Overview of control approaches and algorithms for distributed space systems

Danil Ivanov, Uliana Monakhova

Keldysh Institute for Applied Mathematics, Moscow, Russia
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- Fuelless satellite formation flying control and algorithms
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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

DSS type

- Swarm
- Formation flying
- Constellation

On-ground control
In-orbit centralized control
In-orbit decentralized control

Autonomy
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:
  o Mother-daughter relationship: mother knows the best for her children and command them
  o 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:

\[
\begin{align*}
\ddot{x} + 2\omega \dot{z} &= 0 \\
\ddot{y} + \omega^2 y &= 0 \\
\ddot{z} - 2\omega \dot{x} - 3\omega^2 z &= 0
\end{align*}
\]

Solution is:

\[
\begin{align*}
x &= -3C_1 \omega t + 2C_2 \cos \omega t - 2C_3 \sin \omega t + C_4 \\
y &= C_5 \sin \omega t + C_6 \cos \omega t \\
z &= 2C_1 + C_2 \sin \omega t + C_3 \cos \omega t
\end{align*}
\]

\[-3C_1 \omega t \quad \text{ - Relative drift}\]
Formation flying specific relative trajectories

- Train formation
- Relative circular orbit
- Docking trajectories

KIKU-7 mission

A-train formation flying

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 tend 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**

\[ d_i = \sum_{j, j \neq i} C_{al} \left( v_{ij} \cdot r_{ij} \right) e^{-\frac{d_{ij}}{R_{al}}} r_{ij} \]

- **Attraction**

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

Equations of motion

\[ m_i \dot{r}_i = -\nabla_i U (r_i) + d_i \]

Fuelless FF Control Concepts

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

<table>
<thead>
<tr>
<th>Advantages</th>
<th>Disadvantages</th>
</tr>
</thead>
<tbody>
<tr>
<td>Full controllability</td>
<td>Fuel consumption limitation</td>
</tr>
<tr>
<td>Maintenance of orbit</td>
<td>Expensive</td>
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</tbody>
</table>

### Aerodynamics

<table>
<thead>
<tr>
<th>Advantages</th>
<th>Disadvantages</th>
</tr>
</thead>
<tbody>
<tr>
<td>Inexpensively</td>
<td>Limitations on control</td>
</tr>
<tr>
<td>No need for engines</td>
<td>Special form of the satellite</td>
</tr>
<tr>
<td>Not creating ionized cloud</td>
<td>Active orientation system</td>
</tr>
<tr>
<td>(Important for the study of the magnetosphere)</td>
<td></td>
</tr>
</tbody>
</table>
Model of aerodynamic force

Equations of relative motion with allowance for aerodynamic force:

\[
\begin{align*}
\ddot{x} + 2\omega \dot{z} &= f_x, \\
\ddot{y} + \omega^2 y &= f_y, \\
\ddot{z} - 2\omega \dot{x} - 3\omega^2 z &= f_z,
\end{align*}
\]

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

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

\[
\begin{align*}
    x_1 &= 2A\cos(\omega t - \arccos(1/3)), & x_3 &= D, \\
    y_1 &= A\sqrt{3}\sin(\omega t), & y_3 &= 0, \\
    z_1 &= A\sin(\omega t - \arccos(1/3)), & z_3 &= 0, \\
    x_2 &= 2A\cos(\omega t), & x_4 &= -D, \\
    y_2 &= A\sqrt{3}\sin(\omega t + \arccos(1/3)), & y_4 &= 0, \\
    z_2 &= A\sin(\omega t). & z_4 &= 0.
\end{align*}
\]

- 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 = 20s
- 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

\[ u_{i}^{\text{max} R} = \frac{-\omega C_{1}^{ij}}{\Delta T}, \quad J = \arg \left( \max_{j} \left( R_{ij} \right) \right), \quad j \in [1, \ldots, N_{\text{comm}}], \quad j \neq i, \quad R_{ij} \leq R_{\text{comm}} \]

• Maximum drift elimination

\[ u_{i}^{\text{max} C} = \frac{-\omega C_{1}^{ij}}{\Delta T}, \quad J = \arg \left( \max_{j} \left( C_{ij} \right) \right), \quad j \in [1, \ldots, N_{\text{comm}}], \quad j \neq i, \quad R_{ij} \leq R_{\text{comm}} \]

• Average drift elimination

\[ \bar{C}_{1}^{i} = \sum_{j=1}^{N_{\text{comm}}} C_{1}^{ij} / N_{\text{comm}}, \quad \bar{u}_{i} = \frac{-\omega \bar{C}_{1}^{i}}{\Delta T} \]
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!