Robot Trajectory Optimisation for On-orbit Servicing and Uncooperative Rendezvous

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Outline

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On the 10th of February of 2009 the Iridium 33 and Cosmos 2251 satellites collided.

The collision was catastrophic producing tens of thousands of fragments large enough to catastrophically breakup other satellites.
Introduction

- Space Shuttle STS-109 Columbia Hubble Space Telescope Servicing Mission
Motivation and background

- What is ADR?
- Why do we need?
Motivation and background

- What is On-orbit servicing?
- Why do we need it?
  - Active Debris Removal
  - On-Orbit assembly of large structures
  - Servicing: refuelling, inspection and maintenance of space station or satellites.
  - To eliminate the need of dangerous and expensive astronaut servicing;
  - Inter-planetary missions.
Motivation and background

What is a Space robot?
Motivation and background

- Space robot control modes:
  - Free-flying
  - Free-floating

- Space manipulators introduce new challenges:
  - Dynamic coupling between the robotic arm and spacecraft
  - Path dependent singularities -> Reduced workspace
  - Non-holonomic motion
Motivation and background

Space robot control modes:

- Free-floating
  - The GNC OFF
    - Less fuel expenses
    - High risk of collision
  - 1. Mission failure
  - 2. Increase of space debris
- Free-flying
  - GNC is ON
    - Large fuel consumption
    - Higher performance
    - 1. Extra load
      2. Higher cost
      3. Reduced lifetime
  - CAM maneuvers
    - Increased safety!
Research topic overview

- The optimisation is needed!

**Attitude and Orbital Control System**

**GNC architecture**

- Guidance
- Navigation
- Control

Path planning: Safe trajectory for Spacecraft + robotic arm
Safe trajectories for autonomous rendezvous

The criticality of the trajectory is principally given by:

- Safety requirements
- Technical requirements:
  - Propellant consumption
  - Illumination (Power)
  - Communication (Antenna pointing)
  - Time
  - Robustness
  - Line of sight
  - Computational power

Limited number of algorithms that can be applied
Safe trajectories for autonomous rendezvous

- Some heuristic approaches:
  - Cooperative target
  - Non-tumbling target

Safe trajectories for autonomous rendezvous

Synchronised motion:

- **Advantages**
  - Null relative motion
  - No forces or torques during the grasping
  - Safe approach

- **Disadvantages:**
  - Unknown rotation state
  - High fuel consumption
Safe trajectories for autonomous rendezvous

Forced approach through rotation axis:

- **Advantages:**
  - Safe approach

- **Disadvantages:**
  - Unknown rotation state
  - High fuel consumption
  - Forces or torques during the grasping

- Nonlinear trajectory optimization:
  - Offline optimisation for pre-capture and pos-capture
  - Free-flying dynamics
  - Null relative dynamics at grasping point
  - Time optimal

- Shortcomings:
  - Fuel consumption not optimised
  - No collision avoidance
State of Art


- Nonlinear trajectory optimization:
  - Offline optimisation
  - Collision avoidance
  - Free-floating dynamics

- Shortcomings:
  - Grasping point specified
  - Limited tumbling motion of the target
  - Transfer of angular momentum not treated
  - Data based system unable to respond to unexpected conditions
State of Art


- Nonlinear trajectory optimization:
  - Trajectory generated to match: position, velocity and acceleration;

- Shortcomings:
  - Fuel consumption not optimised
  - No collision avoidance
  - System limitation no considered
Problem formulation

Mathematical model: Lagrangian approach

\[ M_s \begin{bmatrix} \dot{r}_s \\ \dot{q}_m \end{bmatrix} + C \begin{bmatrix} \dot{q}_m, q \end{bmatrix} \begin{bmatrix} \dot{q}_m \end{bmatrix} + g \begin{bmatrix} r_s \end{bmatrix} = \begin{bmatrix} f_s \\ \tau_m \end{bmatrix} \]

Free-flying dynamics

With:

- \( r_s \) and \( v_s \) as the spacecraft position and velocity
- \( q_m \) as the manipulator joint angles
- \( M_s \) as the generalized mass matrix
- \( C \) as the generalized Coriolis and centrifugal effect
- \( g \) the gravity vector
- \( f_s \) the force and momentum on the base of the spacecraft
- \( \tau_m \) joint torque
Problem formulation

System constraints:

Mechanical limits
\[
\begin{aligned}
q_{\text{min}} \leq q(t) &\leq q_{\text{max}} \\
\dot{q}_{\text{min}} \leq \dot{q}(t) &\leq \dot{q}_{\text{max}}
\end{aligned}
\]

Minimum safety distance
\[
D(i) > d_{\text{safety}}
\]

Rendezvous constraints
\[
\begin{aligned}
r_{EE}(t_f) - r_{\text{grasp}}(t_f) &= 0 \\
\omega_s(t_f) - \omega_{\text{target}}(t_f) &\leq \omega_{\text{limit}}
\end{aligned}
\]

With:

- $r_{EE}$ end-effector position
- $r_{\text{grasp}}$ position of the grasping point
- $\omega_s$ and $\omega_{\text{target}}$ angular velocity of the chaser and target
Problem formulation

Performance metrics:
- Safety
- Fuel usage
- Time
- Suitability to grasp and stabilisation
- System constraints:
  - Maximum thrust
  - Minimum Impulse Bit (MIB)

The cost function can be defined as a path integral:

\[ P(v) = \int_{t_0}^{t_f} g(path_v(t))dt + h(path_v(t)) + l(path_v(t_f)) \]
Problem formulation

Objective: To find a trajectory to match at time $t_f$ satisfies all the constraints and such that

$$v^* = \min_v (P(v))$$

- Local minima problem: If the optimization routine search for the global minimum different solutions can be found:
  1. Same cost
  2. Different cost -> heuristic acceptable path good choice as starting point
- In order to relax the constraints and reduce the computational time, the algorithm can instead search for a solution that already satisfies the mission requirements.
The ESA Clean Space Initiative requested a joint ESA/DLR study to be carried out in the CDF. This study, named d.Deorbit was a feasibility study of a joint ESA/DLR On-Orbit Demonstration mission designed to reduce the risk to the future e.Deorbit mission.
d. Deorbit mission

Mission scenario:

- Target vehicle: Envisat
  - Tumbling motion:
    - Spin axis in body frame is aligned with the +Zs axis.
    - Spin axis in LVLH frame is at an angle of 45 degrees with respect to the +H-bar axis and is fixed in an inertial reference frame.
    - Spin rate is 5 deg/s.

Chaser spacecraft:

- 7 DoF robotic manipulator
- GNC activated during all phases
- Grasping point is known
- X = -3 Km Z = 500 m in LVLH frame
d. Deorbit mission

[source: Jacobsen, S. et. al., *Planning of safe kinematic trajectories for free flying robots approaching an uncontrolled spinning satellite, ASME DETC 2002*]
The rendezvous and capture sequence consist of five phases, divided by holding points:

- Far range rendezvous -> Orbit transfer
- Close range rendezvous -> Hopping phase
- Final approach
- Inspection:
  - Forced Motion
  - Inspection
  - Synchronised motion
- Capture phase
- Target stabilisation phase
- De-orbiting phase
d. Deorbit mission
50% of the fuel is spent only in the synchronisation!
Simulation results

ESA Active Debris Removal Scenario
DLR Modelica Space System Library
Bruno Brito, ESA
Conclusions

We need:

1. Optimal control to improve the system performance;
2. Optimal estimators to reduce the noise effect in the sensor measurements;
3. Optimal path planning for the success of the mission.

The optimisation is needed to solve the problem!
References


References


Thank you for your attention!

Questions?