Nanosatellite Attitude Control System for the Oculus
A Space-Based Imaging Platform for Space Situational Awareness

Mary Farmer
Gordon Parker
Lyon B. King
Peter Radecki
Jeff Katalenich

Michigan Tech
Michigan Technological University
Outline

1. Motivation for Space-based SSA
2. Enterprise Program at Michigan Tech
3. Satellite Configuration
4. Dynamics and Kinematics
5. Reaction Wheel Control Law
6. Stewart Platform Testbed
Space-Based Space Situational Awareness

“Space Situational Awareness means knowing the location of every object orbiting the earth, active or inactive, big or small; and knowing why it is there, what it is doing now, and what we think it will be doing in the future.”

-Lt. Col. Shoemaker
Oculus Roll in Space Situational Awareness (SSA)

- The Oculus project is part of the University Nanosat program.
- 50 kg Nanosat with two imagers and precise 3-axis attitude control system.
- Low-cost testbed to detect and monitor solar illuminated objects.
  - Demonstrate new in-space imaging technologies.
  - Demonstrate 3-axis, visually referenced, attitude control.
- A fleet of satellites with this technology could fulfill need for space-based SSA.
Organization and Involvement

- Faculty & Staff
- Graduate & Undergraduate Researchers
- HAARP Glider
- Oculus
- Can Sat

The enterprise program includes:
- Michigan Tech
- blue marblE security
- C-Racing
- nanotech innovations
- IT@xygen enterprise
Satellite System Configuration

- **Sensors**
  - 3-Axis Gyroscope
  - 3-Axis Magnetometer
  - Raytheon NFOV, Low Light Imager
  - SAIC WFOV Imager

- **Actuators**
  - Magnetic Torque Rods
  - 3 Reaction Wheels
Attitude Control Mission Evolution

- Inertial referenced attitude control
  - initial detumble
  - communications
  - orientation before visual servoing
- SAIC wide field of view imager
  - initial visual servoing for close targets
  - initially orient satellite for imaging targets
- Raytheon narrow field of view low light imager
  - used for tracking distant objects
  - detailed imaging of targets
Satellite Dynamics

Attitude Dynamic Equation

\[
M = (I + J)\dot{\omega} + J\dot{\Omega} + \omega \times ((I + J)\omega + J\Omega)
\]

\[
T = J(\dot{\omega} + \dot{\Omega})
\]

\[
I = \begin{bmatrix}
I_{11} & I_{12} & I_{13} \\
I_{12} & I_{22} & I_{23} \\
I_{13} & I_{23} & I_{33}
\end{bmatrix}
\]

\[
J = \begin{bmatrix}
J_{s1} & 0 & 0 \\
0 & J_{s2} & 0 \\
0 & 0 & J_{s3}
\end{bmatrix}
\]

\(H\) Angular momentum
\(\Omega\) Sum of reaction wheel angular velocities relative to the body frame

\(M\) External moment vector
\(T\) Reaction wheel torque
\(\omega\) Absolute angular velocity of satellite
Attitude Kinematics

Euler parameters are used for the Oculus Simulation and are defined as follows:

\[
\begin{align*}
    e_1 &= r_1 \sin \frac{\Phi}{2} \\
    e_2 &= r_2 \sin \frac{\Phi}{2} \\
    e_3 &= r_3 \sin \frac{\Phi}{2} \\
    e_4 &= \cos \frac{\Phi}{2}
\end{align*}
\]

Modified Rodrigues parameters (MRP) are used in the controllers and relate to Euler parameters as shown:

\[
\begin{align*}
    \sigma_1 &= \frac{e_1}{1 + e_4} \\
    \sigma_2 &= \frac{e_2}{1 + e_4} \\
    \sigma_3 &= \frac{e_3}{1 + e_4}
\end{align*}
\]

At \(e_4 = -1\) the MRP is unbounded, to prevent this from occurring shadowed MRPs are used when \(|\sigma| > 1\).

\[
\begin{align*}
    \sigma_1^s &= \frac{-e_1}{1 - e_4} \\
    \sigma_2^s &= \frac{-e_2}{1 - e_4} \\
    \sigma_3^s &= \frac{-e_3}{1 - e_4}
\end{align*}
\]
Reaction Wheel Control

Reaction wheel controller was developed by Junkin & Schaub in the book Analytical Dynamics of Space Systems.

The controller design starts with the following Lyapunov equation:

\[ V(\sigma, \delta \omega) = \frac{1}{2} \delta \omega^T I \delta \omega + 2K \ln(1 - \sigma^T \sigma) \]

Differentiating with respect to time yields the following equation which is set equal to the negative definite function shown.

\[ \dot{V}(\sigma, \delta \omega) = \delta \omega^T I \frac{dB}{dt} \delta \omega + \delta \omega^T K \sigma \]

\[ = -\delta \omega^T P \delta \omega \]

Using the satellite dynamics, the function above can be rearranged into the following control law:

\[ T = -\omega \times I \omega - \omega \times J(\omega + \Omega) + M \]
\[ + K \sigma + P \delta \omega - I(\dot{\omega}_r - \omega \times \omega_r) \]
Satellite Mass Properties (kg m$^2$)

<table>
<thead>
<tr>
<th>$I_{11}$</th>
<th>1.61725</th>
<th>$I_{12}$</th>
<th>-0.01700</th>
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<tr>
<td>$I_{22}$</td>
<td>1.31325</td>
<td>$I_{13}$</td>
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<td>$I_{33}$</td>
<td>1.09700</td>
<td>$I_{23}$</td>
<td>-0.00100</td>
</tr>
</tbody>
</table>

The spin axis inertia for each reaction wheel is 0.00188 kg m$^2$. 
Satellite Simulation Results

Initially referenced attitude change

Initially referenced rate tracking
Simulated Flyby

- Simulates the motion required to track a target passing by the Oculus.
- The greatest error occurred at the greatest acceleration.
- The performance demonstrated is sufficient to keep the target within the field of view of the camera.
From Simulation to Hardware

- Simulation is a good tool for testing and evaluating control systems.
- Adding hardware to the simulation creates a powerful tool allowing developers to easily visualize system performance.
- Flight hardware can be integrated into a hardware-in-the-loop system to verify performance and operation.

- The Stewart platform was chosen for the demonstrating the Oculus visual servoing using the satellite dynamics model.
- Inverse kinematics of the Stewart platform are simple to calculate and have a unique solution.
The Stewart platform hardware-in-the-loop setup utilizes the satellite dynamics model to simulate the satellite motion.

- Stewart platform is rotated about the z-axis and y-axis to orient the imager.
- Pixel error from center of the frame is converted to MRP representation of that error.
Stewart Platform Movie 1
Conclusions

• A three-axis attitude control system was developed for space-based SSA.
• Satellite dynamics and control laws were simulated for inertially referenced maneuvers.
• Visually referenced maneuvers were demonstrated using the hardware-in-the-loop Stewart platform setup.
• The demonstrations proved the ability of the control laws to accomplish the visual servoing task and the ability of the Stewart platform to demonstrate image-based control systems.
• In the future we will use the Stewart platform to test actual flight software in a hardware-in-the-loop setup before putting our satellite into space.