Magnetic Plasma De-orbit (MPD) system using MTQs for nano-satellites

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Space applications using nano- and micro-satellites (1kg-100kg)

**Features of nano-satellites**

- Nano-satellites can be developed and launched with
  - Shorter development time.
  - Smaller costs.

- Many nano-satellites have been applied to various missions such as
  - Remote sensing.
  - Astronomical observations.

More and more nano-satellites will be developed and launched to LEO orbits.
Space debris caused by nano- and micro-satellites

- Almost all satellites
  - stay at their orbits after their missions because of small drag forces.
  - cannot install any de-orbit systems because of their strict constraints of mass and cost.

Orbital space debris caused from these satellites are of increasing concern to all satellites.

- Nano-satellites need deorbit systems to prevent generating space debris in their orbits.
Previous methods for the satellite de-orbit

**Deorbit using thrusters**
- Nano-satellites achieve the deorbit using a propulsion force.
- Nano-satellites need additional propellant for the deorbit.

**Deorbit using an air drag force**
- Nano-satellites achieve a large area and make a large air drag force in orbit with extensible structures.
- Nano-satellites need additional structures for the deorbit.

Few nano-satellites have de-orbit systems, because they make nano-satellites larger mass, higher cost, and lower reliability satellites.
Requirements for deorbit systems in nano-satellites

The reasons why nano-satellites cannot utilize the previous deorbit systems

- For the deorbit operation, nano-satellites need additional thruster, propellant, and structures.
  - larger mass,
  - higher cost,
  - lower reliability caused by complicated deorbit components.

Requirements for deorbit systems

Satellites
- do not need additional components (or small costs for additional components).
  - The deorbit components should not decrease the probability of mission success.
- can obtain an effective force for the deorbit to complete the operation relatively small period.
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Magnetic Plasma Deorbit (MPD) Satellite Deorbit using in-orbit Plasma

- Nano-satellite generates a magnetic moment using MTQs which interacts with the space plasma in a LEO orbit and makes a drag force.

\[ F = C_d \frac{1}{2} \rho u_{sw}^2 S \pi L^2 \]

\[ L = \left( \frac{M_d^2}{8 \mu_0 \pi^2 n m_i u_{sw}^2} \right)^{1/6} \]

- Satellites do not need to install additional components for the de-orbit operation.
  - Almost all nano-satellites generally utilize MTQs for their attitude control system.
- The proposed method can be utilized in many nano-satellites.

Scale dependency of the proposed MPD method

A satellite is assumed to be uniform density.

\[ S \propto l^2 \]

\[ M \propto l^3 \]

Plasma drag force

\[ F = C_d \frac{1}{2} \rho u_s^2 S \pi L^2 \]

\[ L = \left( \frac{M_d^2}{8 \pi^2 n_i u_s^2} \right)^{1/6} \]

The satellite can make a stronger force in larger satellites.

\[ \cdot F \propto M_d^{2/3} \propto S^{2/3} \propto l^{4/3} \]

The strength of the MTQ is assumed to be proportional to \( S \).

The satellite can make larger acceleration for orbit control in smaller size satellites.

\[ \cdot a \propto F/M \propto l^{4/3}/l^3 \propto l^{-5/3} \]

The proposed magnetic plasma deorbit is more effective in smaller satellites.
Analysis using a simple model

**Assumption ①**
The density of the space plasma is assumed to be constant in time. The density is assumed to be as follows:

\[ \rho = \rho_r \exp\left(-\frac{a^{0.5} - a_r^{0.5}}{H}\right) \]

\( \rho: \text{plasma density} \)
\( a: \text{semi-major axis} \)

**Assumption ②**
The orbit is assumed to be a circular orbit:

\[ v = \sqrt{\frac{\mu}{a}} \]

The perturbation of orbital parameters except for semi-major axis is ignored.

**Assumption ③**
Plasma drag force

\[ F = C_d \frac{1}{2} \rho \mu u_{sw}^2 S \]

**Perturbation equation for the semi-major axis:**

\[ \frac{da}{dt} = \frac{2a^2 v}{\mu} - \frac{1}{2m} C_p \rho S v^2 \]

\( m: \text{satellite mass} \)
\( v: \text{satellite velocity} \)
\( C_p: \text{drag coefficient} \)

**Analytical solution**

\[ a = H^2 \left( \ln \left( \frac{-C_d S \mu^{\frac{1}{2}} \rho_r \frac{1}{m} v + C_0}{2} \right) + a_r^{\frac{1}{2}} \right)^2 \]

\[ C_0 = 2 \exp \left( \frac{\frac{1}{a_0^{\frac{1}{2}}} - \frac{1}{a_r^{\frac{1}{2}}}}{H} \right) \]
Result of the analysis

Fig. 1. Analysis results representing descend trajectories using the proposed de-orbit system.

- Satellite mass
  - 10kg

- MTQ
  - 20Am$^2$
  - 2kg
  - 1w

- A satellite completes de-orbit within 2 years, if the initial altitude is lower than 650 km.
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Plasma simulation with Particle In Cell

Particle-in-cell (PIC) Method

Rarefied fluid simulation by tracking particles in grid system

Plasma Simulation with PIC

Ions’ and Electrons’ Motion Calculation

4th-order Runge-Kutta

Electrostatic Field Calculation

2nd-order Poisson’s equation solver

Motion of ions around magnetic field of MTQs
Plasma drag forces calculated by PIC

Plasma drag forces are calculated by momentum change of ions

Drag force table is created with parameters of
- Ion number density
- Satellite velocity
- Magnetic moment

Utilized in satellite’s orbit simulation
Numerical simulations

- Include International Standard Atmosphere model.
- Include Plasma density and drag force model obtained by the PIC simulations.

Table 1 Parameters for the numerical simulations

<table>
<thead>
<tr>
<th>Satellite</th>
<th>Size</th>
<th>200 × 200 × 200 mm</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mass</td>
<td>10 kg</td>
<td></td>
</tr>
<tr>
<td>Magnetic moment</td>
<td>20 Am²</td>
<td></td>
</tr>
<tr>
<td>MTQ</td>
<td>Mass 2 kg</td>
<td></td>
</tr>
<tr>
<td>Power consumption</td>
<td>1 w</td>
<td></td>
</tr>
</tbody>
</table>

Fig. 2. Analysis results representing descend trajectories using the proposed de-orbit system.

A 10 kg and 650 km altitude nano-satellite completes its de-orbit operation within 2 years with a 20 Am² MTQ.
Conclusion

- Almost all nano-satellites do not have any de-orbit systems, because they make nano-satellites larger mass, higher cost, and lower reliability satellites.

- Nano-satellite generates a magnetic moment using MTQs which interacts with space plasma and makes a drag force.
  - Satellites do not need to install any additional components for the de-orbit operation.

- A 10 kg and 650 km altitude nano-satellite completes its de-orbit operation within 2 years with a 20 Am² MTQ.
Future works

- Shorten the MPD operation time.
  - Improve magnetic field shapes.
  - Improve orbit control methods.
- On-orbit experiments.
  - We have plans for on-orbit experiments using nano-satellites.

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Comparison between proposed MPD and the previous methods

<table>
<thead>
<tr>
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<tbody>
<tr>
<td>• Deorbit using an air drag force. Nano-Satellites …</td>
</tr>
<tr>
<td>– Need additional extensible structures to achieve a large area in orbit.</td>
</tr>
<tr>
<td>– Generate only a time constant force which is not useful for orbit control for other purpose such as formation flight.</td>
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</tbody>
</table>

<table>
<thead>
<tr>
<th>Proposed method</th>
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</thead>
<tbody>
<tr>
<td>• Deorbit using an plasma drag force. Nano-Satellites …</td>
</tr>
<tr>
<td>– Do not need additional structure</td>
</tr>
<tr>
<td>– Need only MTQs for their deorbit operations.</td>
</tr>
<tr>
<td>– Generate <strong>time-variable force which is useful for orbit control such as formation flight.</strong></td>
</tr>
</tbody>
</table>
Effect of satellite attitude - Coil tilt angle

- \( n_p \): plasma density
- \( v_p \): satellite velocity
- \( i_c \): current in MTQ