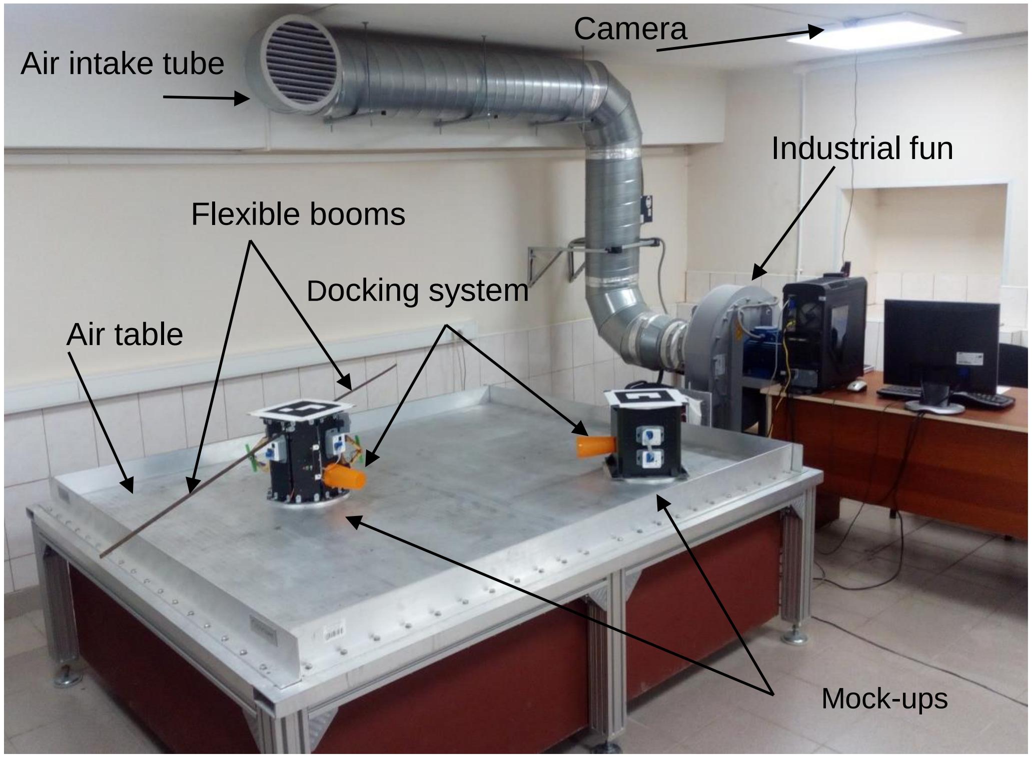


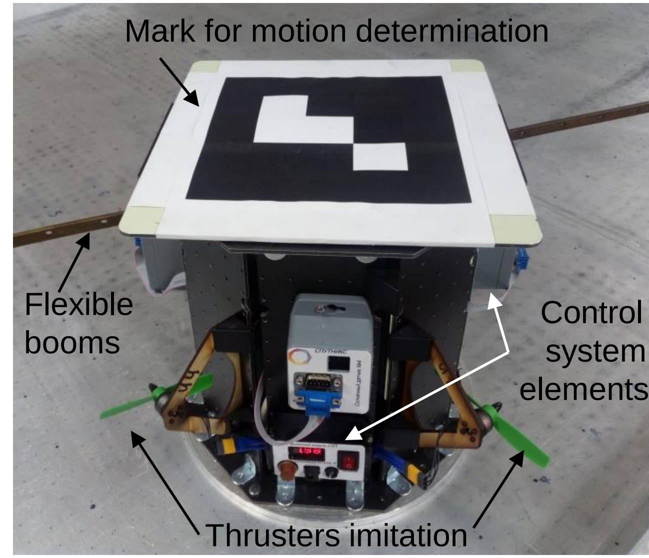
Test facility in the Technion Univercity



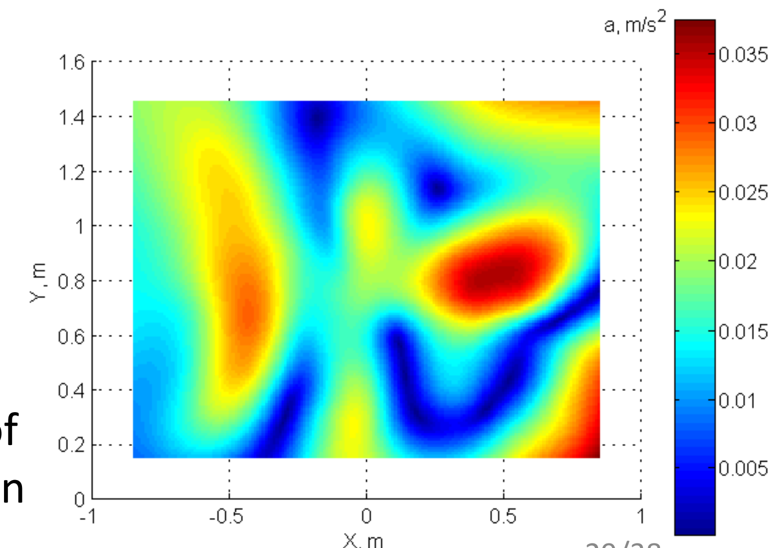
SPHERES mock-up on board the ISS

Planar Air Bearing Test-Bench in KIAM





Test Bench COSMOS
(COmplex for Satellites MOtion Simulation)



The magnitude of linear acceleration

Conclusion

- The formation flying 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
- And may the fourth be with us

Thank you for your attention!

Our research team in KIAM

Our web-site:

http://keldysh.ru/microsatellites/eng/