GNC TECHNIQUES FOR PROXIMITY MANOEUVRING WITH UNCOORDERATIVE SPACE OBJECTS

Riccardo Benvenuto, Michèle Lavagna

Politecnico di Milano
Department of Aerospace Science and Technologies
Via La Masa 34, 20156, Milano, Italy
Background – ACTIVE DEBRIS REMOVAL

- Active servicer s/c
  - Non-cooperative tumbling target
  - Approach & Docking
  - De/Re-Orbiting

- GNC challenges – autonomy

- Preferred strategies for ADR:
  - ROBOTIC ARM - rigid connection
  - THERED-NET - flexible connection

- 6000 satellites into orbit, <1000 still operational

- LEO and GEO orbits

- ADR focused on massive elements, effective if 10 objects removed per year

Figure 1. LEGEND-simulated LEO debris populations (objects 10 cm and larger) between 1957 and 2006 (historical), and between 2007 and 2206 (future projection). Each curve represented the average of 100 Monte Carlo runs.

Credits Liou, NASA, IAC 2007
Background – ON ORBIT SERVICING

- Active servicer s/c
  - Partially cooperative target
  - Approach & Docking
  - Refuelling
  - Repairing/Maintenance

- GNC challenges – autonomy

- Strategy for OOS:
  - ROBOTIC ARM with end-effector
  - Grippers/Clamping mechanisms

RESEARCH OBJECTIVES

1. Develop fast & reliable dynamics models for ADR and OOS system and GNC design

2. Implement GNC laws for proximity manoeuvring to increase level of autonomy

3. Validating dynamics and test control – experimental activities and HIL
Table of Contents

• Multibody dynamics simulation environment

• **Tethered Tug** scenario
  • Overview and GNC design
  • Analysis and experimental validation

• **Capture Net** scenario
  • Modelling and simulation results
  • Experimental validation

• **Robotic Arm** scenario
  • Overview and GNC design
  • Analysis and results

• Conclusion
ADR/OOS Simulation Environment

- Fast simulation environment to support GNC design
  - Born for ESA’s study **MUST** [Benvenuto, 2014]
  - Further upgrades after activity
- Fully integrated in Matlab/Simulink
  - **Simulink libraries**
  - **SimMechanics**
- Describe 6-DOF orbital and attitude bodies dynamics with:
  - Flexible **tethers/nets**
  - **Robotic manipulators**
  - Flexible appendages and sloshing
  - Environment and perturbations
  - GNC blocks
- Tool **validated** by means of benchmarking and experimental activities
Flexible models based on **lumped parameters methods**

- Model **higher order modes**
- Approximate flexing/whipping - arbitrary number of discretizing elements
- **Fast computations**
- Accounting for different viscoelastic laws
- **Parametric**, different configurations
Tethered Tug Scenario

- Original concept for **SPACE TRANSPORTATION**:
  - Exploitable for Active Debris Removal
  - Passive target connected to an active chaser, its thrusters exciting stack
  - **Fixed-length flexible tethers**
  - V-bar alignment configuration - **unstable**
  - **Fast dynamics**
  - Target mass > chaser mass
Tethered Tug Scenario

Critical modes and instabilities

- **Whiplash effects:** leading to difficult control recovery, (necessary tether tensioning and stabilization)

- **Bounce-Back effects:** post burn phase-slash tether and possible collisions due to residual tension

- Tether entanglement and breakage: avoid free motion and slack tether

- Atmospheric re-entry: chaser control authority holds till a minimum altitude where drag on target prevails

Stack G&C

Closed loop:

Stabilization + Bang-off + post-burn recovery

[Benvenuto, 2014]

Tension feedback to reduce bounce-back

Open loop:

Feed-forward shaping of commanded thrust profile

[Jasper, 2014]

- Input shaping
- Command smoothing/filtering

Closed loop attitude control
Tethered Tug Scenario

Input Shaping

- Signal convolved with series of impulses
- Thrust modified by steps
- Achievable with thrusters’ cluster (on-off)
- Increased time to obtain same $\Delta V$

Command smoothing

- Signal filtered
- Thrust modified continually
- Need continuous thrust modulation - throttling
- Increased time > shapers
- Robustness to uncertainties ($\omega, \xi$) > shapers
Tethered Tug Scenario

ZVD Shaper

\[
\begin{bmatrix}
A_i \\
\frac{1}{1 + 2K + K^2} \\
0
\end{bmatrix} = 
\begin{bmatrix}
\frac{2K}{1 + 2K + K^2} \\
\frac{K^2}{1 + 2K + K^2} \\
\frac{0.5T_d}{T_d}
\end{bmatrix}
\]

\[K = e^{(-\xi \pi / \sqrt{1 - \xi^2})}\]

Command Smoother

\[G(s) = \frac{\xi^2 \omega^2}{(1 - M)^2} \frac{(1 - K^2 e^{-T_d s})^2}{(s + \xi \omega)^2}\]

\[\xi = 0\]

\[\xi = 0.1\]
Tethered Tug Scenario

Simulation results

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Chaser Mass [kg]</td>
<td>1300</td>
</tr>
<tr>
<td>Target Mass [kg]</td>
<td>5000</td>
</tr>
<tr>
<td>Initial orbit altitude [km]</td>
<td>600</td>
</tr>
<tr>
<td>Thrust [N]</td>
<td>800</td>
</tr>
<tr>
<td>Tether Young’s modulus [GPa]</td>
<td>32</td>
</tr>
<tr>
<td>Tether damping factor [-]</td>
<td>0.1</td>
</tr>
<tr>
<td>Tether length [m]</td>
<td>60</td>
</tr>
<tr>
<td>Tether diameter [m]</td>
<td>0.003</td>
</tr>
</tbody>
</table>

$\Delta V$ [m/s] 160

Flight angle at 120 Km [deg] -1.6
Tethered Tug Scenario

Experimental Microgravity Validation

- PoliTethers Team selected for ESA’s Education Fly Your Thesis! 2016
- **Parabolic flight campaign** October 2016
- Release and retrieval of **tethered floating module**
- Actuator to **simulate thrust profiles**
- Stereo-vision reconstruction + acceleration/tension sensors
Capture Net Scenario

Benefits
- Larger capture distance
- Isotropic loads
- Partially independent from target features (physical and dynamic)
- **Centre of mass alignment with thrust axis not a constraint**
- Scalable device, light payload

Criticalities
- Passive device (except if controlled bullets)
- Non repeatability - one shot chance
- Difficulty in detecting capture
- Possible slippages: closing device
Capture Net Scenario

Enhanced modelling

- **Collision detection**
  - Multi-step refinement — computational time
  - Hierarchical bounding boxes
  - Avoid interpenetration
  - Auto-collisions

- **Contact dynamics**
  - Non-linear contact law (H-C)
    - Avoid shock loads
    - Avoid sticking effects
  - Regularized friction law
  - Coefficients determined through lab tests — characterization of mechanical properties
Capture Net Scenario

G&C

• RDV along track

• No reaction compensation at shooting occurrence (limited bandwidth)

• Chaser attitude controlled (eigenaxis)

\[ u = \omega_C \times I_C \omega_C - D \omega_C - K q_e \]

\[ K = \omega_{BW}^2 I_C \quad D = 2\xi \omega_{BW} I_C \]

• Tumbling target passive angular momentum damping

Friction damping effect during towing [Benvenuto, 2015]
Capture Net Scenario

*Parabolic flight campaign to validate net flexible model and contact model*

ESA’s sponsored activity **PATENDER** [Medina, 2015]:
PoliMi in consortium with GMV Spain and Prodintec Spain

**Experiment design:**

- Nets shot at target mock-up
- Reconstruction of net 3D trajectory thought high resolution- high speed cameras
- Reconstruction process: based on net colour-coding, stereo-matching and knots tracking
- Target position and attitude reconstruction based on mock-up markers
- Simulator validation based on trajectory comparison

*Novespace, Bordeaux, June 2015*
Robotic Arm Scenario

GNC

- Different guidance phases:
  - Motion synchronization at safe distance
  - **Final approach along H axis and arm deployment**
  - Capture & rigidization
  - De-tumbling and disposal
- **Coordinated control strategy** (decoupled):
  - Chaser:
    - LQR for relative position control
    - Eigenaxis attitude control
  - Arm:
    - Joints coordinates & Cartesian coordinates (IK)
  - Noisy measurements + Kalman Filter
### Robotic Arm Scenario

<table>
<thead>
<tr>
<th><strong>Target</strong></th>
<th><strong>Value</strong></th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Target Mass [kg]</strong></td>
<td>1450</td>
</tr>
<tr>
<td><strong>Target (simplified model)</strong></td>
<td><strong>Envisat</strong></td>
</tr>
<tr>
<td><strong>Target angular velocity [deg/s]</strong></td>
<td>3.5 (H-axis)</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th><strong>Arm</strong></th>
<th><strong>Value</strong></th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Arm Mass [kg]</strong></td>
<td>30</td>
</tr>
<tr>
<td><strong>Arm links [#]</strong></td>
<td>2 + Gripper</td>
</tr>
<tr>
<td><strong>Arm DOF [#]</strong></td>
<td>4</td>
</tr>
<tr>
<td><strong>Forward reach [m]</strong></td>
<td>3.1</td>
</tr>
<tr>
<td><strong>Control set-point rate [Hz]</strong></td>
<td>10</td>
</tr>
<tr>
<td><strong>Joints angular accuracy [deg]</strong></td>
<td>0.3</td>
</tr>
</tbody>
</table>

**Capture simulation results**

- **Chaser Control Force**
- **Chaser Control Torque**
- **Joints angle error**
- **Joint torque**

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**Distance Gripper-Desired position**

<table>
<thead>
<tr>
<th>d_distance [m]</th>
<th>time [s]</th>
</tr>
</thead>
<tbody>
<tr>
<td>7</td>
<td>1500</td>
</tr>
<tr>
<td>6</td>
<td>1000</td>
</tr>
<tr>
<td>5</td>
<td>500</td>
</tr>
<tr>
<td>4</td>
<td>0</td>
</tr>
</tbody>
</table>

**Chaser Control Force**

- **F1c**
- **F2c**
- **F3c**

**Chaser Control Torque**

- **T1c**
- **T2c**
- **T3c**
- **T4c**

**Joints angle error**

<table>
<thead>
<tr>
<th>angle [deg]</th>
<th>time [s]</th>
</tr>
</thead>
<tbody>
<tr>
<td>200</td>
<td>1500</td>
</tr>
<tr>
<td>150</td>
<td>1000</td>
</tr>
<tr>
<td>100</td>
<td>500</td>
</tr>
<tr>
<td>50</td>
<td>0</td>
</tr>
</tbody>
</table>

**Joint torque**

<table>
<thead>
<tr>
<th>torque [N]</th>
<th>time [s]</th>
</tr>
</thead>
<tbody>
<tr>
<td>10</td>
<td>1500</td>
</tr>
<tr>
<td>5</td>
<td>1000</td>
</tr>
<tr>
<td>10^{-3}</td>
<td>500</td>
</tr>
<tr>
<td>0</td>
<td>0</td>
</tr>
</tbody>
</table>
Conclusions

- **Autonomous servicing/removal missions:**
  - complex, multidisciplinary and challenging task
  - capturing tumbling objects not equipped with dedicated docking ports
  - sophisticated technologies and reliable lightweight manipulators

- Developed **dynamics simulator** allowed
  - to assess the capture technique feasibility
  - **to drive system design**
  - **to support GNC design**
  - selected mathematical model ensures
    - fast and numerically stable simulations
    - flexibility in different scenarios analysis
  - **Experimental activities on-going to validate simulation models and test G&C**

- **Throw-nets and towing-tethers VS. robotic manipulators**
  - different scenarios analysed
  - preliminary G&C laws tested in simulation
    - Open loop preferred for tether
    - Closed loop preferred for arm
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