Robotic Capture and De-Orbit of a Tumbling and Heavy Target from Low Earth Orbit

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Introduction – Space Debris

Note: Artist's impression; size of debris exaggerated as compared to the Earth

Source: ESA
Introduction – Space Robotics

- Future and already deployed robot applications in space:
  
  - **In-space robotic assembly (ISRA):** SSRMS, SPDM
  - **EVA assistance:** SSRMS, Robonaut, DLR’s Justin, (small) satellites for inspection: SPHERES
  - **Robotic exploration:** MER’s
  - **On-orbit servicing (OOS)** for prolonging lifetime of operational satellites, repair & refuel (RRM), extend or upgrade functionality (Hubble)
    - Hot topic: OOS for active debris removal from LEO or re-orbiting into graveyard orbit in GEO (DEOS)
  
  - **Dexterous manipulators** play essential role robotic manipulation in space – based on DLR’s 7-DoF lightweight robot (LWR) → Rokviss (middle) and 7-DoF space manipulator (bottom) with impedance control concept
Challenges of Robotic Spacecraft
Intelsat VI Capture on STS-49 (NASA)

Source: Youtube (edited)
Challenges of Robotic Spacecraft for OOS

- In general: complex contact operations in **close-proximity**

- **Unintended contact** can lead to unsuccessful capture

- **uncertain environment** (target not prepared for servicing)

- Free-floating dynamics: manipulator has **direct physical feedback** on its floating base

- Consequences:
  - Upon contact with capture tool, capture needs to be assured
  - High Attitude and Orbit Control System (AOCS) requirements
  - Distributed control problem, integrated spacecraft: Satellite turns into **Space Robot**
  - High computation power demands
Robot Capture Technology

1. Capture Operations
2. Arm Technology
3. Arm Camera System for Visual Servoing
4. Gripper
5. Stabilization
6. Clamping Device
e.Deorbit - Capture and Stabilization with a 7-DoF Robotic Manipulator
Arm Technology

- 7-DoF, total length of approx. 4m
- Max. nominal torque of 160Nm
- Torque-based impedance control concept for compliant grasp
- Redundant mechatronic design
- Gripper for capturing Ariane launch adapter ring of ENVISAT
- Stereo-camera system at arm wrist for visual servoing
Joint Technology

- Integrated joint design from ROKVISS heritage with motor, brake, gear, position and torque sensor, and sensor electronics
- Electronics integrated in arm assembly
- EtherCAT bus system for single joint actuation in case of joint failure
Workspace Analysis

- Capability map – quantification of possible discretized directions in subspace
- Analysis and verification of arm kinematics
- Accounts for self-collision
Workspace Analysis – Joint Failure
Manipulator Camera System

- Edges on adapter ring used for model-based tracking
- Vertical stereo layout
- Grasp point visible throughout the approach and grasp process
Simulation of Arm Approach

- Approach from 1m distance (gripper to grasp frame)
- Only the ring structure is used for tracking
- Simulation yields grasp point estimation error
Visual Servoing Simulation Results – Stereo

- Visual Servoing using 4-DoF-estimation (rotation around center of cylinder and tangential translation are fixed), however all relevant dimensions for successful grasp are covered

- Translational error **below 1mm**, rotational error **below 0.2deg**
Gripper Design
Robotic Grasp Simulation

- Haptic real-time simulation using the Voxelmap-Pointshell (VPS) algorithm
- Two kinds of models: voxel model (adapter ring) and pointshell model (gripper) with surface normal vectors, 3mm resolution both
- Penalty-based method for calculating interaction force (buoyancy)

- Although not optimal for the given problem, it yields a qualitative analysis of capture
e.Deorbit - Haptic Grasp Simulation with the Voxelmap-Pointshell (VPS) Algorithm
Robotic Grasp Simulation – Results (Position)

- Plot: position of dynamic two-finger gripper bracket
- Gripper is pulled towards the ring
Robotic Grasp Simulation – Results (Force)

- Plot: interaction forces acting on dynamic two-finger gripper bracket
- Vertical and horizontal forces pull gripper towards the final grasp force
Rigidization

- Relative motion is actively damped out with the arm
- High robustness w.r.t. residual relative motion between satellites
Clamping Mechanism

- Seat on top of ENVISAT with aligned COG’s
- achieve stiff connection
- arm only for re-positioning
- Robust to surface unevenness and flexibility
Ready for De-Orbit...
The future of robots in space…

robotic exploration  satellite servicing  EVA support
Development Approach

- Independent joint testbed
- DLR free-floating dynamics simulator with gravity compensation device (rope setup)

- SoftwareL On-orbit verification of framework on ESA cubesat mission OPSSAT - simultaneous operation of robot control and additional avionics functions such as AOCS

![DLR HiL-OOS-Simulator (free-floating dynamics)](image1)

![OPS-SAT](image2)
AOCS Reaction to Arm Movement

- Arm introduces disturbance forces and torques on its satellite base

- Disturbances must be smaller than capabilities of AOCS during stabilized approach

- Simulated AOCS reaction shows that resulting error in
  - Position < 6mm
  - Orientation < 0.5deg

- Does not bring targeted grasp point out of FoV of arm camera
Capability Map

- **Reachability Map**: discretized structure describing reachable poses of robots end-effector
- Method of analysis accounts for
  - Robot kinematics
  - Self-collision
- Reachability index quantifies how well can a robot operate in a small subspace (voxel) of its workspace.
- The index is a per-voxel absolute measure of how many of the discretized directions are reachable by the end-effector.
- Within the blue area the end-effector has excellent manipulability for grasping, green indicates insufficient reachability
Visual Servoing Simulation - Summary

- Very accurate stereo results (position below 1mm, rotation below 0.2deg)

- Sufficient results for mono-matching (position below 5mm, rotation below 0.2deg)

- Mono results deal as worst-case assumption for updated error budget

- Hardware-in-the-loop tests with adapter ring mockup and realistic lighting advised for further mission phases to check effects reflections (MLI & radiator tape)
Visual Servoing Simulation Results – Mono

- Translational error **below 5mm**, rotational error **below 0.2deg** during final approach

- Used as worst-case assumptions for updated error budget
Robotic Grasp Simulation – Summary

- Execution of multiple start configurations with representative errors in all axes
- The gripper was never pushed out, in contrast it was pulled towards the ring through the inclined area of contact
- VPS method is not optimal for the given full force closure problem, only limited realness through
  - Temporal discretization (real-time), one cycle (1ms) computation time
  - Spatial discretization (model detail)
  - Oscillations when grasped
  - Internal forces are not equalized
- However, direction of generated force is empirically proven to be accurate
- Simulation could show general feasibility of chosen approach