Advanced Concepts Team European Space Agency

Swarm Intelligence Methods for Orbital Control Applications

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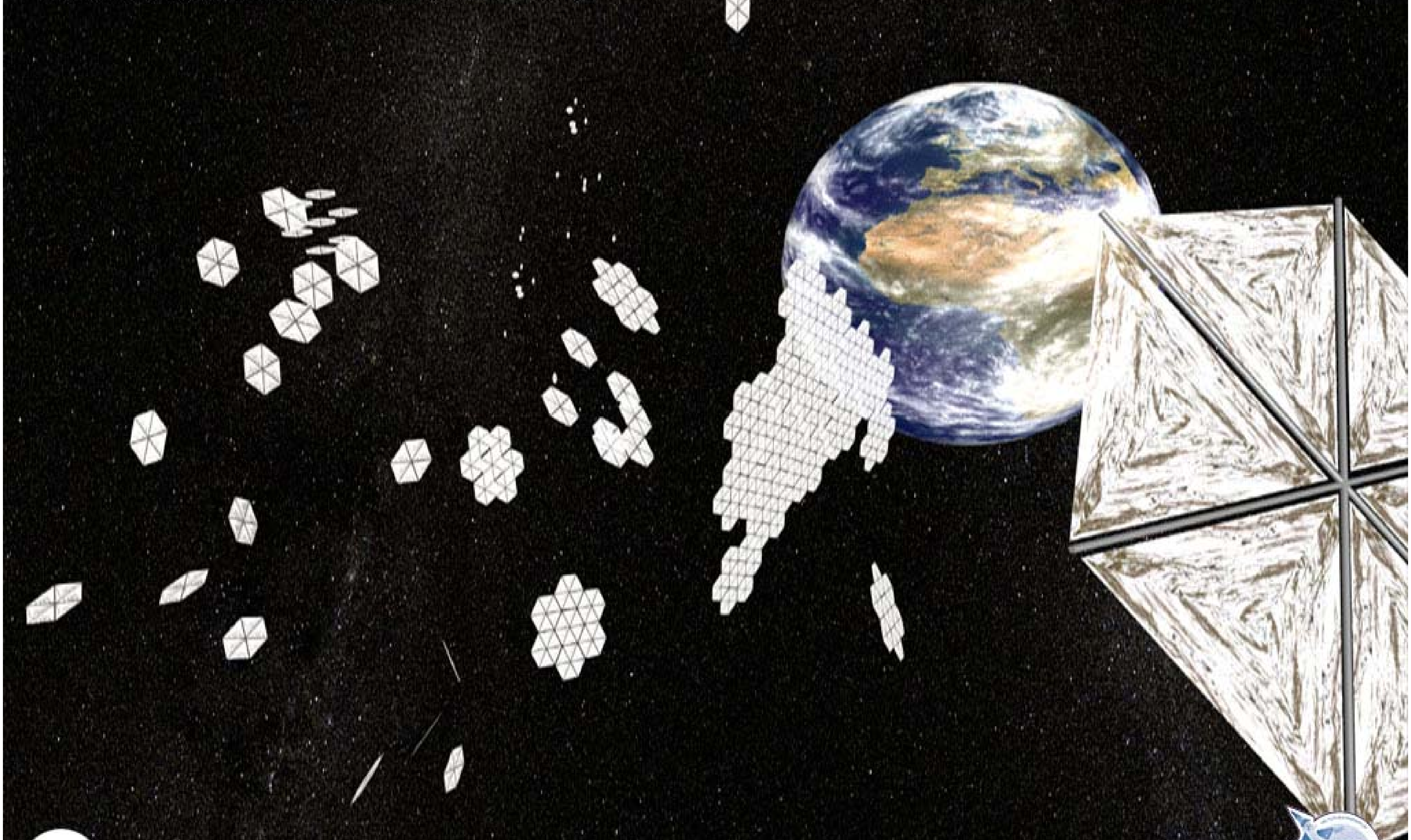


esa

Workshop on Artificial Intelligence for Space Applications
@ IJCAI 2007

ZARM

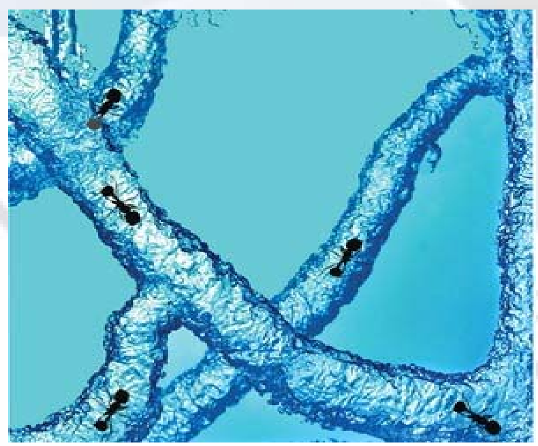
Swarm Intelligence

- Swarm intelligence (SI) is an artificial intelligence technique based around the study of collective behavior in **decentralized**, **self-organized** systems (Source: Wikipedia)

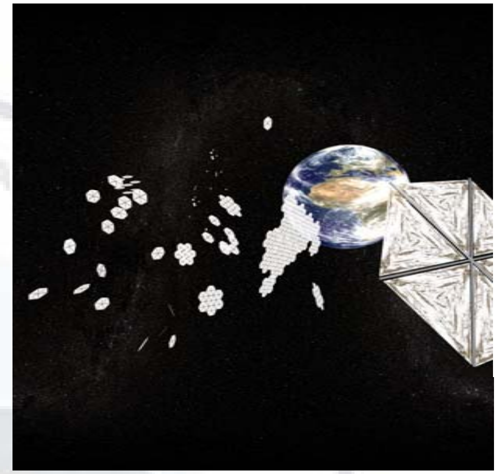
- SI systems are typically made up of a population of simple agents **interacting locally** with one another and with their environment.

- Although there is normally no centralized control structure dictating how individual agents should behave, local interactions between such agents lead to the **emergence** of **global behavior**.

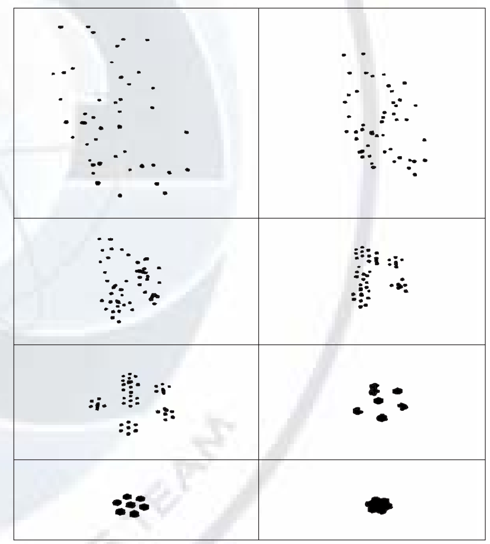
Open question: can we design the control system of a swarm element setting as a requirement for the swarm to achieve a predefined global behaviour?



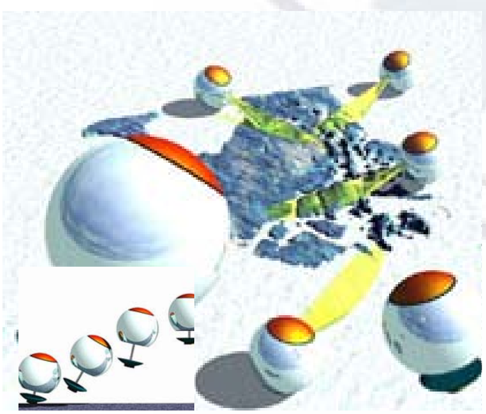
Useful in Space?

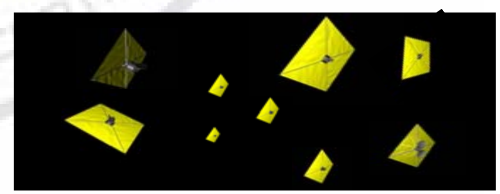


- **Decentralization** and **self-organization** are very attractive properties for space systems. The first attribute is traditionally discussed for **formation-flying** missions, the latter commonly referred to as **autonomy**.
- The particular nature of harsh unexplored environments makes **limited interactions** between satellites the only possible ones.
- It makes a lot of sense to consider a number of complex undertakings (**satellite aggregation**, **on-orbit self-assembly**, **formation acquisition** and **reconfiguration**, **planetary surface exploration**) as the global emerging behaviour of a swarm.



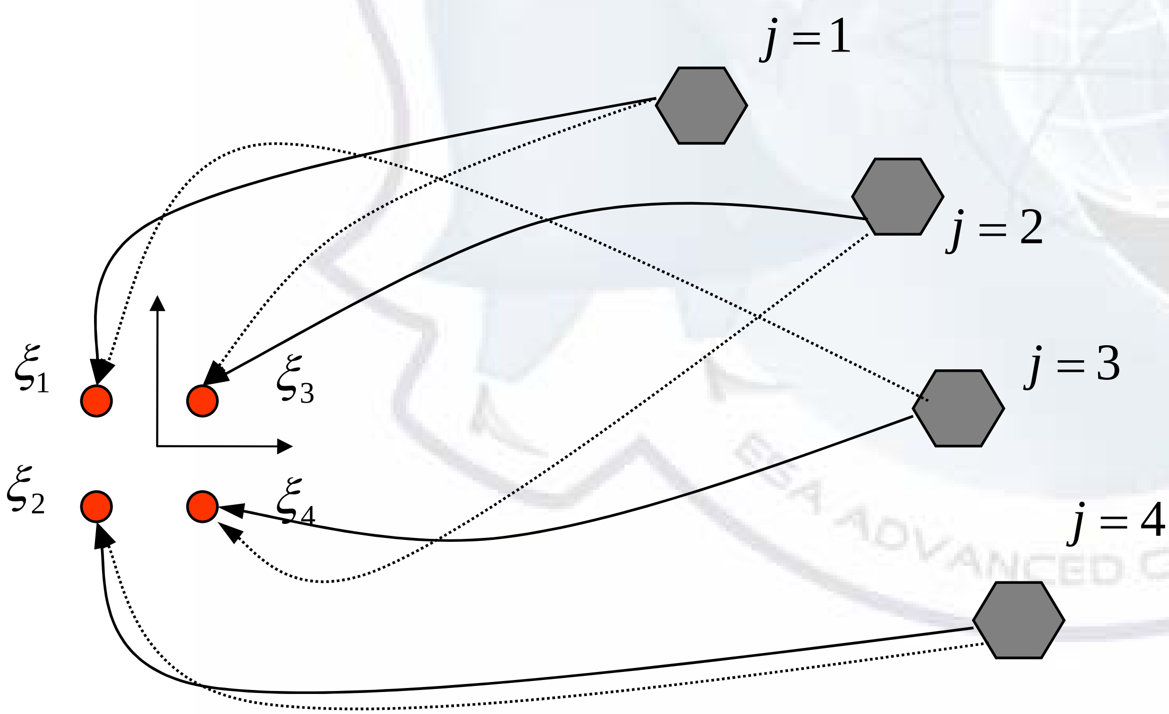
Note: for space applications, mass and volume are the two criteria to compare a single unit to a swarm (when both do meet the requirements)

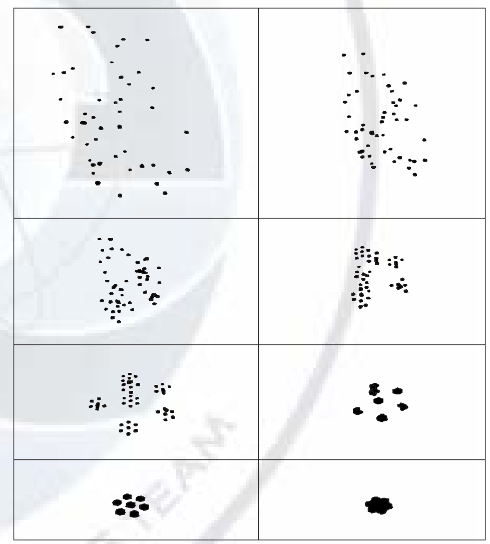


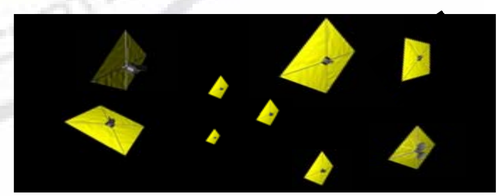


Example: orbital swarm

- N satellites orbiting around a celestial body and randomly distributed within some volume
- The task of planning the path towards some given final relative configuration is considered
- Each swarm component is identical and may thus occupy any of the target positions







The equilibrium shaping

- Inspired by the work on swarm aggregation by Gazi & Passino (2004),

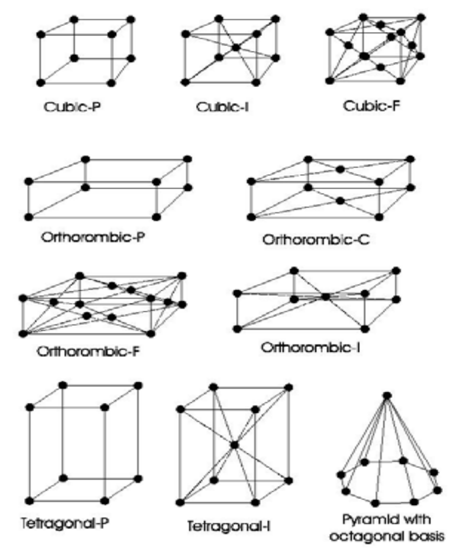
Gazi, V. and Passino, K., “A Class of Attraction/Repulsion Functions for Stable Swarm Aggregations,” *International Journal of Control* , Vol. 77, No. 18, 2004, pp. 1567–1579.

- Exploits geodesics at a behavioural level for propellant saving

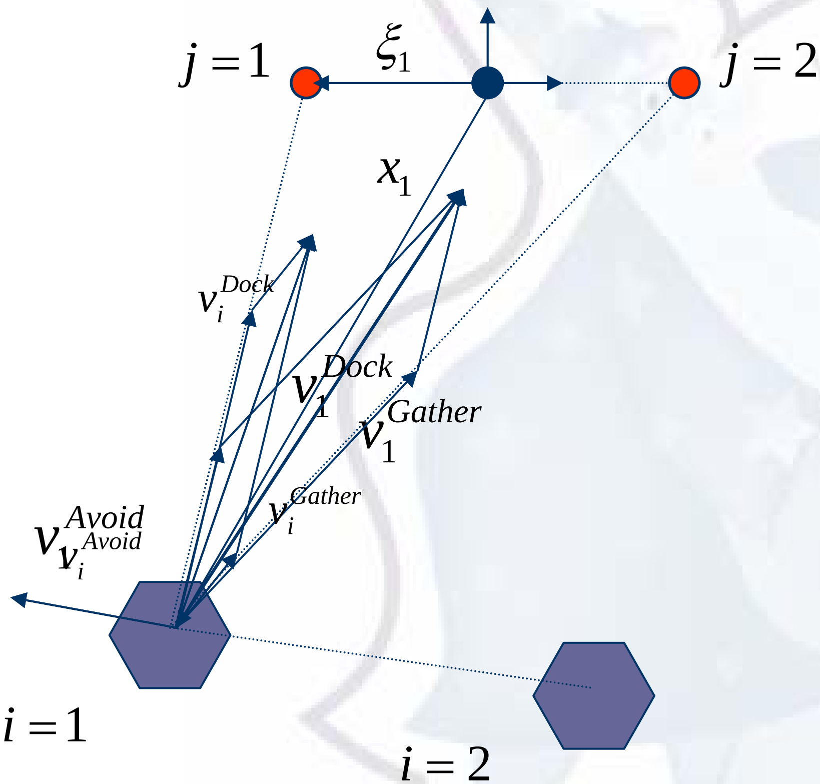
- Does not pre-assign the agent positions in the final desired configuration

Izzo, D., Pettazzi, L. : “Autonomous and Distributed motion planning for satellite swarm” *Journal of Guidance Control and Dynamics, to appear in 2007*

Note: the Equilibrium Shaping does not allow to achieve any arbitrary final configuration, only a countable number.



The equilibrium shaping



$$v_i^{Gather} = \sum_j c_j \psi_G(\| \xi_j - x_i \|)(\xi_j - x_i)$$

$$v_i^{Dock} = \sum_j d_j \psi_D(\| \xi_j - x_i \|, k_D)(\xi_j - x_i)$$

$$v_i^{Avoid} = \sum_j b \psi_A(\| x_j - x_i \|, k_A)(x_j - x_i)$$

$$\boxed{v_{d_i} = \dot{x}_i = v_i^{Gather} + v_i^{Dock} + v_i^{Avoid}}$$

- The gather behaviour needs to **account for the gravity differential** (rectilinear paths are expensive in orbit)
- The center position may be defined as **absolute** (each agent needs to sense the environment globally), or **relative** (only local sensing is needed)

The equilibrium shaping

•We then enforce that the desired velocity of each agent vanishes in the final configuration

•This procedure “shapes” the equilibrium of the dynamical system.

$$v_{d_i} = \dot{x}_i = v_i^{Gather} + v_i^{Dock} + v_i^{Avoid} = 0$$

$$i = 1........N$$

$$\sum_{j=1}^{N} \left[b\,\psi_A(\| \xi_i - \xi_j \|, k_A) - c_j \psi_G(\| \xi_i - \xi_j \|) - d_j \psi_D(\| \xi_i - \xi_j \|, k_D) \right](\xi_i - \xi_j) = 0$$

$$A[c_1,..,c_N, d_1,..,d_N] = 0$$

That is a linear system of 3N equations in 2N unknowns

The equilibrium shaping

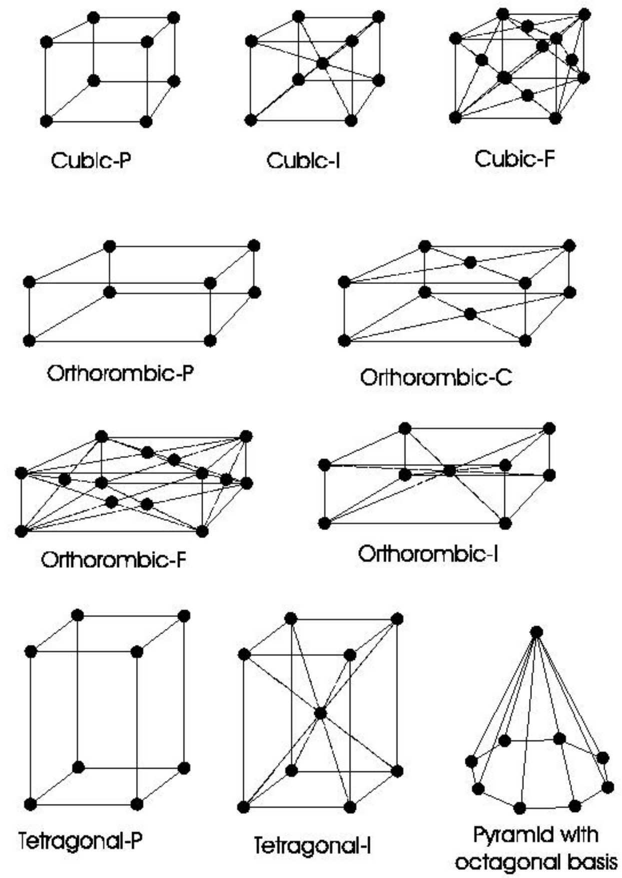
$v_{d_i} = 0, i = 1,\ldots,3$

3N equations for 2N unknowns

if $\exists G_{ij} : \xi_i \rightarrow \xi_j$ and $c_i = c_j, d_i = d_j$	➡	$v_{d_i} = 0, v_{d_j} = 0$ are linearly dependendent
if $\xi_i \in$ Formation symmetry plan	➡	$v_{d_i} = 0$ Reduces to two independent scalar equations
if $\xi_i \in$ Formation symmetry axis	➡	$v_{d_i} = 0$ Reduces to one independent scalar equation

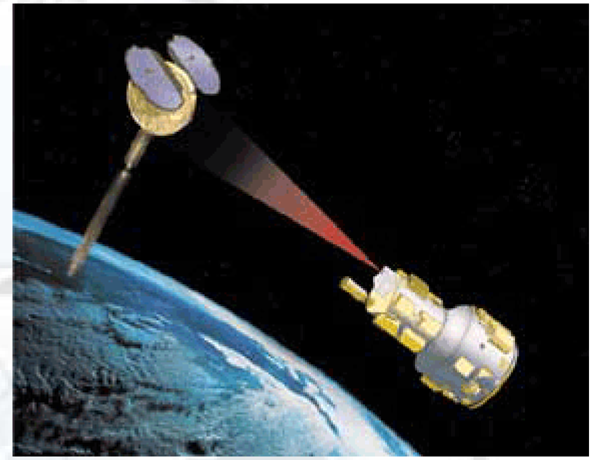
Possible final configurations

Formation shape	Number of equations	Number of unknowns
Regular solids	1	2
Regular polygons	1	2
Pyramids with a regular basis	3	4
Cubic-P	1	2
Cubic-I	1	4
Cubic-F	2	4
Tetragonal-P	2	2
Tetragonal-I	2	4
Orthorhombic-P	3	2
Orthorhombic-I	3	4
Orthorhombic-C	4	4
Orthorhombic-F	6	4
Hexagonal-P	3	4



Modified gather behaviour

Start from the analytical solution for Hill equations



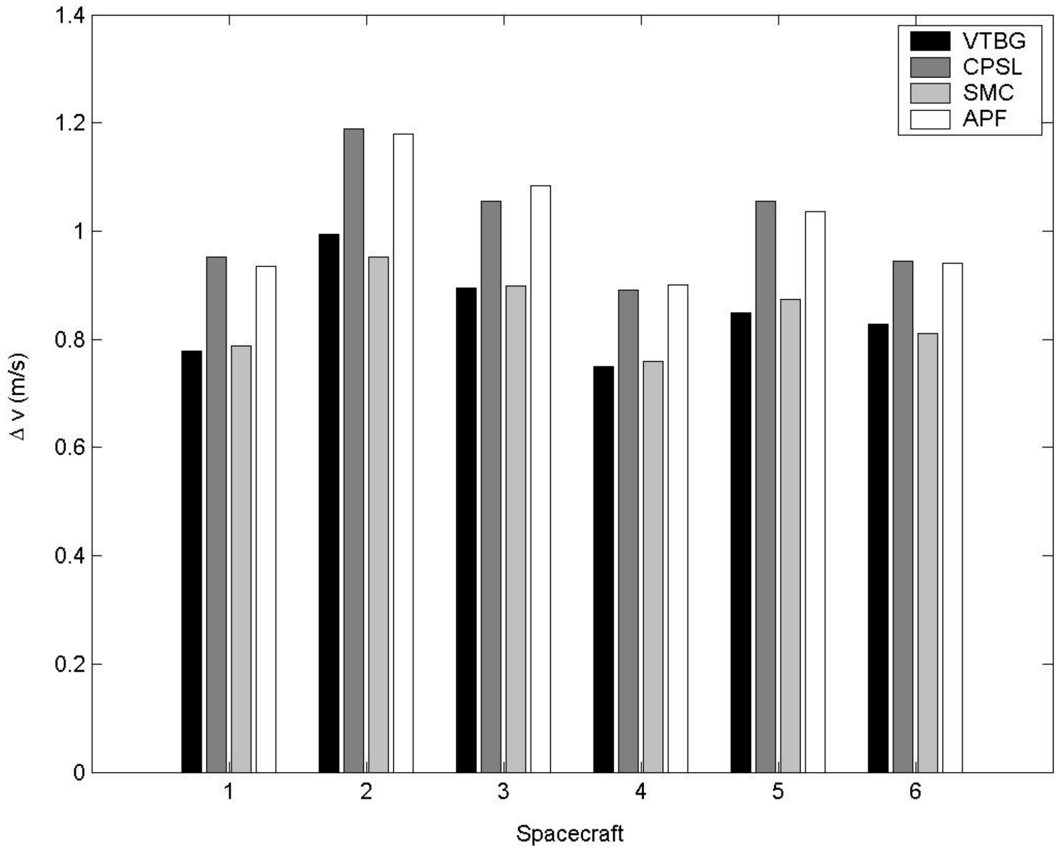
$$\begin{bmatrix} \rho \\ \dot{\rho} \end{bmatrix} = \begin{bmatrix} A(\tau) & B(\tau) \\ C(\tau) & D(\tau) \end{bmatrix} \begin{bmatrix} \rho_0 \\ \dot{\rho}_0 \end{bmatrix}$$

Each spacecraft has to follow a geodetic trajectory that will bring it towards a desired position ρ_d of the target formation in a desired time τ_d .

$$\rho_d = \rho(\tau_d - t) = A(\tau_d - t)\rho(t) + B(\tau_d - t)\dot{\rho}(t)$$

$$v_i^{Gather} = \dot{\rho}(\tau) = \frac{1}{N} B^{-1}\left(\sum_j \xi_j + A(\tau_d - t)x_i\right)$$

Formation acquisition in GEO



Simulation Data:

-Initial average distance=1000m

-Initial velocities=0m/s

-Thrust to mass ratio=.005

-Total acquisition time=20000sec

-Radius of the sphere of flat space=30m

-Radius of the final formation=6m

On-orbit assembly in GEO

How can we use ES to build LATTICE STRUCTURES?

The agents are divided into two different groups: Seeds (j) and Agents (i).

The equilibrium shaping technique is applied to the seeds with a larger radius of influence.

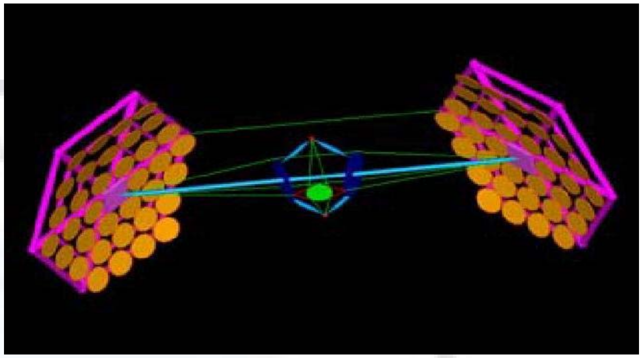
$$v^j_{des}$$

The equilibrium shaping technique is applied to the agents near a seed.

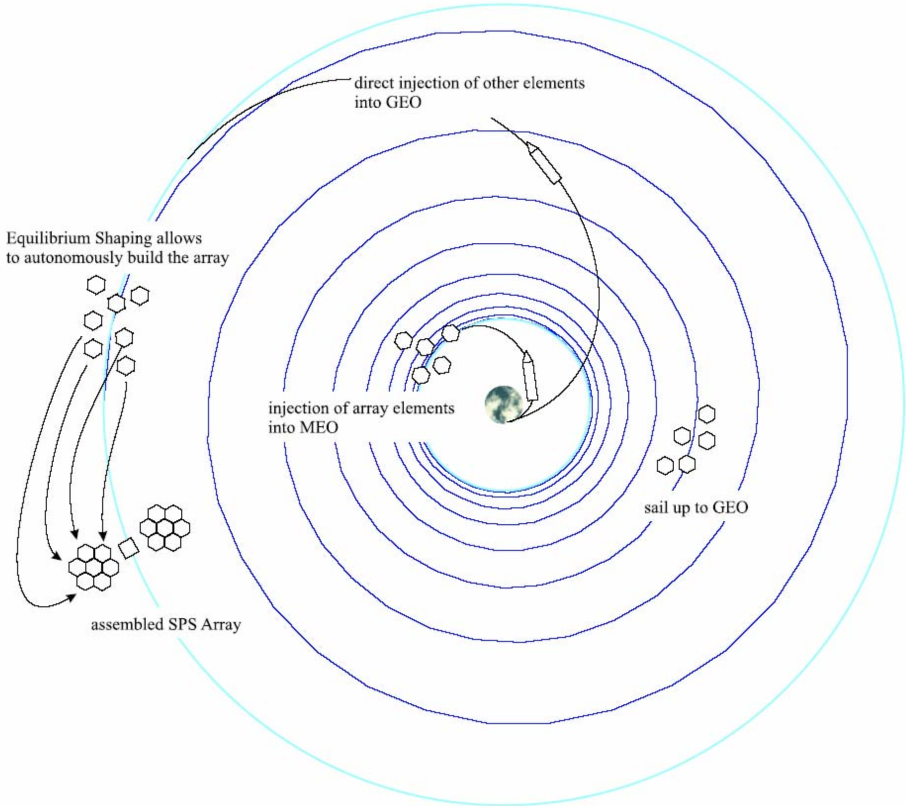
$$v^i_{des}$$

$$v^i_a = v^i_\tau + v^i_{rel}$$

SPS assembly concept

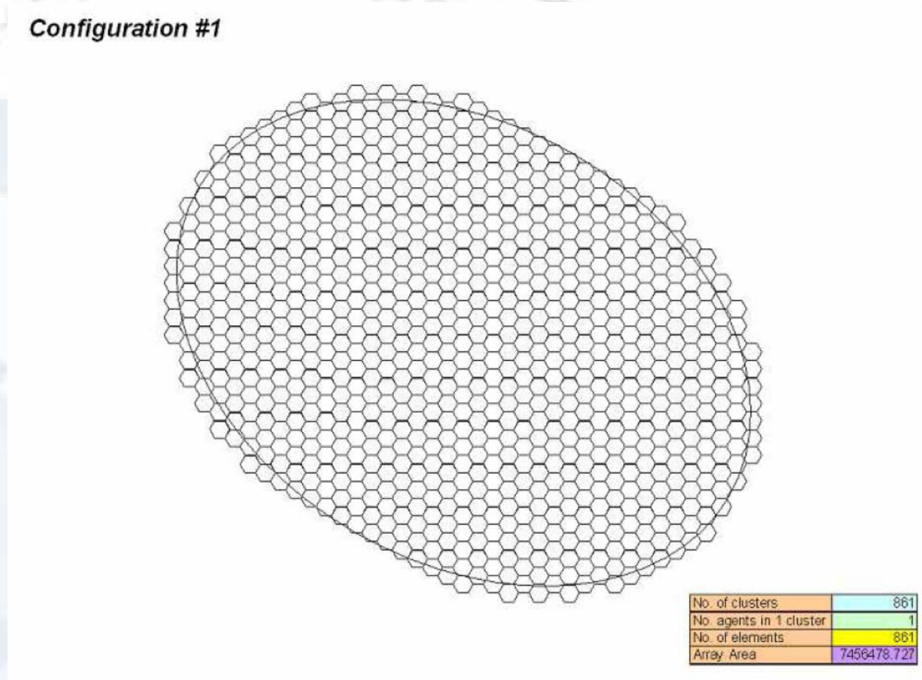


- On-orbit self assembly of a large mirror in space
- Preliminary analysis performed
- Assess the magnitude of the putative benefit coming from the spiralling out of the swarm
- Number of required launches significantly reduced
- Terminal assembly driven via Equilibrium Shaping
- The swarm needs to remain grouped during the spiralling out (emerging behaviour to be achieved using solar sailing as actuation)



SPS assembly concept

- No. Agents: 861
- Agent size: 100m
- Array area 7.456 km^2 (Mori et al. 2001)



M. Mori, H. Nagayama, Y. Saito, and H. Matsumoto. Summary of studies on space solar power systems of national space development agency of Japan. *International Astronautical Congress 2001* Paper IAF-01-R.1.04.

Izzo, D., Pettazzi, L. : “Self-assembly of large structures in space using identical components” *International Astronautical Congress 2006. Paper* IAC-06-C3.4/D3.4.07

Coulomb swarm

•Coulomb satellites invented and thoroughly studied by **Hanspeter Schaub**, **Gordon Parker** and **Lyon King** (2001-2007) in the States, researches in Europe focussed on swarm of Coulomb satelites and include efforts by **ACT**, **ZARM** and **Surrey**

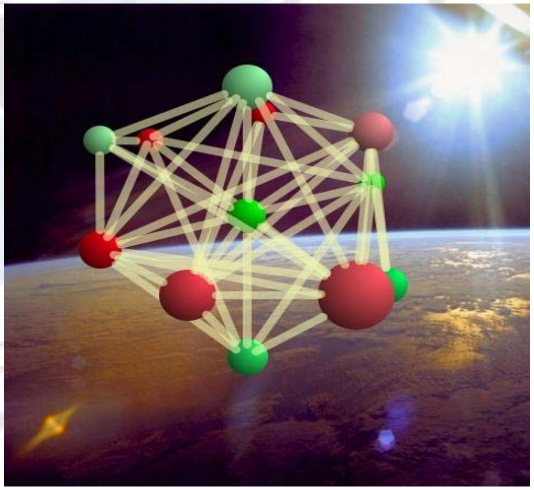
•Satellites naturally interact with the plasma **acquiring** some net **electric charge**.

•The effect has to be accounted for in space missions as it influences the mission performances in terms of dynamics and payloads (e.g. Cluster II implements an active charge control system).

•In close formations (hundreds of meters) the resulting force, attenuated by the plasma shielding, is of the order of mN and **could** therefore **be exploited** rather than just accounted for or feared.

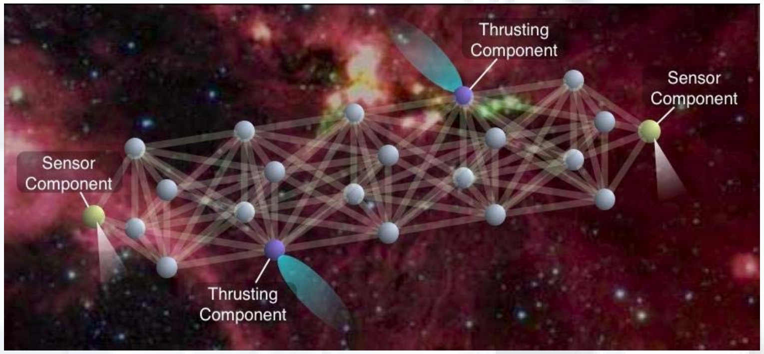
•A charge control system would have an **extremely high bandwidth** allowing to vary the satellite potential from –20 kV to +20 kV in milliseconds

•The **power** needed to perform charge control is **very small**, of the order of Watts



Coulomb swarm: challenges

•High electrical charges create **arcs**, only levels of **micro Coulomb** seem to be **tolerable**



•Coulomb forces are internal forces, **center of mass control is very limited** (via the gravity gradient)

•No charging control technology has ever been developed for the purposes of relative motion control

•Complicated dynamic and control

•No formation is controllable in open loop: the **system** is intrinsically **unstable**

•**Not every reconfiguration\movement is possible only with Coulomb forces** even if the initial and final configuration conserve the center of mass \ angular momentum. Hybrid control could be interesting

Feasibility of hybrid control

$$\ddot{\mathbf{r}}_i + \frac{\mu}{r_i^3}\mathbf{r}_i = \boxed{-\frac{k_c q_i}{m_i}\sum_{j=1, j\neq i}^{N} \frac{q_j}{r_{ij}^2}\exp\left(-\frac{r_{ij}}{\lambda_D}\right)\mathbf{r}_{ij}} + \mathbf{u}_{t_i}$$
$$\dot{q}_i = u_{q_i}$$

Swarm dynamic equations

$$\mathbf{a}_i^{el} = \boxed{-\frac{k_c q_i}{m_i}\sum_{j=1, j\neq i}^{N} \frac{q_j}{r_{ij}^2}\exp\left(-\frac{r_{ij}}{\lambda_D}\right)\mathbf{r}_{ij}} = \boxed{q_i \mathbf{R}_i \mathbf{q}} \qquad \boxed{\mathbf{R}_i := \mathbf{G}_i \boldsymbol{\Lambda}_i}$$

Electrostatic acceleration

Swarm geometry matrices →

$$\mathbf{G}_i = -\frac{k_c}{m_i}\begin{bmatrix} | & | & & | & & | \\ \mathbf{r}_{i1}/r_{i1}^2 & \mathbf{r}_{i2}/r_{i2}^2 & \dots & 0 & \dots & \mathbf{r}_{iN}/r_{iN}^2 \\ | & | & & | & & | \end{bmatrix}$$

Plasma shielding matrices →

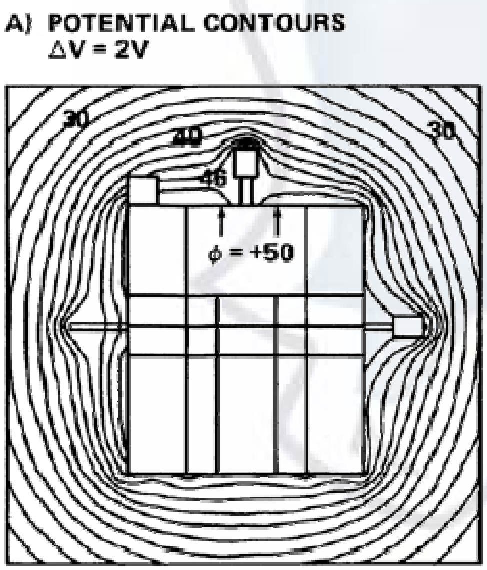
$$\boldsymbol{\Lambda}_i = \begin{bmatrix} e^{-\frac{r_{i1}}{\lambda_D}} & 0 & \dots & 0 \\ 0 & e^{-\frac{r_{i1}}{\lambda_D}} & \dots & 0 \\ 0 & 0 & \ddots & 0 \\ 0 & 0 & \dots & e^{-\frac{r_{i1}}{\lambda_D}} \end{bmatrix}$$

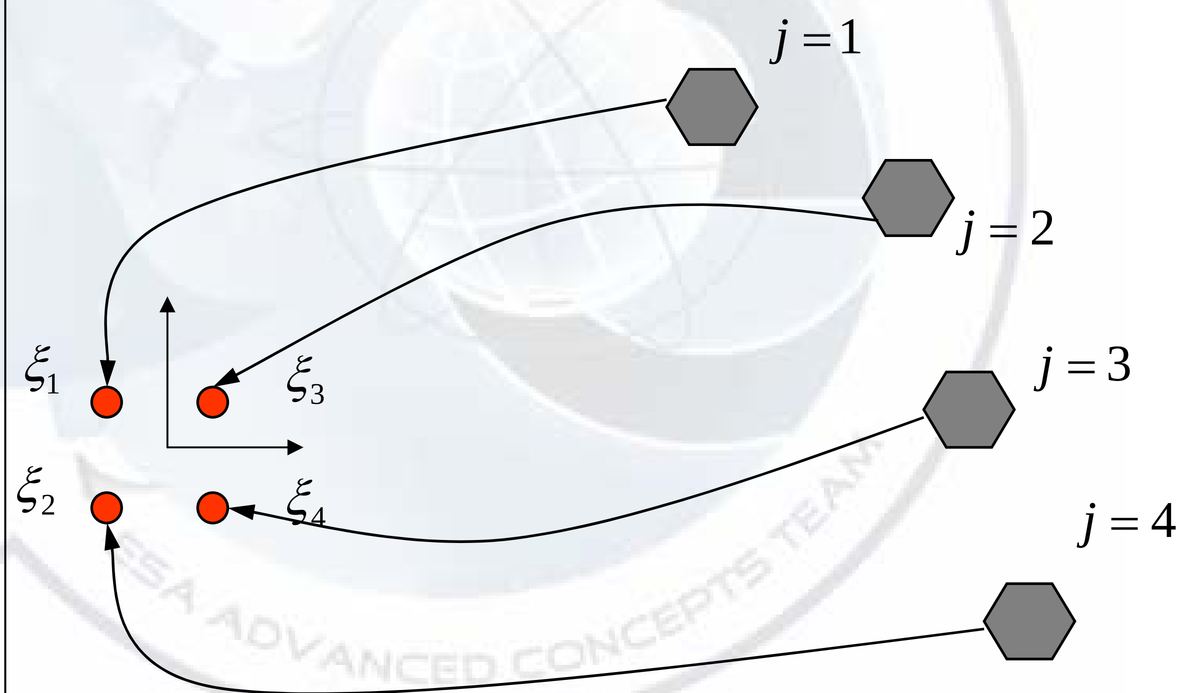
Feasibility of hybrid control

Find: $\mathbf{u}_{t_j}(\mathbf{r}, \dot{\mathbf{r}}, q_j)$

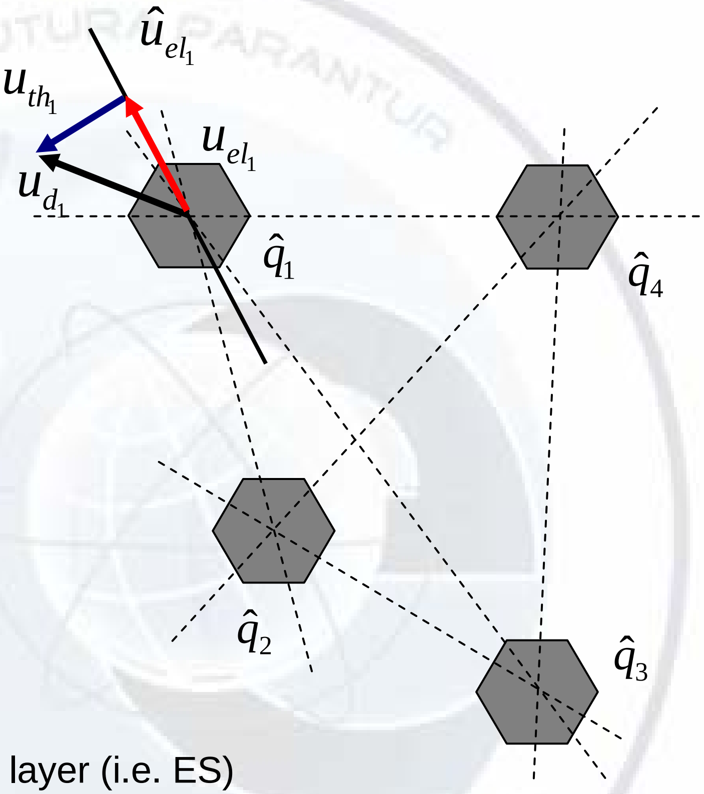
$u_{q_j}(\mathbf{r}, \dot{\mathbf{r}}, \mathbf{q})$

“to acquire a given swarm geometry with a minimum fuel consumption”





Behaviour-based charge control



$$\boxed{q_{des_i} = \mathbf{u}_{d_i} \cdot \mathbf{R}_i \mathbf{q} / |\mathbf{R}_i \mathbf{q}|^2}$$

$$\boxed{\mathbf{I} = \dot{\mathbf{q}} = k(\mathbf{q}_{des} - \mathbf{q})}$$

$\mathbf{u}_{d_i} \longrightarrow$ Provided by the path planning layer (i.e. ES)

$$\ddot{\mathbf{r}}_i + \frac{\mu}{r_i^3}\mathbf{r}_i = \overbrace{-\frac{k_c q_i}{m_i} \sum_{j=1, j\neq i}^{N} \frac{q_j}{r_{ij}^2} \exp\left(-\frac{r_{ij}}{\lambda_D}\right)\mathbf{r}_{ij}} + \mathbf{u}_{t_i}$$

$$\dot{q}_i = u_{q_i}$$

Equilibrium study

4 $\mathbf{I} = \dot{\mathbf{q}} = k(\mathbf{q}_{des} - \mathbf{q})$

5 $q_{des_i} = \mathbf{u}_{d_i} \cdot \mathbf{R}_i\mathbf{q}/|\mathbf{R}_i\mathbf{q}|^2$

$$q_{des_i} = \hat{q}_i \frac{\mathbf{R}_i\hat{\mathbf{q}} \cdot \mathbf{R}_i\mathbf{q}}{\mathbf{R}_i\mathbf{q} \cdot \mathbf{R}_i\mathbf{q}}$$

Theorem 1 *The differential system defined by Eq. (4) and Eq.(5) admits the equilibrium position $\hat{\mathbf{q}}$ if and only if $\mathbf{u}_{d_i} = \hat{q}_i\mathbf{R}_i\hat{\mathbf{q}} + \mathbf{u}_\perp$ where $\mathbf{u}_\perp$ represents any vector perpendicular to $\mathbf{R}_i\hat{\mathbf{q}}$*

Theorem 2 *If $\hat{\mathbf{q}}$ is an equilibrium condition for the differential system defined by Eq. (4) and Eq.(5) then also $-\hat{\mathbf{q}}$ will be equilibrium position.*

Stability

Linear:

Non linear system:

$$\mathbf{I} = \dot{\mathbf{q}} = k(\mathbf{q}_{des} - \mathbf{q})$$

$$q_{des_i} = \hat{q}_i \frac{\mathbf{R}_i\hat{\mathbf{q}} \cdot \mathbf{R}_i\mathbf{q}}{\mathbf{R}_i\mathbf{q} \cdot \mathbf{R}_i\mathbf{q}}$$

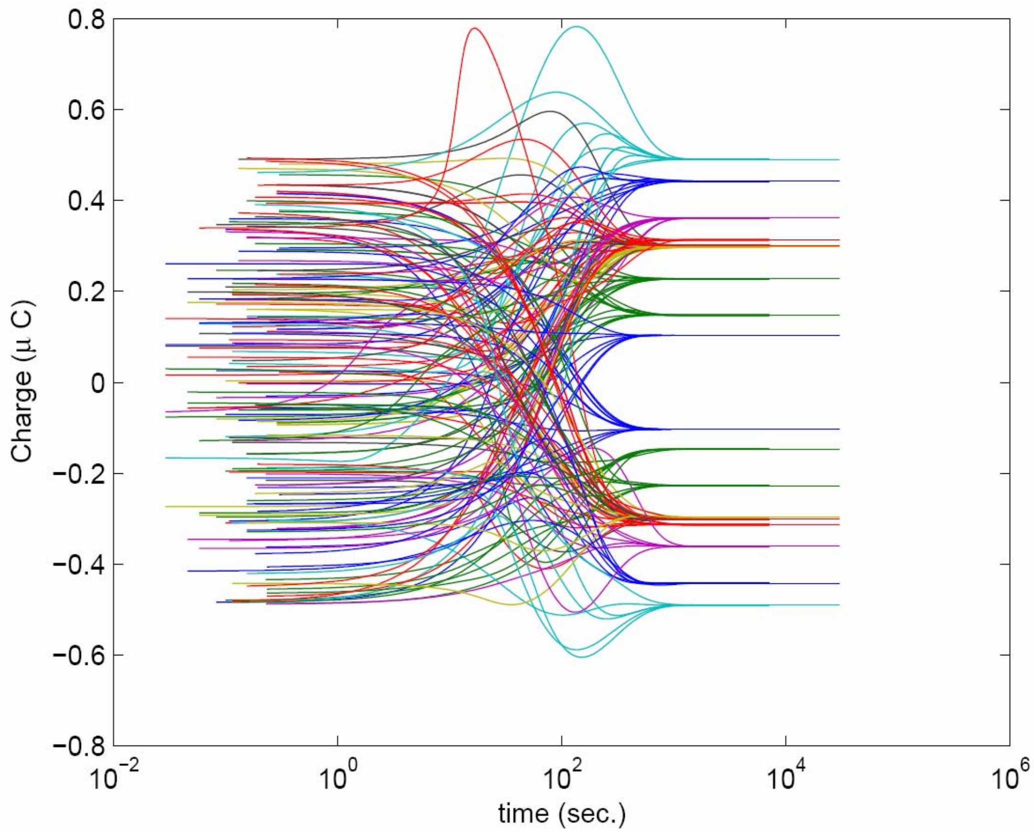
$\longrightarrow$

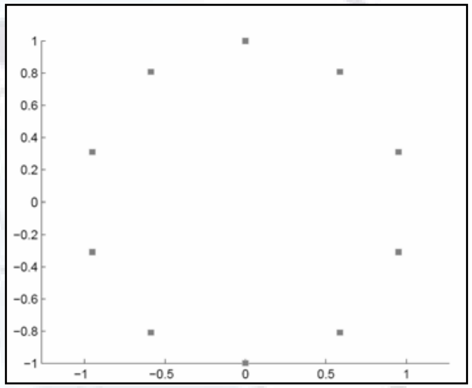
$$\dot{\mathbf{x}} = \mathbf{A}\mathbf{x}$$

$$\mathbf{A} = k\left(\left.\frac{\partial \mathbf{q}_{des}}{\partial \mathbf{q}}\right|_{\mathbf{q}=\hat{\mathbf{q}}} - \mathbf{I}\right)$$

$$\left.\frac{\partial q_{des_i}}{\partial \mathbf{q}}\right|_{\mathbf{q}=\hat{\mathbf{q}}} = -\hat{q}_i \frac{\mathbf{R}_i^T\mathbf{R}_i\hat{\mathbf{q}}}{\mathbf{R}_i\hat{\mathbf{q}} \cdot \mathbf{R}_i\hat{\mathbf{q}}}$$

Stability

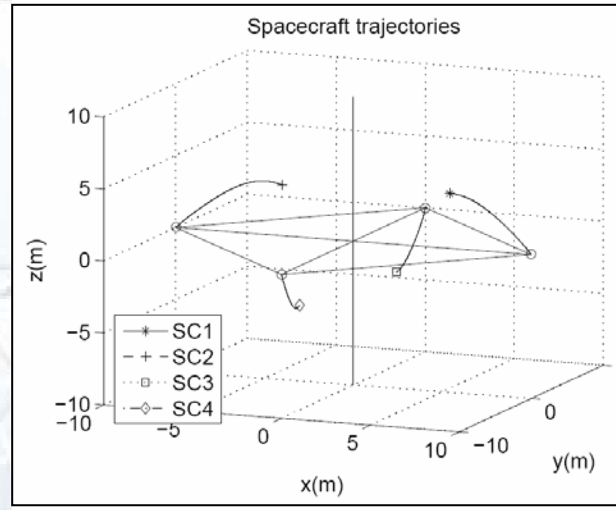


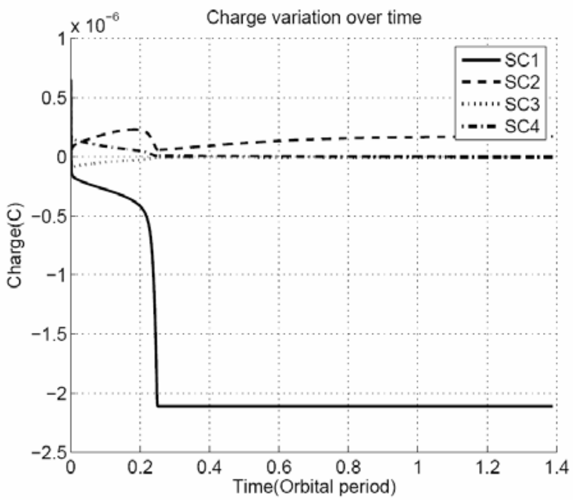


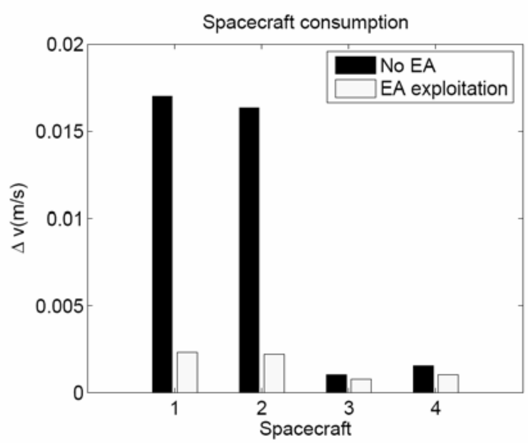
Monte Carlo simulation

Example: reconfiguring a Coulomb swarm

- **Mass**: 50 kg
- **Intersatellite final distance**:10 meters of
- **Maximum thrust**: 0.005 N
- **Maximum charge**: 2 e-6 C
- **Orbit**: Geostationary
- Reconfiguration completed in more than one orbit







Conclusions

- Swarm intelligence has several attractive features for space applications
- A number of space mission concepts require the clever use of a large number of interacting agents with limited capabilities
- Coupled with developments in miniaturization of spacecraft systems (nanotechnology based) SI could be a major player of future space research
- The preliminary results here briefly introduced show that emerging behaviours of use in space may indeed be obtained using technique rooted in SI research.

Final remark: much more detailed studied are needed to understand whether other techniques, based on more classical approaches would be able to solve the problems here approached.