# TRAJECTORY OPTIMIZATION AND CONTROL OF MULTIPOD ROBOTS IN ON-ORBIT SERVICING OPERATIONS

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**Jorge Pomares, José L. Ramón,**
**Leonard Felicetti, M. Olivares-Mendez**

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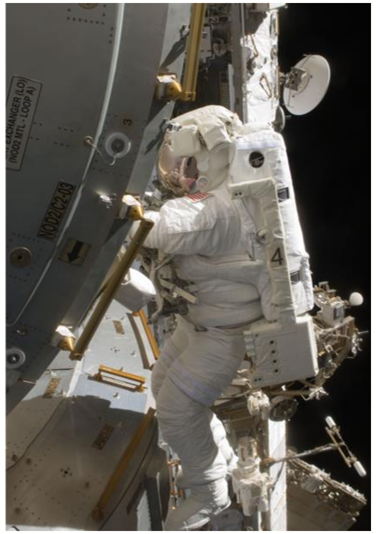
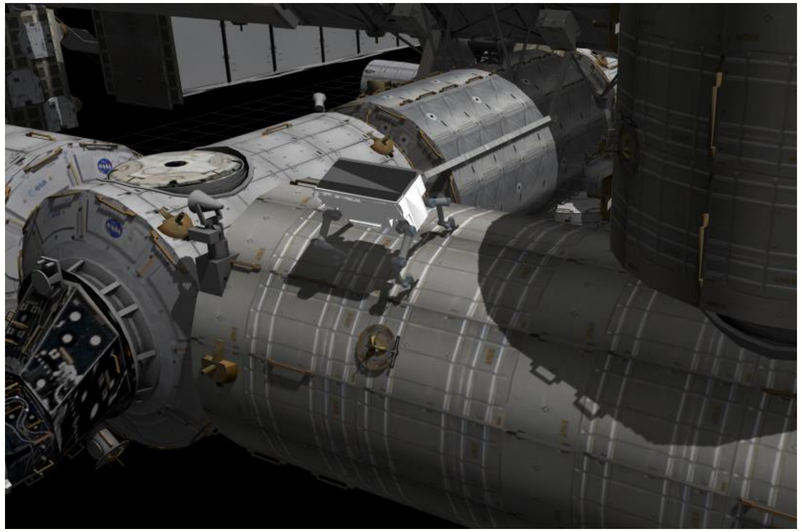
# Multipod robots in extravehicular activities







Future and under-development missions will require extensive use of on-orbit assembling and manufacturing.

**High requirements of on-orbit assembly tasks:**

- Reliability, efficiency, and safety

**Deployment of autonomous robots, particularly for tasks characterized by operations:**

- Repetitive, structured, and standardized

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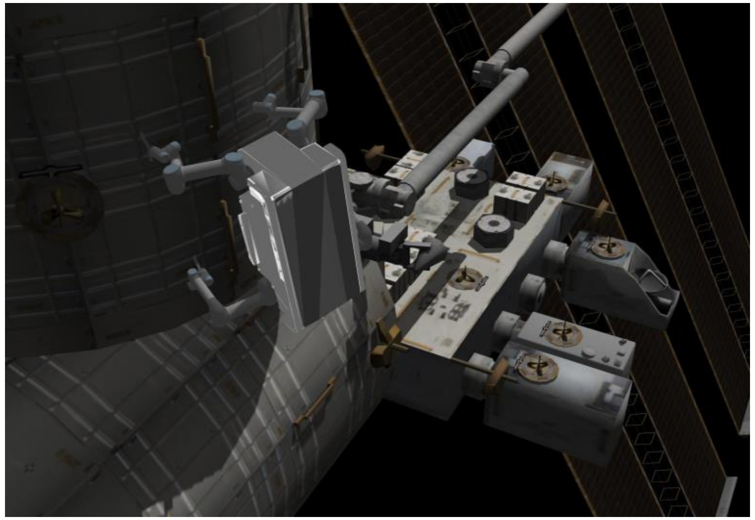
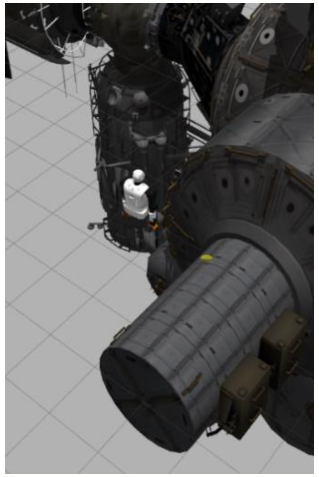
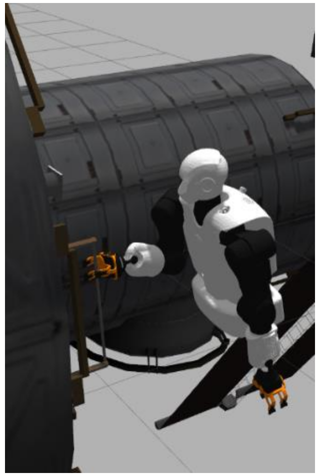
# System architecture









Multipod with 4 legs and 6 dof each with gecko gripers at their end-effectors.

3D camera located at the robot body.

| Input | | | |
| --- | --- | --- | --- |
| Robot configuration | Desired location | Maneuver duration | Number of steps |

| Output | |
| --- | --- |
| Robot base trajectory | End-effectors trajectories and forces |

The presented approach is also evaluated with a humanoid robot:

- Two robotic arms with grippers.
- Seven degrees of freedom each arm.
- Robot head with a range camera



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# Trajectory optimization



Task → Optimization problem → Path planning → Actuators

**COMPLEX TASK**

| ROBOT | | OBJECTIVE | | | WORKSPACE | |
|---|---|---|---|---|---|---|
| KINEMATICS | DYNAMICS | ROBOT BODY LOCATION | NUMBER OF STEPS | MANEUVER DURATION | 3D MAP OF THE WORKSPACE | FRICTION |

**Nonlinear programming solver**

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# Trajectory optimization

## Decision variables and trajectory optimization objective

Find $\boldsymbol{r}(t) \in \mathbb{R}^3$ (Base position, CoM)

$\boldsymbol{\theta}(t) \in \mathbb{R}^3$ (Base orientation)

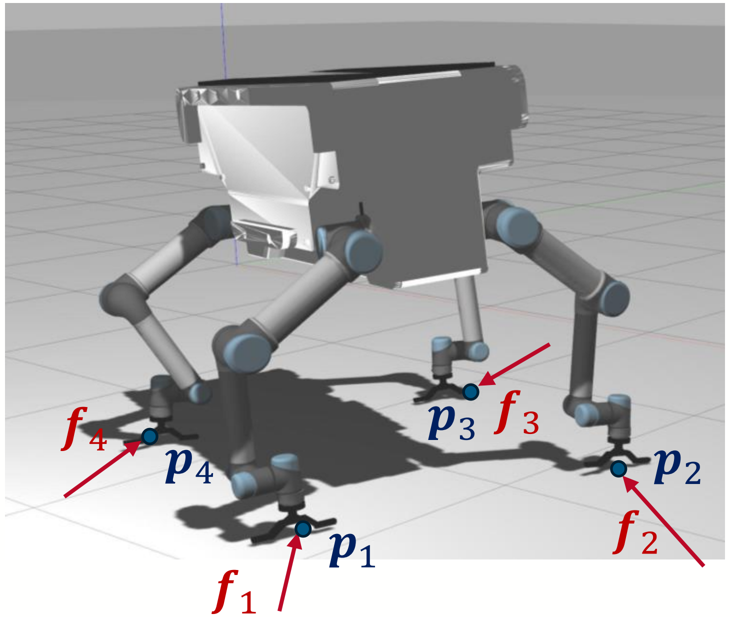
for each leg $i \in \{1, \ldots, N\}$:

$\boldsymbol{p}_{\mathrm{i}}(t) \in \mathbb{R}^3$ (end-effector leg trajectory)

$\boldsymbol{f}_{\mathrm{i}}(t) \in \mathbb{R}^3$ (force at a contact point)

Cost function to be minimized:

$$\Phi = \int_0^T \sum_1^N \left[\sigma_{i1}\left(\boldsymbol{f}_i^x(t)\right)^2 + \sigma_{i2}\left(\boldsymbol{f}_i^y(t)\right)^2 + \sigma_{i3}\left(\boldsymbol{f}_i^z(t)\right)^2\right] + \sigma_4\left(\dot{\boldsymbol{r}}^x(t)\right)^2 + \sigma_5\left(\dot{\boldsymbol{r}}^y(t)\right)^2 + \sigma_6\left(\dot{\boldsymbol{r}}^z(t)\right)^2$$



# Trajectory optimization

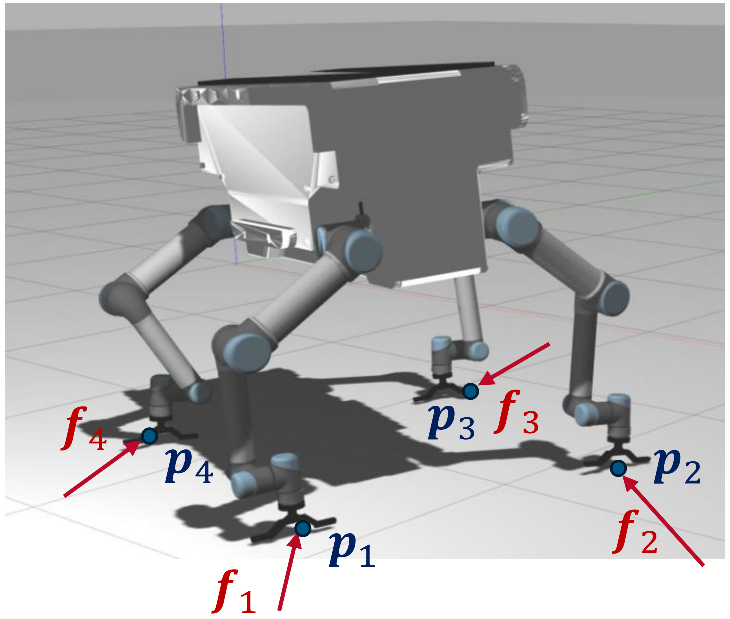
## Leg trajectories and decision variables

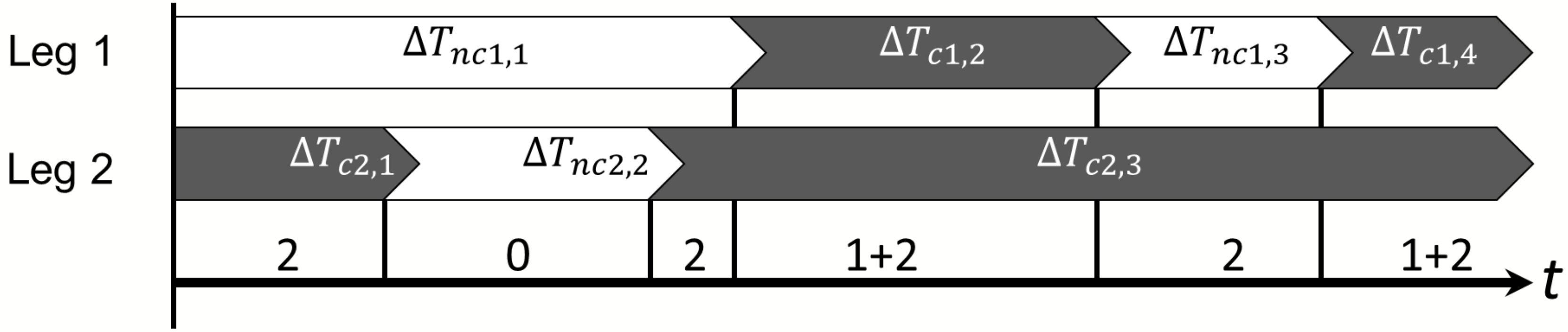
Multipod centre trajectory: $\boldsymbol{r}(t)$

Mutipod centre attitude: $\boldsymbol{\theta}(t)$

For each leg i ($i = 1 \dots \zeta$)

- Phase durations: $\Delta T_{ci,1}, \Delta T_{nci,1}, \dots, \Delta T_{ci,N}, \Delta T_{nci,N}$
  - Leg trajectory: $\boldsymbol{p}_i(t, \Delta T_{ci,1}, \Delta T_{nci,2} \dots)$
  - Interaction force: $\boldsymbol{f}_i(t, \Delta T_{ci,1}, \Delta T_{nci,2} \dots)$



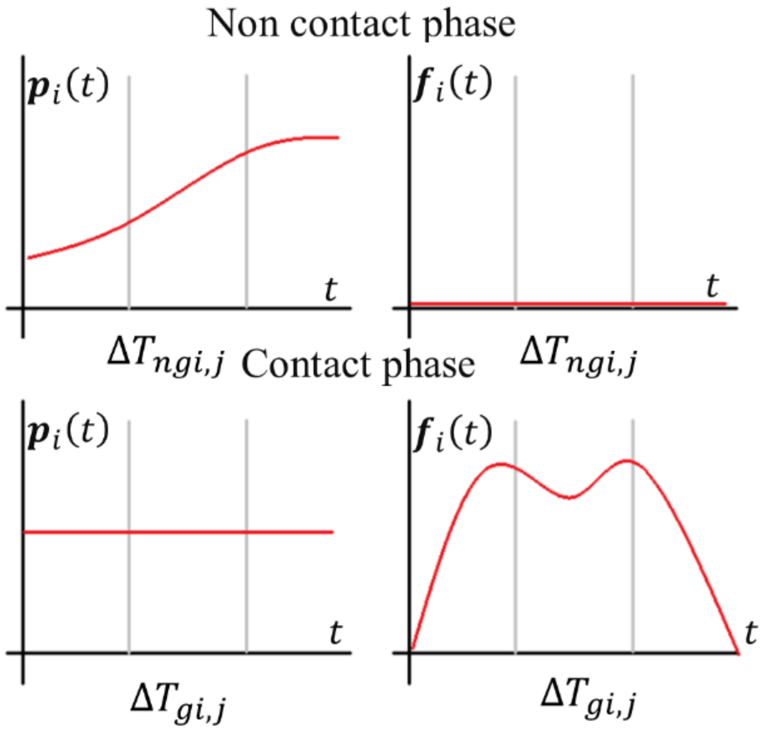

Leg movements are defined by the duration of the continuous phases $\Delta T_i$

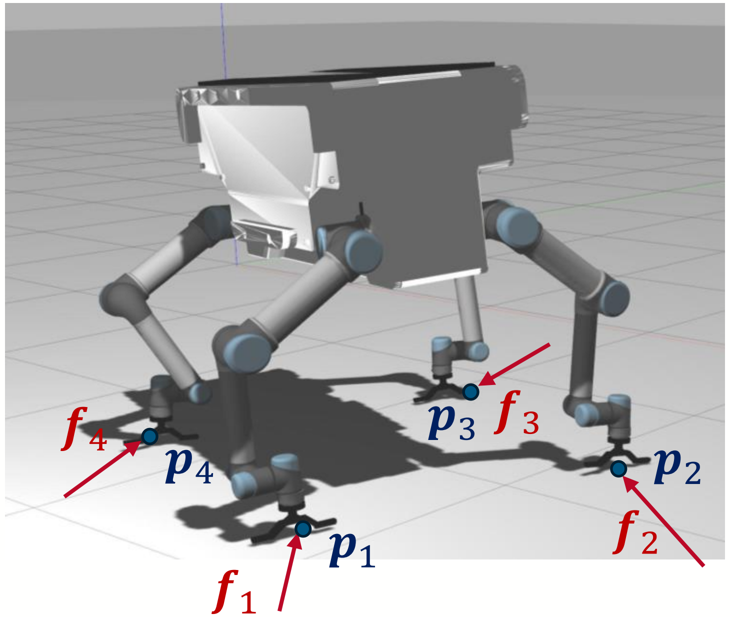
The legs alternate between Contact and Non-Contact

# Trajectory optimization



## Force and position parameterization




Splines are used to code the end-effector trajectories and contact forces depending on the grasping or free phase

*Physic constraints*

The end-effector position $\boldsymbol{p}_i(t)$ cannot be moved during the grasping

Contact forces $\boldsymbol{f}_i(t)$ cannot appear during the free phase

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# Trajectory optimization

## Kinematic constraint

$$|\boldsymbol{R}_b[\boldsymbol{p}_i(t) - \boldsymbol{r}(t)] - \boldsymbol{p}_{ni}| < \mathrm{L}_i$$

## Dynamic constraint

Input vector

External disturbances

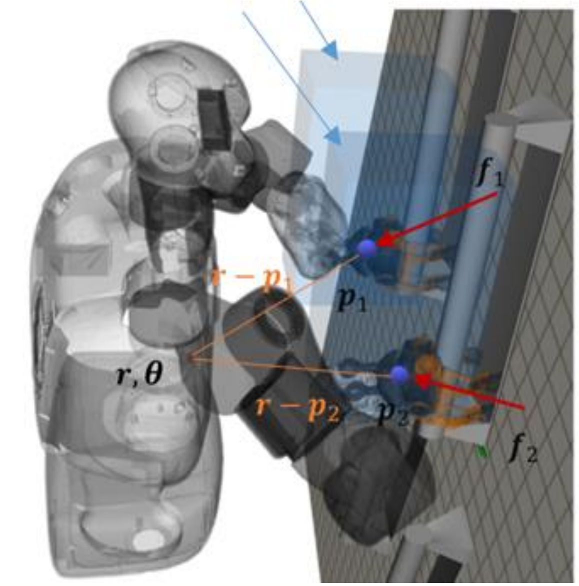
$$\boldsymbol{u} - \boldsymbol{u}_e = \begin{bmatrix} \boldsymbol{M}_{bb} & \boldsymbol{M}_{bi} \\ \boldsymbol{M}_{bi}^T & \boldsymbol{M}_{ii} \end{bmatrix} \ddot{\boldsymbol{\epsilon}} + \begin{bmatrix} \boldsymbol{c}_b \\ \boldsymbol{c}_i \end{bmatrix}$$

Body inertia and coupled inertia matrix between body and legs

$$\boldsymbol{\epsilon} = \left[\boldsymbol{r}^T, \boldsymbol{\theta}^T, \boldsymbol{q}_i^T\right]^T$$

Robot body and legs joint acceleration

Kinematic constraints




$$m\ddot{\boldsymbol{r}} = \sum_{i=1}^{2} \boldsymbol{f}_i(t)$$

$$\boldsymbol{M}_I\dot{\boldsymbol{\omega}}(t) + \boldsymbol{\omega}(t) \times \boldsymbol{M}_I\boldsymbol{\omega}(t) = \sum_{i=1}^{2} \boldsymbol{f}_i(t) \times \left(\boldsymbol{r}(t) - \boldsymbol{p}_i(t)\right)$$

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# Trajectory optimization



## Trajectory optimization constraints

Initial multipod body state: $\boldsymbol{r}(t=0)=\boldsymbol{r}_0, \boldsymbol{\theta}(t=0)=\boldsymbol{\theta}_0$
Desired multipod body state: $\boldsymbol{r}(t=T)=\boldsymbol{r}_\mathrm{d}, \boldsymbol{\theta}(t=T)=\boldsymbol{\theta}_\mathrm{d}$
Multipod dynamics constraint: $[\ddot{\boldsymbol{r}}(t), \dot{\boldsymbol{\omega}}(t)]^\mathrm{T}=\boldsymbol{F}_\mathrm{d}\big(\boldsymbol{r}(t), \boldsymbol{p}_\mathrm{i}(t), \boldsymbol{f}_\mathrm{i}(t)\big)$

For each leg *i* ($i=1 \ldots \zeta$)

- Multipod kinematics constraint: $\boldsymbol{p}_\mathrm{i}(t) \in \mathcal{K}_\mathrm{i}\big(\boldsymbol{r}(t), \boldsymbol{\theta}(t)\big)$
- If leg *i* is in contact with the workspace ($t \in \mathcal{C}_\mathrm{i}$):
  - The leg end-effector does not slip: $\dot{\boldsymbol{p}}_\mathrm{i}(t \in \mathcal{C}_\mathrm{i})=0$
  - The leg maintains the contact with the workspace: $\boldsymbol{p}_\mathrm{i}^\mathrm{z}(t \in \mathcal{C}_\mathrm{i})=\boldsymbol{m}\big(p_\mathrm{i}^\mathrm{x}, p_\mathrm{i}^\mathrm{y}\big)$
  - Friction constraints $\boldsymbol{f}_{t1}<\mu \boldsymbol{f}_i^T \boldsymbol{n}\big(p_i^x, p_i^y\big), \ \boldsymbol{f}_{t2}<\mu \boldsymbol{f}_i^T \boldsymbol{n}\big(p_i^x, p_i^y\big)$
- If leg *i* is not in contact with the workspace ($t \notin \mathcal{C}_\mathrm{i}$):
  - The leg does not exert forces: $\boldsymbol{f}_\mathrm{i}(t \notin \mathcal{C}_\mathrm{i})=0$

$$\sum_{\mathrm{j}=1}^{\mathrm{N}} \Delta \mathrm{T}_{\mathrm{ci,j}}+\Delta \mathrm{T}_{\mathrm{nci,j}}=\mathrm{T}$$



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# Tracking controller



## Weighted controller defined as a convex optimization problem

**Controller objective**: to determine the values of the accelerations of all the robot degrees of freedom, end-effector forces and forces/torques to be applied in all the actuated joints ($\ddot{\boldsymbol{q}}$, $\boldsymbol{f}$ y $\boldsymbol{\tau}$).
**Controller definition**: optimization of an objective function that allows the system to perform a set of $m$ tasks, $\boldsymbol{\psi}_k, k = 1 \dots m$. c

Tasks optimization

$$\min_{\ddot{\boldsymbol{q}},\boldsymbol{f},\boldsymbol{\tau}} \sum_{k=1}^{m} \frac{1}{2} \rho_k \left\| \boldsymbol{\psi}_{rk} \right\|^2$$

Task to be optimize for the joint trajectory tracking:

$$\min_{\ddot{\boldsymbol{q}},\boldsymbol{f},\boldsymbol{\tau}} \left\| \boldsymbol{\psi}_{rk} \right\|^2 = \min_{\ddot{\boldsymbol{q}},\boldsymbol{f},\boldsymbol{\tau}} \frac{1}{2} \ddot{\boldsymbol{q}}^T \boldsymbol{I} \ddot{\boldsymbol{q}} - \left[ \ddot{\boldsymbol{c}}_{dk} + \boldsymbol{K}_d \dot{\boldsymbol{\psi}}_k + \boldsymbol{K}_p \boldsymbol{\psi}_k \right]^T \ddot{\boldsymbol{q}}$$

**Constraints**

Dynamic model:

$$\begin{bmatrix} \boldsymbol{M}_{ii}^* & -\boldsymbol{J}_i^T & -\boldsymbol{I} \end{bmatrix} \begin{bmatrix} \ddot{\boldsymbol{q}}_i \\ \boldsymbol{f}_i \\ \boldsymbol{\tau}_i \end{bmatrix} = -\boldsymbol{C}_i^* + \boldsymbol{\tau}_e$$

Static kinematics:

$$\begin{bmatrix} \boldsymbol{J}_{gi} & 0 & 0 \end{bmatrix} \begin{bmatrix} \ddot{\boldsymbol{q}}_i \\ \boldsymbol{f}_i \\ \boldsymbol{\tau}_i \end{bmatrix} = -\dot{\boldsymbol{J}}_{gi} \dot{\boldsymbol{q}}_i - \dot{\boldsymbol{v}}_{ge}$$

Additional constraints: friction, maximum torque, etc.



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# Simulation system



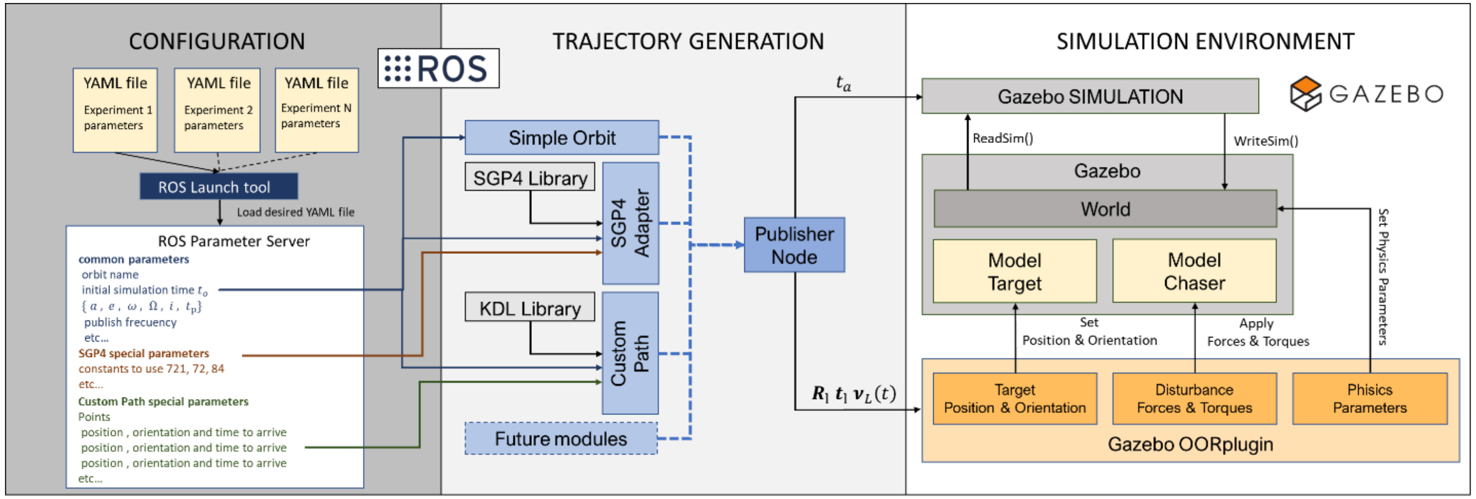
## OnOrbit ROS

**ROS/Gazebo:** standard tool for testing and developing control algorithms for **ground-based robotic systems**.

**OnOrbitROS**:

- A unified open-source **tool for on orbit space-robotics**
- Simulation of **complex space robotic systems**
- Using packages already developed in ROS for control, vision, teleoperation,etc.

It is possible to simulate robotic operation for OOS, without the need of ad-hoc coded simulation tools but relying on a well-validated tool.




https://github.com/OnOrbitROS

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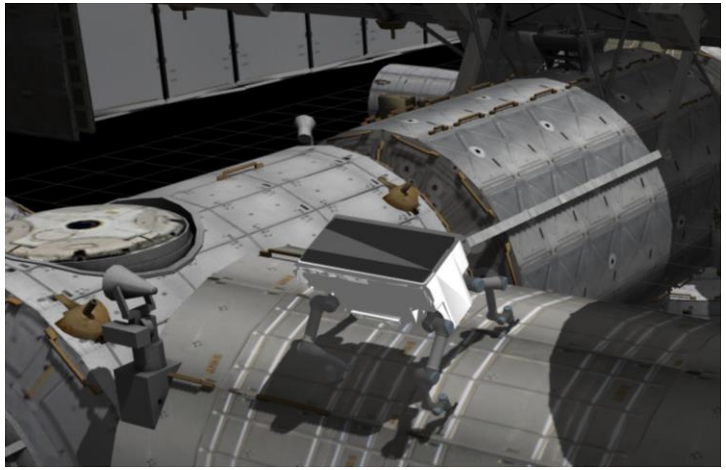
# Results

## System setup

**Configuration 1**: Multipod robot



**Configuration 2**: Humanoid robot

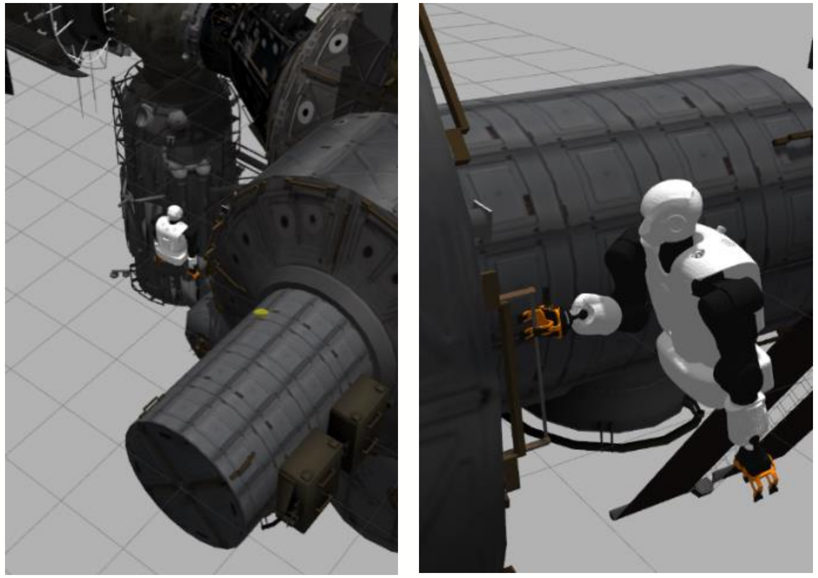
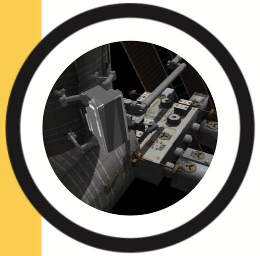


Table 2. Main dynamic parameters of the robot body.

| | Mass (kg) | Height (m) | Inertia (kg·m2) Ixx | Iyy | Izz | Ixy | Ixz | Iyz |
|---|---|---|---|---|---|---|---|---|
| Body Parameters | 40 | 0.843 | 18.6 | 15.4 | 4.1 | -0.008 | -0.027 | 0.058 |

Table 3 Main dynamic parameters of the robot legs.

| | Mass (kg) | Length (m) | Inertia (kg·m2) Ixx | Iyy | Izz | Ixy | Ixz | Iyz |
|---|---|---|---|---|---|---|---|---|
| Link 1 | 2.741 | 0.28 | 0.0124 | 0.0042 | 0.0136 | 3.6e-05 | 7.1e-05 | -0.0002 |
| Link 2 | 2.425 | 0.144 | 0.013 | 0.0138 | 0.0049 | 1.2e-05 | -0.0032 | -0.0001 |
| Link 3 | 0.877 | 0.274 | 0.0025 | 0.0027 | 0.0012 | 0.0001 | -0.0003 | 0.0004 |
| Link 4 | 1.878 | 0.265 | 0.0035 | 0.0044 | 0.0023 | 1.3e-05 | 1.03e-05 | -9.7e-05 |
| Link 5 | 0.409 | 0 | 0.0001 | 0.00014 | 0.00015 | -8.9e-08 | -4.4e-08 | 4.2e-07 |
| Link 6 | 0.308 | 0 | 0.0003 | 0.0002 | 0.00017 | -1.6e-06 | 1.7e-06 | -1.2e-05 |



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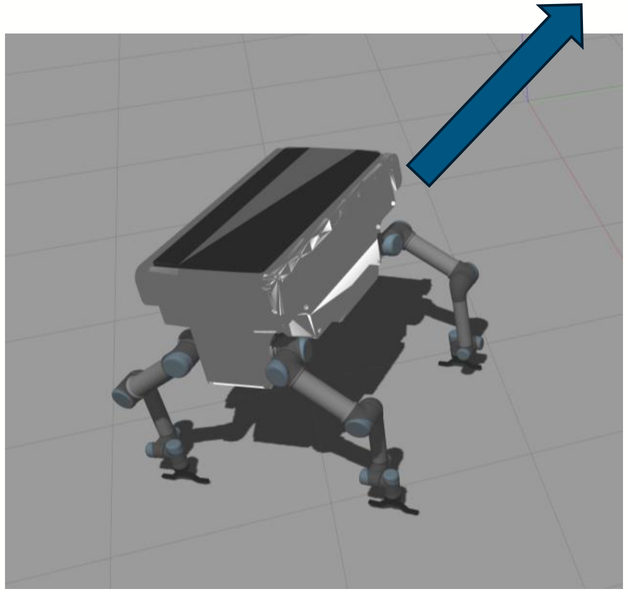
# Results

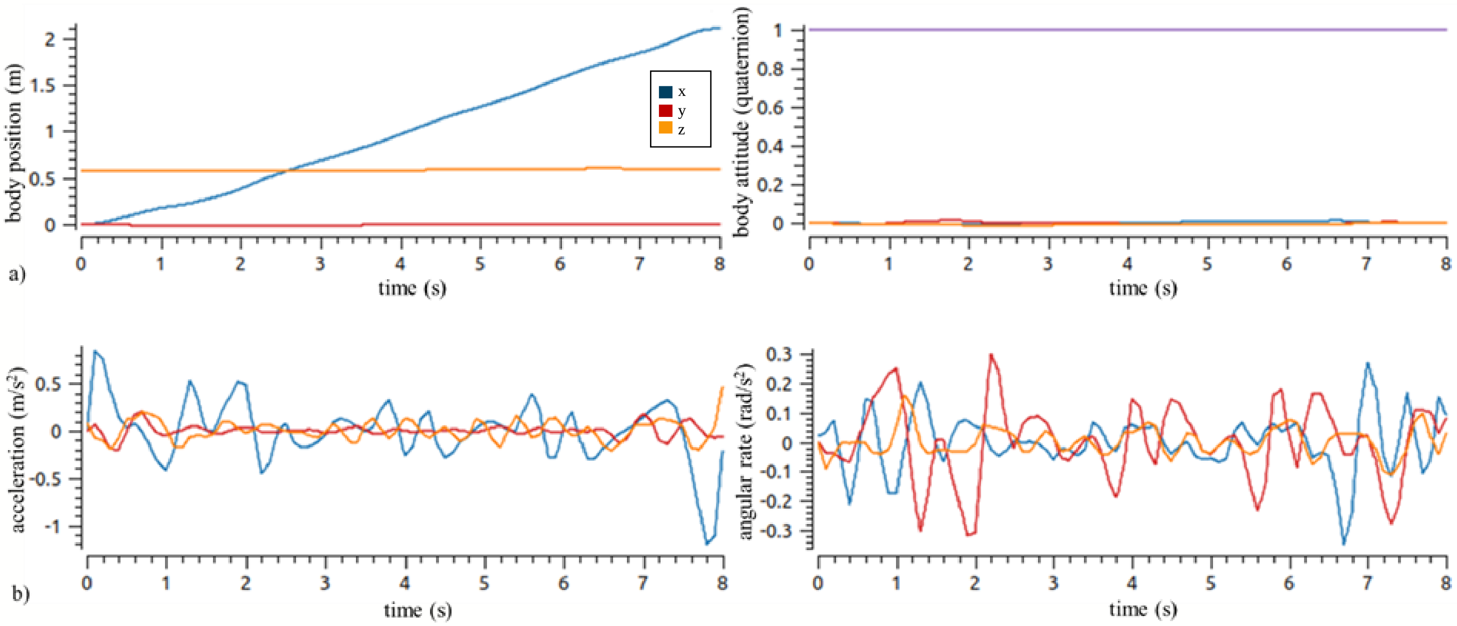


## Experiment 1. Multipod robot.

Displacement of 2.1 *m* along *x* direction



Position and orientation of the robot body




Lineal and angular acceleration of the robot body

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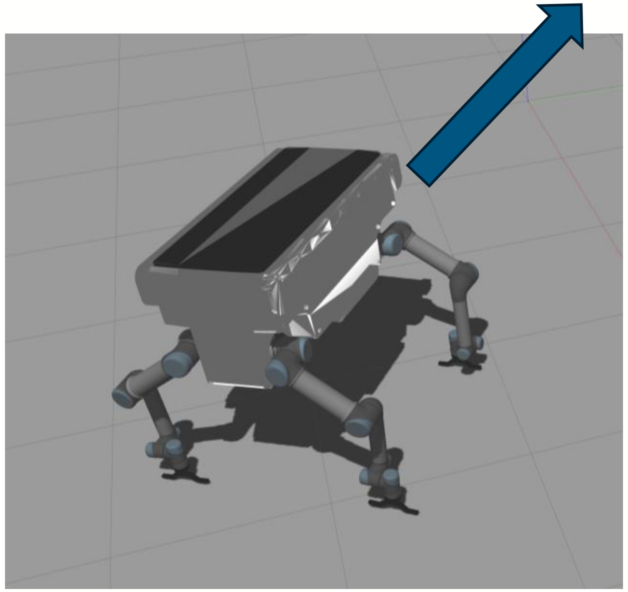
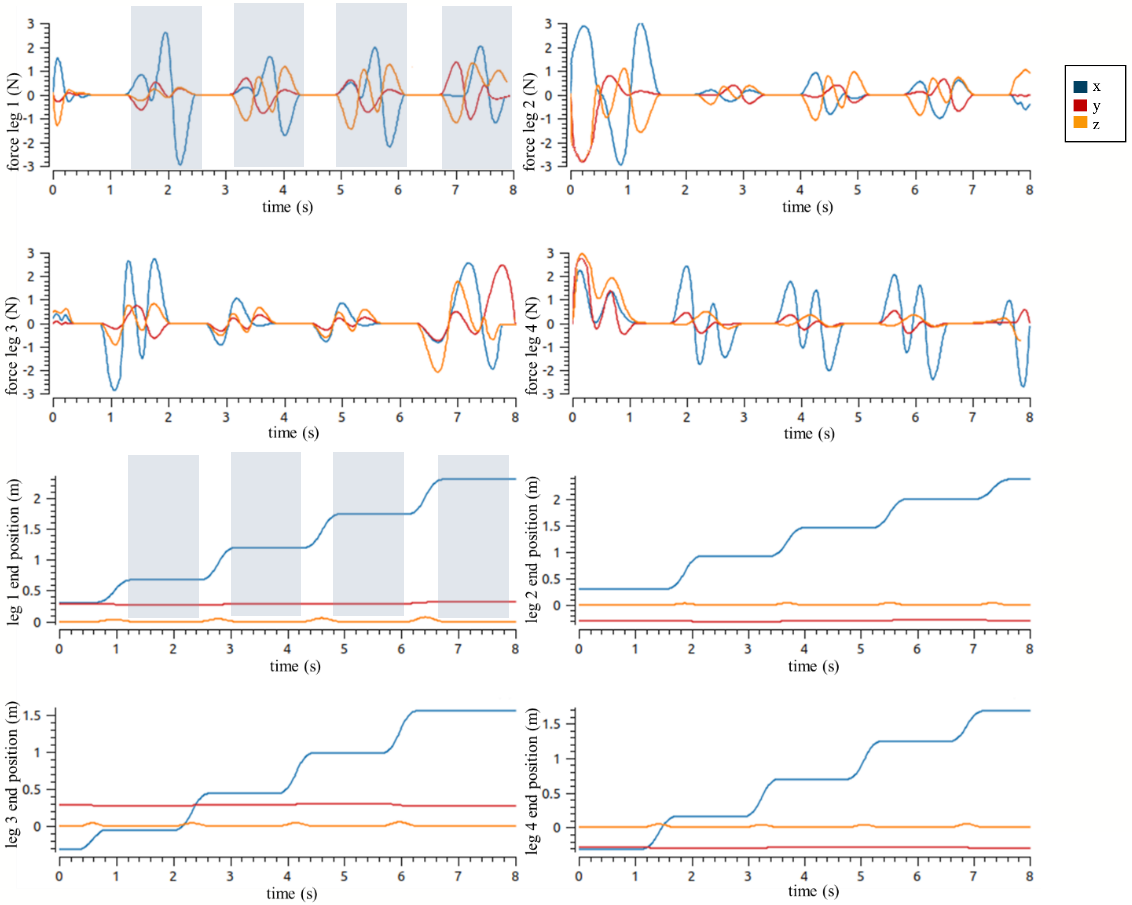
# Results

## Experiment 1. Multipod robot.

Displacement of 2.1 *m* along *x* direction






Legs end-effector forces 3D position

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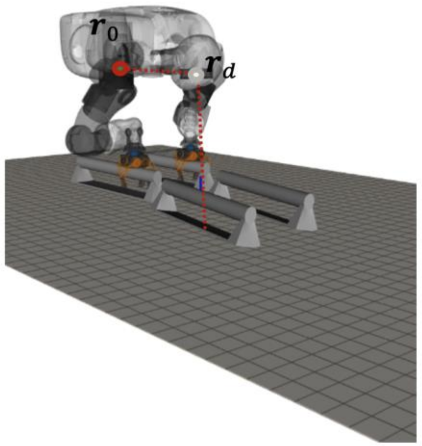
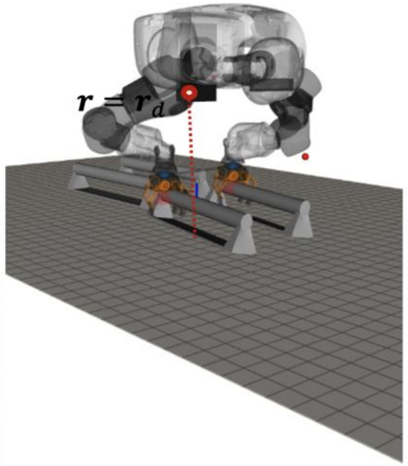
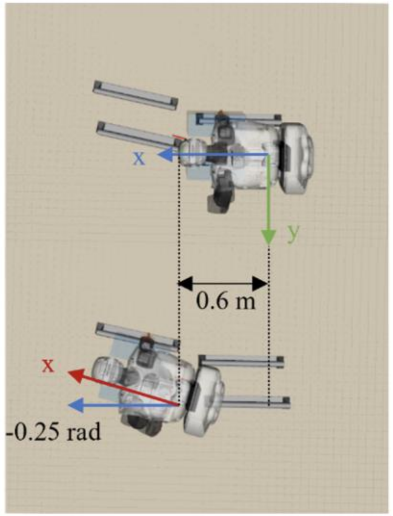
# Results

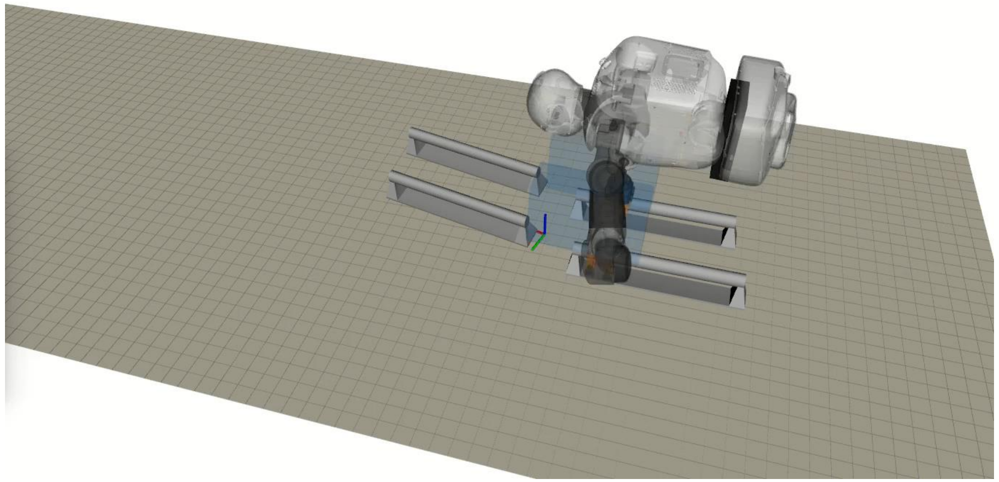
## Experiment 2. Humanoid robot.

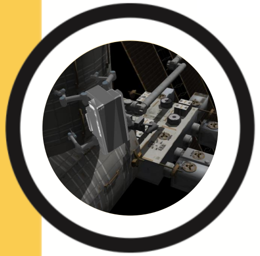
Displacement of 0.6 *m* along *x* direction and rotation of -0.25 *rad* around *z* axis





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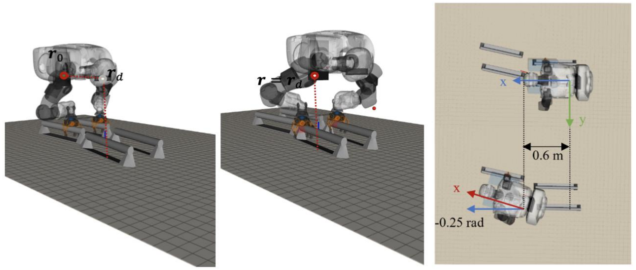
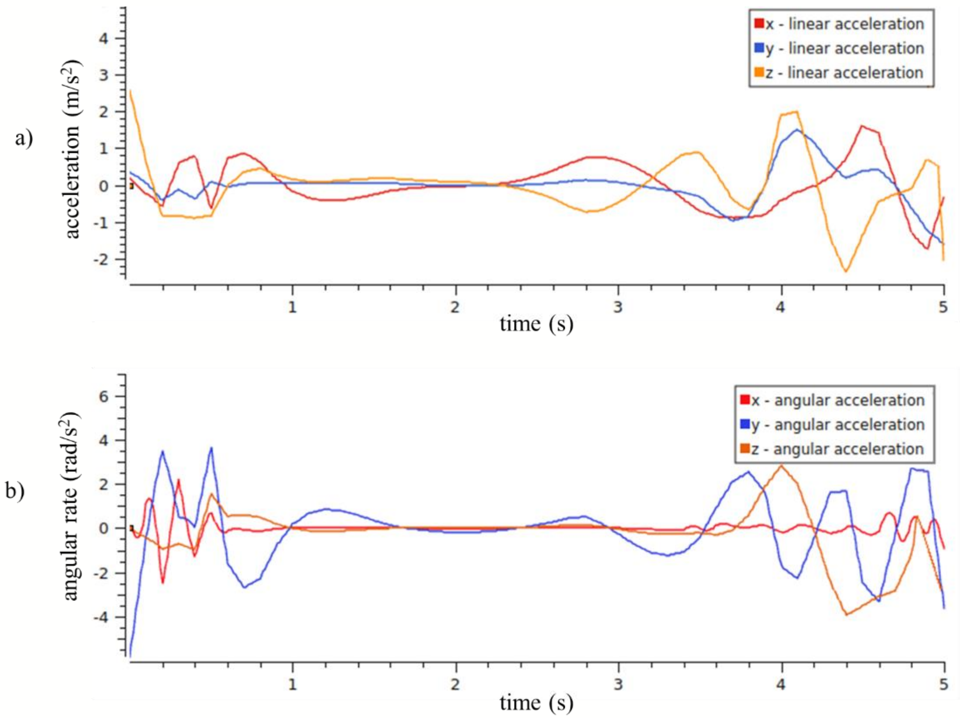
# Results

Trajectory optimization and control of multipod robots

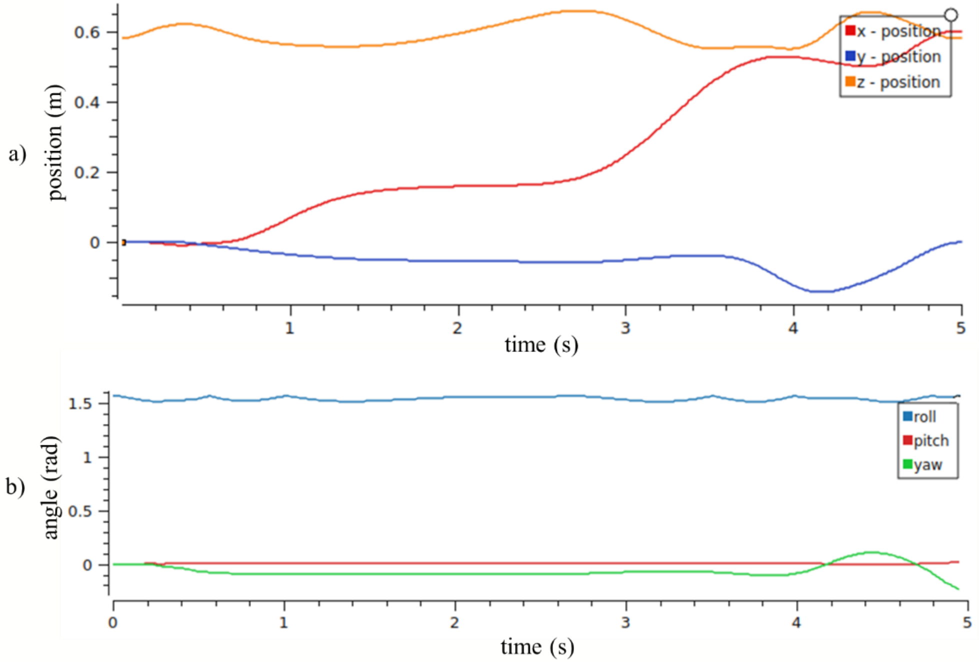
## Experiment 2. Humanoid robot.




Displacement of 0.6 *m* along *x* direction and rotation of -0.25 *rad* around *z* axis




Lineal and angular acceleration of the robot body




Position and orientation of the robot body

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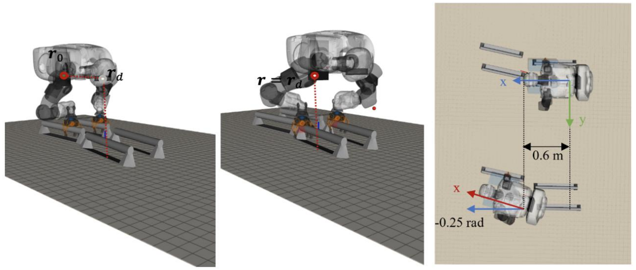
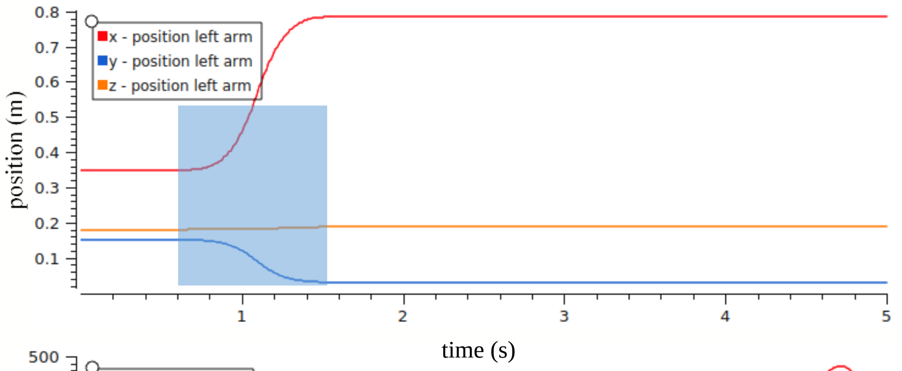
# Results

## Experiment 2. Humanoid robot.

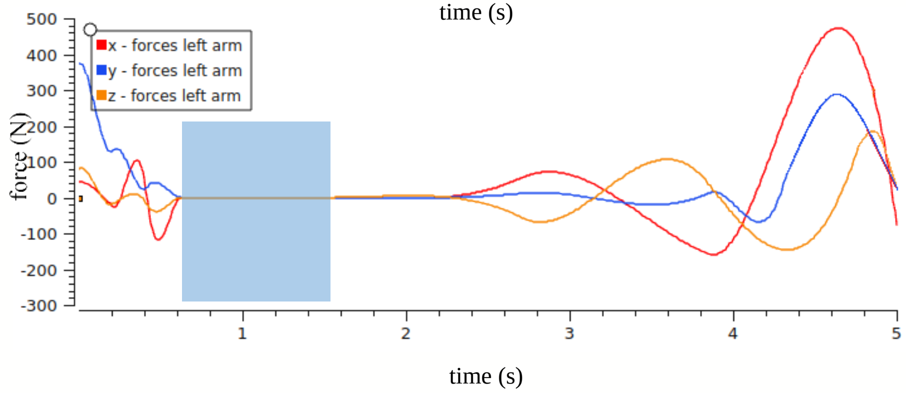



Displacement of 0.6 *m* along *x* direction and rotation of -0.25 *rad* around *z* axis

a)



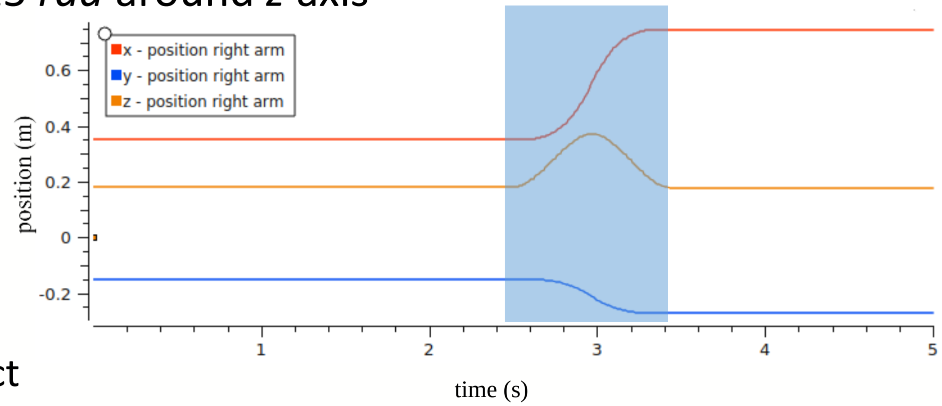

b)



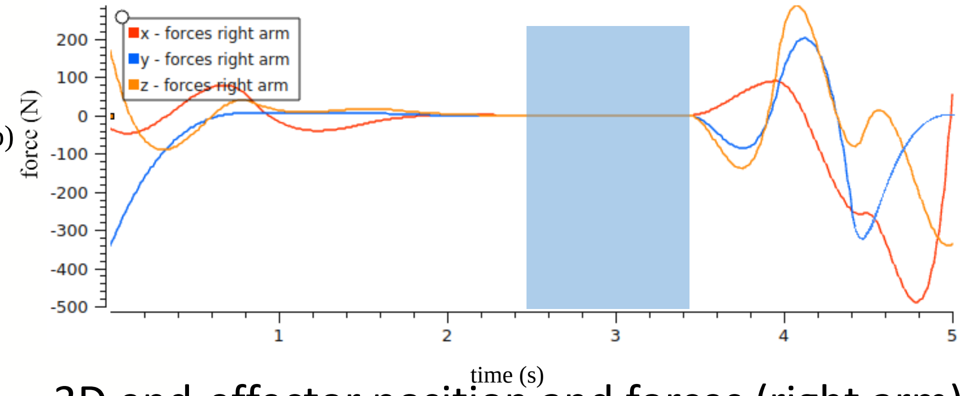

3D end-effector position and forces (left arm)

Non-contact

a)




b)




3D end-effector position and forces (right arm)

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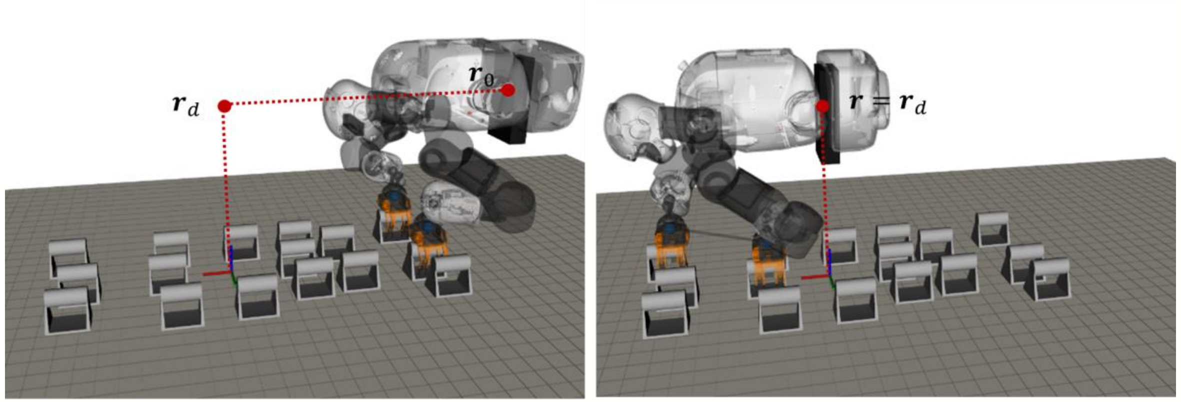
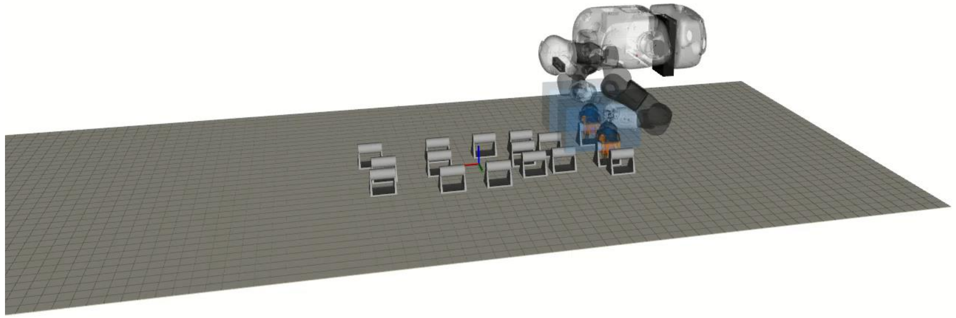
# Results

## Experiment 3. Humanoid robot.

Movement of 1 *m* along the *x* direction. Use of multiple handrails.





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# Final remarks



- **Path planning and control of multipod robots in on-orbit servicing scenarios.**
- **A trajectory optimization formulation is presented to define the path planning problem. The control problem is defined as a weighted controller proposed as a convex optimization problem.**
- **Simulation results carried on in ROS/Gazebo environment show that the overall control architecture (trajectory optimizer + controller) is sufficiently robust and allows for complex and articulated motion.**
- **Future work:**
  - To include additional perturbations in the simulation system such as drag perturbations.
  - Simulation and evaluation of the trajectory generation with thrusters.
  - Application to on orbit manufacturing

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# TRAJECTORY OPTIMIZATION AND CONTROL OF MULTIPOD ROBOTS IN ON-ORBIT SERVICING OPERATIONS

**Questions?**

**jpomares@ua.es**

**Jorge Pomares, José L. Ramón,**
**Leonard Felicetti, M. Olivares-Mendez**

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