Grasping On The Move using a mobile manipulator

Claudio Schiavella 1884561
Lorenzo Cirillo 1895955
Lorenzo Cirone 1930811

Tutor - **Francesco D’Orazio**

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Prof: **Giuseppe Oriolo**
Sapienza University of Rome

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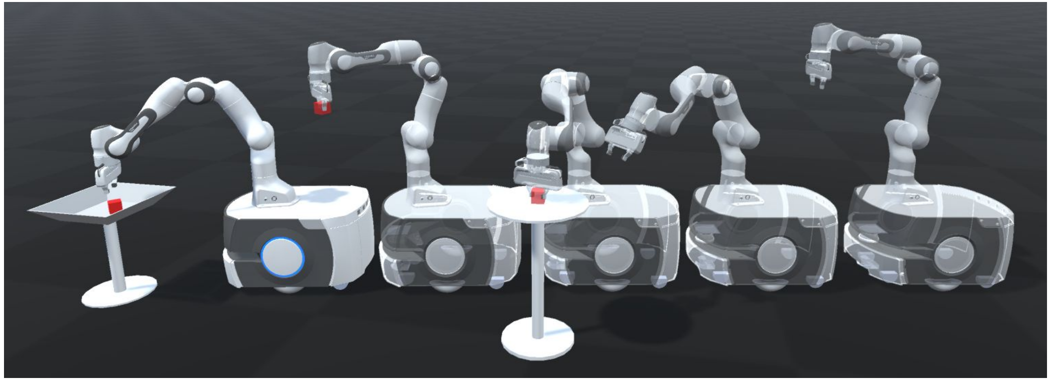
Task - Object Pick and Place

- Object **pick** and **place.**

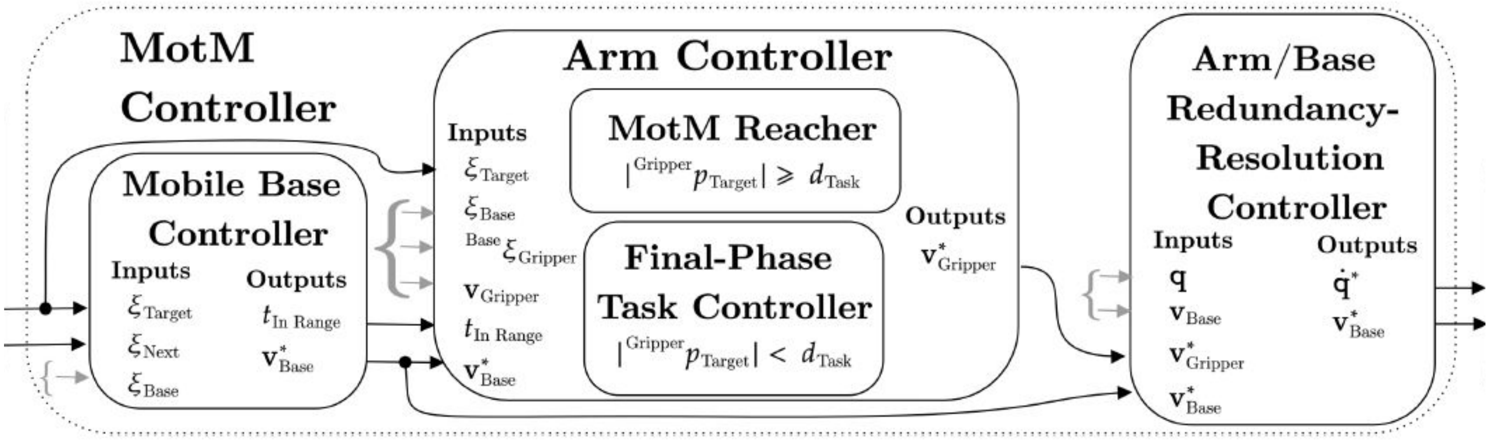
- **Grasping** an object **while the robot is in motion** to **decrease the execution time** compared to when the base stops to pick up the target.

- Develop a **reactive controller** to **improve robustness** against perception errors, environmental disturbances, and inaccuracies in robot control.

- **Reactive** and **Non-Reactive approaches** comparison.

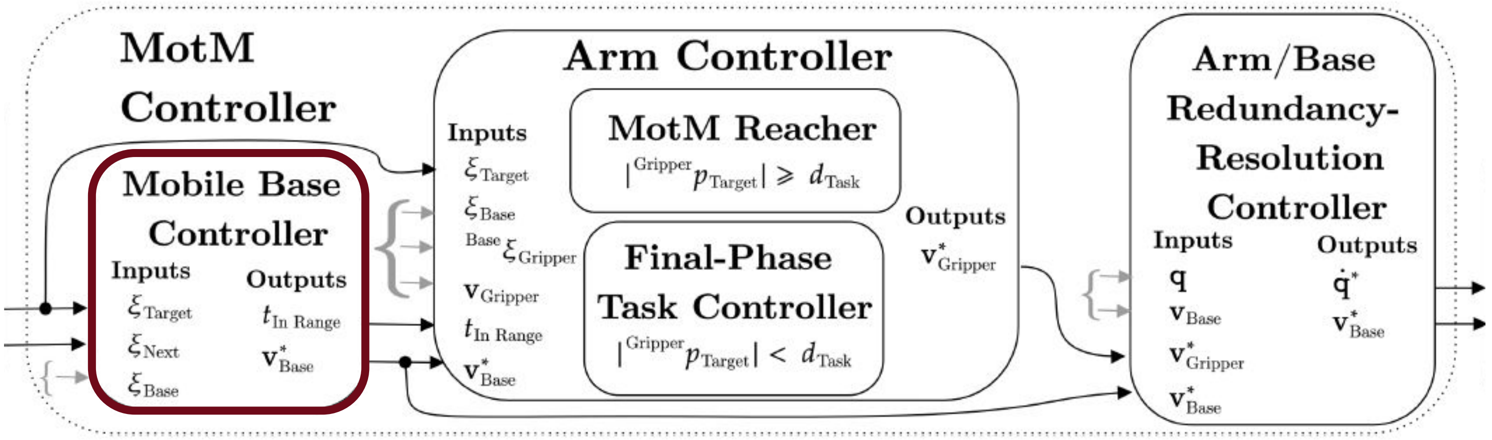


Architecture



- **Mobile Base Controller:** approaching the robot to the grasping and final target.
- **Arm Controller:** guides the arm to the grasping target considering base motion.
- **Redundancy Resolution Controller:** smoothly coordinates arm and base motion.

Mobile Base Controller



- **Navigate** the robot base to a desired pose ξ_C
  - In which the target can be reached by the arm.

- **Key point**: Penalize the steering velocity ω_B when the robot is oriented towards the desired pose and penalize the forward velocity v_B when the robot has reached the desired pose.

Mobile Base Controller

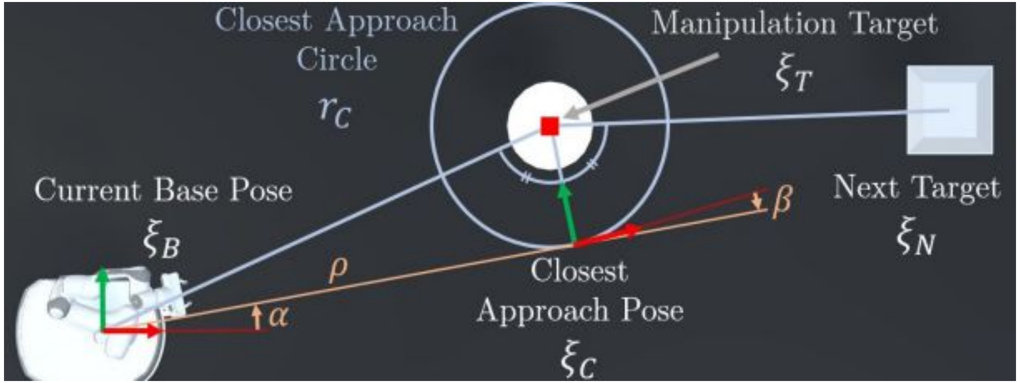
Driving and steering velocities:

- Grasping phase

$$v_B = cost.$$
$$\omega_B = (k_\alpha \alpha)\frac{v_B}{\rho}$$

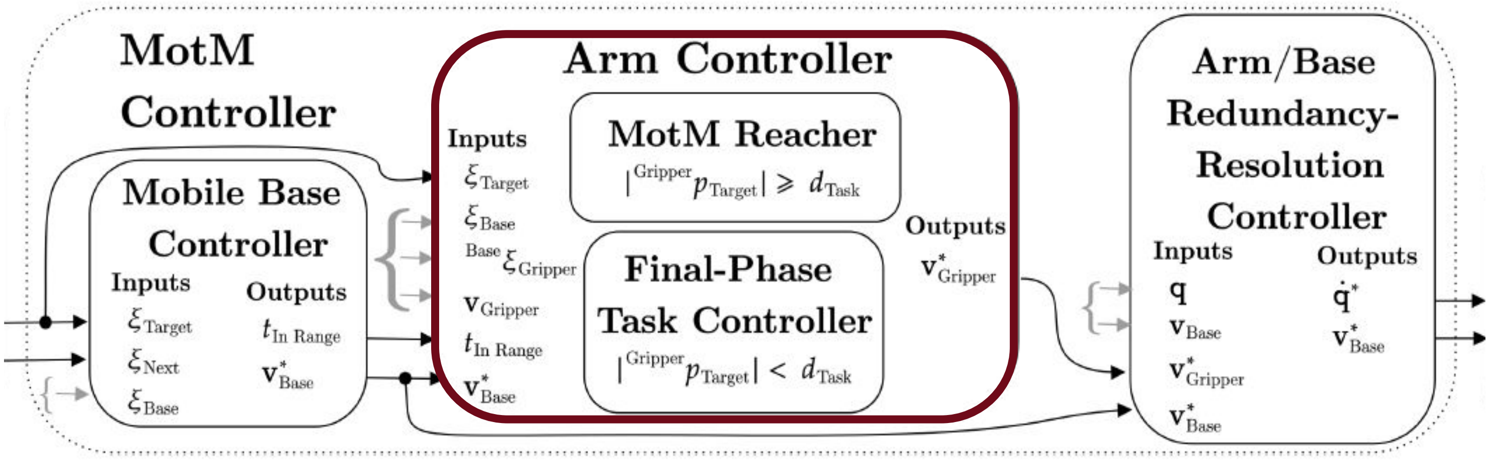
- Placing phase

$$v_B = cost.$$
$$\omega_B = (k_\beta \beta)\frac{v_B}{\rho_n}.$$



- **Base-Target distance:** $d = \sqrt{(\xi_{T,x} - \xi_{B,x})^2 + (\xi_{T,y} - \xi_{B,y})^2}.$
- **Distance error:** $\rho = \sqrt{d^2 - r_C^2}.$
- **Orientation error:** $\alpha = \text{atan2}(\xi_{B,y} - \xi_{C,y}, \xi_{B,x} - \xi_{C,x}) + \pi - \theta.$

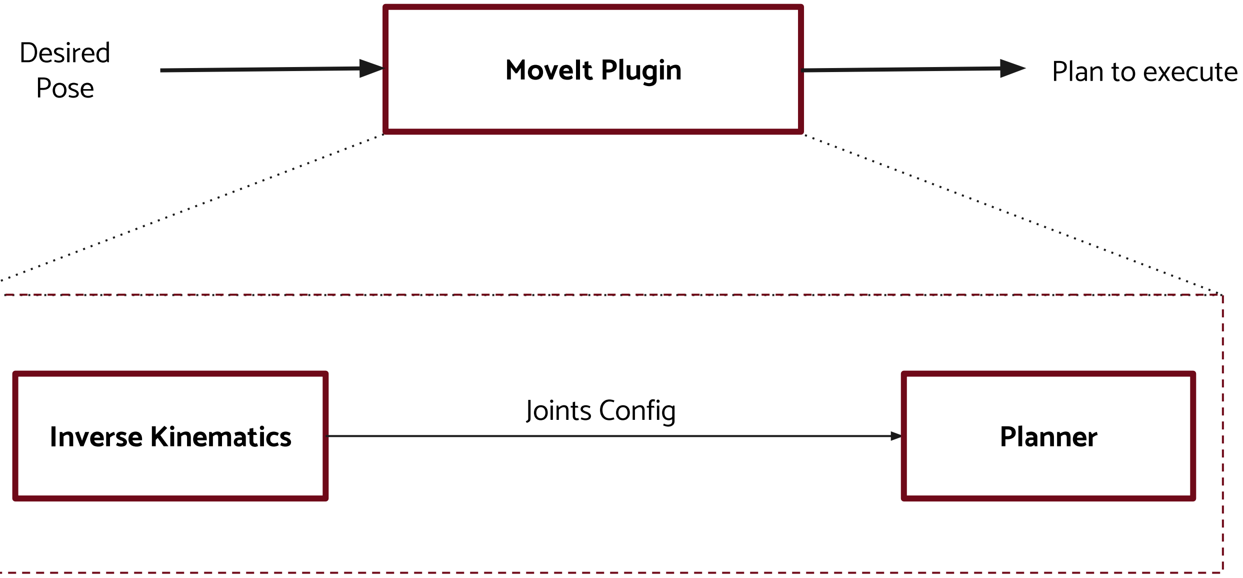
Arm Controller



- **Arm controller:** guides the arm to desidered end effector pose considering the motion of the base.

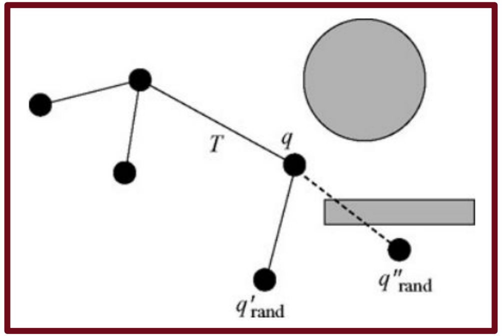
Arm Controller - Non Reactive Approach

- **MoveIt Approach: motion planning** plugin for ROS.
  - Move **TIAGo's gripper** grasping frame to a **desired pose** in **Cartesian space**
  - Given the desired pose, an arm joints config is computed and the planner generates the plan to reach it.

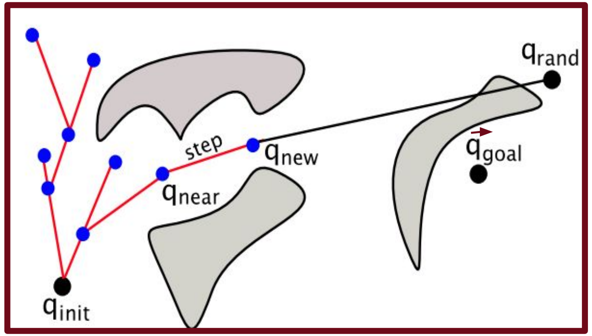


Arm Controller - Non Reactive Approach

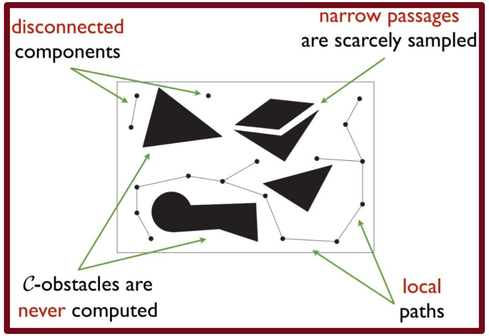
- **Open Motion Planning Library** planners family
  - Single-query Bi-directional Lazy Collision Checking **(SBLK)**
  - Rapidly-exploring Random Tree **(RRT)**
  - Probabilistic RoadMap **(PRM)**



SBLK



RRT



PRM

Arm Controller - Reactive Approach

- **Quintic polynomial** timing law $s(\tau)$ over a total time T
  - End-effector progress along a desired **linear cartesian trajectory**
  - From an initial position ξ_i to a final position ξ_f
  - The trajectory is computed online from the current end effector position

- Rest-to-rest trajectory:

$$s(\tau) = 6\tau^5 - 15\tau^4 + 10\tau^3.$$
$$\dot{s}(\tau) = 30\tau^4 - 60\tau^3 + 30\tau^2.$$
$$\ddot{s}(\tau) = 120\tau^3 - 180\tau^2 + 60\tau.$$

$$\xi_{des}(s(\tau)) = \xi_i + s(\tau)(\xi_f - \xi_i).$$
$$\dot{\xi}_{des}(s(\tau)) = \dot{s}(\tau)(\xi_f - \xi_i).$$
$$\ddot{\xi}_{des}(s(\tau)) = \ddot{s}(\tau)(\xi_f - \xi_i).$$

$$\tau = \frac{t}{T} \qquad s(\tau) \in [0, 1]$$

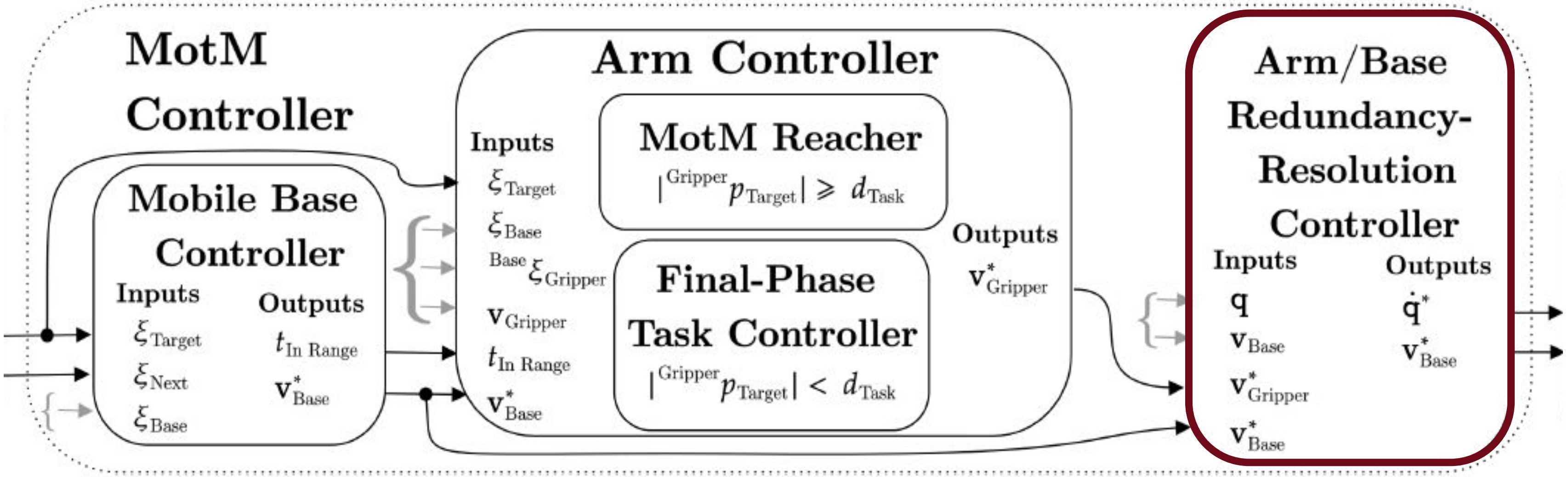
Arm Controller - Reactive Approach

- **Proportional control:** $\dot{\xi}_r = \dot{\xi}_{des} + k\Delta\xi$
  - **Cartesian error:** $\Delta\xi = \xi_{des} - \xi_i$
  - **Gains:** k

- **TIAGo arm** controlled in position
  - **Joint velocities:** $\dot{q} = J^{\dagger}\dot{\xi}_r$
  - **Euler integration:** $q_{k+1} = q_k + \dot{q}\Delta t$
    - To get joint positions

Redundancy Resolution Controller

- Formulated as a **Quadratic Programming** (QP) problem
  - Ensures **motion coordination** between the **arm and base.**



Redundancy Resolution Controller

$$\begin{aligned} \underset{x}{\text{argmin}} \quad & f(x) = \tfrac{1}{2} x^T H x \\ \text{subject to} \quad & \mathcal{J} x = \nu \\ & \mathcal{A} x \leq \mathcal{B} \\ & \mathcal{X}^- \leq x \leq \mathcal{X}^+ \end{aligned}$$

- **Optimization variable** $x = (\omega_L \quad \omega_R \quad \dot{q}_a \quad \delta)^T$
  - Wheels angular velocities (ω_L , ω_R)
  - Joint velocities $\dot{q}_a$
  - Slack variables $\delta = (\delta_a \quad \delta_{\nu_r})$

- **Costs:** $H = diag\{\lambda_q, \lambda_\delta\}$

- **Velocities:** $\nu = \begin{pmatrix} \dot{\xi}_r \\ \hline \nu_r \end{pmatrix}$

Redundancy Resolution Controller - Costs

$$
\begin{aligned}
\underset{x}{\operatorname{argmin}} \quad & \boxed{f(x) = \tfrac{1}{2} x^T H x} \\
\text{subject to} \quad & \mathcal{J} x = \nu \\
& \mathcal{A} x \leq \mathcal{B} \\
& \mathcal{X}^- \leq x \leq \mathcal{X}^+
\end{aligned}
$$

- **Joints costs** consider
  - A factor **inversely proportional** to **base error** for **angular velocities**
  - A **constant factor** for **joint velocities**

$$\lambda_q = \left(\frac{1}{\|\rho\|}, \frac{1}{\|\rho\|}, k_a, k_a, k_a, k_a, k_a, k_a, k_a \right)$$

- **Slack variables costs** consider
  - A factor **inversely proportional** to the **end-effector error**

$$\lambda_\delta = \left(\frac{1}{\|\Delta\xi\|}, \frac{1}{\|\Delta\xi\|}, \frac{1}{\|\Delta\xi\|}, \frac{1}{\|\Delta\xi\|} \right)$$

Redundancy Resolution Controller - Equality constraints

$$
\begin{aligned}
\underset{x}{\operatorname{argmin}} \quad & f(x) = \tfrac{1}{2} x^T H x \\
\text{subject to} \quad & \boxed{\mathcal{J} x = \nu} \\
& \mathcal{A} x \leq \mathcal{B} \\
& \mathcal{X}^- \leq x \leq \mathcal{X}^+
\end{aligned}
$$

- **End-effector velocity** comes from **direct differential kinematics**
  - Can be **decreased to improve coordination** with **base movement**

$$J\dot{q}_a = \dot{\xi}_r - \delta_a$$

  - where $\dot{\xi}_r$ is the **end effector velocity**.

- **Moving base speed** is linked to the **wheels angular velocity**
  - Can be **decreased to improve coordination** with the **arm movement**

$$\frac{\omega_L + \omega_R}{2} = \nu_r - \delta_\nu$$

Redundancy Resolution Controller - Inequality constraints

$$
\begin{aligned}
\underset{x}{\operatorname{argmin}} \quad & f(x) = \frac{1}{2} x^T H x \\
\text{subject to} \quad & \mathcal{J} x = \nu \\
& \boxed{\begin{aligned} & \mathcal{A} x \leq \mathcal{B} \\ & \mathcal{X}^- \leq x \leq \mathcal{X}^+ \end{aligned}}
\end{aligned}
$$

- Future **arm joint positions** must **fall within** the system **mechanical limits**
  - Considering the used integration method (**Euler**)

$$q_{k+1} = q_k + \dot{q}\Delta t \in [q_{a,min}, q_{a,max}]$$

- The values of the **slack variables must be positive**

$$\delta = (\delta_a \quad \delta_{\nu_r}) \geq 0$$

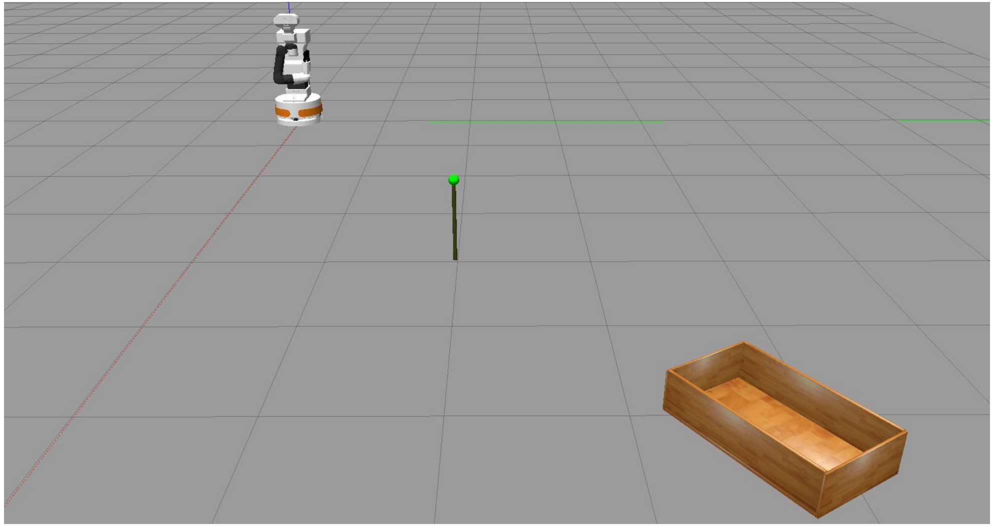
- Joint **position and velocity** must satisfy **limits**

$$\mathcal{X}^- \leq x \leq \mathcal{X}^+$$

Simulation Settings - Environment

- Gazebo simulation environment.

- **Task:**
    - Grasp the green ball
    - Place it inside the brown box



Simulation Settings - TIAGo Robot

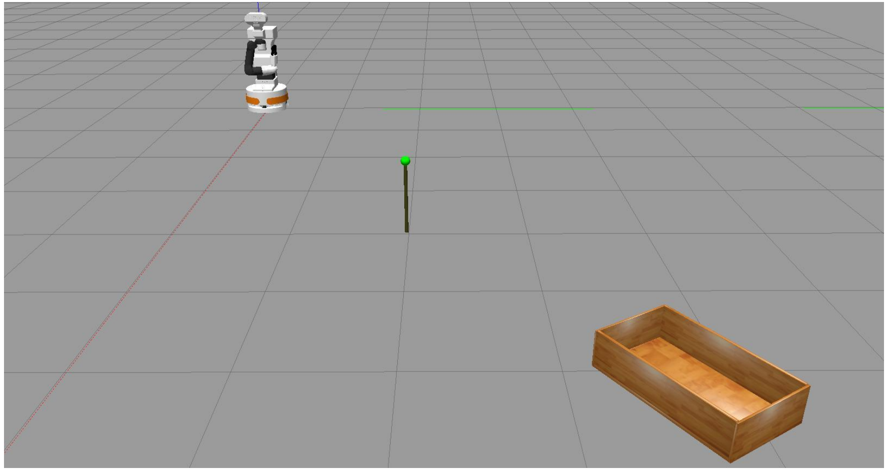
- Developed by **PAL Robotics.**

- Main features:
  - **Differential Drive Robot** as mobile base
  - **Articulated arm** with 7 degrees of freedom
  - **Extendable Torso** with a Prismatic Joint
  - **Gripper** or customizable end-effector

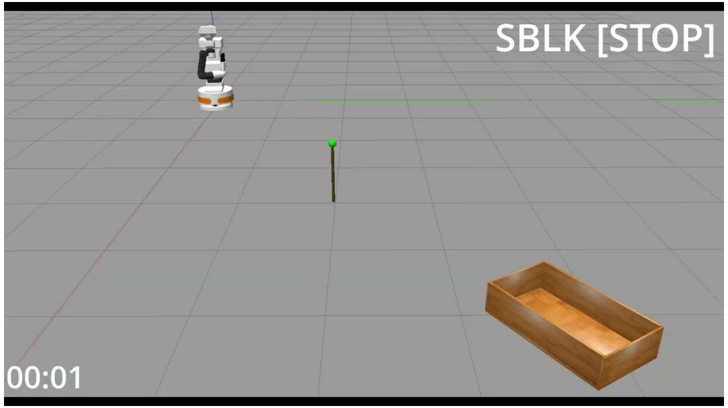
- Based on **ROS** (Robot Operating System).

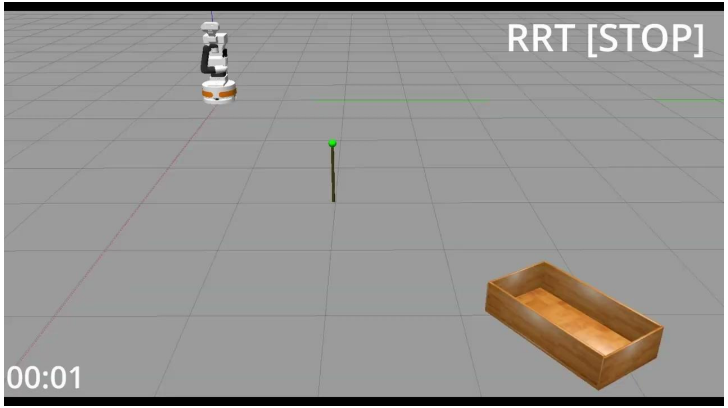
Simulations

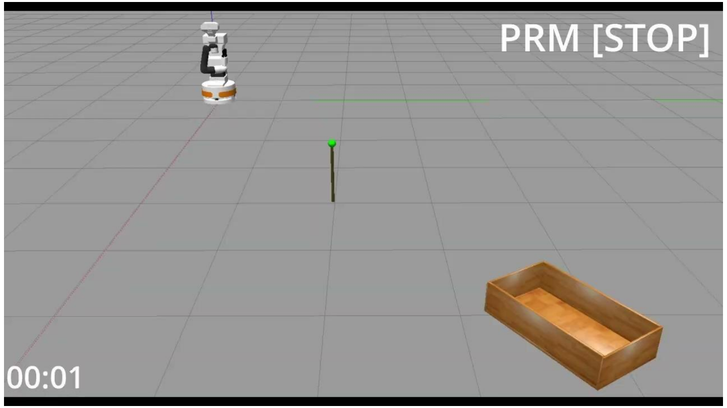
- **On-the-stop simulations:**
  - MoveIT planners
  - Quintic polynomial
- **On-the-move simulations:**
  - MoveIT planners
  - Quintic polynomial
  - Redundancy resolution controller
- **Measurements:**
  - Task completion
  - Grasping trajectory
  - Plan finding (only for MoveIT planners)
  - Success rate



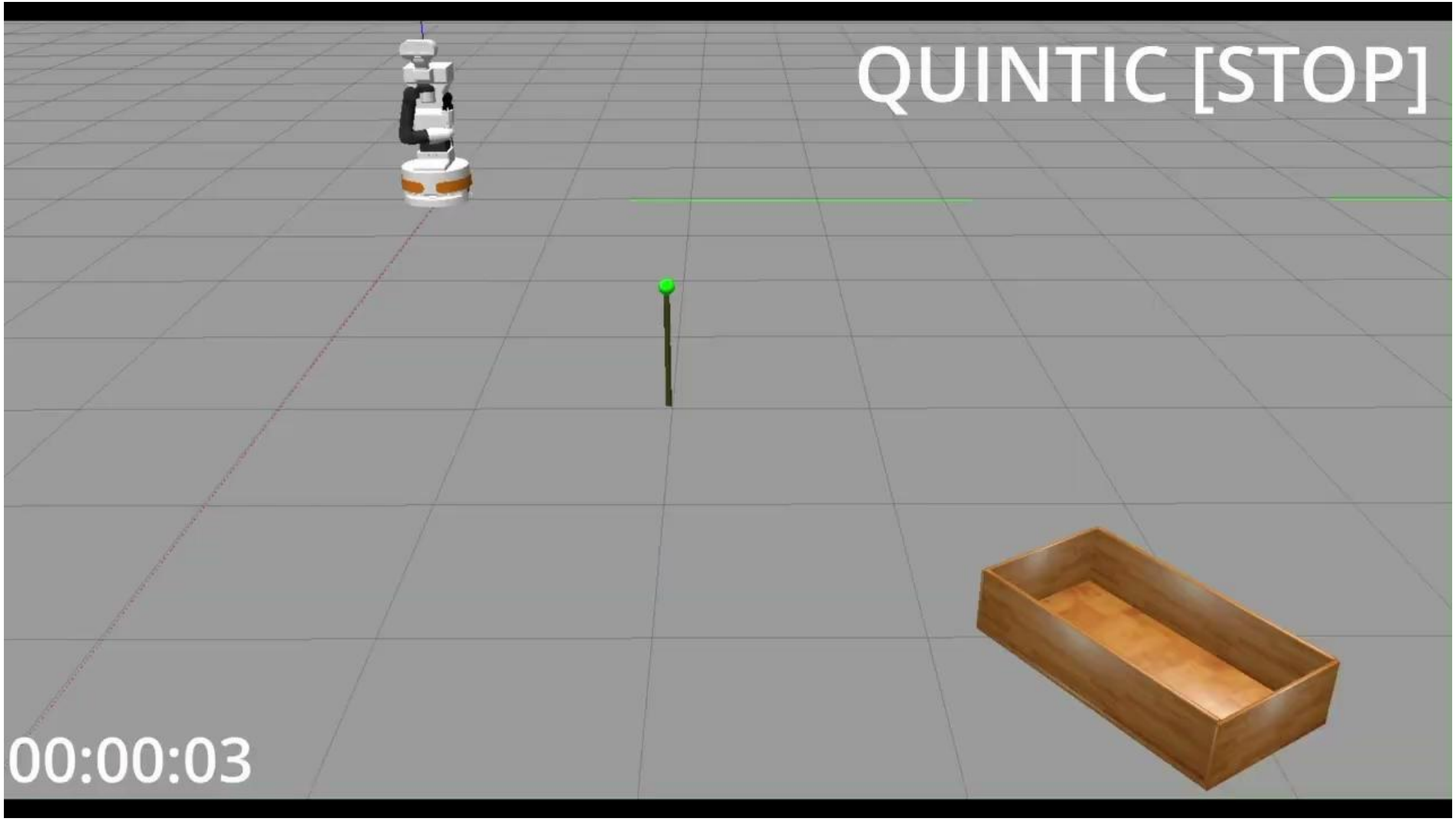
Simulations - On the stop - Moveit



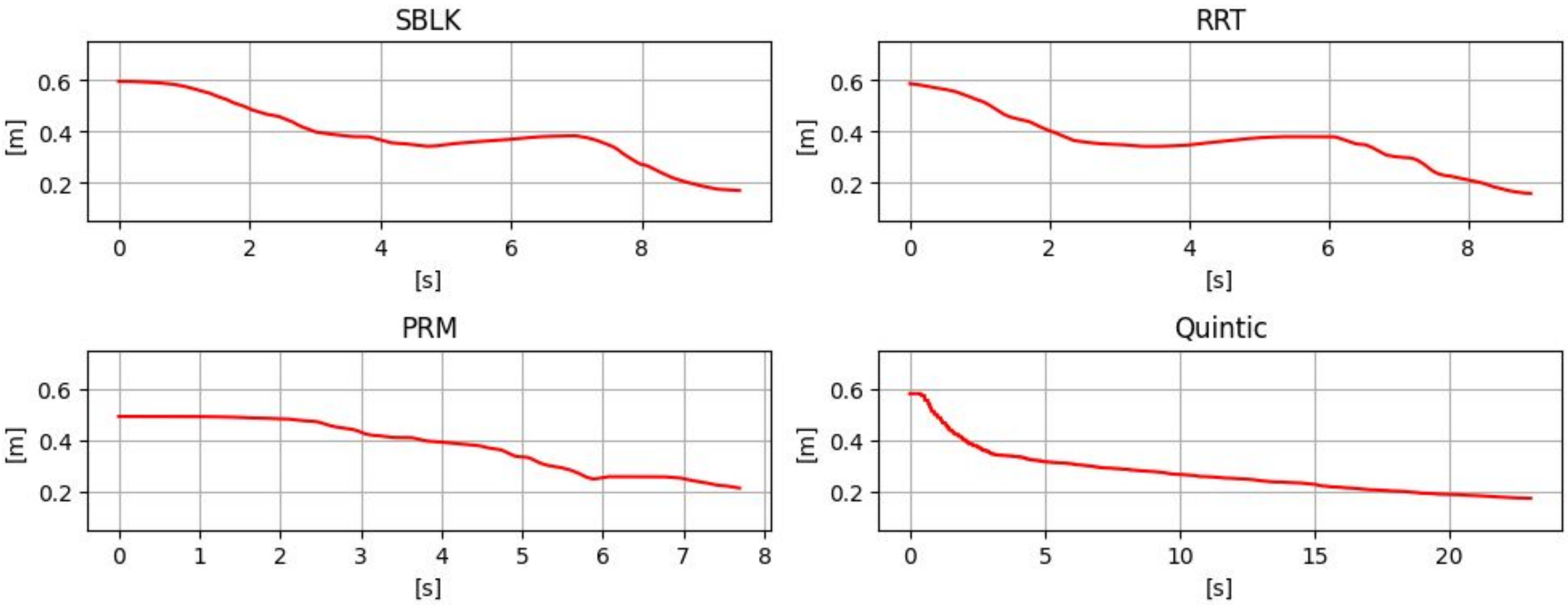




Simulations - On the stop - Quintic

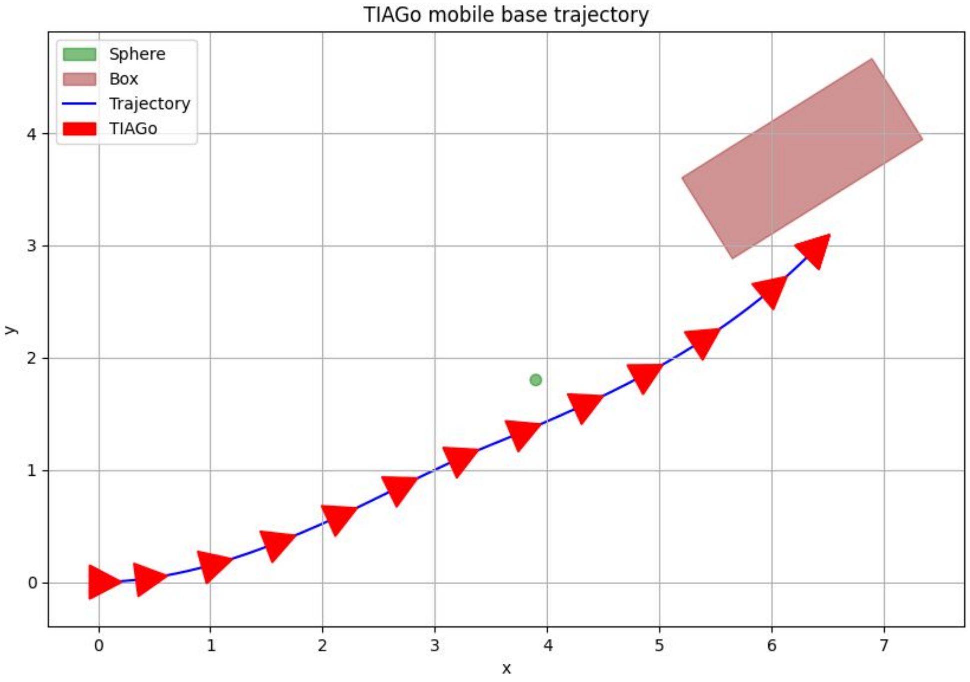


Simulations - On the stop - Planners & Quintic

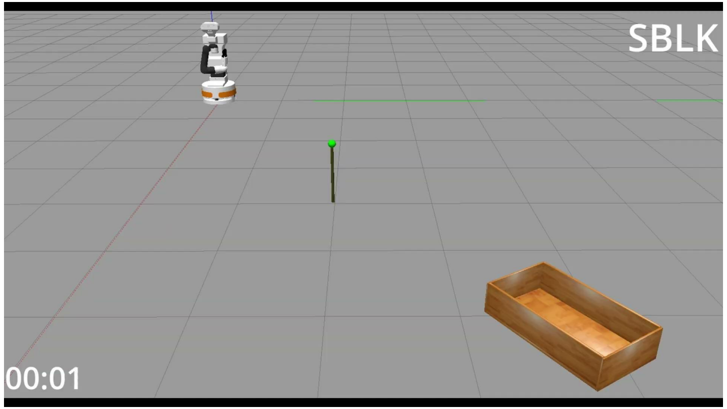


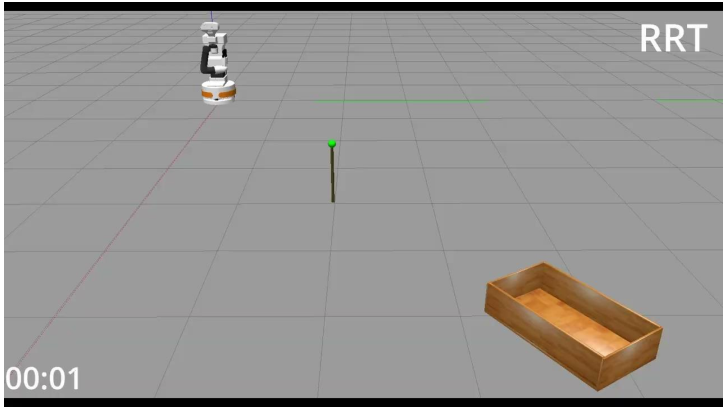
Simulations - On the move - Base trajectory

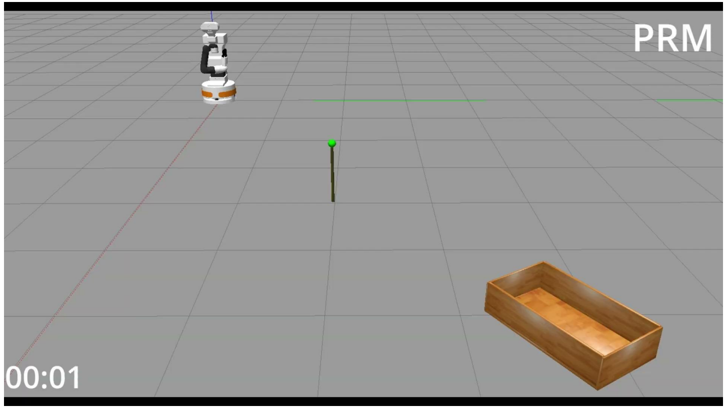
- Simulation base trajectory
- Grasping phase:
  - Ball approaching
  - Ball grasping
- Placing phase:
  - Box approaching
  - Ball placing



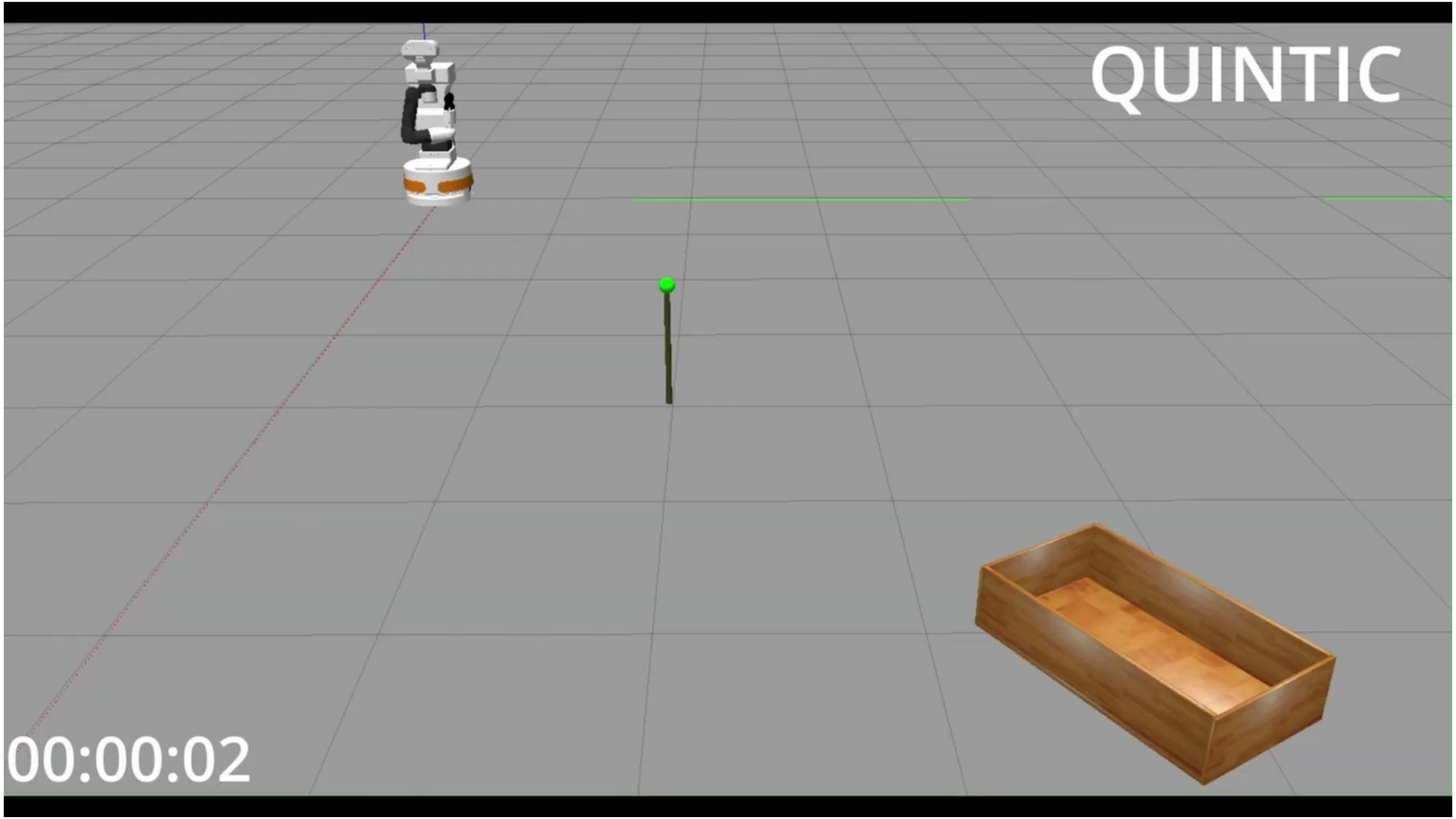
Simulations - On the move - SBLK



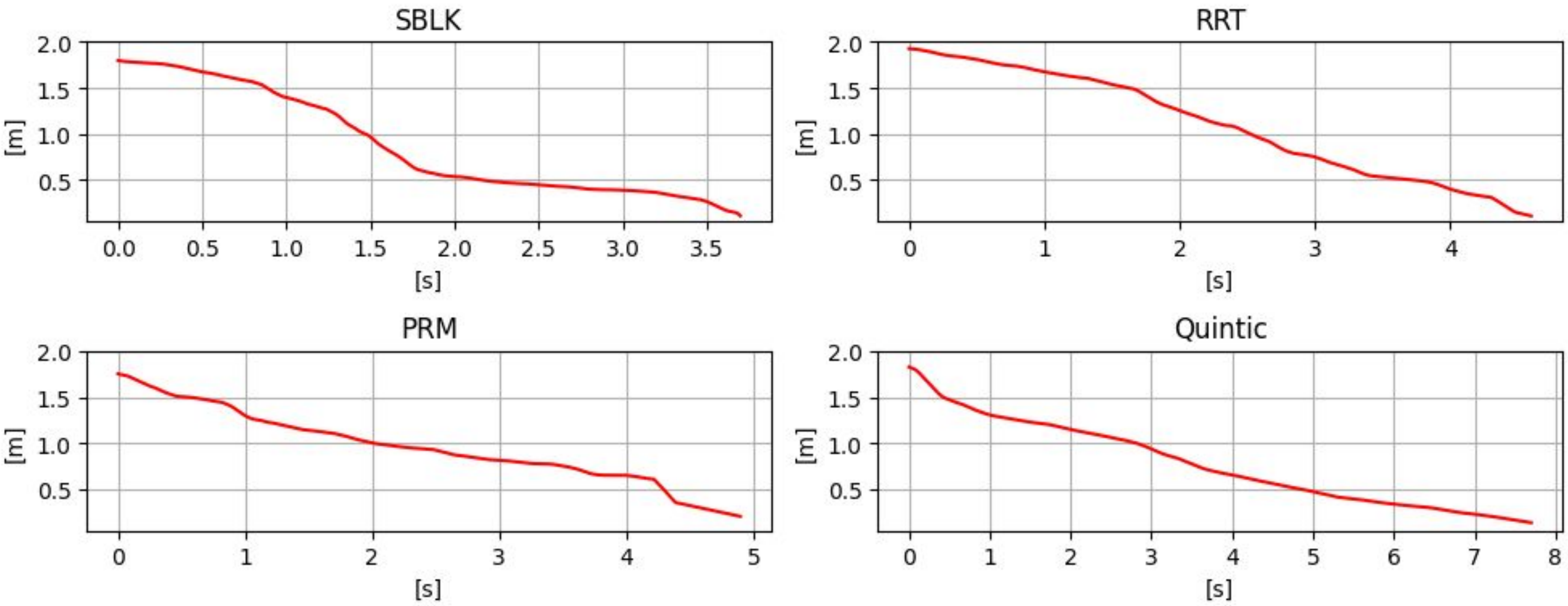




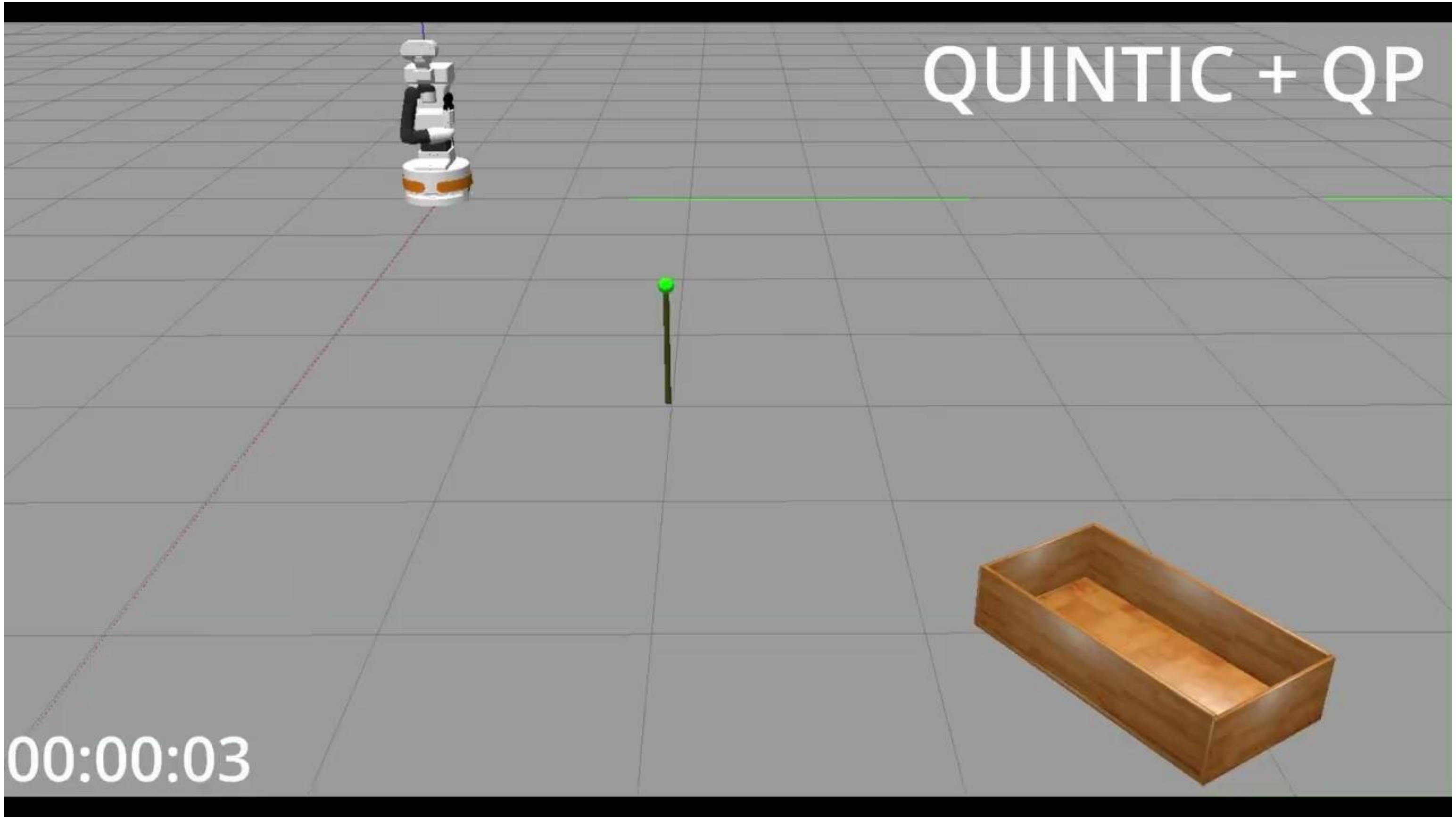
Simulations - On the move - Quintic polynomial



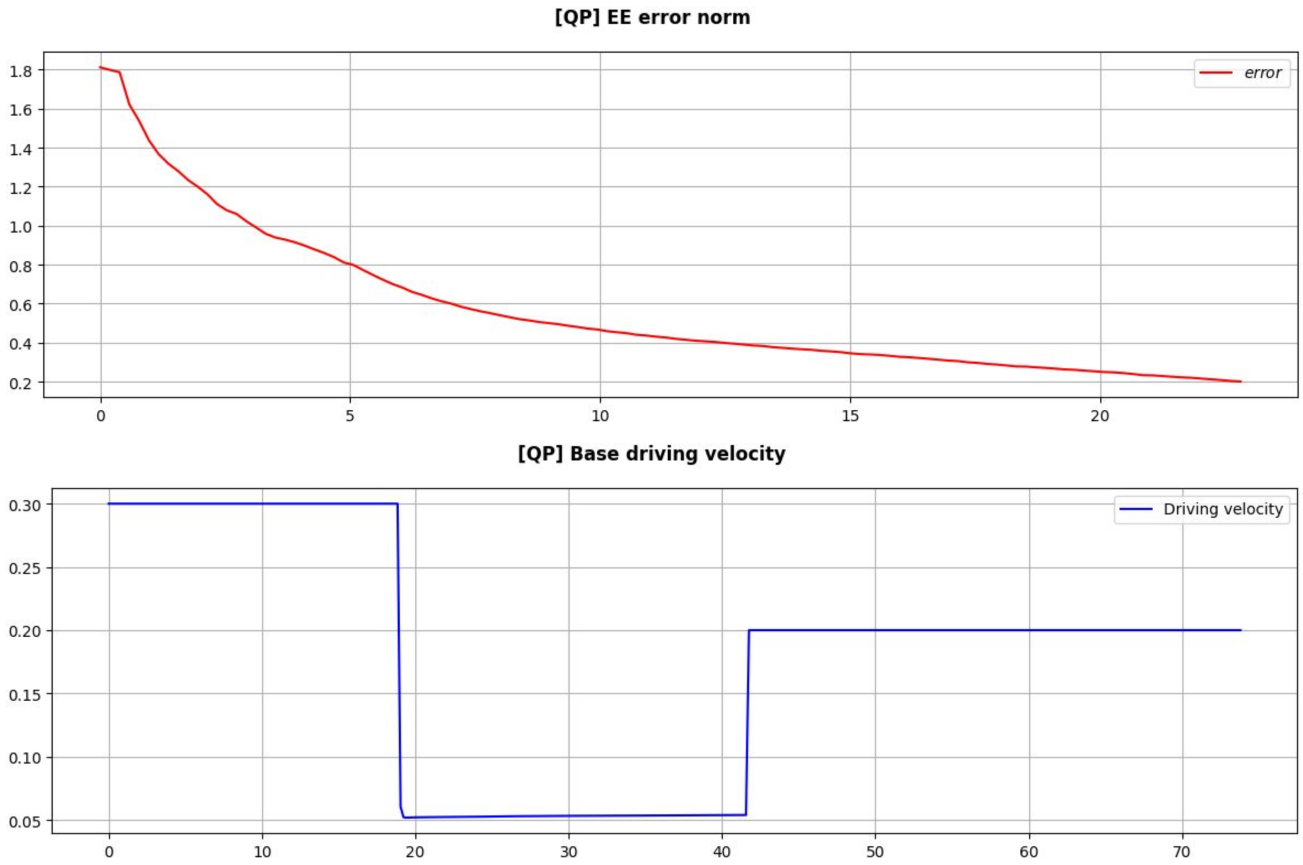
Simulations - On the move - Planners & Quintic



Simulations - On the move - Quintic + QP



Simulations - On the move - Quintic + QP



Simulations - Times and Success Rate

	On-The-Stop			On-The-Move			
Approach	$T_{plan}[s]$	$T_{traj}[s]$	$T_{tot}[s]$	$T_{plan}[s]$	$T_{traj}[s]$	$T_{tot}[s]$	sr
QQP	-	-	-	-	23.00	74.00	**10/10**
Quintic	-	23.02	60.00	-	7.67	37.80	9/10
SBLK	6.29	9.17	49.00	3.38	**3.58**	25.00	3/10
RRT	10.01	8.64	50.00	3.35	4.53	23.00	4/10
PRM	6.39	7.12	42.00	3.73	4.49	**22.00**	2/10

- Simulations time measurements comparison
  - QQP: Quintic + QP

- **Values:**
  - Planning time T_{plan}
  - Trajectory time T_{traj}
  - Total time T_{tot}
  - Success rate sr

Conclusions

- **On-The-Move problem** solved with a different approaches
  - **Base Controller** as a Geometric Regulation Task
  - **Arm Controller** performing planning in Cartesian Space
    - **Non reactive** with MoveIt plugin.
    - **Reactive** with Quintic Polynomial and Kinematic Integration.
  - **Redundancy Resolution Controller** as a QP
    - Motion coordination between arm and base.
- **Reactive** approach allows **real-time adaptation**
- **Reduction** of task execution time on-the-move.
- **Best approach**: Quintic Polynomial + Redundancy Resolution Controller
  - In terms of success rate.

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