Autonomous GN&C for Satellite Inspection, Rendezvous, and Docking Missions

David C. Woffinden
David K. Geller

28 February 2006
Motivation

With space becoming more accessible for commercial, military, and other government purposes, there is a growing number of possible inspection, rendezvous, and docking missions in the near future.

1. Commercial
   - Inspect, trouble shoot, repair, or refuel malfunctioning satellites
   - Inspect launch vehicles to validate performance
   - Assembly, maintenance and safety maneuvers for future space hotels/resorts

2. Military
   - Retrieve, capture, and return spacecraft
   - Monitor military’s expanding space assets

3. Government Research
   - Inspect Space Shuttle for possible external damage
   - Surveillance of the International Space Station (AERcam)
   - Repair or de-orbit malfunctioning space telescopes
   - Planetary sample return missions
   - Uncrewed vehicles to ISS for reboost and/or resupply
   - Human exploration missions to the Moon and Mars
Fundamental Question

Majority of experience with rendezvous and docking in space comes from the U.S. and Russian Space programs.

**U.S. Space Program**
- Manual approach
- Mission specific
- Crew interaction with GN&C system
- Cooperation between vehicles
- Rendezvous radar system
- Optical cameras

**Russian Space Program**
- Automated Approach
- Standardized Operations
- Crew has monitoring/backup role
- Significant cooperation between vehicles
- Complex rendezvous radar system (Kurs)
- Optical cameras

**Question:**
Can similar rendezvous missions be performed autonomously with limited or even no cooperation with the target vehicle while minimizing the complexity, power, mass, and volume of the GN&C system?
Agenda

1. Angles-Only Navigation
2. High Fidelity 6-DOF Simulation Environment
3. Relative Maneuvers and Navigation and Δv Results
   - Rotating Football (Circumnavigating) Trajectory
   - Tear Drop Trajectory
   - Stationary Trajectory
4. Conclusion
Angles-Only Navigation

Objective:
Estimate the inertial position and velocity of two orbiting spacecraft using *azimuth* and *elevation* measurements to:

1. Determine the relative position and velocity
2. Perform Maneuvers

While taking into account the following affects:

1. Camera measurement errors (biases)
2. Instrument mounting uncertainties
3. Thermo-mechanical effects (bending)
4. Inertial Attitude Uncertainties
5. Unmodeled Accelerations (SRP, drag, etc.)

Solution:
26 State Extended Kalman Filter
* States 1-12: Inertial Position and Velocity vectors
* States 13-20: 1st Order Markov Processes
* States 21-26: Attitude Uncertainty and Gyro Drift
Simulation Models

Non-Linear Dynamics of Target and Chaser
- Translational
- Rotational

Sensors
- Navigation Camera
- Star Camera
- Gyros

Actuators
- Single-Axis Thruster
- Ideal Momentum Wheels

Space Environment
- J2 Gravity Models
- Unmodeled accelerations
- Eclipses
- Sun Constraints
Translational Control System

- Angles-Only Navigation Filter
- Inspection Logic
- Lambert $\Delta v$ Targeting Logic
Rotational Control System

- Attitude Determination
- Pointing Logic (Target and Maneuver Pointing)
- Attitude Controller (PD and Steering Controllers)
Orbital Rendezvous Scenarios

- **Football Orbit**
  - Downrange: $3\sigma_x = 300$ m
  - Cross-Track: $3\sigma_y = 150$ m
  - Altitude: $3\sigma_z = 30$ m
  - Downrange Rate: $3\sigma_x = 0.03$ m/s
  - Cross-Track Rate: $3\sigma_y = 0.15$ m/s
  - Altitude Rate: $3\sigma_z = 0.3$ m/s
  
  (Camera Accuracy: $3\sigma = 0.01$ deg)
  (Disturbance Accelerations: $70$ m $3\sigma$)

- **Tear Drop**
  - Relative Trajectory

- **Stationary**

*Industry Day 2006*
RESULTS: Rotating Football

- Large number of possible viewing angles for a nadir pointing Target
- A repeating natural relative trajectory requiring limited Δv maneuvers
- 2:1 elliptical trajectory with a period equivalent to orbital period
- Passive abort capabilities
Rotating Football Inspection Results
RESULTS: Rotating Football

Navigation Position Errors
RESULTS: Rotating Football

Rotating Football $\Delta v$ Profile

<table>
<thead>
<tr>
<th>Maneuver</th>
<th>Nominal</th>
<th>Actual</th>
</tr>
</thead>
<tbody>
<tr>
<td>Approach $\Delta v$</td>
<td>0.00 m/s</td>
<td>0.14 m/s</td>
</tr>
<tr>
<td>Entrance $\Delta v$</td>
<td>0.55 m/s</td>
<td>0.65 m/s</td>
</tr>
<tr>
<td>Maneuver $\Delta v$/orbit</td>
<td>0.22 m/s</td>
<td>0.25 m/s</td>
</tr>
<tr>
<td>Total Maneuver $\Delta v$</td>
<td>0.89 m/s</td>
<td>0.99 m/s</td>
</tr>
<tr>
<td>Total Inspection $\Delta v$</td>
<td>1.44 m/s</td>
<td>1.77 m/s</td>
</tr>
</tbody>
</table>
Tear Drop Trajectory

Stationary *top* or *bottom* maneuver

Studied extensively in the past at Draper Labs by D. Gustafson and B. Kriegsman

Tear drop period is a function of the relative height above the target and size of the tear drop

\[ P_{\text{tear}} = \frac{2}{\omega} \sqrt{\frac{6h}{9z_{\text{min}} + 4h}} \]

The \( \Delta v \) consumption is related to time-average altitude above target

\[ \Delta v_{\text{orbit}} = 6\pi\omega |\vec{z}| \]

“Forced” trajectory so it has a larger \( \Delta v \) requirement
Tear Drop Inspection
Navigation Position Errors
# Tear Drop $\Delta v$ Profile

## Results

<table>
<thead>
<tr>
<th>Maneuver</th>
<th>Nominal</th>
<th>Actual</th>
</tr>
</thead>
<tbody>
<tr>
<td>Approach $\Delta v$</td>
<td>0.00 m/s</td>
<td>0.14 m/s</td>
</tr>
<tr>
<td>Entrance $\Delta v$</td>
<td>----- m/s</td>
<td>1.98 m/s</td>
</tr>
<tr>
<td>Maneuver $\Delta v$/orbit</td>
<td>13.99 m/s</td>
<td>13.73 m/s</td>
</tr>
<tr>
<td>Total Maneuver $\Delta v$</td>
<td>55.96 m/s</td>
<td>55.16 m/s</td>
</tr>
<tr>
<td>Total Inspection $\Delta v$</td>
<td>----- m/s</td>
<td>57.28 m/s</td>
</tr>
</tbody>
</table>
Stationary Inspection

- A constant front or back viewing angle
- Simple concept
- Fuel efficient
RESULTS: Stationary Inspection
Navigation Position Errors

RESULTS: Stationary Navigation Position Errors
RESULTS: Stationary

Stationary Δv Profile

<table>
<thead>
<tr>
<th>Maneuver</th>
<th>Nominal</th>
<th>Actual</th>
</tr>
</thead>
<tbody>
<tr>
<td>Approach Δv</td>
<td>0.00 m/s</td>
<td>0.14 m/s</td>
</tr>
<tr>
<td>Entrance Δv</td>
<td>0.56 m/s</td>
<td>0.65 m/s</td>
</tr>
<tr>
<td>Stop Δv</td>
<td>1.11 m/s</td>
<td>1.10 m/s</td>
</tr>
<tr>
<td>Maneuver Δv/orbit</td>
<td>0.00 m/s</td>
<td>0.02 m/s</td>
</tr>
<tr>
<td>Total Maneuver Δv</td>
<td>0.00 m/s</td>
<td>0.09 m/s</td>
</tr>
<tr>
<td>Total Inspection Δv</td>
<td>1.66 m/s</td>
<td>1.97 m/s</td>
</tr>
</tbody>
</table>
Conclusions

Navigation and Δv Performance

- Angles-only navigation filter perform sufficiently well to perform the various maneuvers for each inspection strategy. Typically, it is capable of estimating Chaser’s position to a 3σ accuracy of 10-20 meters downrange, 1-5 meters cross-track, and 5-12 meters in altitude direction.

- Neither the eclipses periods or sun blinding conditions caused any mission failures. The sun blinding affects were not a major factor and only observed in 2 of the 3 inspection runs. Expected to have significant impacts in limited scenarios, but can be avoided with pointing logic.

- Loss of angle measurements during maneuvers appears insignificant.

- Relative motion with respect to target is necessary to maintain stable navigation performance.

- For “natural” relative trajectories, large number of possible viewing angles can be achieved at the expense of minimal amounts of fuel compared to powered flight.
Questions / Comments
Additional Slides
Angular Rates

RESULTS: Rotating Football
Velocity and Attitude Errors

RESULTS: Rotating Football
RESULTS: Tear Drop

Velocity and Attitude Errors

Inertial Attitude Errors

Navigation Velocity Errors
Angular Rates

RESULTS: Tear Drop
Stationary Inspection
RESULTS: Stationary Angular Rates
Velocity and Attitude Errors

Stationary Velocity and Attitude Errors

Inertial Attitude Errors

Navigation Velocity Errors
## Initial Conditions

### Simulation

<table>
<thead>
<tr>
<th>Target and Chaser</th>
<th>Navigation Filter</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Position &amp; Velocity Errors</strong></td>
<td><strong>Downrange:</strong> $3\sigma_x = 300$ m</td>
</tr>
<tr>
<td></td>
<td><strong>Cross-Track:</strong> $3\sigma_y = 100$ m</td>
</tr>
<tr>
<td></td>
<td><strong>Altitude:</strong> $3\sigma_z = 30$ m</td>
</tr>
<tr>
<td></td>
<td><strong>Downrange Rate:</strong> $3\sigma_x = 0.03$ m/s</td>
</tr>
<tr>
<td></td>
<td><strong>Cross-Track Rate:</strong> $3\sigma_y = 0.15$ m/s</td>
</tr>
<tr>
<td></td>
<td><strong>Altitude Rate:</strong> $3\sigma_z = 0.3$ m/s</td>
</tr>
</tbody>
</table>

### Target Vehicle

<table>
<thead>
<tr>
<th>Orbital Elements</th>
</tr>
</thead>
<tbody>
<tr>
<td>$a = 6,878,130$ m</td>
</tr>
<tr>
<td>$e = 0.00000149$</td>
</tr>
<tr>
<td>$i = 27.9998423$ deg</td>
</tr>
<tr>
<td>$f = 30.1236667$ deg</td>
</tr>
<tr>
<td>$\omega = 29.8751818$ deg</td>
</tr>
<tr>
<td>$\Omega = 119.999654$ deg</td>
</tr>
</tbody>
</table>

### Chaser Vehicle

<table>
<thead>
<tr>
<th>Orbital Elements</th>
</tr>
</thead>
<tbody>
<tr>
<td>$a = 6,879,153$ m</td>
</tr>
<tr>
<td>$e = 0.0000103$</td>
</tr>
<tr>
<td>$i = 27.999680$ deg</td>
</tr>
<tr>
<td>$f = 33.273725$ deg</td>
</tr>
<tr>
<td>$\omega = 26.803218$ deg</td>
</tr>
<tr>
<td>$\Omega = 120.00088$ deg</td>
</tr>
</tbody>
</table>
System Parameters

Simulation

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>$3\sigma_e$</td>
<td>0.01 deg</td>
</tr>
<tr>
<td>$3\sigma_\alpha$</td>
<td>0.01 deg</td>
</tr>
<tr>
<td>$3\sigma_{Bias}$</td>
<td>0.001 deg</td>
</tr>
<tr>
<td>$3\sigma_{Stat, Algn}$</td>
<td>0.01 deg</td>
</tr>
<tr>
<td>$3\sigma_{Dyn, Algn}$</td>
<td>0 deg</td>
</tr>
<tr>
<td>$\tau_{Bias}$</td>
<td>$1 \times 10^{-6}$ sec</td>
</tr>
<tr>
<td>$\tau_{Stat, Algn}$</td>
<td>$1 \times 10^{-6}$ sec</td>
</tr>
<tr>
<td>$\tau_{Dyn, Algn}$</td>
<td>3000 sec</td>
</tr>
</tbody>
</table>

Navigation Filter

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>$3\sigma_e$</td>
<td>0.01 deg</td>
</tr>
<tr>
<td>$3\sigma_\alpha$</td>
<td>0.01 deg</td>
</tr>
<tr>
<td>$3\sigma_{Bias}$</td>
<td>0.001 deg</td>
</tr>
<tr>
<td>$3\sigma_{Stat, Algn}$</td>
<td>0.01 deg</td>
</tr>
<tr>
<td>$3\sigma_{Dyn, Algn}$</td>
<td>0 deg</td>
</tr>
<tr>
<td>$\tau_{Bias}$</td>
<td>$1 \times 10^{-6}$ sec</td>
</tr>
<tr>
<td>$\tau_{Stat, Algn}$</td>
<td>$1 \times 10^{-6}$ sec</td>
</tr>
<tr>
<td>$\tau_{Dyn, Algn}$</td>
<td>3000 sec</td>
</tr>
</tbody>
</table>

Navigation Camera

- $3\sigma_{Gyro\, Drift}$ = 3 deg/hr
- $3\sigma_{Tracker}$ = 0.1 deg/hr

(MEMS Gyros & Star Tracker) (Star Tracker Update Once Every Minute)

Inertial Stellar Compass

- $3\sigma_{Gyro\, Drift}$ = 3 deg/hr
- $3\sigma_{Tracker}$ = 0.1 deg/hr

Process Noise

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>$k_{Target}$</td>
<td>$1 \times 10^{-10}$ m$^2$/s$^3$</td>
</tr>
<tr>
<td>$k_{Chaser}$</td>
<td>$1 \times 10^{-10}$ m$^2$/s$^3$</td>
</tr>
</tbody>
</table>
LVLH Reference Frame

Rotating reference frame with the Target at the origin. Useful in analyzing rendezvous maneuvers.

Reference frame for the Clohessy-Wiltshire Equations (CW Equations) or Hill’s Equations.

\[ e_z = \frac{r_{\text{Target}}}{\|r_{\text{Target}}\|}, \quad \text{Altitude} \]

\[ e_y = \frac{\omega_{\text{Target}}}{\|\omega_{\text{Target}}\|}, \quad \text{Cross - Track} \]

\[ e_x = e_y \times e_z, \quad \text{Downrange} \]
Inspection Logic

Pre-determined data arrays defining the specifics of each inspection trajectory

- Maneuver Times: \( M = [M_1, M_2, \ldots, M_n] \)
- Transfer Times: \( T = [T_1, T_2, \ldots, T_n] \)
- Desired Relative Positions: \( P = [P_1, P_2, \ldots, P_n] \)

\( M_i = \text{Maneuver Time} \)
\( T_i = \text{Transfer Time} \)
\( P_i = \text{Desired Position} \)
Lambert $\Delta v$ Targeting Controller

- 3 minutes prior to ignition, calculates required $\Delta v$ for maneuver
- Must estimate Chaser’s actual inertial position at time of ignition and desired inertial position at time of arrival using data from Inspection Logic.
Attitude Determination

- From the gyros, measure the change in rotation angles
  \[ \Delta \hat{\theta}_i \]

- Estimate the angular velocity by dividing the change in angle measurement by the time step.
  \[ \hat{\omega}_{est_i} = \frac{\Delta \hat{\theta}_i}{\Delta t} \]

- Estimate the orientation of the body with respect to the inertial frame by calculating the quaternion rate of change and integrating
  \[ \ddot{\hat{q}}_{est_i} = \frac{1}{2} \hat{\omega}_{est_i} \otimes \hat{q}_{est_i} = \frac{1}{2} \Omega_i \hat{q}_{est_i} \]
  \[ \hat{q}_{est_i} = \int_{t_i}^{t_{i+1}} \dot{\hat{q}}_{est_i} dt + \hat{q}_{est_i} \]

- Use the star camera every 1-5 minutes to update the estimated orientation where the update rate is driven by the gyro drift.
  \[ \hat{q}_{est0} = \hat{q}_{star\ tracker} \]
Pointing Logic

- Target Pointing and Maneuver Pointing
- 3 minutes prior to maneuver, pointing logic switches from Tracking mode to Maneuver Mode
Tracking Mode

During the tracking phase of the inspection mission, the pointing algorithm points the x-axis of the Chaser towards the Target, the y-axis is perpendicular to orbital plane, and the z-axis is defined to complete the orthogonal basis.

\[ x_b = \frac{\rho_{\text{Target}}}{\|\rho_{\text{Target}}\|} \]

\[ y_b = x_b \times \frac{\omega_{\text{Chaser}}}{\|\omega_{\text{Chaser}}\|} \]

\[ z_b = x_b \times y_b \]
Maneuver Mode

During the tracking phase of the inspection mission, the pointing algorithm points the x-axis of the Chaser along the $\Delta v$ vector, the y-axis is perpendicular to orbital plane, and the z-axis is defined to complete the orthogonal basis.

\[
x_b = \frac{\Delta v}{\|\Delta v\|}
\]

\[
y_b = x_b \times \frac{\omega_{\text{Chaser}}}{\|\omega_{\text{Chaser}}\|}
\]

\[
z_b = x_b \times y_b
\]
Attitude Control System

**PD Controller:** Gains are computed as a function of the desired natural frequency, $\omega_n$, and the desired damping ratio, $\zeta$

\[
k_{\text{att}} = \frac{\omega_n}{2\zeta}
\]

\[
k_{\text{sys}} = 2\zeta\omega_n I
\]

**Steering Controller:** For large rotation angles, allows maximum rotation rate of $1\text{deg/sec}$
Sensor Data

MEMS Gyros
- Scale Factor Matrix (calibration error) = 70, 100, or 200 ppm
- Non Orthogonal Matrix (placement error) = 0.2 mrad
- Drift (constant) = 3 deg/hr
- Quantization (precision of gyro data) = 0.000001 rad/sec
- Markov Tau (interval of correlation) = 100 sec
- Markov Standard Dev. = 5-10 (deg/hr) "In-run stability"
- Random Walk Std. Dev. (white noise) = 0.1 deg/sqrt(hr)

Star Camera
- Standard Deviation = 0.1 deg/axis
- Biases = 20 arcsec/axis
- Update Rate = Once every minute

Camera
- Field of View (FOV) = 10 deg
- Number of Pixels = 1000
- Angle Standard Deviation = 0.01 deg
- Angle Bias = 0.01 deg
- Range Bias = 0 deg
Future Work

Modeling Improvement
- Improve the existing PD attitude control law with a more modern technique.
- Use the actual filter implemented in ISC for attitude determination system.
- Develop more “realistic” actuator models to replace the current ideal momentum wheel and thruster models.
- Replace pre-defined data arrays for the inspection logic with a guidance algorithm that can think “real time”.

Analysis Approach
- Verify results using Monte Carlo Analysis techniques.
- Perform extensive trade study. Identify key factors that limit performance (pointing accuracy, sensor precision, actuator quality, etc.)

Inspection Concepts
- Research possible inspection metrics similar to those applied to constellation design (MVT: Maximum Visit Time, AVT: Average Visit Time, MRT: Maximum Re-visit Time, ART: Average Re-visit Time, image resolution, etc.).
- Develop “optimal” inspection trajectories based on these metrics.