MOTION CONTROLLER FOR THE TITAN ROBOTIC MANIPULATOR DEDICATED FOR ON-ORBIT SERVICING OPERATIONS

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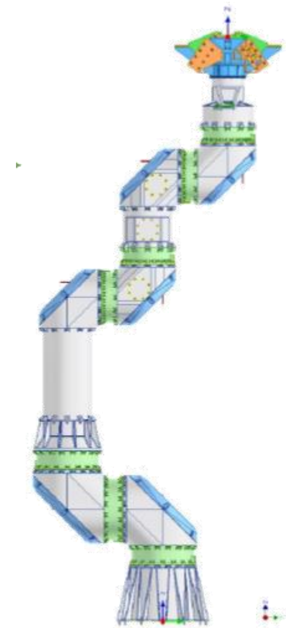
Outline

- TITAN robotic arm
- Motion Controller
- Stability analysis
- Motion Controller validation
- Conclusions

TITAN Robotic Arm

"Robotic Arm Development for On-Orbit Servicing Operations"

- PIAP Space (leader of the consotrium)
- CBK PAN
- Spacive



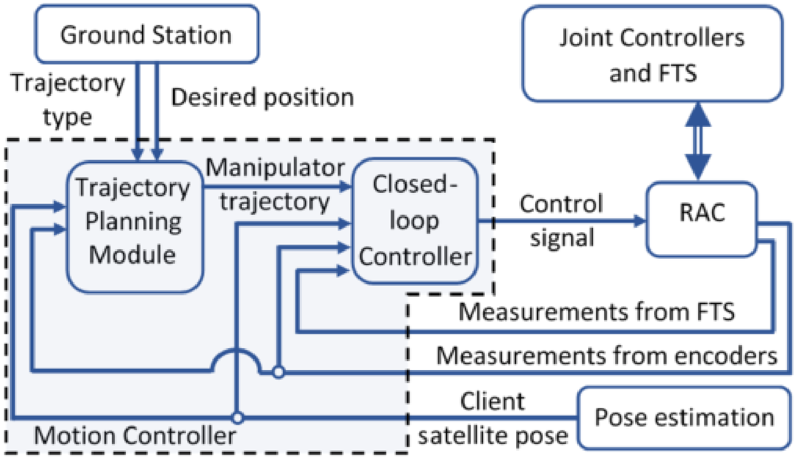
- Application in OOS and ADR missions.
- 7 degrees of freedom.
- Equipped with a gripper for grasping LAR.
- Visual pose estimation system.
- Force/Torque sensor.

DH parameters

Joint	θ_i [rad]	λ_i [m]	L_i [m]	α_i [rad]
1	θ_1	0.37	0	$\pi/2$
2	θ_2	0.314	0	$-\pi/2$
3	$\theta_3+\pi$	0.7	0	$\pi/2$
4	θ_4	0.264	0	$-\pi/2$
5	θ_5	0.4	0	$\pi/2$
6	θ_6	0.264	0	$-\pi/2$
7	θ_7	0.5435	0	0

Motion Controller

- The Motion Controller is responsible for the control of the robotic arm and allows it to perform on-orbit capture and servicing tasks.
- Trajectory Planning Module is used for transmitting the desired (commanded) trajectory.
- Closed-loop controller is responsible for real-time control of the manipulator.
- The Motion Controller generates the desired joint velocity that is sent to Joint Controllers.



Motion Controller – modes

Control modes:

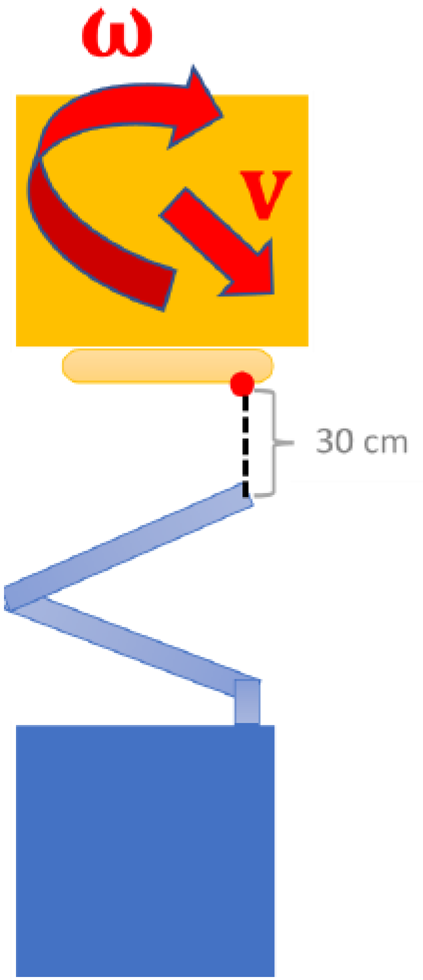
- Braked/Standby mode.
- Passive mode.
- Joint Position control mode.
- Joint Velocity control mode.
- Cartesian Control mode
- Active 6 DoF Force/Torque Control mode (the compliant control).
- Direct Drive mode (open loop control).
- Joint Torque control mode.

Modes of operation:

- Single Control Mode Execution.
- Interactive Autonomy.
- Full Autonomy (realized on the mission level).

Nominal scenario

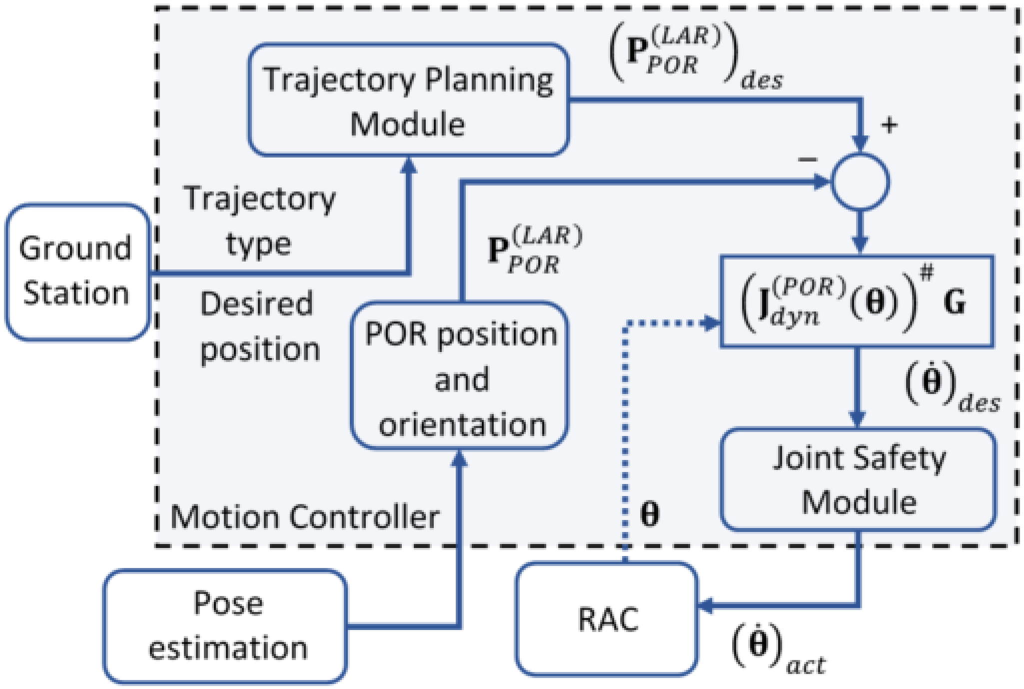
1. Manipulator deployed using Joint Position mode.
2. Synchronous flight of the chaser and the client.
3. Point of Resolution is 30cm away from the LAR.
4. Chaser enters free drift.
5. Manipulator is controlled using Cartesian mode.
6. In close proximity to the LAR, the control is switched to compliant control.
7. During grasping, the manipulator is controlled in compliant control mode or Passive mode.
8. After grasping the manipulator is stopped and prepared for servicing operations.



Cartesian control

$$(\dot{\boldsymbol{\theta}})_{des} = \left(\mathbf{J}_{dyn}^{(POR)}(\boldsymbol{\theta})\right)^{\#} \mathbf{G} \begin{bmatrix} \left(\mathbf{p}_{POR}^{(LAR)}\right)_{des} - \mathbf{p}_{POR}^{(LAR)} \\ \left(\boldsymbol{\epsilon}_{POR}^{(LAR)}\right)_{des} - \boldsymbol{\epsilon}_{POR}^{(LAR)} \end{bmatrix}$$

$$\mathbf{G} = \begin{bmatrix} \mathbf{Rot}_{LAR}^{POR}\mathbf{K}_{lin} & \mathbf{0}_{3\times4} \\ \mathbf{0}_{3\times3} & \mathbf{Rot}_{LAR}^{POR}\mathbf{T}_{qtn}^{\#}\mathbf{K}_{qtn} \end{bmatrix}$$



Motion Controller – additional features

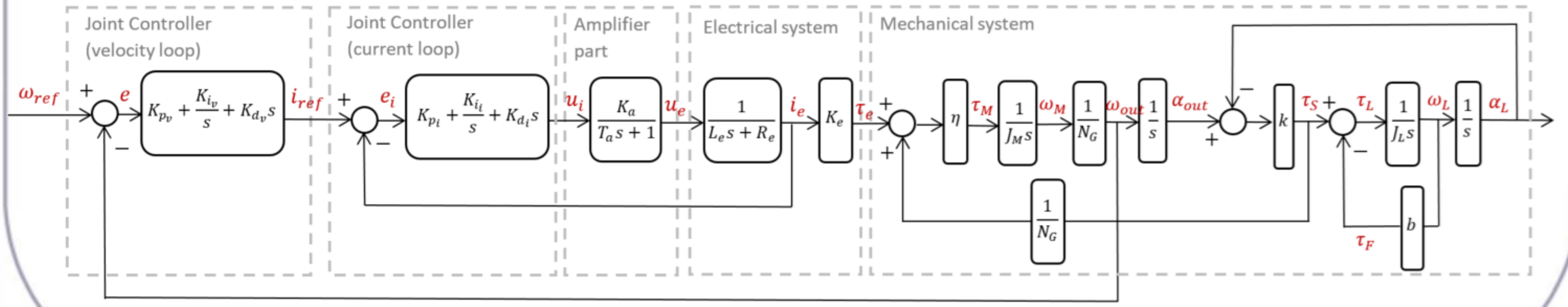
- Joint Safety Module → real-time check if the desired (commanded) set-point does not exceed the limitations.
- Null-space control → taking advantage of the manipulator's kinematic redundancy.
  - Arbitrary joint position tracking.
  - Singularity avoidance.
  - Self-collision avoidance.
- Error Handling → reaction to critical errors that may occur during manipulator's operations.

Stability analysis

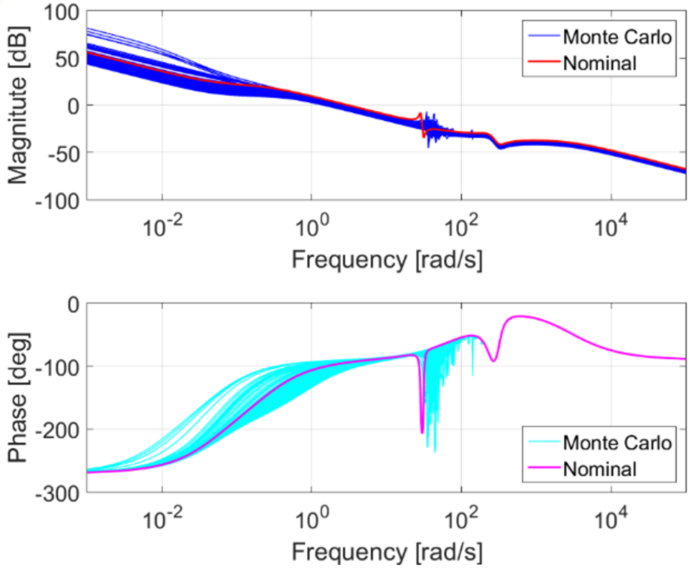
- Stability analysis with evaluation of gain and phase margins is a very important part of designing a control system.
- However, in the case of free-floating manipulators such analysis is nontrivial. As the system is nonholonomic and the model cannot be linearized directly, there is no straightforward way to evaluate stability margins for the full dynamic model.
- Therefore, stability analysis is divided into two parts.
  - Joint level stability – the linear servo-mechatronic system model is derived in order to analyse the joint control stability in terms of stability margins.
  - Manipulator level stability – the Monte Carlo method is used in order to perform multiple simulations that will conclude about the Motion Controller stability on the system level.

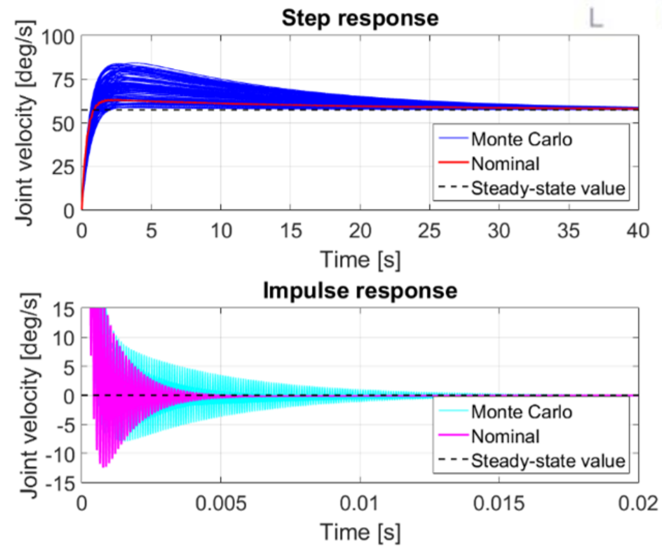
Joint level stability – model

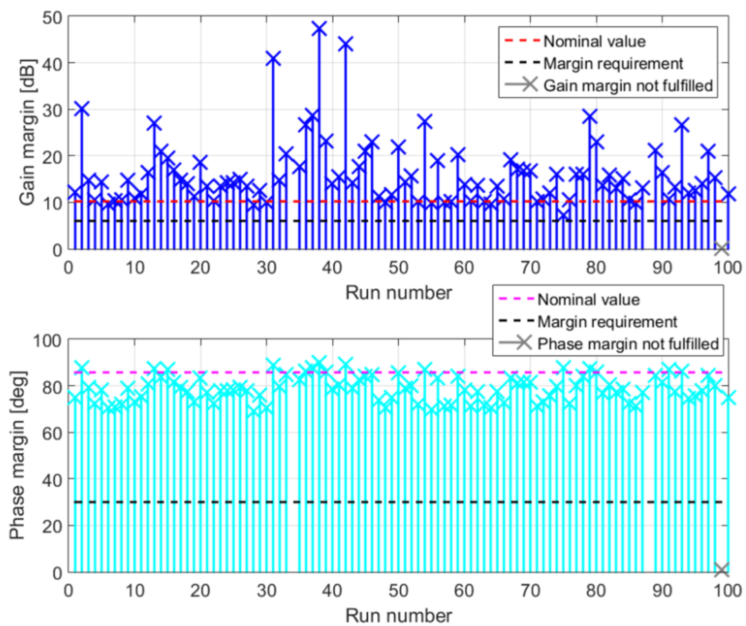
- The following aspects are considered in the joint model:
  - Gearbox efficiency.
  - Joint flexibility.
  - Joint viscous friction.
  - Electrical system dynamics.
- In addition to stability margins evaluation, the influence of the control saturation and external loads on the control system are analysed.



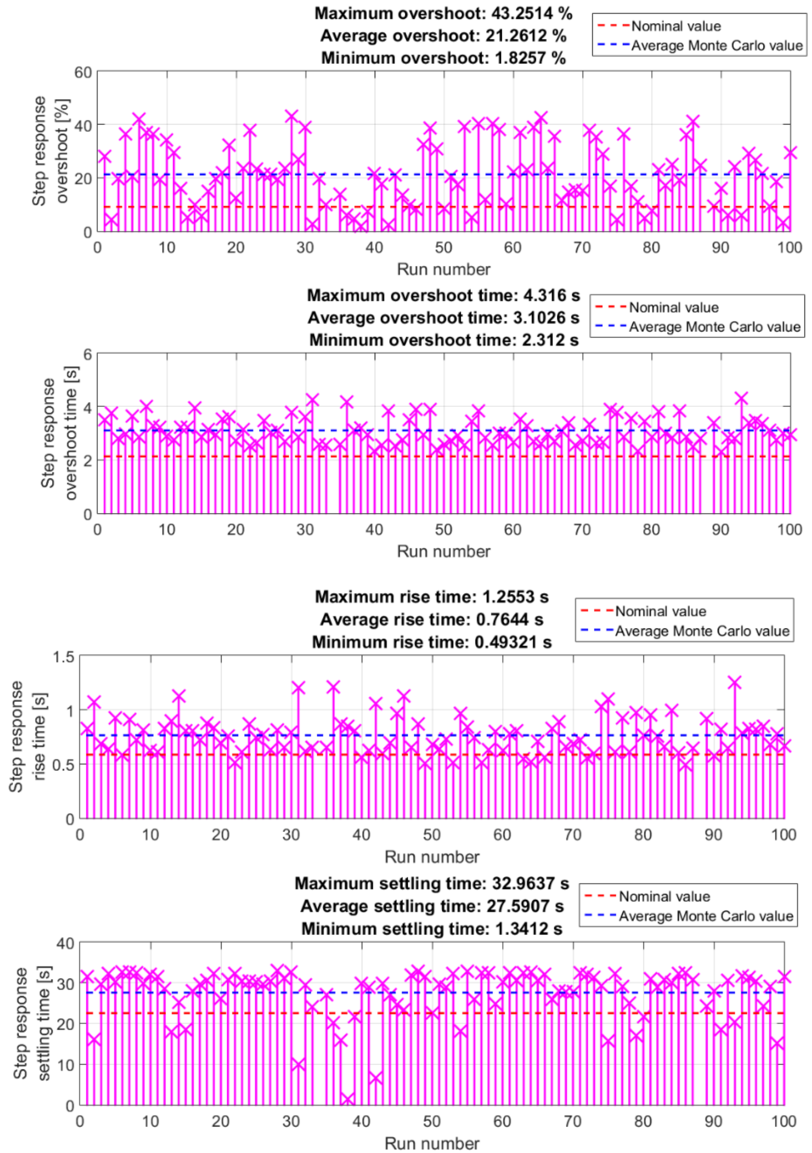
Joint level stability results







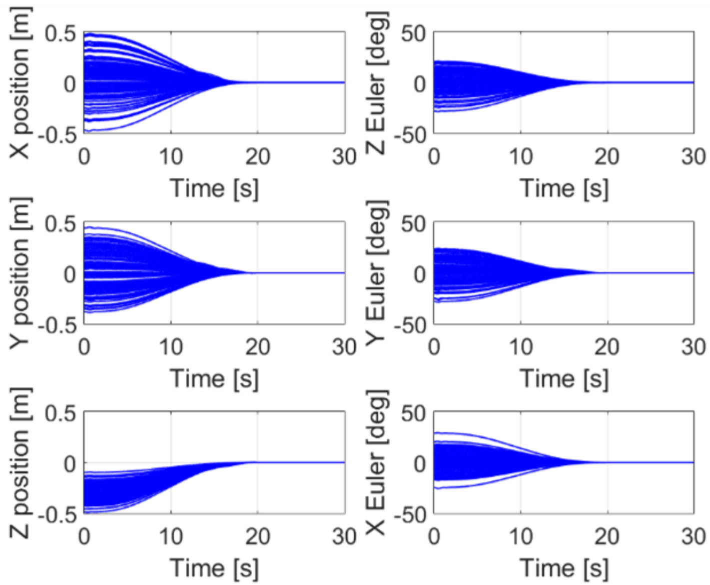
Joint level stability results

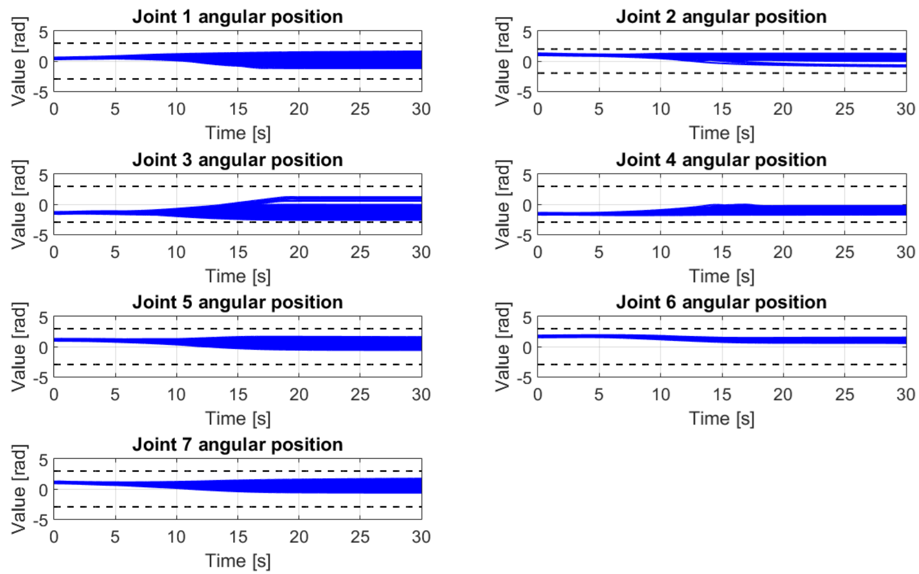


Manipulator level stability

- A variety of initial conditions are checked in order to perform multiple simulations of the full model of the satellite-manipulator system controlled by the Motion Controller.
- As an example, results for the Cartesian Control mode are presented.
- It is assumed that the desired point (the LAR) is non-moving as a reference case to the stability analysis. Otherwise there is no straightforward way to distinguish if the control system is unstable or simply too slow to reach the moving point.

Manipulator level stability results



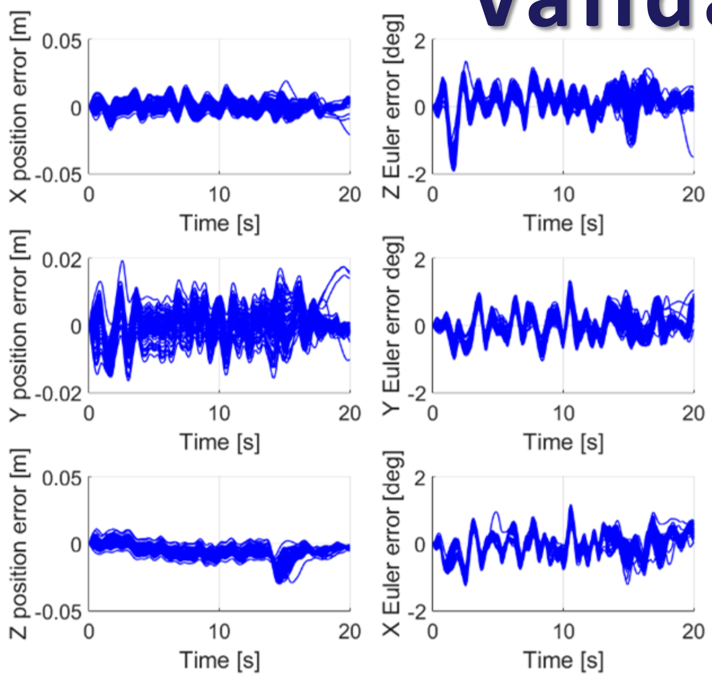


Parameter	POR X [m*s]	POR Y [m*s]	POR Z [m*s]	POR XYZ norm [m*s]	POR Euler Z [rad*s]	POR Euler Y [rad*s]	POR Euler X [rad*s]	POR Euler XYZ norm [rad*s]
Maximum integral quality $*10^{-4}$ s	50.651	55.570	39.686	3688.599	19.611	34.652	19.924	2218.864
Minimum integral quality $*10^{-4}$	0.004	0.013	0.811	644.647	0.009	0.009	0.016	194.159
Average integral quality $*10^{-4}$	3.939	4.178	8.501	1480.512	3.311	3.477	2.665	1107.858

Motion Controller validation

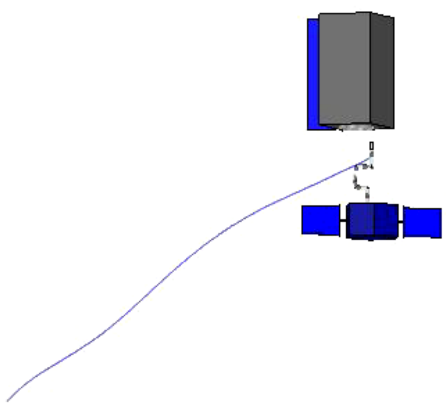
- The Motion Controller was validated in numerical simulations using the Monte Carlo method.
- The entire capture operation was considered, but the contact between the gripper and the LAR was neglected due to computational complexity.
- Additional simulations were performed with a high-fidelity contact model in order to analyse the behaviour of the control system during grasping procedure.
- In each Monte Carlo run, the initial velocity of the client satellite was randomly selected in order to verify multiple initial conditions.
- Random noise was included in the measurements from the visual pose estimation system.

Motion Controller validation – results



Maximal joint torques

Joint	Phase 1 [Nm]	Phase 2 [Nm]	Phase 3 [Nm]
1	3.6827	4.1044	0.4596
2	5.22	5.7367	0.8027
3	2.5886	2.2629	1.0053
4	2.5791	4.0471	1.2695
5	1.9802	4.9062	1.1782
6	0.7371	4.9529	1.2912
7	0.3276	2.0292	0.6462



Maximal joint velocities

Joint	Phase 1 [rad/s]	Phase 2 [rad/s]	Phase 3 [rad/s]
1	0.2523	0.1845	0.0161
2	0.2395	0.1924	0.0189
3	0.2573	0.2536	0.0189
4	0.3303	0.2445	0.0155
5	0.2461	0.2373	0.0142
6	0.2532	0.1389	0.0191
7	0.4235	0.1894	0.0194

Conclusions

- Motion Controller developed for TITAN manipulator will allow control of the robotic arm during On-Orbit Servicing and Active Debris Removal missions.
- The Motion Controller is responsible for trajectory planning and closed-loop control of manipulator motion.
- It can be operated in multiple modes including Cartesian control and compliant control.
- Multiple practical aspects, such as error handling and singularity avoidance and self-collision avoidance were taken into account.
- The stability of the control system is proved analytically on the joint level and numerically on the system level.
- The Motion Controller was validated in Monte Carlo simulations.
- PIAP Space is now working on hardware implementation. The Joint Controller will be tested in emulated micro-gravity environment.

Thank you for your attention!

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