COBRA: CONTACTLESS METHOD FOR DETUMBLING SPACE DEBRIS OBJECTS

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INTRODUCTION

- COBRA overview
- COBRA context
- Plume modeling
- Despinning control strategies
- Envisat & PROBA 2 test cases
- Simulation
**COBRA OVERVIEW**

- Momentum exchange between chaser and target through plume impingement
  - Chaser fires thruster in direction of target
  - (Part of) plume intercepted by target
  - Plume pressure generates force and torque on target
- COBRA initially developed for orbit modification
  - Found to be expensive in terms of $\Delta V$, **but:**
  - Rotation state modification feasible and fairly cheap

COBRA concept requires no additional payload apart from what is already present for performing rendezvous

- At least one thruster needs to point in the direction of the relative sensors

\[
F_{\text{deb}} = \eta \cdot F_{\text{push}}
\]

\[
F_{\text{balance}} = \left(1 + \eta \cdot \frac{m_{\text{chs}}}{m_{\text{deb}}} \right) \cdot F_{\text{push}}
\]
**COBRA CONTEXT: DEBRIS REMOVAL**

- **Removal options**
  - Removal of tiny & small debris not practical
  - Removal of large objects removes potential sources of fragments in case of collision

- **Conclusion:** remove large objects

- **Recent interest in removing Envisat in particular**

- **Trial mission could focus on smaller target, such as PROBA2**

### Type Characteristics Hazard

<table>
<thead>
<tr>
<th>Type</th>
<th>Characteristics</th>
<th>Hazard</th>
</tr>
</thead>
<tbody>
<tr>
<td>Tiny</td>
<td>Not tracked, &lt;1 cm</td>
<td>Shielding exists, damage to satellites may occur</td>
</tr>
<tr>
<td>Small</td>
<td>Not tracked, diameter 1 - 10 cm, 98% of lethal objects, ~400,000 objects in LEO</td>
<td>Too small to track and avoid, too heavy to shield against</td>
</tr>
<tr>
<td>Medium</td>
<td>Tracked, diameter &gt;10 cm, &lt;2 kg, 2% of lethal objects, ~24,000 objects in LEO, &gt; 99% of mass (incl. large objects)</td>
<td>Avoidance manoeuvres performed most often for this category</td>
</tr>
<tr>
<td>Large</td>
<td>Tracked, &gt;2 kg, &lt;1% of lethal objects, &gt; 99% of mass (incl. medium objects)</td>
<td>Primary source of new small debris, 99% of collision area and mass</td>
</tr>
</tbody>
</table>
An ADR mission is being studied to de-orbit Envisat
- Robotic arm concept requires risky and expensive ($\Delta V$) synchronization manoeuvre

Detumble Envisat using plume impingement
- Reduce risk of collision by easing / removing need for attitude synchronization
- Synchronization $\Delta V \sim 20$ m/s
- S.K. $\Delta V \sim 2.2$ m/s/min

Envisat rotation state
- Spin rate of 3.5 °/s, around body z-axis
  - Possibly around y-axis or intermediate axis
- Spin rate of 5 °/s around y-axis assumed for simulation
Plume model based on work by G. A. Simons
- High-power cosine law in isentropic core
- Exponential decay in boundary layer
- Analytical & fast model

Verification and parameter settings
- ESA DSMC data available for 1 N thruster
- Analysis of experimental data in literature ongoing

Interaction with target assumed to occur in free molecular flow regime
- Transition is estimated to occur (Flow “freezes”) at about 0.3 m to about 2 m
SURFACE INTERACTION

- Simplifying assumptions made for speeding up calculations
  - Few special functions to limit number of function evaluations
  - Coarse, low detail model of target

Assumptions
- Simplify Schaaf & Chambré model
  - Collisions of gas molecules assumed Maxwellian
- Thermal motion negligible compared to flow velocity (hyperthermal flow) (in reality up to 20%)
- Zero wall temperature (in reality flow velocity up to 20% of incoming flow velocity)

- Simplifying assumptions reduce fidelity but reduce computation time
  - Full model should be used to check results
  - Still, force components will be present in the direction of panel normal and direction of incoming flow
Narrower plume desirable
- Larger operating distance possible (larger portion of jet intercepted)
- Torque depends on
  - Dynamic pressure variation (depending on $d\rho/d\theta$) so the narrower the plume, the higher the torque
  - Part of plume intercepted
- Narrow plume behaves more like force application at single point instead of over an area
  - Less “unexpected” behaviour if a single force application point is used in control model
CONTROL STRATEGY 1/2

- Two effects
  - Target object asymmetry
    - chaser imparts torque on target even if gas jet is directed at centre of mass
  - Gas jet pointing away from centre of mass
    - pressure distribution is non-symmetrical with respect to centre of mass (even if target is symmetric)

- Envisat panel causes large asymmetry

- Control strategy
  - Based on pointing and switching
  - Can control two axes at a time
CONTROL STRATEGY 2/2

Direction calculation

- Step 1: desired torque on target is computed based on target angular momentum
- Step 2: direction $u$ of force application is calculated
  - Perpendicular to torque and direction to target
- Step 3: off-centre angle $\alpha$ is calculated based on target shape
  - i.e., a sufficiently large portion of plume must be intercepted

Switching calculation

- Check whether desired torque is close to perpendicular to direction to target (threshold)
SIMULATION CASES

Simulations performed
- To establish detumbling $\Delta V$ and duration
- To check sensitivity to model parameters

<table>
<thead>
<tr>
<th>Case #</th>
<th>Description</th>
<th>Distance [m]</th>
<th>Wall temperature [K]</th>
<th>Ratio of specific heats</th>
<th>Tangential accommodation factor</th>
<th>Normal accommodation factor</th>
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<tbody>
<tr>
<td>1</td>
<td>nominal</td>
<td>22</td>
<td>300</td>
<td>1.37</td>
<td>0.97</td>
<td>1</td>
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<tr>
<td>2</td>
<td>rotation around z</td>
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<td>300</td>
<td>1.37</td>
<td>0.97</td>
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<tr>
<td>3</td>
<td>low wall temperature</td>
<td>22</td>
<td>0</td>
<td>1.37</td>
<td>0.97</td>
<td>1</td>
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<tr>
<td>4</td>
<td>high $\gamma$</td>
<td>22</td>
<td>300</td>
<td>1.66</td>
<td>0.97</td>
<td>1</td>
</tr>
<tr>
<td>5</td>
<td>low accommodation</td>
<td>22</td>
<td>300</td>
<td>1.37</td>
<td>0.5</td>
<td>0.5</td>
</tr>
<tr>
<td>6</td>
<td>high distance</td>
<td>30</td>
<td>300</td>
<td>1.37</td>
<td>0.97</td>
<td>1</td>
</tr>
</tbody>
</table>
SIMULATION RESULTS 1: NOMINAL

- $\Delta V \sim 23$ m/s
- 50 – 100 min to despin below $1^\circ$/s
- Variability in de-spin rate due to rotation around intermediate inertia axis

$\Delta V \sim 23$ m/s, 50 – 100 min to despin below $1^\circ$/s
**SIMULATION RESULTS 2: ROTATION AROUND Z**

- Higher $\Delta V$ (~37 m/s)
- Longer duration
- More constant de-spin rate
  - Envisat rotating around stable inertia axis
SIMULATION RESULTS 3: LOW WALL TEMPERATURE

- Higher $\Delta V \sim 27$ m/s
- Longer duration
- Zero wall temperature removes impulse due to thermal motion for molecules leaving surfaces of Envisat
SIMULATION RESULTS 4: HIGH RATIO OF SPECIFIC HEATS

- Much lower $\Delta V \sim 10$ m/s
- Shorter duration
- Narrower plume leads to higher portion of plume to be intercepted and better controllability
SIMULATION RESULTS 5: LOW ACCOMMODATION

- Lower $\Delta V \sim 16$ m/s
- Shorter duration but greater spread
- More specular reflection leads to higher force on target, but also to undesirable variation in direction of force
SIMULATION RESULTS 6: HIGH DISTANCE

- Higher $\Delta V \sim 30$ m/s
- Longer duration
- Smaller portion of plume intercepted; however, detumbling still possible at safer distance of 30 m
CONCLUSION

- COBRA de-tumbling satellites is promising technique for de-tumbling space debris objects.
  - No additional equipment on chaser apart from equipment already there for performing rendezvous with the object
    - Configuration of thrusters can be optimised (adding pushing + compensating thrusters)
  - Detumbling Envisat can be performed within 1 – 2 orbital revolutions, with a $\Delta V$ of $\sim 23$ m/s
    - further optimisation is possible

- Improved models
  - Improved plume model
  - more realistic (albeit highly simplified) model of surface interaction of plume exhaust gases with surface of target object
  - Variation of model parameters shows that COBRA detumbling works even for large uncertainty in plume impingement behaviour

- Simulations have shown that de-tumbling by means of plume impingements is possible
  - Even if target object is in unfavourable rotation state
  - Even if inter-satellite distance is large (30 m)
Thank you

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