Design and Performance Analyses of the DLR Robotic Manipulator Arm for the e.deorbit Mission

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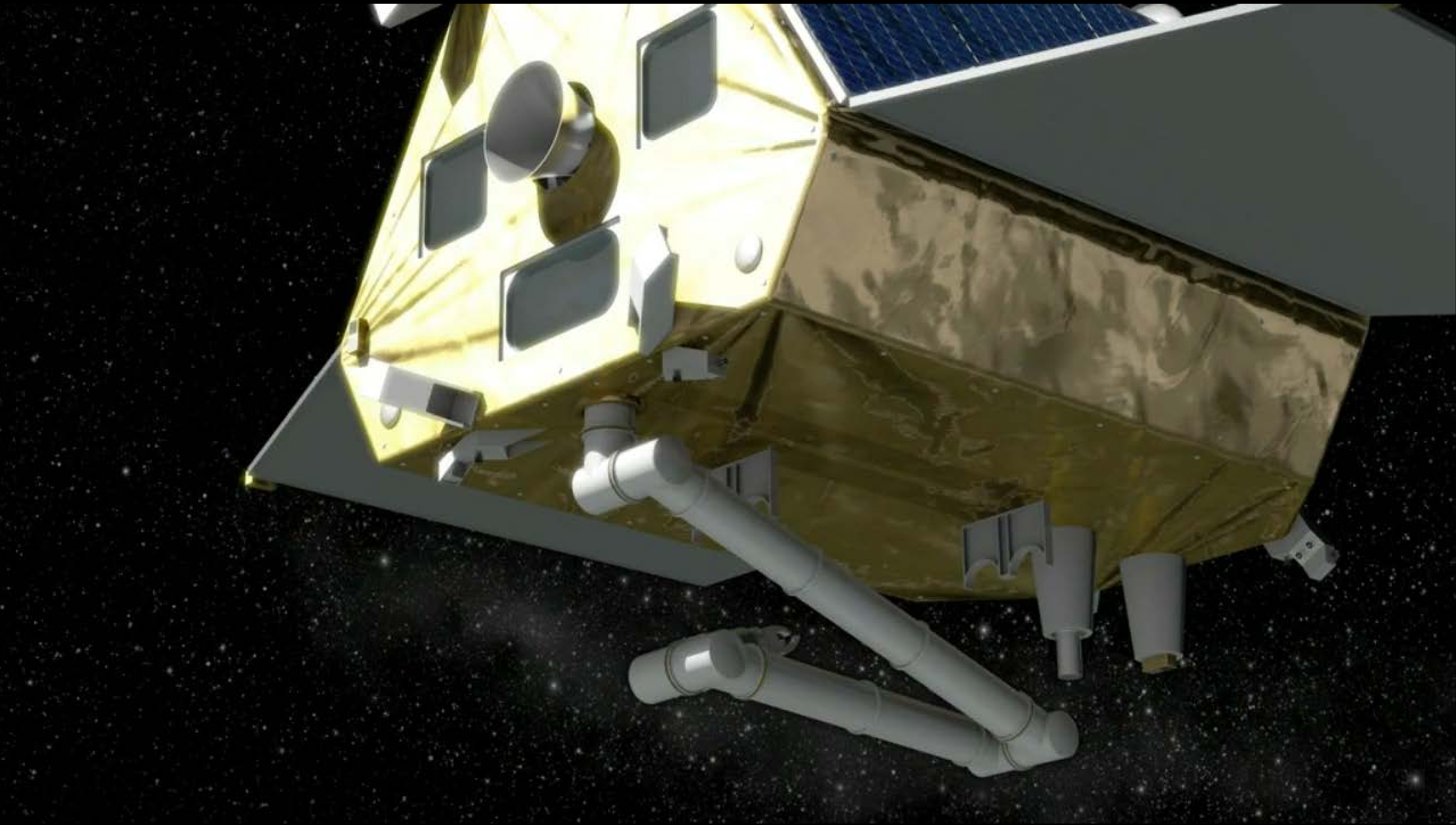
Note: Artist's impression; size of debris exaggerated as compared to the Earth

Source: ESA



Source: Airbus, DLR

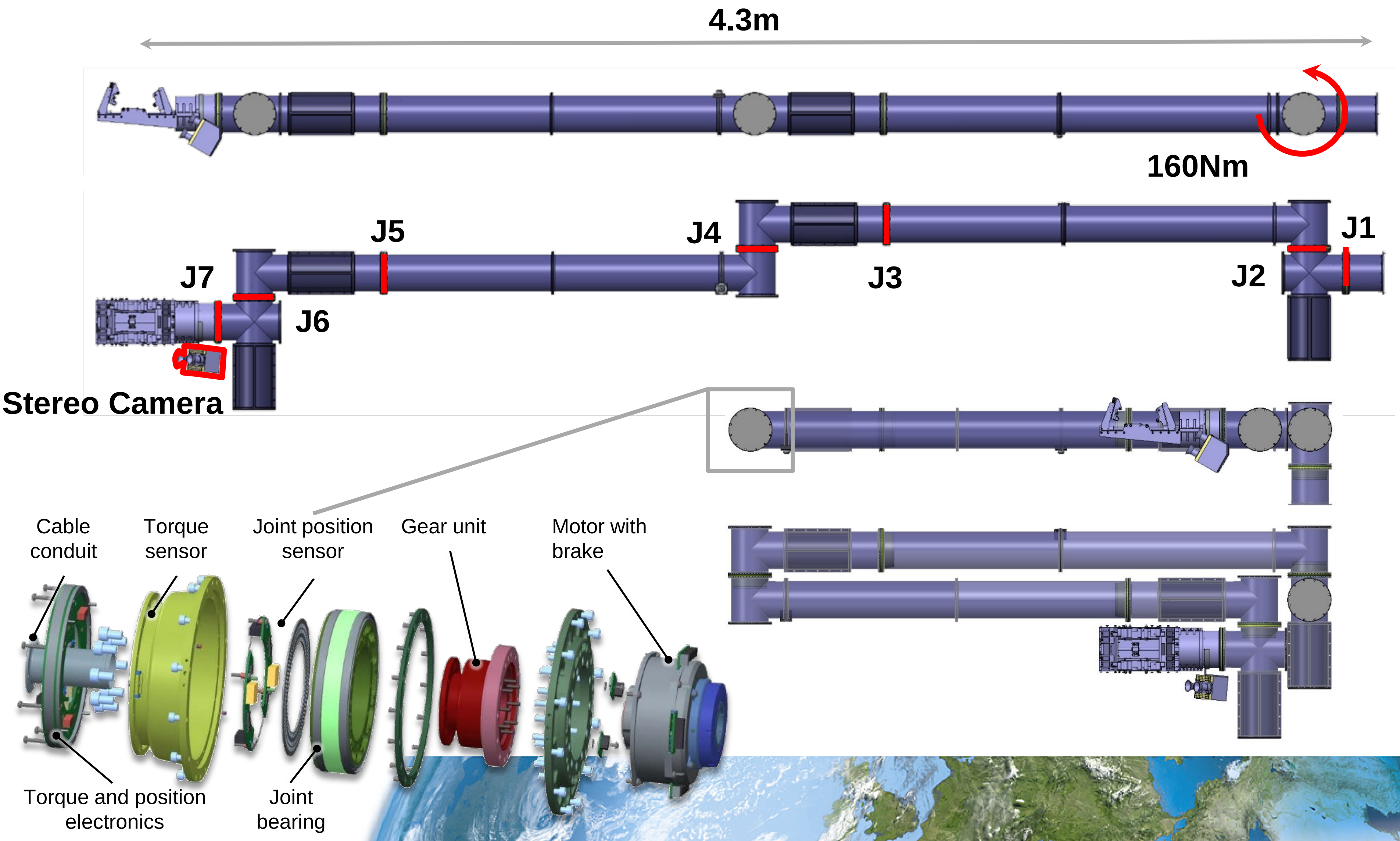
Source: Youtube (edited)

Challenges of Robotic Spacecraft for OOS and ADR

- In general: complex free-floating contact operations in **close-proximity**
- **Unintended contact** can lead to unsuccessful capture: upon contact capture needs to be assured
- **uncertain environment** (target not prepared for servicing)
- Free-floating dynamics: manipulator has **direct physical feedback** on its floating base: GNC stabilization

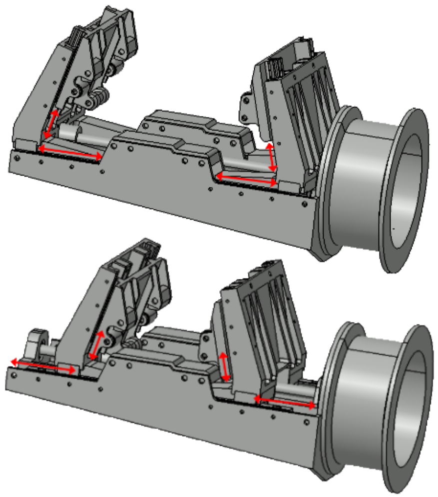
e.deorbit - Phase B1 Baseline Capture Concept

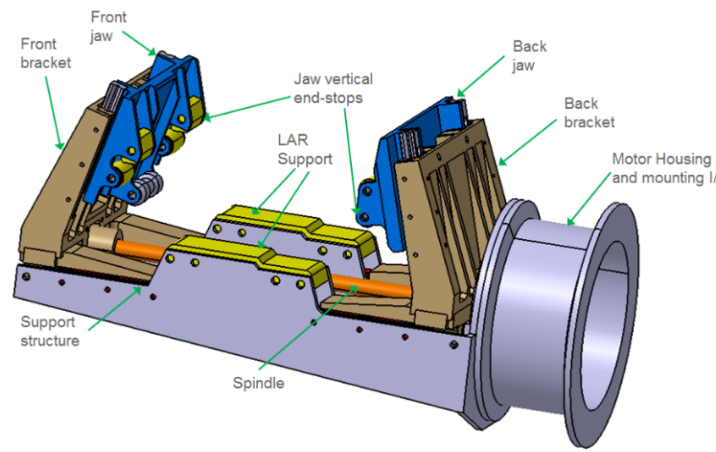
Arm Technology

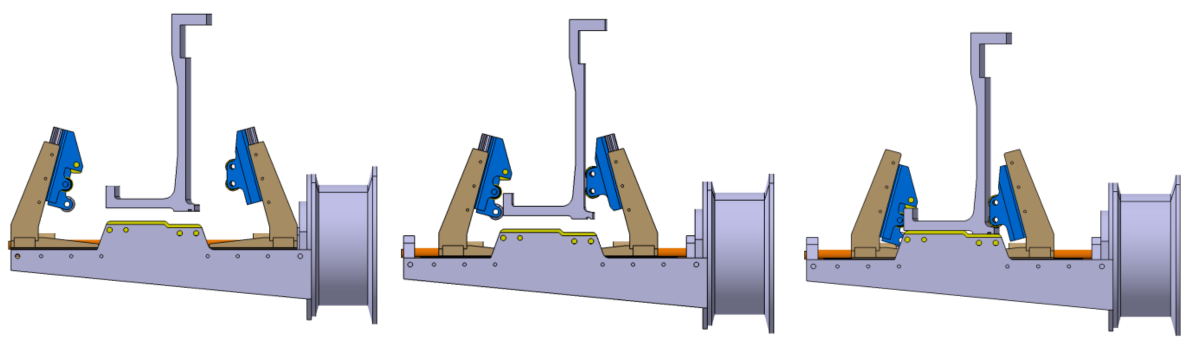


Gripper (OHB)

- Two spindle-driven brackets
- Movable, spring-driven, inclined grip jaws on each side
- Contact points only on dedicated rolls
- Inclined, movable brackets: horizontal force increases vertical force
- Full form closure with Ariane launch adapter ring





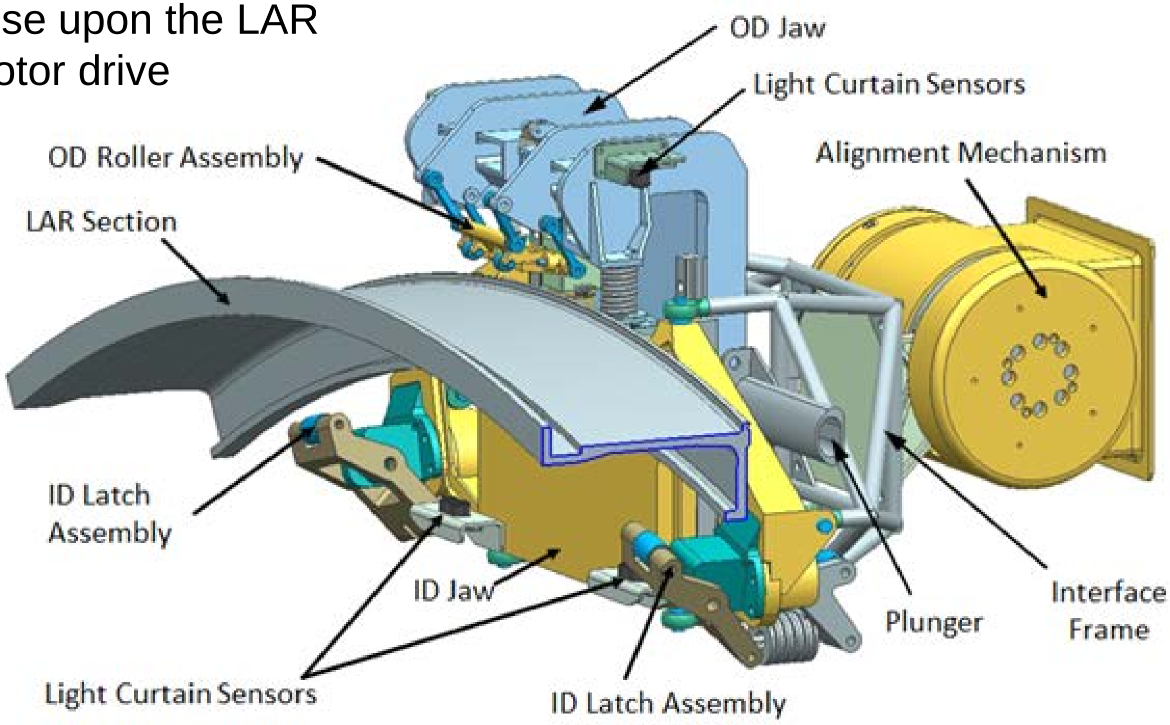


Gripper (OHB): Grasping Process

Clamp (MDA)

- Achieve stiff force closure between spacecraft
- Alignment mechanism for adjusting de-orbit thrust

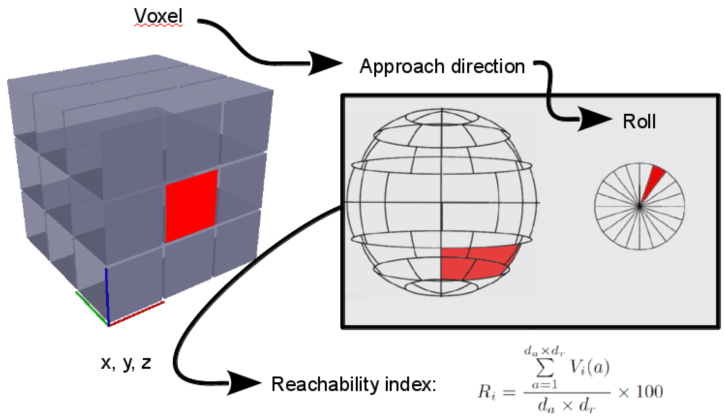
- Light curtain to determine LAR in capture envelope
- Spring-loaded latch close upon the LAR
- Jaws fully closed by motor drive

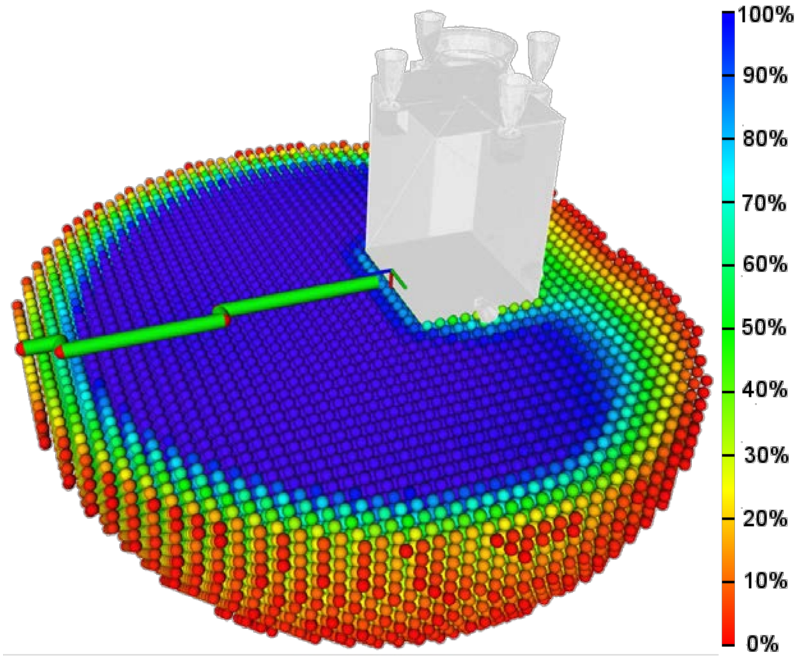


Workspace Analysis

- Capability map – quantification of possible discretized directions in subspace

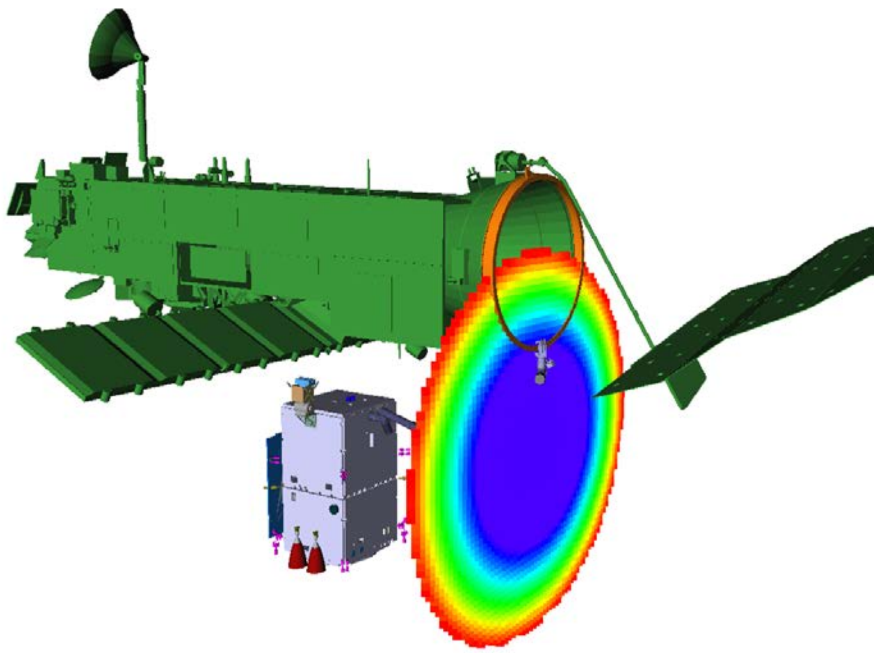
- Eucleadian space is discretized into voxels and orientations (RPY)
- Color intensity identifies feasible end-effector poses
- Direct insight into workspace of the robot
- Used for validation of kinematics
- Accounts for self-collision

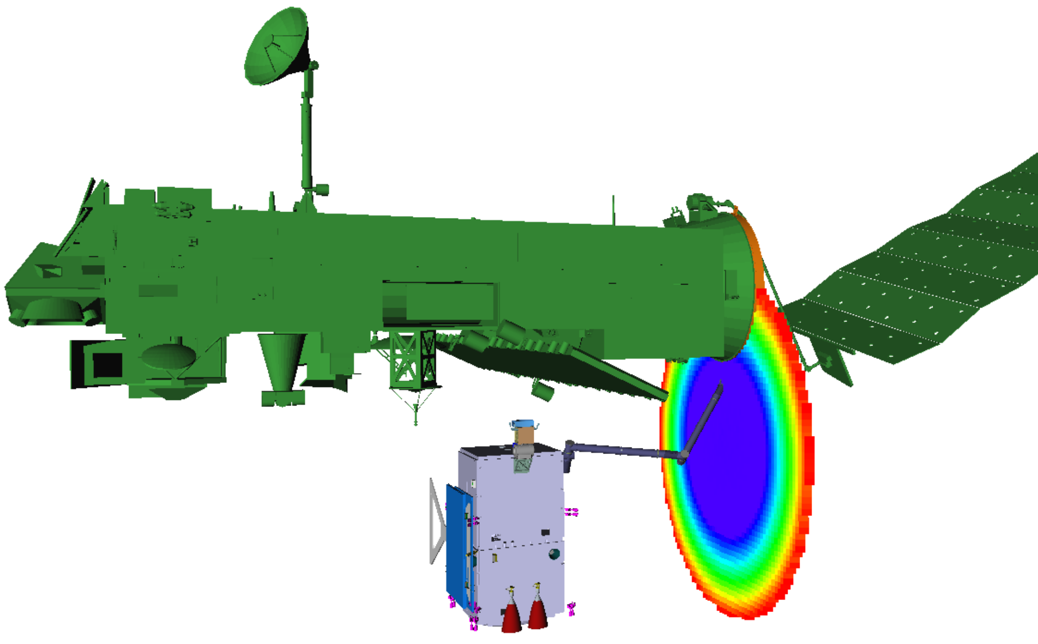


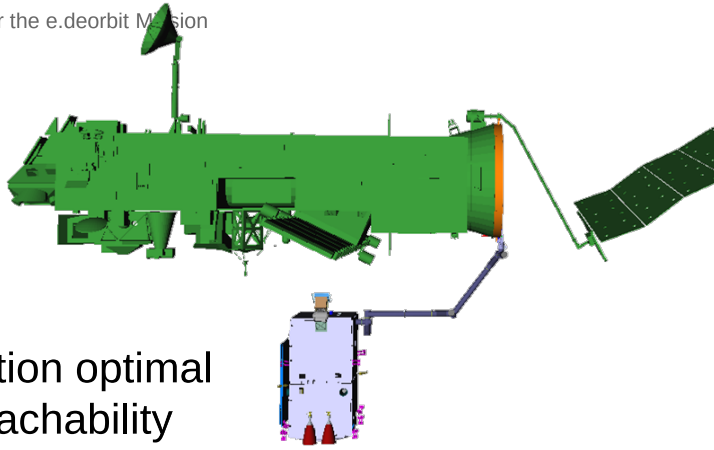


Workspace Analysis: Capture

- Capture configuration at arm delivery point (satellites CoG's are aligned)
- Good reachability robustness in case of unexpected drift

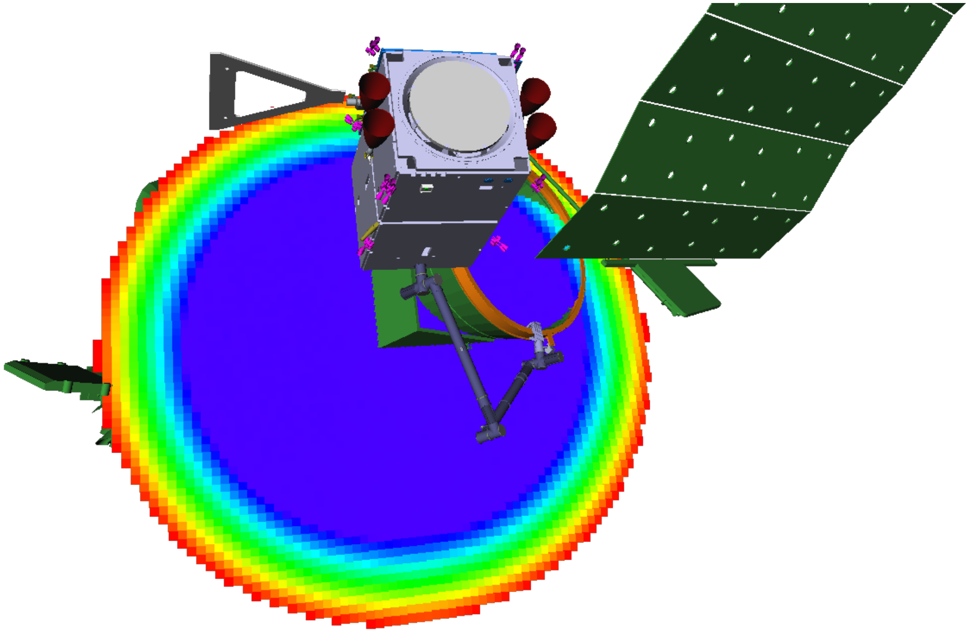


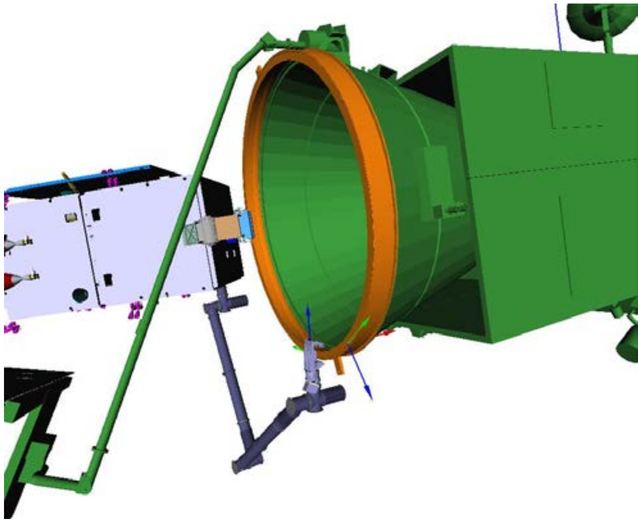




Workspace Analysis: Clamping

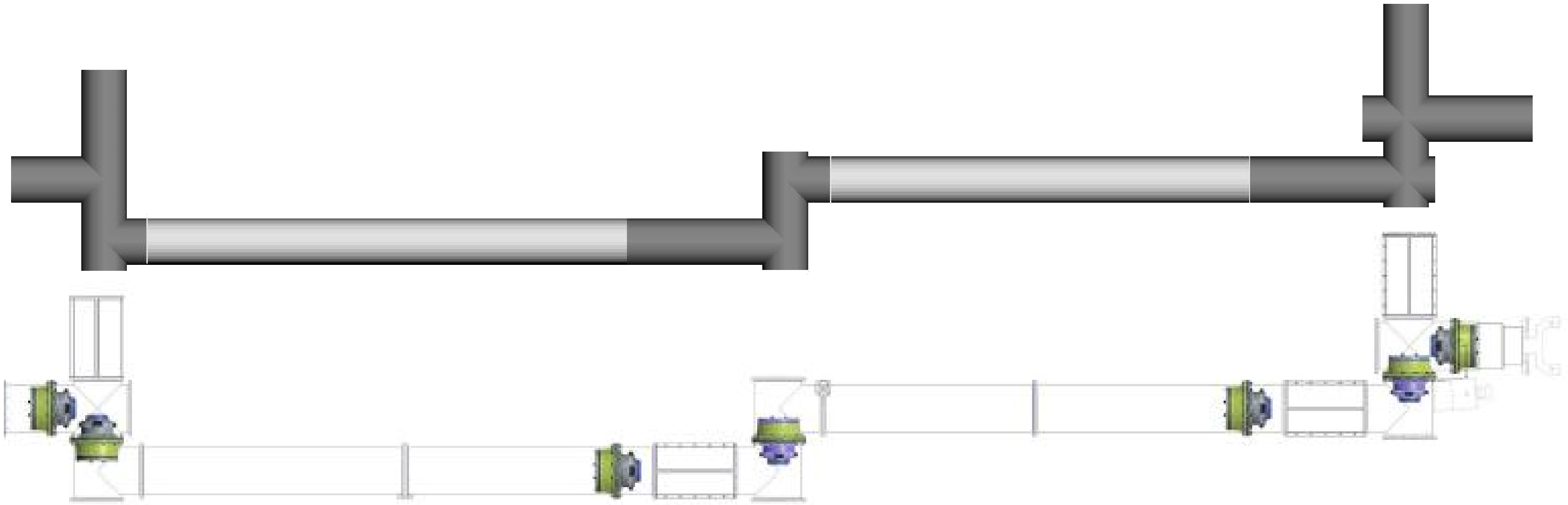
- Clamping position analysis: 90deg clamp configuration optimal considering possible grasp point, safe trajectory, reachability
- Some distance required between grasp point and clamp point due to reachability and to allow better elbow placement (pointing away from potential collisions)





Arm Flexibility

- Multi-body simulation in Simulink/SpaceDyn and SIMPACK with free-floating target, chaser and attached manipulator
- Dynamic modes and frequencies of manipulator assembly and stack
- Impacts of arm structural flexibility on accuracy and control approach

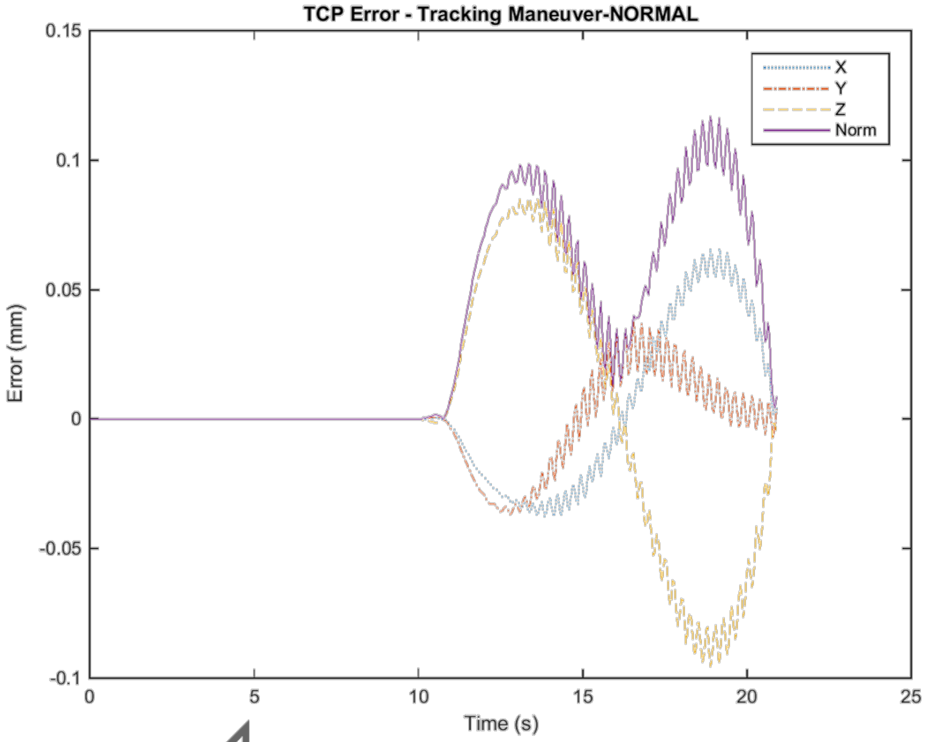


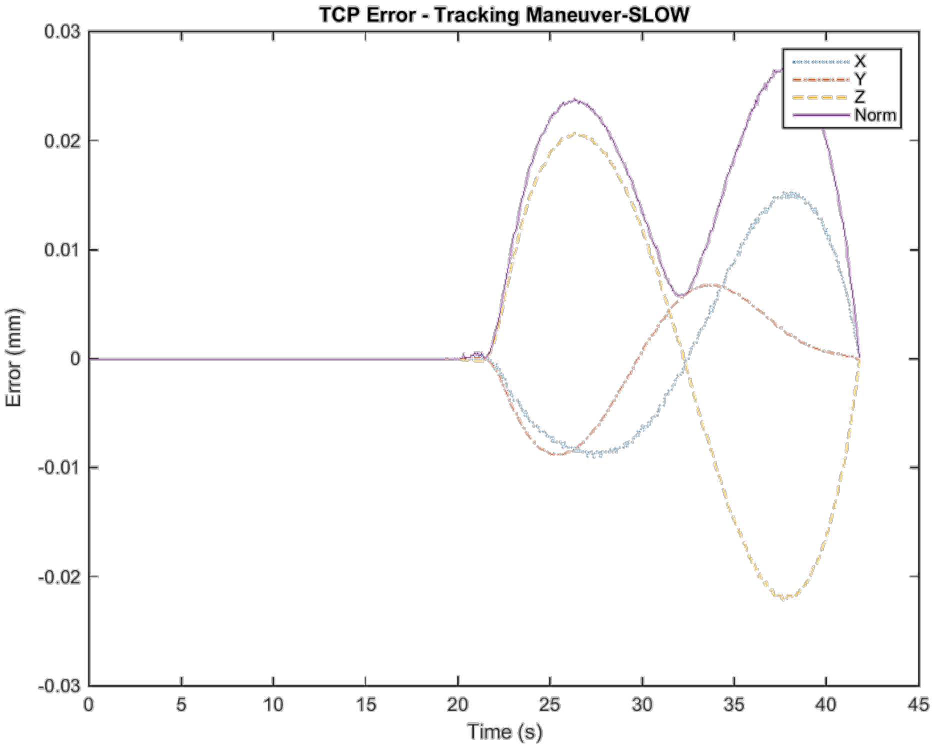
Arm Flexibility: Grasped 1st Mode

Arm Flexibility: Docking 1st Mode

Arm Flexibility: Induced TCP Error for Capture

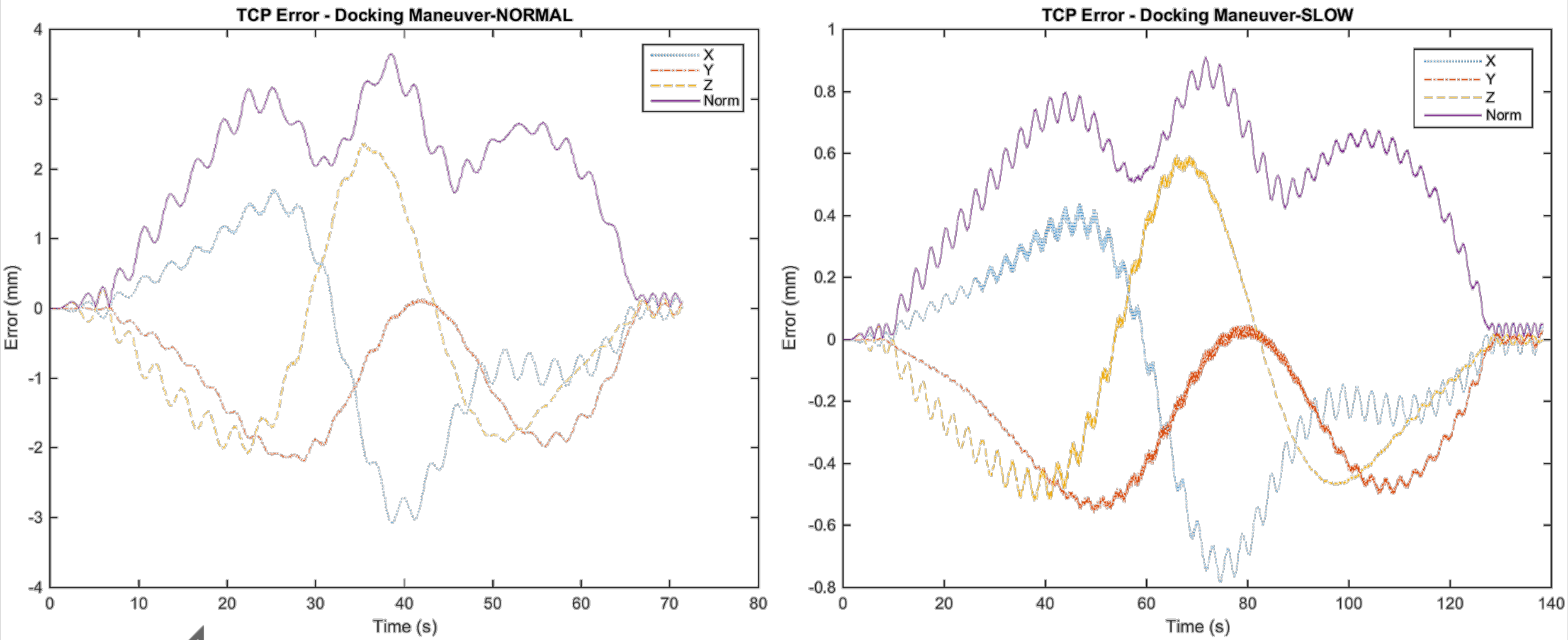
- Arm capture maneuver, speed normal (up to 6deg/s, 10s maneuver time) and slow (up to 3 deg/s, 20s maneuver time)
- Resulting error: 0.1mm (normal) and 0,02mm (slow)





Arm Flexibility: Induced TCP Error for Docking

- Docking maneuver, speed normal (up to 5deg/s, 50s maneuver time) and slow (up to 2.5 deg/s, 100s maneuver time)
- Resulting error: 3.5mm (normal) and 1mm (slow)



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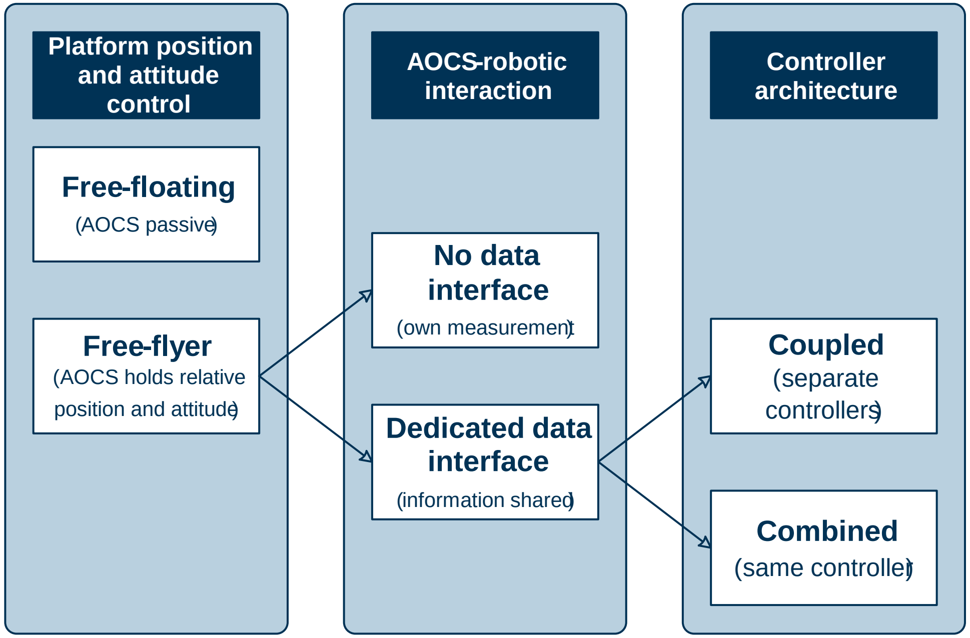
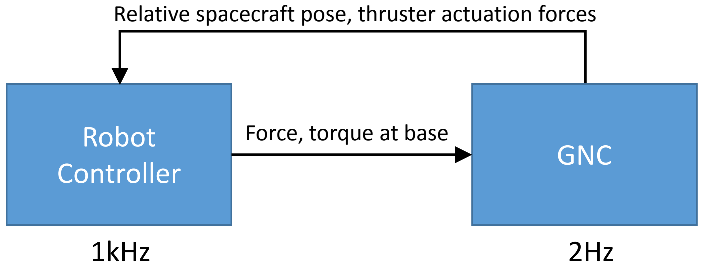
Controller Interaction: Free-Floating vs. Free-Flyer

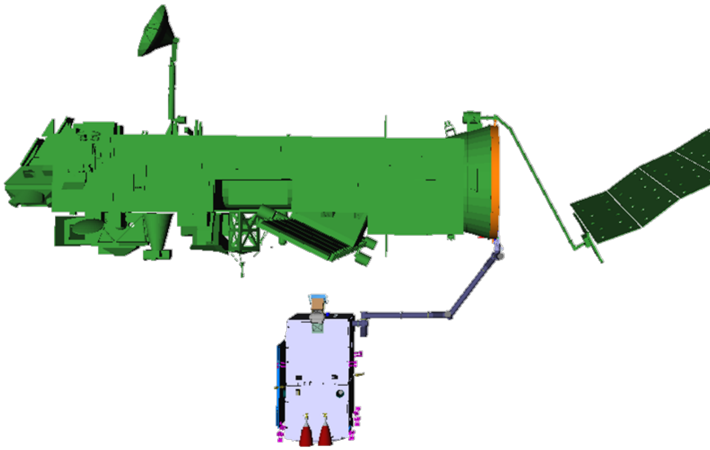
- Space robot: Free-flyer: two controllers (robot control and GNC) simultaneously act on the same system and could challenge each other
- Open loop (no direct information shared) vs. Closed loop (direct information shared)
- Coupled (two distinct controllers) vs. Combined (one mighty controller) approach
- Potential problems: different sampling rate (1kHz vs. 1-10Hz) and bandwidths, delays and stability

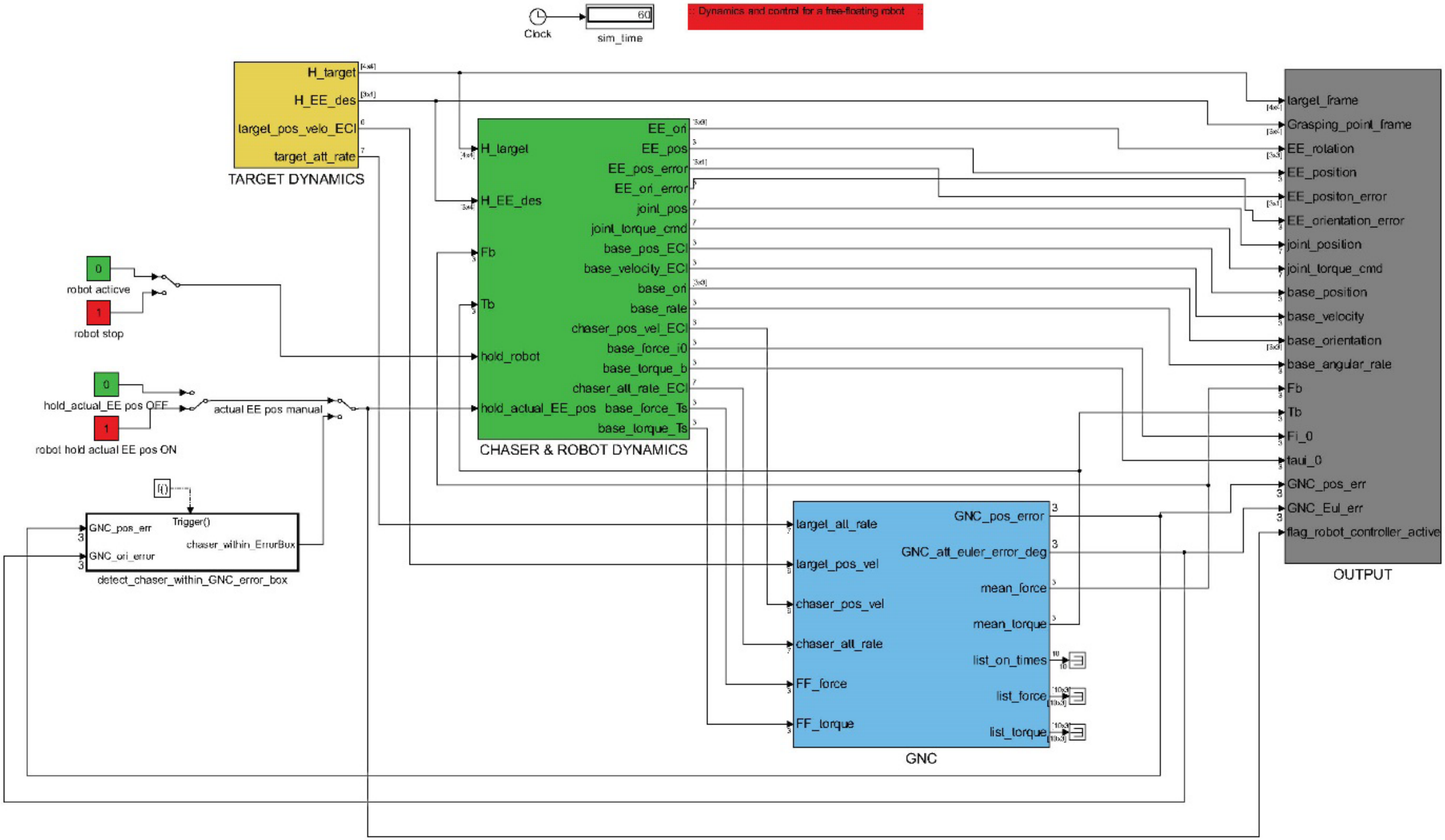


Controller Interaction

- From GNC to robotic controller
  - Thruster actuation forces
  - Satellites relative pose and derivative (from relative navigation sensors)
  - Inertial pose and derivative (w.r.t. orbit position, for computing centrifugal forces)
- From robotic controller to GNC
  - Forces and torques acting on base
  - Robot CoM w.r.t. base (for global CoM and inertia update)

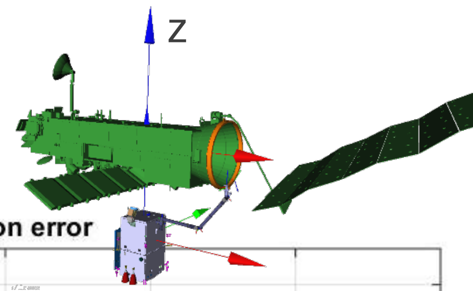


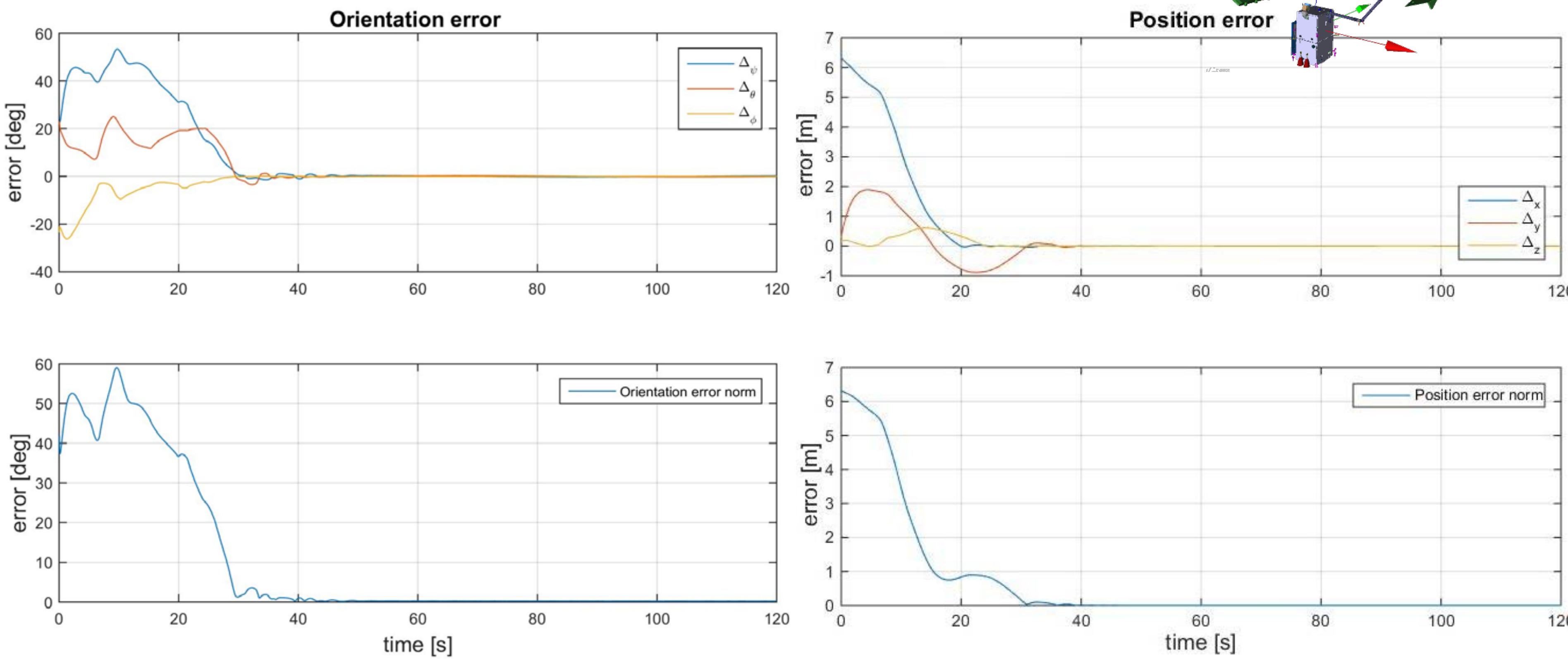




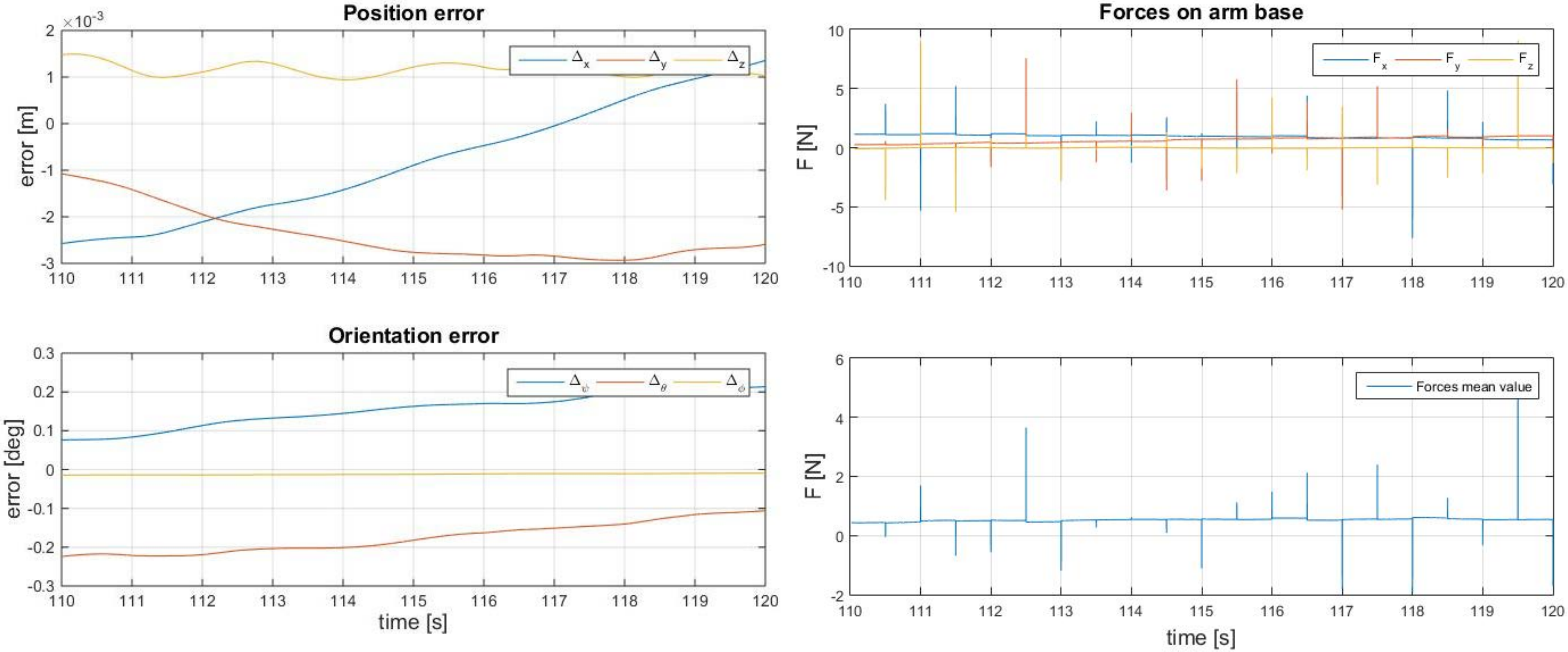
Clock
60
sim_time
:: Dynamics and control for a free-floating robot ::
H_target
H_EE_des
target_pos_velo_ECI
target_att_rate
TARGET DYNAMICS
H_target
H_EE_des
Fb
Tb
hold_robot
hold_actual_EE_pos
EE_ori
EE_pos
EE_pos_error
EE_ori_error
joint_pos
joint_torque_cmd
base_pos_ECI
base_velocity_ECI
base_ori
base_rate
chaser_pos_vel_ECI
base_force_i0
base_torque_b
chaser_att_rate_ECI
base_force_Ts
base_torque_Ts
CHASER & ROBOT DYNAMICS
robot acticve
robot stop
hold_actual_EE pos OFF
actual EE pos manual
robot hold actual EE pos ON
Trigger()
GNC_pos_err
GNC_ori_error
chaser_within_ErrorBox
detect_chaser_within_GNC_error_box
target_att_rate
target_pos_vel
chaser_pos_vel
chaser_att_rate
FF_force
FF_torque
GNC_pos_error
GNC_att_euler_error_deg
mean_force
mean_torque
list_on_times
list_force
list_torque
GNC
target_frame
Grasping_point_frame
EE_rotation
EE_position
EE_positon_error
EE_orientation_error
joint_position
joint_torque_cmd
base_position
base_velocity
base_orientation
base_angular_rate
Fb
Tb
Fi_0
taui_0
GNC_pos_err
GNC_Eul_err
flag_robot_controller_active
OUTPUT

Controller Results – Z-Rot, TCP

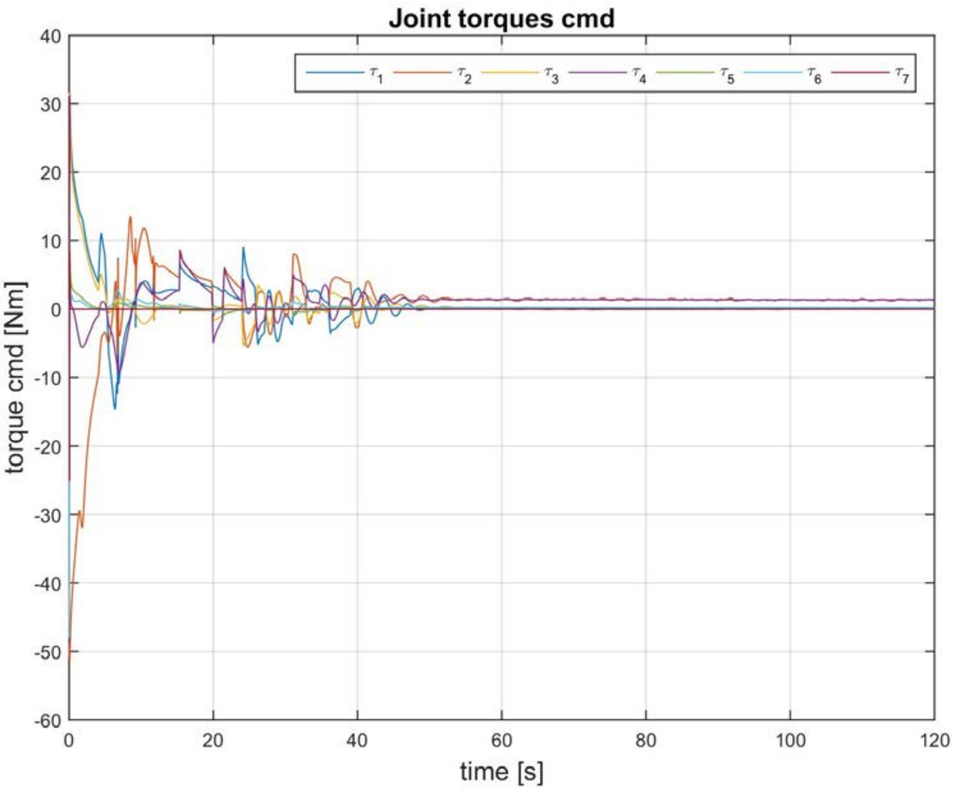


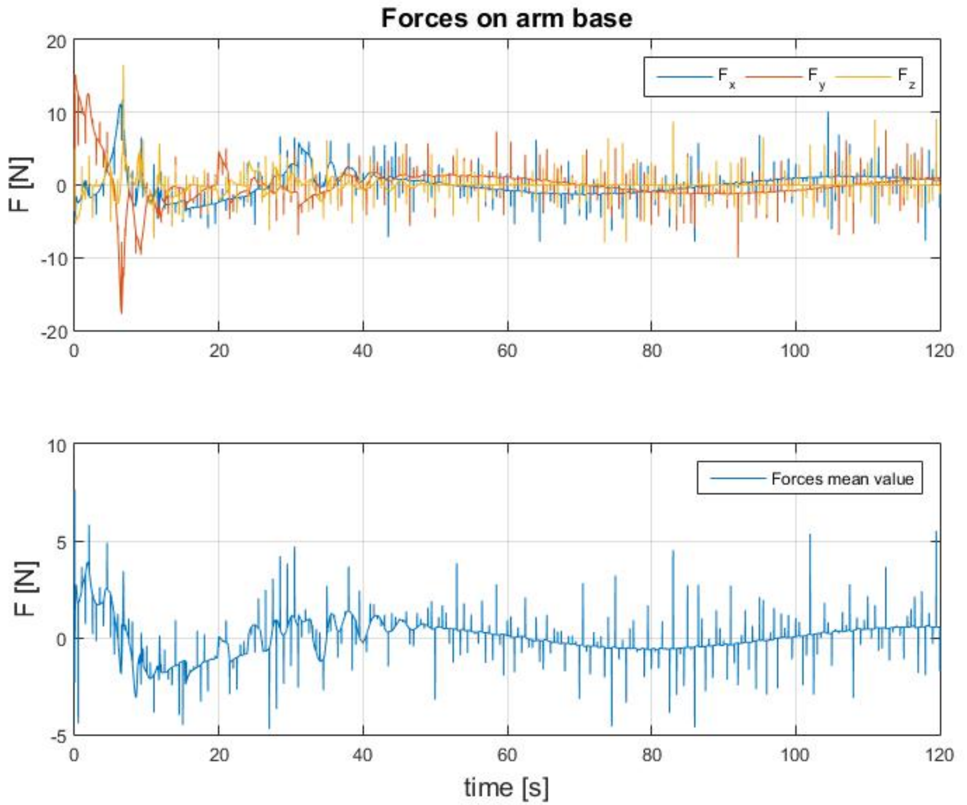


Controller Results – Z-Rot, TCP Zoom-In



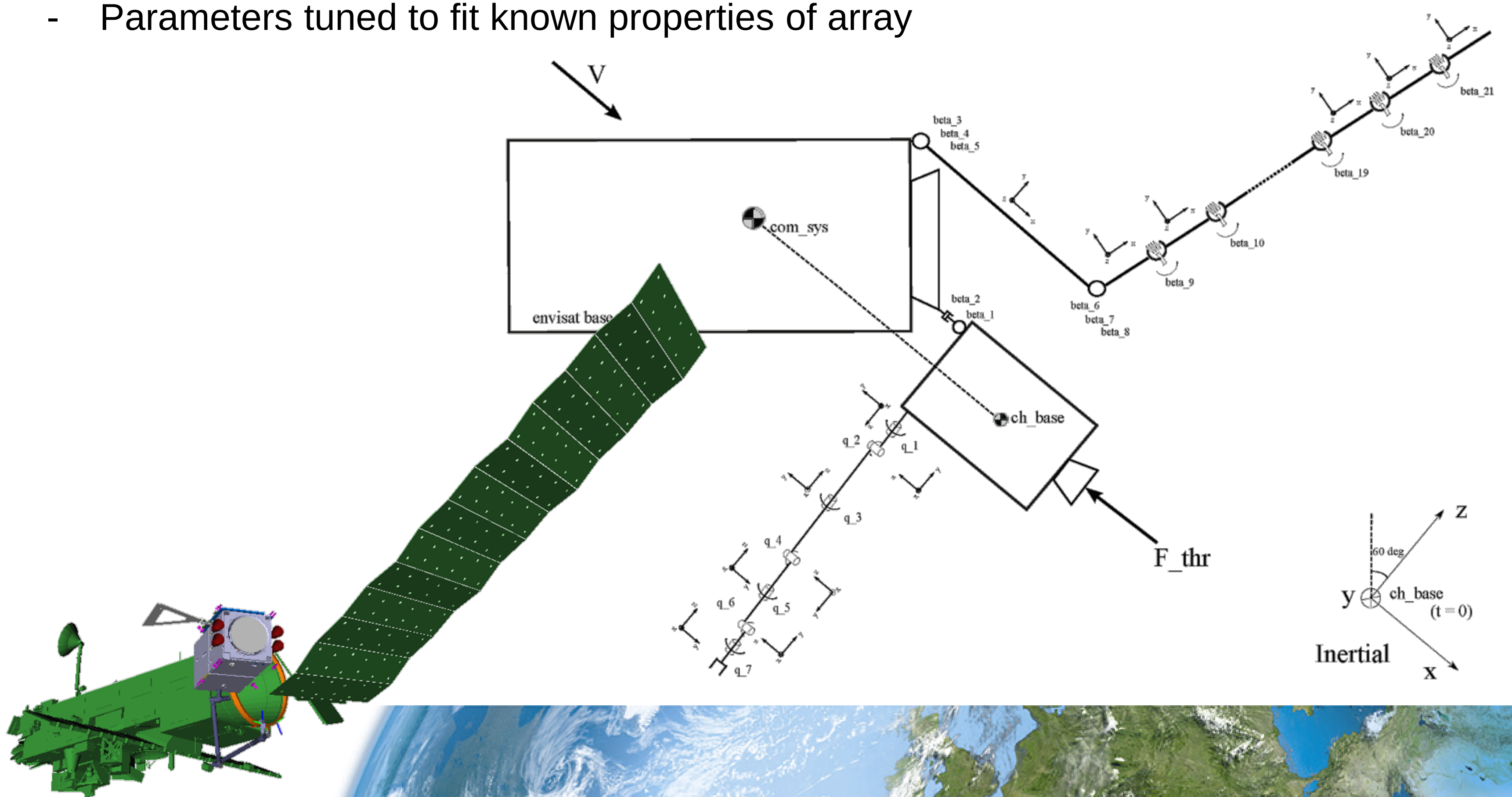
Controller Results – Z-Rot, Arm





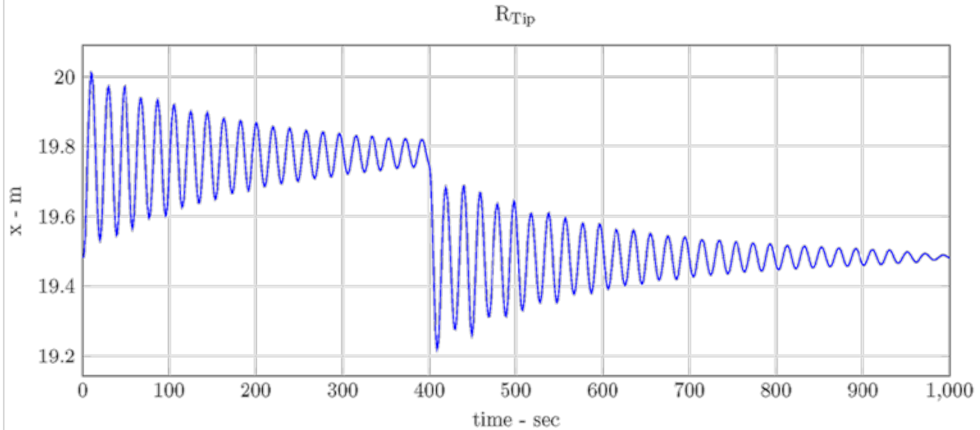
De-Orbit: Solar Array Behavior

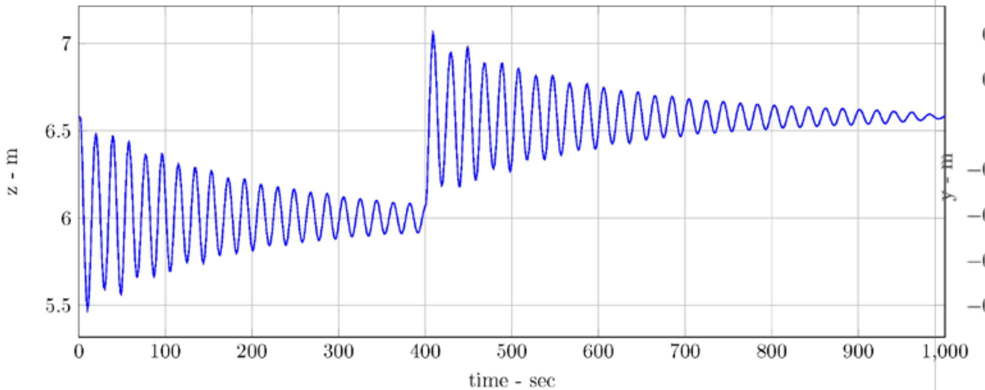
- Multi-body dynamics model in Matlab/Simulink environment using the SpaceDyn library and SIMPACK for verification
- Solar array modelled as rigid panel segments conected by flexible joints
- Parameters tuned to fit known properties of array

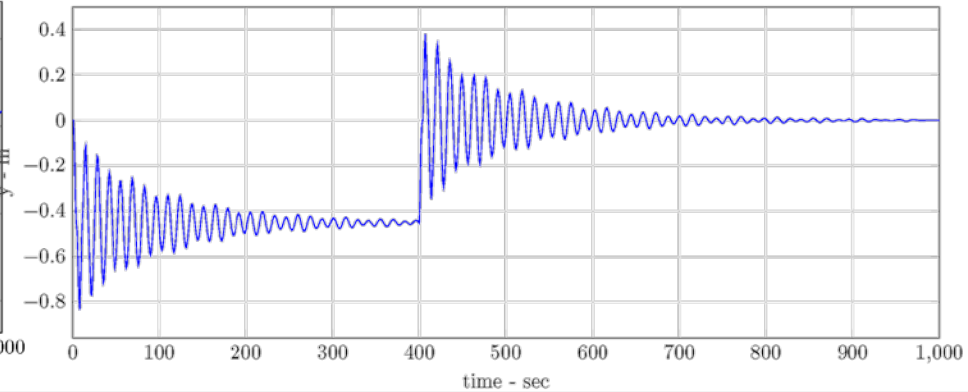


Solar Array Dynamics – Solar Array Tip (90deg Clamp)

- Solar array tip position relative to platform COG for 90deg clamping position
- Less movement compared with 180deg clamp

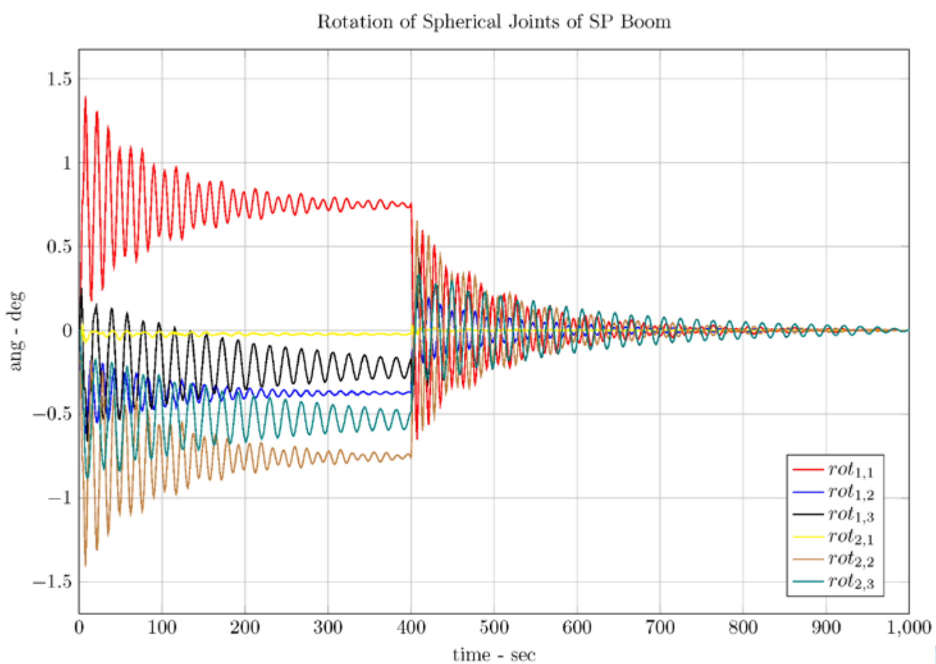


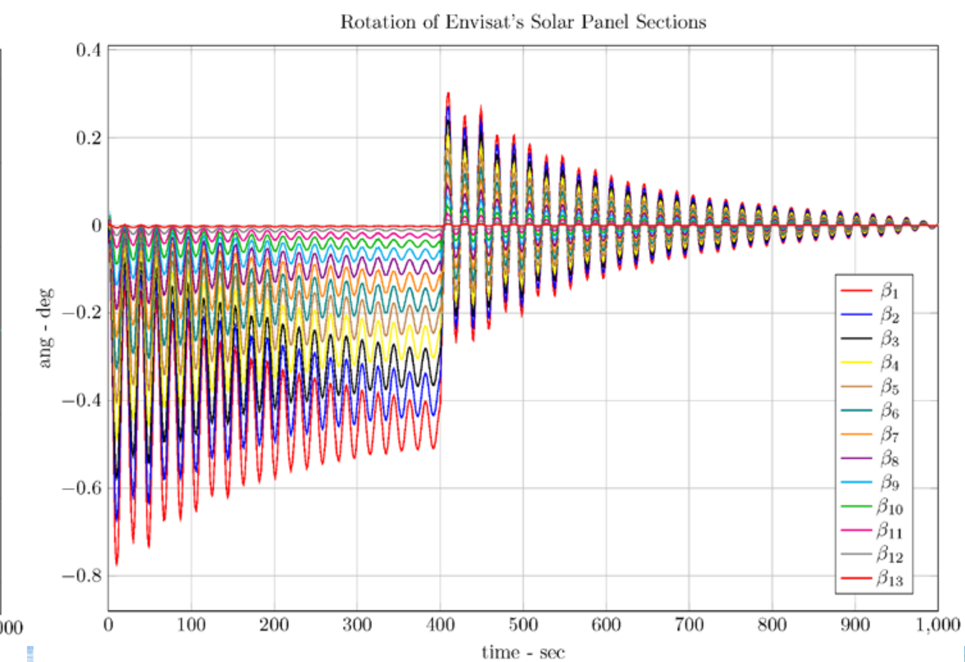




Solar Array Dynamics – Boom and Array Joints (90deg Clamp)

- Rotation angle of boom (left) and solar array (right) joints for 90deg clamping position
- Less rotation compared with 180deg clamp (1.5deg vs. 0.8deg)

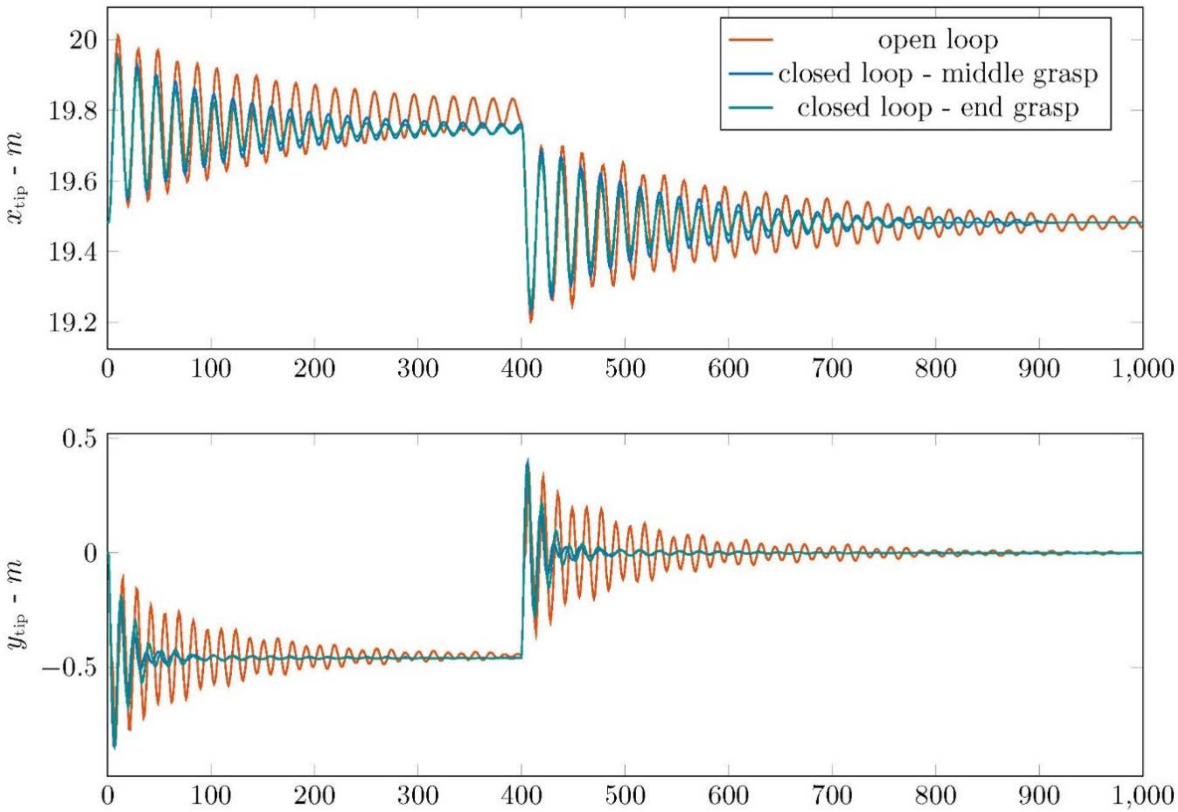




e.deorbit - Analysis of De-Orbit Maneuver for 180deg clamping position

Solar Array Dynamics – Solar Array Tip (Damped, 90deg Clamp)

- Solar array tip position relative to platform COG for 90deg clamping position
- Robot arm is grasping at the solar array boom (middle and end) and passively damping its motion (600Nm/rad)
- Better timely behavior, absolute peak is not damped significantly
- **Can improve de-orbit pointing accuracy but does not decrease chance of breaking**



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Thank you!

Introduction – Space Robotics

- Future and already deployed robot applications in space:
  - **In-space robotic assembly** (ISRA): Shuttle Arms
  - **EVA assistance:** Robonaut, DLR‘s Justin, small satellites for inspection
  - **Robotic exploration**: MER‘s
  - **On-orbit servicing** (OOS) for prolonging lifetime of operational satellites, repair & refuel (RRM), extend or upgrade functionality (Hubble)
    - 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

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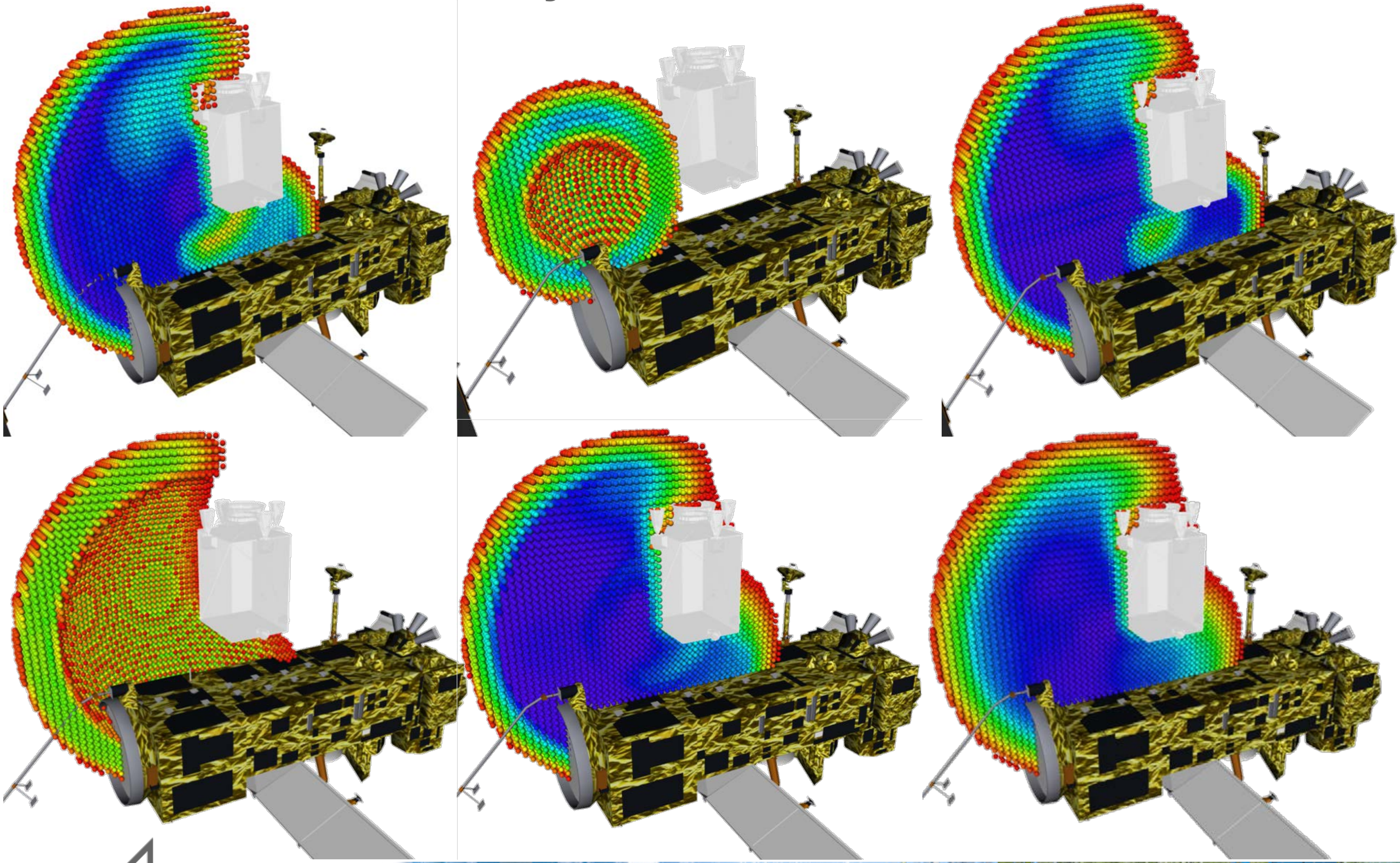
Workspace Analysis – Joint Failure



Mechatronic Arm Positioning Accuracy

- Following aspects were included in the accuracy analysis:
- Motor-side joint position sensor (motor commutation sensor) resolution, relative accuracy, and absolute accuracy
- Harmonic Drive gearbox friction, stiffness, and backlash
- Output bearing friction and stiffness
- Harness disturbance torque
- Structural manufacturing inaccuracies and thermal effects (worst-case assumptions)
- Joint deadzone measurements
- Different relevant arm configurations

Parameter	Position control	Impedance Control
Absolute	14mm, 1deg	29mm, 7deg
Relative	**0.5mm, 0.02deg**	6.3mm

Arm Worst-Case Error Budget

- Overall positioning error (including mechatronics, flexibility and tracking accuracy) is lower that required positioning accuracy by gripper

Parameter	Position	Orientation
Gripper Req.	15mm	5deg
Max. Error	**9mm**	**0,3deg**

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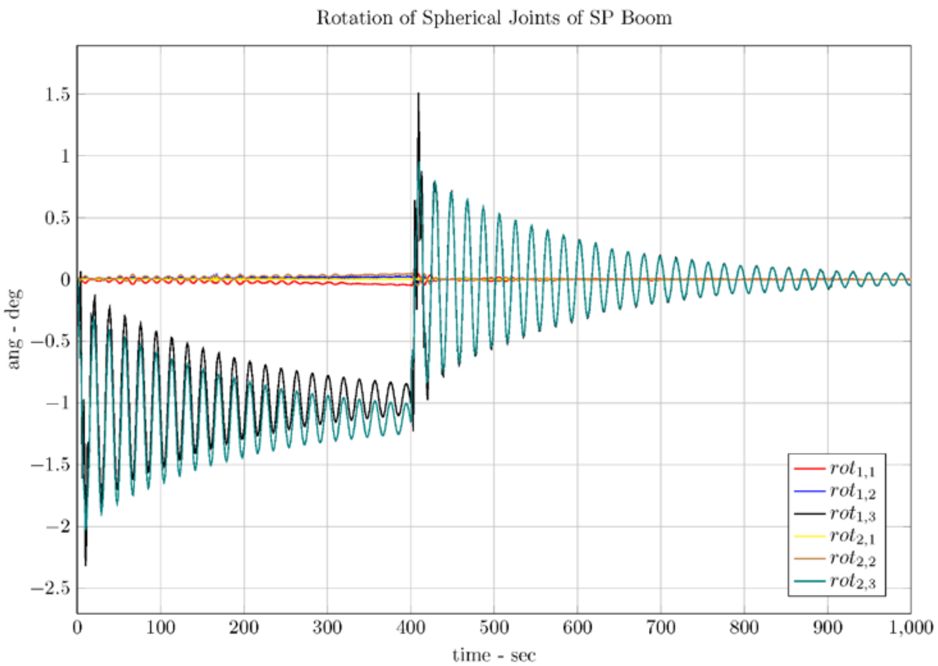
Solar Array Dynamics – Will it break?

- Carbon strength $\sigma\_(flex, long)$>1000MPa
- D=0.06m

$$\sigma_{max} = \frac{k\alpha_{max}D}{2I} \qquad I = \frac{\pi(D^4 - d^4)}{64}$$

Inner diameter d $[m]$	σ_{max} $[MPa]$
0.01	1.81
0.02	1.81
0.03	1.83
0.04	1.93
0.05	2.2



- Suprisingly - not a problem!