In-orbit magnetic disturbance compensation using feed forward control in Nano-JASMINE mission

Takaya Inamori
Faculty adviser: Prof. Shinichi Nakasuka

Nakasuka Lab.
Dept. of Aeronautics and Astronautics, University of Tokyo
Overview

• Nano-JASMINE mission
• Attitude control system’s overview
• Magnetic disturbance and cancellation
  – Estimation using Kalman Filter
  – Alignment error effects
  – Estimation using star images.
• Simulation results
• Conclusions and future works
Introduction

- ISSL Univ. of Tokyo is developing Nano-JASMINE, a 20kg nano-satellite. The main objectives of the mission is to measure the 3D positions of the stars (=Astrometry).
- To meet mission requirements, angular velocity of Nano-JASMINE should be controlled with better than $4 \times 10^{-7}$ rad/s accuracy. Special way is required to achieve this accuracy within the size of Nano-satellite.
- Currently EM development phase.
Nano-JASMINE overview

<table>
<thead>
<tr>
<th>Size</th>
<th>500<em>500</em>500 [mm]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mass</td>
<td>20kg</td>
</tr>
<tr>
<td>Mission</td>
<td>Infrared Astrometry</td>
</tr>
<tr>
<td>Mission Life</td>
<td>2 years</td>
</tr>
<tr>
<td>Orbit</td>
<td>Sun-synchronous Orbit</td>
</tr>
<tr>
<td>Attitude Control</td>
<td>Three Axis Stabilization</td>
</tr>
<tr>
<td>Communication</td>
<td>S-band</td>
</tr>
<tr>
<td>Up link</td>
<td>1kbps</td>
</tr>
<tr>
<td>Down link</td>
<td>100kbps</td>
</tr>
</tbody>
</table>
Mission requirements for AOCS

\[ \omega_z = 1 \times 10^{-3} \pm 4 \times 10^{-7} \text{ rad/s} \]

\[ |\omega_x|, |\omega_y| < 2 \times 10^{-7} \text{ rad/s} \]
Attitude control system overview

- Attitude is stabilized gradually using more accurate sensors and actuators

\[1 \times 10^{-3} \text{ rad/s} \quad 1 \times 10^{-5} \text{ rad/s} \quad 1 \times 10^{-7} \text{ rad/s}\]

Mission Telescope, FOG, STT, MTQ or RW

Mission telescope, RW

Mission requirement: \[4 \times 10^{-7} \text{ rad/s}\]

Gyro, Magnetic Sensor, MTQ
Disturbances

- Gravity gradient
  - $1 \times 10^{-9}\text{Nm}$

- Solar pressure disturbance
  - $1 \times 10^{-9}\text{Nm}$

- Air disturbance
  - $3 \times 10^{-9}\text{Nm}$

- Magnetic disturbance
  - $1 \times 10^{-6}\text{Nm}$ (0.1Am²)

Magnetic disturbance is dominant and should be compensated to $1 \times 10^{-4}\text{Am}^2$ accuracy.
Magnetic disturbance effects

- Residual magnetic moment of the Nano-JAMSINE would be $0.1 \text{Am}^2 (1 \times 10^{-6} \text{Nm})$
- With Magnetic disturbance, satellite cannot be stabilized.
- Residual magnetic moment should be canceled during observations.

**Fig1: With magnetic disturbance**

**Fig2: Without magnetic disturbance**
Magnetic disturbance compensation concepts

- RMM (Residual Magnetic Moment) is result of interference with magnetic field which causes a disturbance.

- Magnetic disturbance can be canceled by a magnetic torquer (MTQ) based on estimated RMM data.

- RMM should be estimated to $1\times10^{-4}\text{Am}^2$ accuracy for Nano-JAMSINE mission.
Residual magnetic moment estimation

- RMM can be estimated using Kalman Filter

\[
I\dot{\omega} = M_d \times B + N - \omega \times (I\omega + h) - \dot{h}
\]

- \( x = \begin{pmatrix} \Delta\omega \\ M_d \end{pmatrix} \)

- \( \dot{x} = Ax + Bw \)

- \( x_k = \Phi_{k-1}x_{k-1} + \Gamma_{k-1}w_{k-1} \)

Md: Residual magnetic moment
The effects of alignment error

- Bias and alignment error in the gyros, Magnetic sensors and MTQs cause serious estimation error.

Fig1: The simulation result of the Gyro bias estimation

- Bias and alignment effects should be canceled before RMM estimation.

Fig2: The simulation result of the RMM estimation
Time varying residual magnetic moment

- MTQ alignment error from thermal distortion, current loop form devices and solar arrays cause the time varying RMM.
- Changes with orbital period time constant.
The estimation of the AC RMM

**Fig 1:** The estimation results (simulation)

Iω = Md × B + N - ω × (Iω + h) - h

\[ \hat{M}_d = -\frac{1}{\tau} M_d + \eta \]

\[ x = \begin{pmatrix} \Delta \omega \\ M_d \end{pmatrix} \]

\[ \dot{x} = Ax + Bw \]

\[ x_k = \Phi_{k-1} x_{k-1} + \Gamma_{k-1} w_{k-1} \]

**Fig 2:** The error of the estimation (simulation)
RMM estimation using star images from mission telescope

- The blurriness of the star images is related to attitude stability.
- RMM can be estimated using star images to a high accuracy.
Attitude determination using star images

- Point-spread function (PSF) is extracted from telescope images.
- Line-spread function (LSF) can be calculated as PSF compressed information.

Fig: The relationships between angular velocity and LSF variance
The simulation results of the RMM estimation using star images.

- RMM can be estimated to a higher accuracy and in shorter time for convergence using star images.
- Some effects of the alignment error can be eliminated.
- Time for convergence depends on how often the star images are obtained.
Conclusions and future works

• Conclusions
  – Residual Magnetic Moment (RMM) should be compensated to $1 \times 10^{-4} \text{Am}^2$, which can be achieved by Kalman Filter.
  – Alignment and bias errors of gyros should be estimated before RMM compensations, which can be achieved by STT observations with Kalman Filter.
  - Star imaged used for astrometry missions provide also enough information to the attitude control system to achieve $1 \times 10^{-4} \text{Am}^2$ accuracy.

• Future works
  – Non-linear effects (ex. RW angular momentum).
  – Hardware in the loop simulator
Appendix
Alignment error estimation

- MTQ’s alignment and Gyro alignment can be estimated using Kalman filter before RMM estimation.
Attitude determination using star image

- Angular velocity is estimated from LSF variance.
- LSF variances can be calculated as follows,

\[
\begin{align*}
\sigma_Z^2 &= A(T)\omega^2 + C_Z(\lambda) \\
\sigma_{XY}^2 &= A(T)\omega^2 + C_{XY}(\lambda)
\end{align*}
\]

T: exposure time

\(\lambda\): wave length

A: The function of the ‘T’

C: The function of the ‘\(\lambda\)’
The effects of star color

- PSF shape depends on the color of the stars.
- The effect of star color should be canceled to meet the attitude determination requirements.

Fig 1: the relationships between star image’s variance and $\omega$ for different wavelengths.
Statistical moment

Second order statistical moment

\[
\sigma_{xy}^2 = E(X^2) - (E(X))^2 \\
\sigma_{XY}^2 = A \omega_{xy}^2 + C_{xy}(\lambda) \\
\sigma_{LSF}^2 = E(Y^2) - (E(Y))^2 \\
\sigma_{z}^2 = A \omega_{z}^2 + C_{z}(\lambda) \\
l^2 = E(XY) - E(X)E(Y) \\
l^2 = L \omega_{xy} \omega_{z}
\]

\(\sigma_{xy}, \sigma_{z}, l\) : observable parameters

\(C_{xy}, C_{z}, \omega_{x}, \omega_{z}\) : parameters to be solved for
Attitude determination using star image

Relation Ships between Cxy and Cz

\[ C_{XY} = RC_z + B \]

Second order statistical moment

\[ \sigma_z^2 = A(T)\omega_z^2 + C_z \]
\[ \sigma_{xy}^2 = A(T)\omega_{xy}^2 + C_{xy} \]
\[ l^2 = L(T)\omega_{xy}\omega_z \]
Simulation results

- Without proposal method
  $1\sigma \sim 4 \times 10^{-7}$ rad/s

- With proposal method
  $1\sigma \sim 7 \times 10^{-8}$ rad/s
Estimate using Kalman Filter -1-

- the step time during which the star image is obtained is arbitrary.
- More than 10 sec in the worst case.

Star density map
• Observation matrix should be changed in each stars by the observation direction (x or y)
• Observation accuracy covariance matrix “R” is calculated from star magnitude.
Simulation results

Fig1 The simulation result of the estimation using kalman filter

Fig 2 The simulation result of the attitude control
Conclusion and future work

• **Conclusions**
  - In order to meet the attitude requirements (less than $4 \times 10^{-7}$ rad/s in Z axis), attitude control using star image is possible.
  - The effect of the star color can be canceled using statistical moment

• **Future work**
  - Hardware-in-the-loop simulator
  - The method to canceled the distortion of the optics after launch.

Thank you for your listening
Attitude determination using star image

The variance of the star image is represented as follows,

\[ \sigma_Z^2 = E(Y^2) - (E(Y))^2 \]
\[ \sigma_X^2 = E(X^2) - (E(X))^2 \]
\[ \sigma_{XY}^2 = A(T) \sigma^2 + C_{XY}(\lambda) \]

Expected value are defined as,

\[ E(X) = \int_{-\infty}^{\infty} xf(x)dx \]

T: exposure time
\( \lambda \): wave length
A: The function of the ‘T’
C: The function of the ‘\( \lambda \)’
X: CCD’s pixel position
f(x): Line Spread Function