UNIVERSITÀ DEGLI STUDI DI NAPOLI FEDERICO II

Integrated Planning and Execution for an Aerial Service Vehicle

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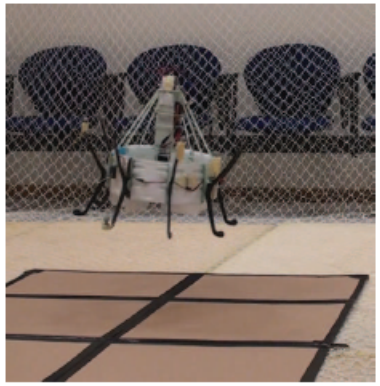
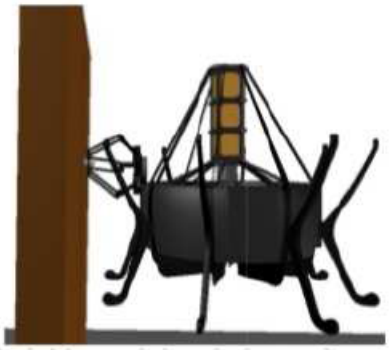
Introduction

- We present the case study of a high-level control system designed for an Aerial Service Vehicle (ASV)

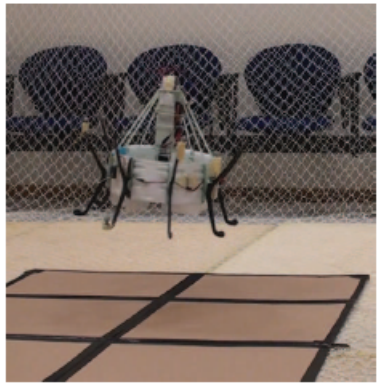
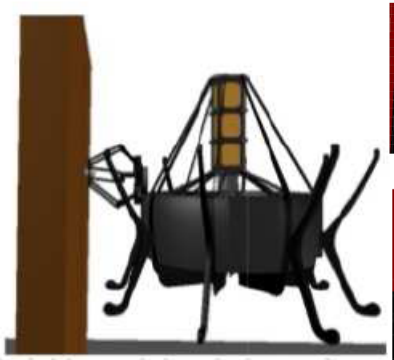
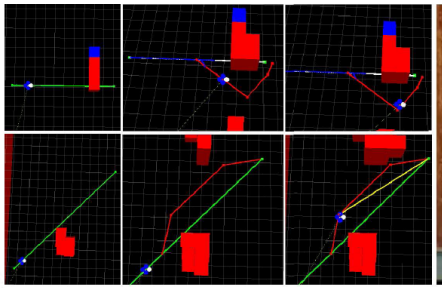
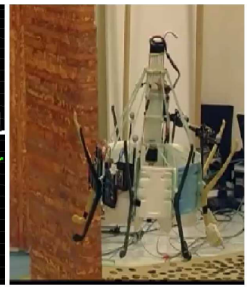
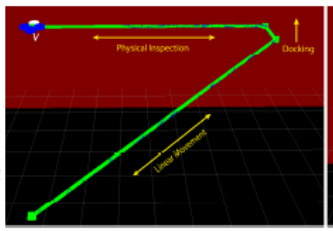
- This work is framed within the the AIRobots project (FP7 ICT2486669, Marconi et al. 2012a):
  - "A new generation of unmanned service helicopters, equipped with sensors and end-effectors, and capable not only to fly, but also to achieve robotic tasks in proximity and in contact with the surface".

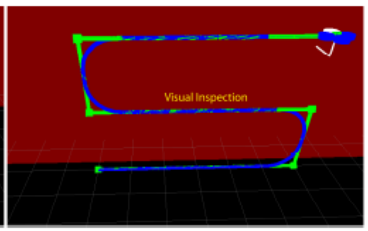




AIRobots Domain

- Remote inspection of industrial plants with ASV
- The ASV operates in proximity and in contact with the surfaces:
  - visual inspection, contact, manipulation, sample picking
- The autonomous control system should supervise and orchestrate a new set of operations:
  - Not only free-flight navigation, but also wall approach, docking, undocking, wall scanning, wall sliding, simple manipulation, etc..



Requirements

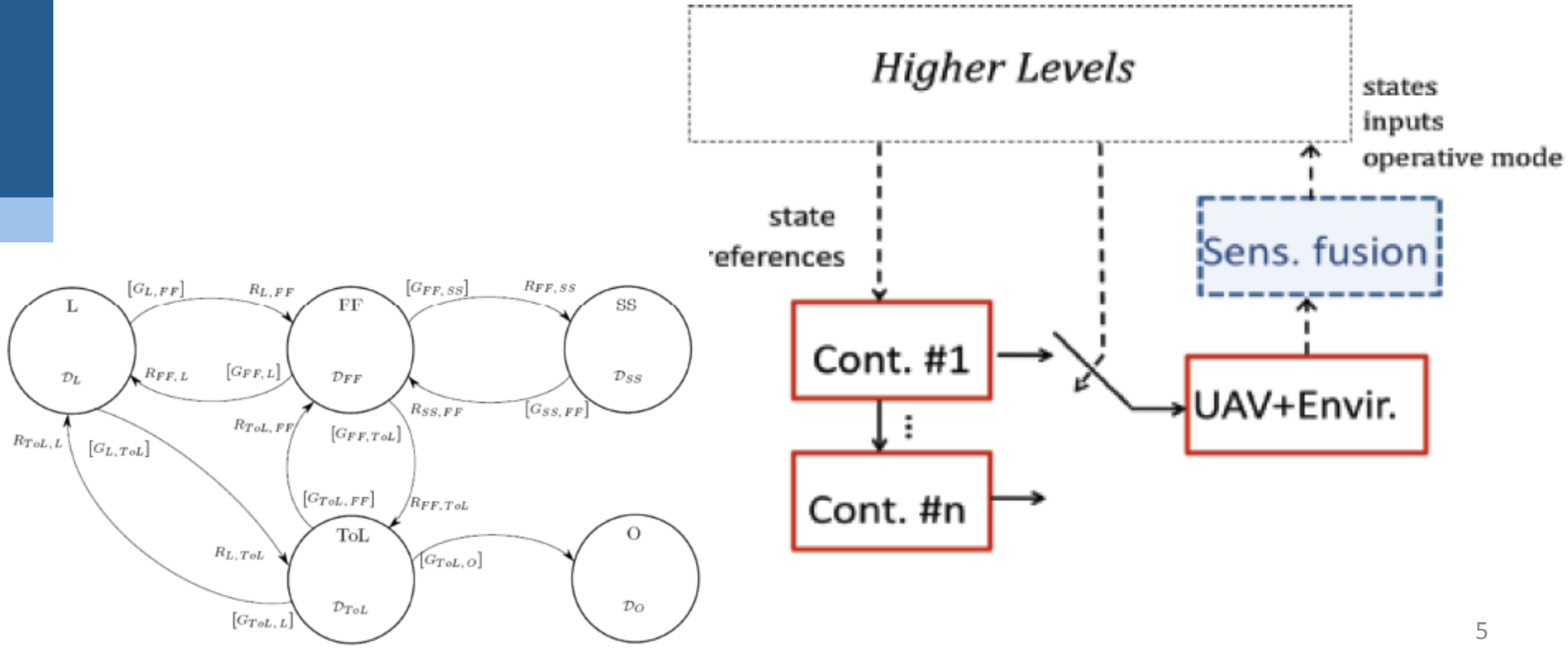
- **Reaction time and replanning:**
  - close interaction with the environment, hence reactive, adaptive, and flexible planning/ replanning capabilities are needed (task/ path/motion).

- **Sliding Autonomy and Mixed Initiative Control:**
  - Both autonomous and human-in-the-loop control modalities should be supported to allow human interventions and teleoperation.

- **High-level/Low-level integration:**
  - High-level control strategies should be defined taking into account the low-level operative modes and constraints;
  - Different control modes, smooth task switching, adjustments on-the-fly.

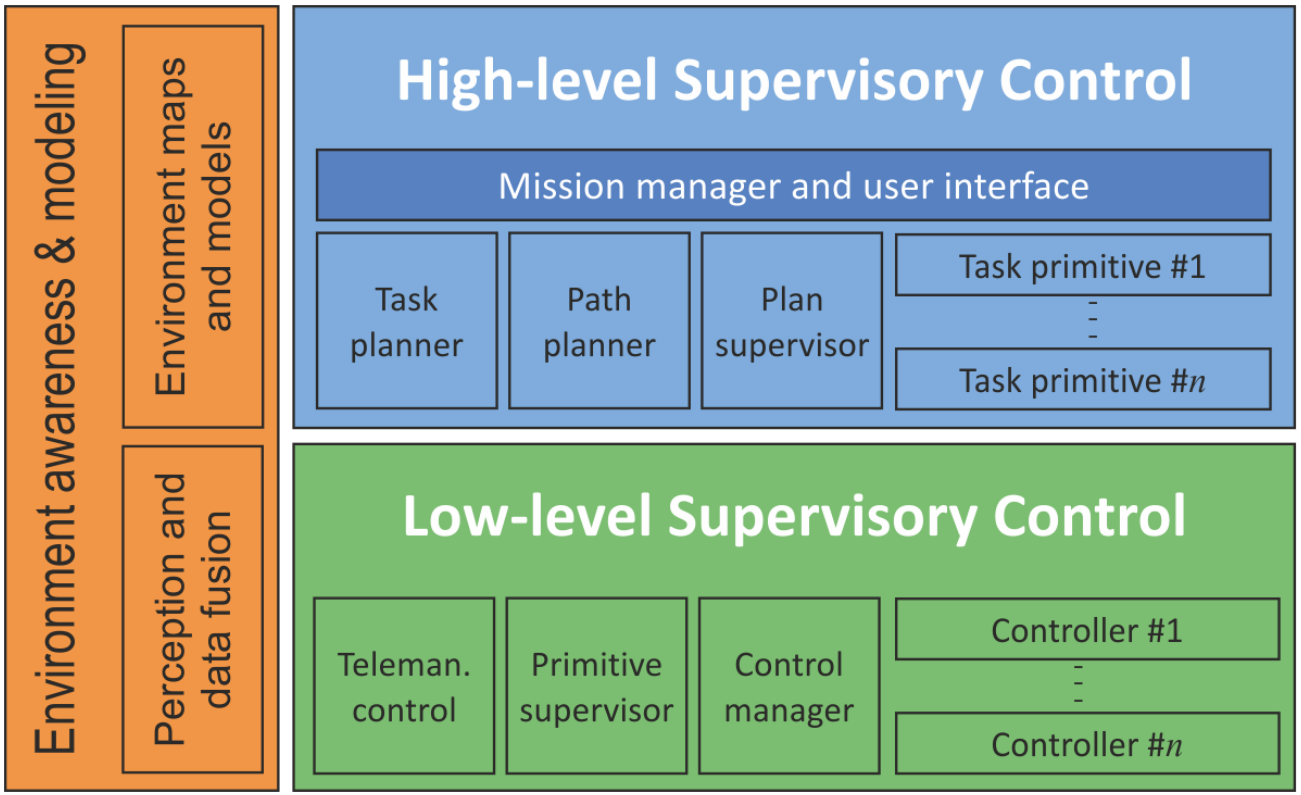
High-level/Low-level integration

- The LL control system can be modeled as a hybrid automaton [Naldi, Marconi, Gentili 2011].
- Each motion primitive has at least one controller for each operative mode.
- More controllers could be designed for a certain motion primitive depending on dynamic parameters (max velocity, maximum acceleration, etc).

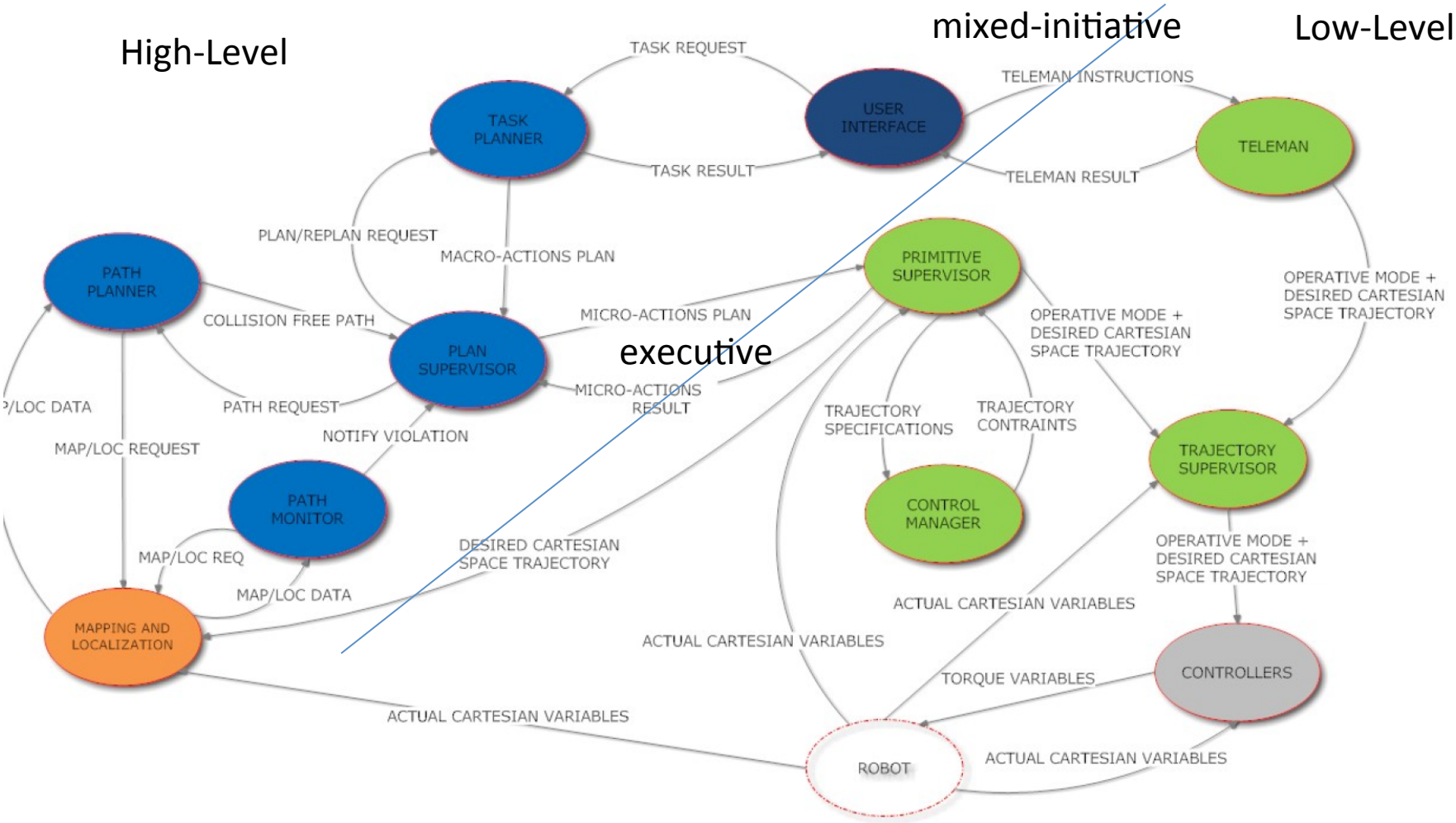


System Architecture

- Path Planner, Task Planner, Plan Supervisor (High Level), Primitive Supervisor manages trajectory planning and execution (Low Level);
- Switches between operative modes depends on HL system decisions;
- Choice of controllers in the current operative mode assigned to the Control Manager of the Low Level Supervisory Control



System Architecture



Task Decomposition

- Task Primitives (out: Task Planner, in: Path Planner):

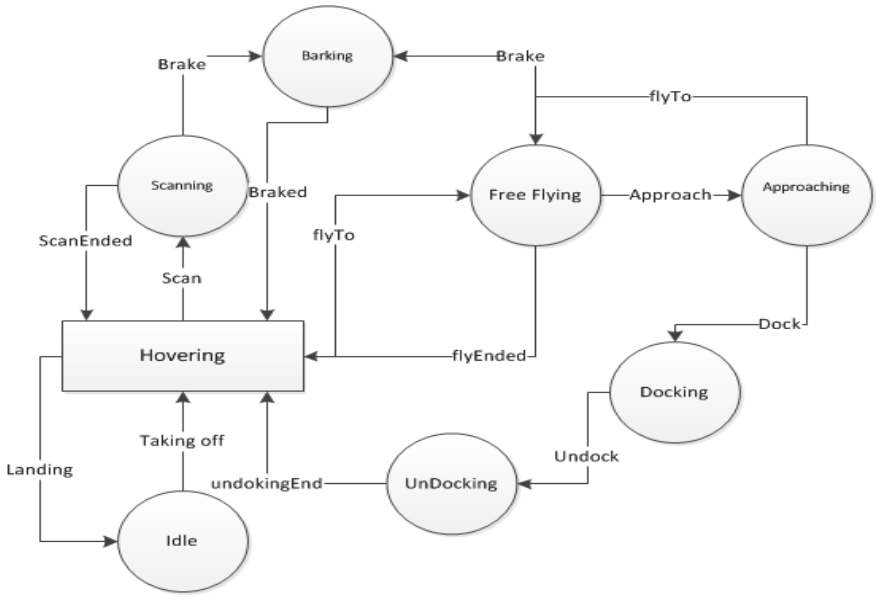
$TakeOff(C, Pos)$	Take off from the current pose and hover in the pose Pos;
$Land(C, Pos)$	Land from the current position to Pos;
$Hover(C, Pos)$	Keep the pose Pos;
$MoveTo(C, Pos)$	Move from the current pose to Pos;
$MoveCircular(C, Pos, I)$	Execute a circular movement around the center P with radius in the interval I ;
$Scan(C, Srf)$	Scan the surface Srf;
$Inspect(C, Obj, P)$	Observe the object Obj in position P;
$Brake(C)$	Execute a hard brake from the current position;
$Approach(C, P)$	Approach the target position P;
$Dock(C, P)$	Dock to a target position P;
$UnDock(C)$	Undock from the current position;
$Manipulate(C, Obj, P)$	Manipulate an object Obj in position P.

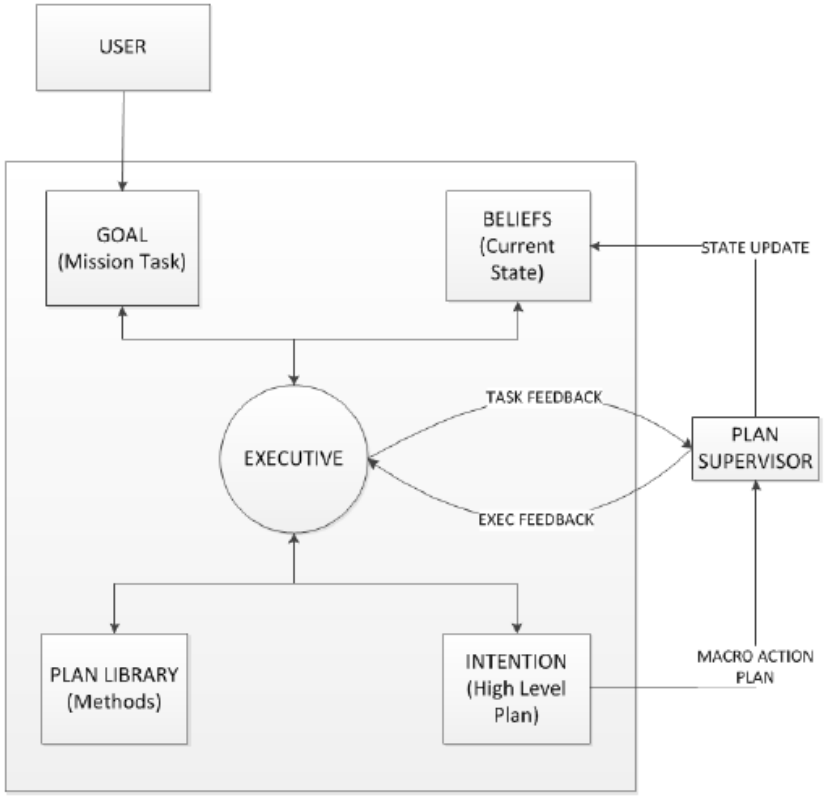
- Motion Primitives (out: Path Planner, in: Motion Planner):

$TakeOff(p)$	take off and hover at the altitude p
$Land$	land from the current position
$FlyLinearTo(\vec{ps})$	free flight from an initial pose till the final one through a set of poses $\vec{ps}$.
$FlyCircular(p_1, p_2, p_3)$	circular flight along the circumference passing through the points p_1, p_2, and p_3.
$FlyArc(p_1, p_2, p_3)$	circular flight along the circumference arc from p_1 to p_2, through p_3.
$Brake$	hard brake.
$Escape(\vec{ps})$	escape from the current position following the waypoints in the set of poses $\vec{ps}$.
$ReplanFlyLinearTo(\vec{ps})$	free flight replan following the set of poses $\vec{ps}$.
$Approach(p, d)$	approach the wall towards the point p and hover at distance of d (before docking).
$Docking$	dock to the wall.
$UnDocking$	undock from the wall.

High-Level Execution Cycle

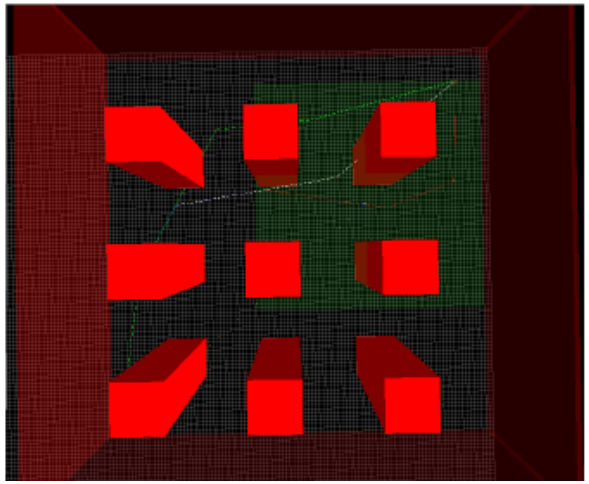
- The high-level executive system exploits a Belief-Desire-Intention (BDI) architecture to coordinate task decomposition, task replanning, path planning, and plan monitoring:
  - Belief base as the current abstract state, plan library, goals are mission tasks, and the intention base rap. the plan to be executed;
  - BDI engine based on PRS.

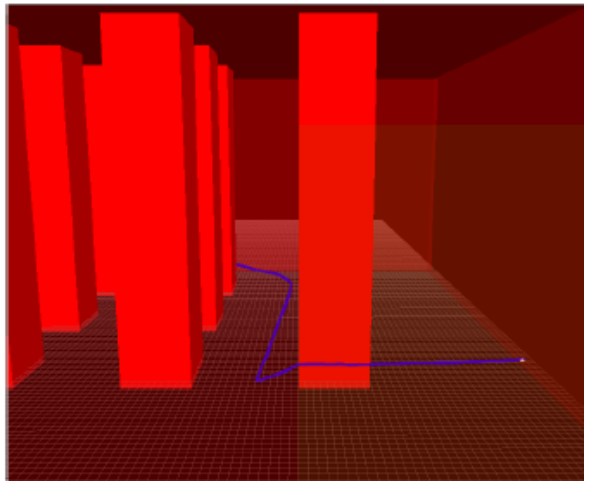




Path Planner

- The Path Planner expands each macro-action into micro-actions;
- Rapidly-exploring Random Tree (RRT) [Lavalle 98]
  - non-convex, high-dimensional search space, efficient, sub-optimal, plan refinement, replanning;
- Discretized 4D search space (N x M x Q grid map + yow)
- Constraints:
  - Min distance from obstacles;
  - Max angles (yow, pitch);
  - Max time to compute (timeout);
  - Cost threshold.



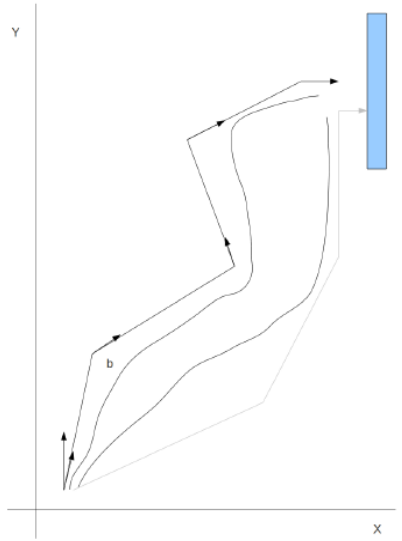


Path Planner

- The RRT planning process generates several solutions to refine the current one (until *cost threshold* or *timeout*)

Algorithm 1 Refine_RRT(q_{init},q_{goal},$threshold$,$timeout$)

initialize($path$,$time$);
while $((time < timeout) \wedge (preempted = false) \wedge (pathCost \geq threshold))$ **do**
  $newPath \leftarrow$ solveRRT(q_{init},q_{goal},$timeout$);
  if $C(newPath) < path$ **then**
    $path \leftarrow newPath$;
    $pathCost \leftarrow C(newPath)$;
  end if
end while
return $path$



- Optimization function minimizes:

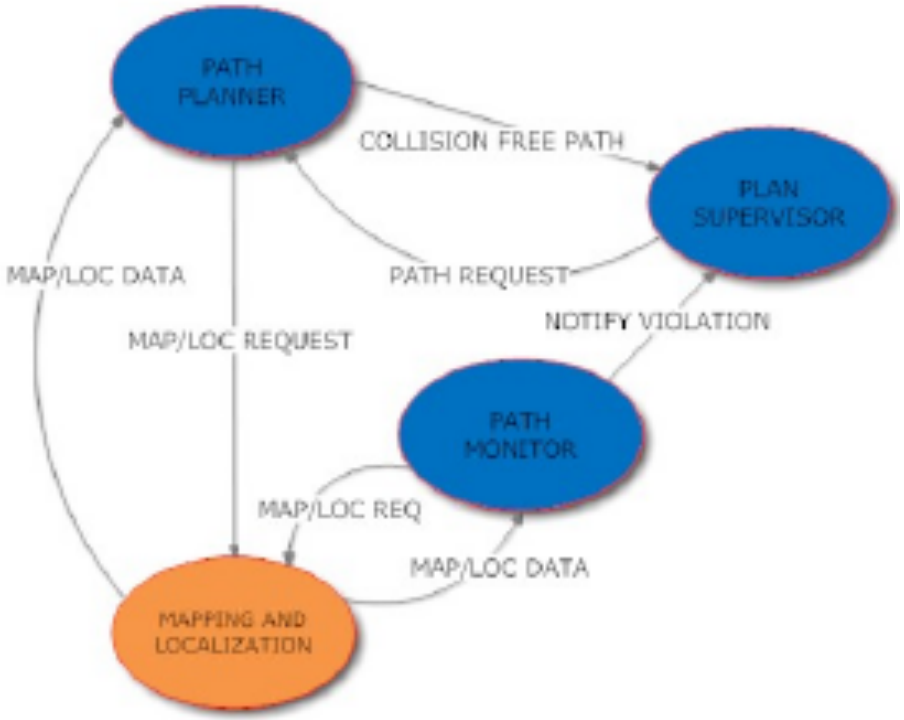
$$\mathbf{c}(path) = \mathbf{c}_{lng}(path) \cdot p_{lng} + \mathbf{c}_{ang}(path) \cdot p_{ang} + \mathbf{c}_{way}(path) \cdot p_{way} + \mathbf{c}_{obs}(path) \cdot p_{obs} + \mathbf{c}_{unk}(path) \cdot p_{unk}$$

i.e. path length ; angular variations; number of waypoints; obstacle distance; unknown space

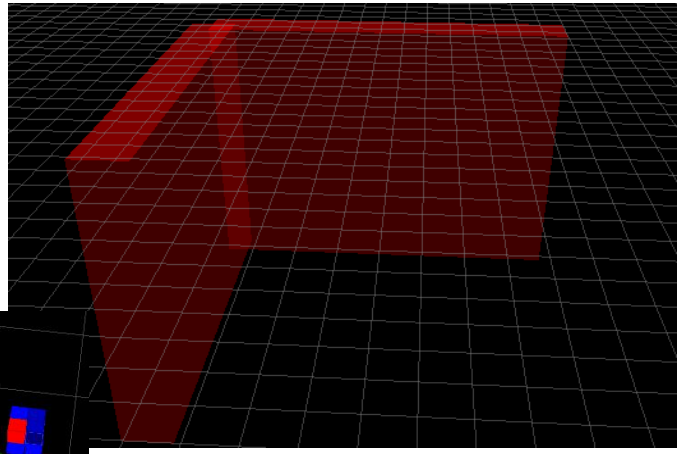
- Constraints for each segment (max speed, min distance, error tolerance).

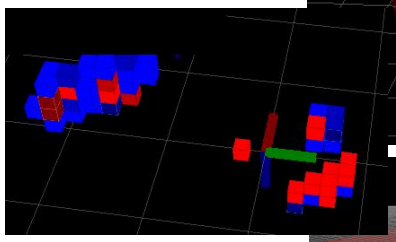
Mapping and Execution

- The 3D grid-map is continuously updated (stereoscan [Geiger et al. 2011])
- The path monitor checks for deviations or collisions
- If collision/deviation detected then replanning

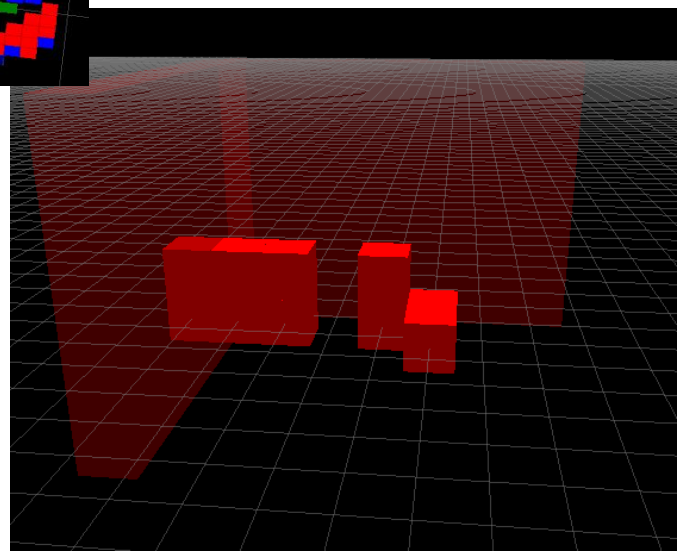


Old map





New data



New map

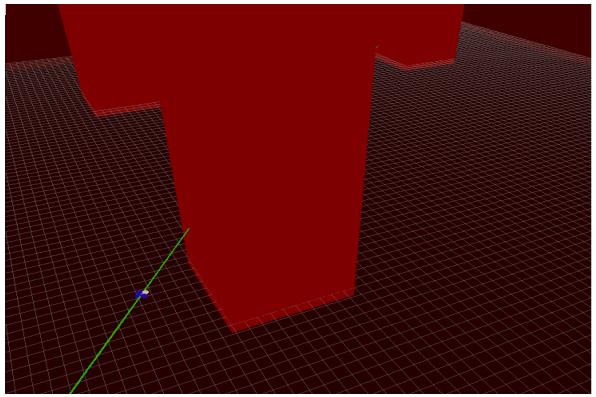
Path Replanning

- Path replanning is managed with different strategies depending on the time available for path generation;
- Given the time to collision t_c we distinguish the following cases:
  - if $(t_c < t_b)$ Brake
  - if $(t_c < t_e)$ Escape
  - Otherwise Replan

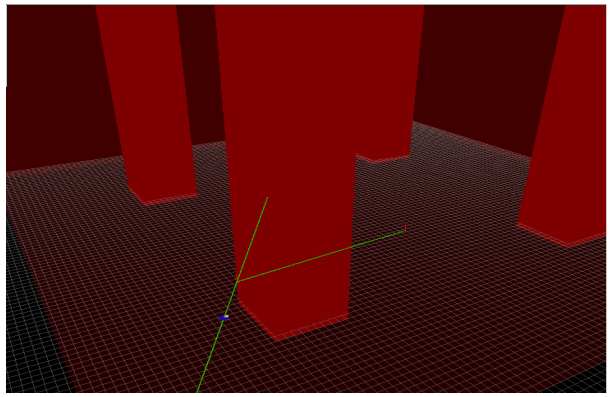
t_c = collision time

t_b = time to brake

t_e = time to escape

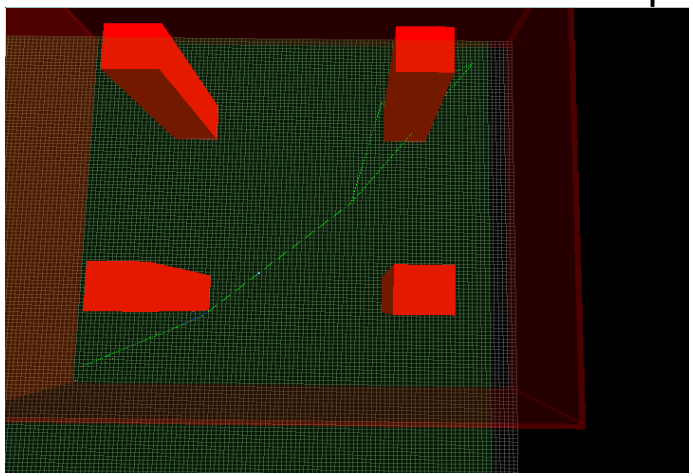


Brake



Escape

Replanning



Path Replanning

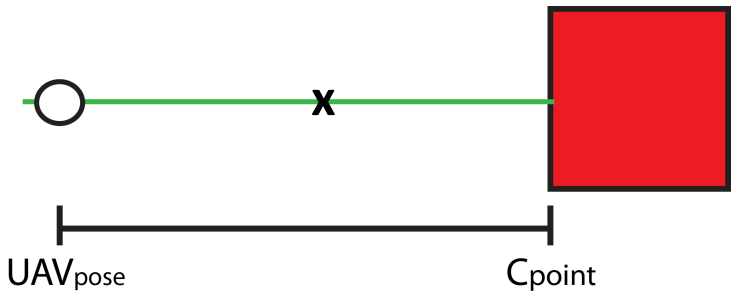
- Path replanning should find an alternative path that connects the old trajectory with a new one_while the robot is flying;

Algorithm 3 Replan(q_{goal}, $path_{old}$, q_{obs}, t_{ttc})

$q_c \leftarrow$ getPosition();
$t_{rp} \leftarrow$ estimatedRepTime(q_c, q_{goal}, $path_{old}$, q_{obs});
$wp_{rp} \leftarrow$ selectDeviationWP(q_c, q_{obs}, $path_{old}$, t_{rp});
$threshold \leftarrow$ setThreshold(wp_{rp}, q_{goal}, t_{rp}, t_{ttc});
$path_{new} \leftarrow$ Refine_RRT(wp_{rp} , q_{goal}, $threshold$, t_{rp});
return $path_{new}$

- Deviation wp:
  - Given the estimated time t_{rp} for replanning, a deviation wp_{rp} is selected: far enough from q_c to replan from wp_{rp}, but not too close to the obstacle

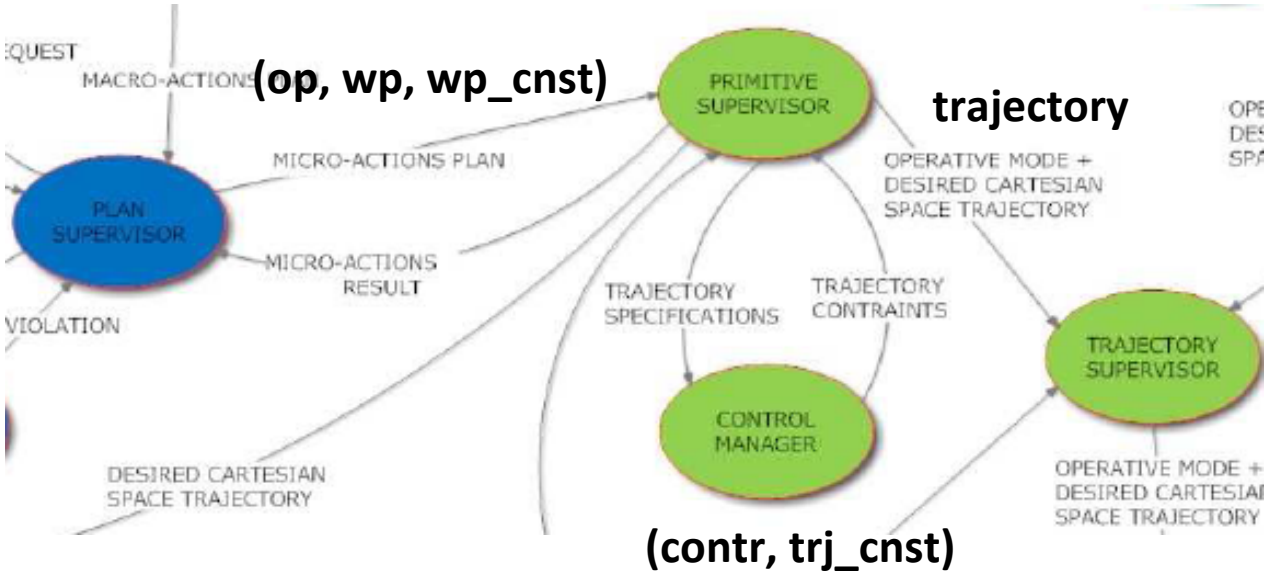
- Video



Low Level Supervisory Control

The **Primitive Supervisor** receives a sequence of micro-actions and constraints from the **Plan Supervisor** and selects the controller, generates and executes the trajectory.

The **Control Manager** selects the right controller depending on the waypoint constraints and the operative mode



Low Level Supervisory Control

The **Control Manager** selects the right controller depending on the constraints and the operative mode:

- Each controller has trajectory constraints (maximum velocity, acceleration, etc.) to guarantee the maximum position error and cruise velocity

- The Control Manager sends to the Primitive Supervisor the controller and the associated trajectory constraints so that the trajectory can be generated.

	e_{max} $[m]$	$\dot{x}_{max}$ $[m/s]$	$\dot{y}_{max}$ $[m/s]$	$\dot{z}_{max}$ $[m/s]$	$\ddot{x}_{max}$ $[m/s^2]$	$\ddot{y}_{max}$ $[m/s^2]$	$\ddot{z}_{max}$ $[m/s^2]$	$\dddot{x}_{max}$ $[m/s^3]$	$\dddot{y}_{max}$ $[m/s^3]$	$\dddot{z}_{max}$ $[m/s^3]$
Cont.1	0.25	0.5	0.5	0.3	0.2g	0.2g	0.2g	2000	2000	2000
Cont.2	0.15	0.25	0.25	0.2	0.1g	0.1g	0.1g	1000	1000	1000
Cont.3	0.1	0.1	0.1	0.1	0.05g	0.05g	0.05g	500	500	500

	$\Delta\theta_{max}$ $[rad]$	$\dot{\theta}_{max}$ $[rad/s]$	$\ddot{\theta}_{max}$ $[rad/s^2]$	$\dddot{\theta}_{max}$ $[rad/s^3]$
All	0.1	0.2	0.2g	2000

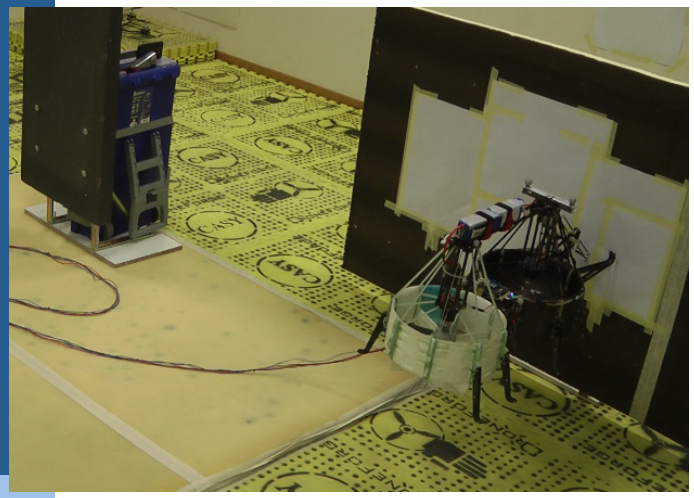
Motion Planning

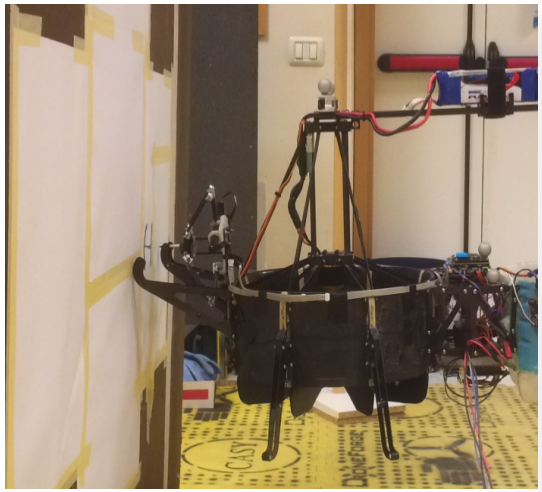
- **Constraints:**
  - Smoothness: The trajectory needs to be continuous up to the acceleration;
  - Limits: Limits on the absolute values of velocities, accelerations and jerk;
  - On-line and incremental: Both a point-to-point and fly motions; addition of new points for a multi-fly movement without modifying the already generated trajectory.

- **Approach:**
  - The motion trajectory is generated as fifth-order polynomials concatenations [Macfalane Croft 2003] (smoothness, jerk-bounded, on-line)
  - Number of waypoints can be incrementally added (dynamic and incremental). This horizon is regulated by the Plan Supervisor.

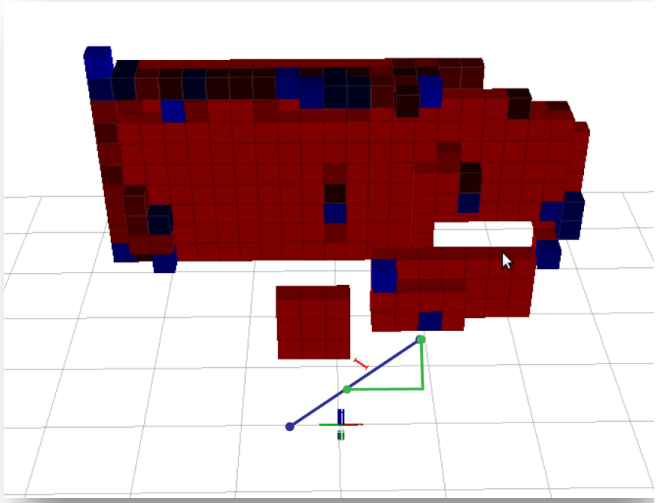
Test: Inspection Tasks

- Inspection tasks (physical contact, visual inspection)



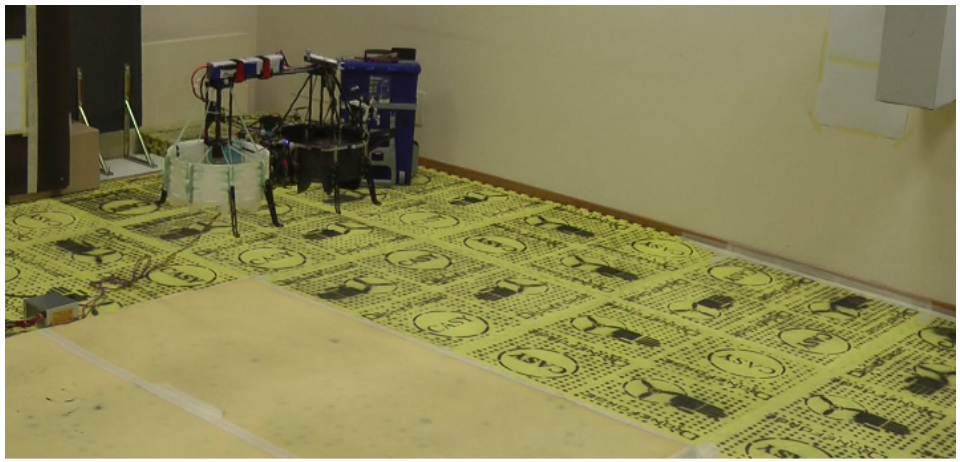


Docking and Manipulation in the real scenario



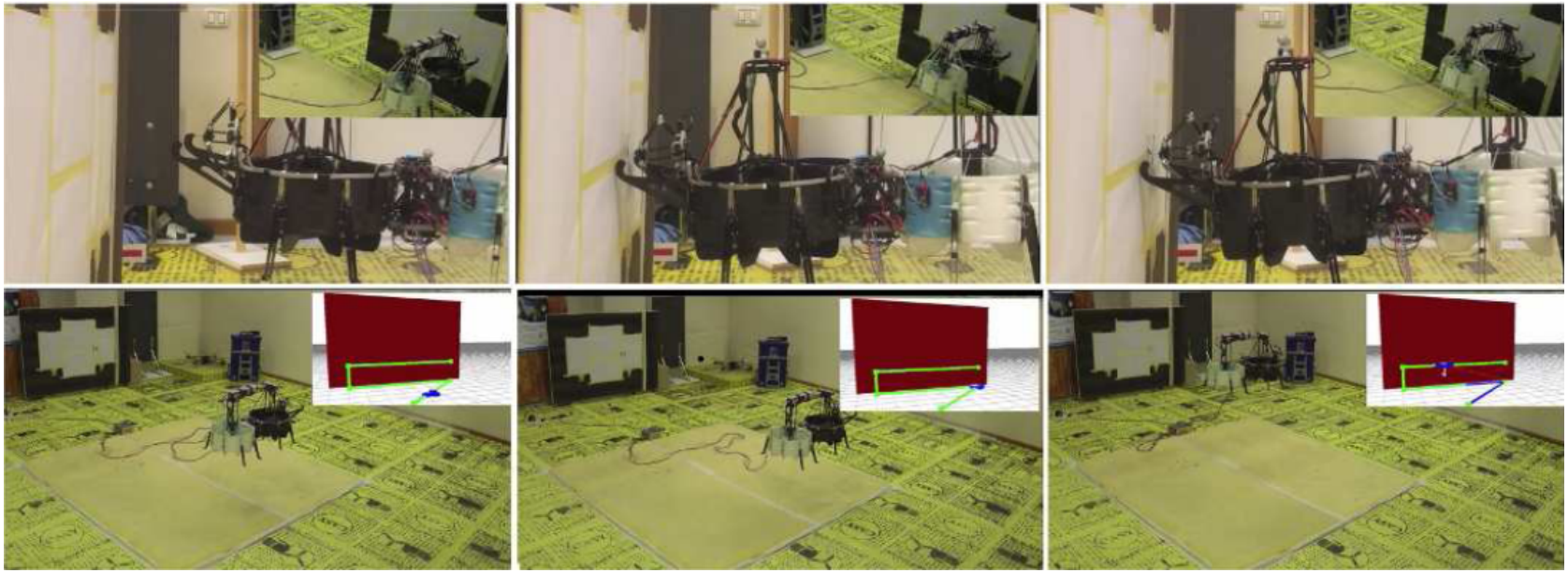
Replan, Execute, and Docking

Wall detection and Visual Inspection in the real scenario



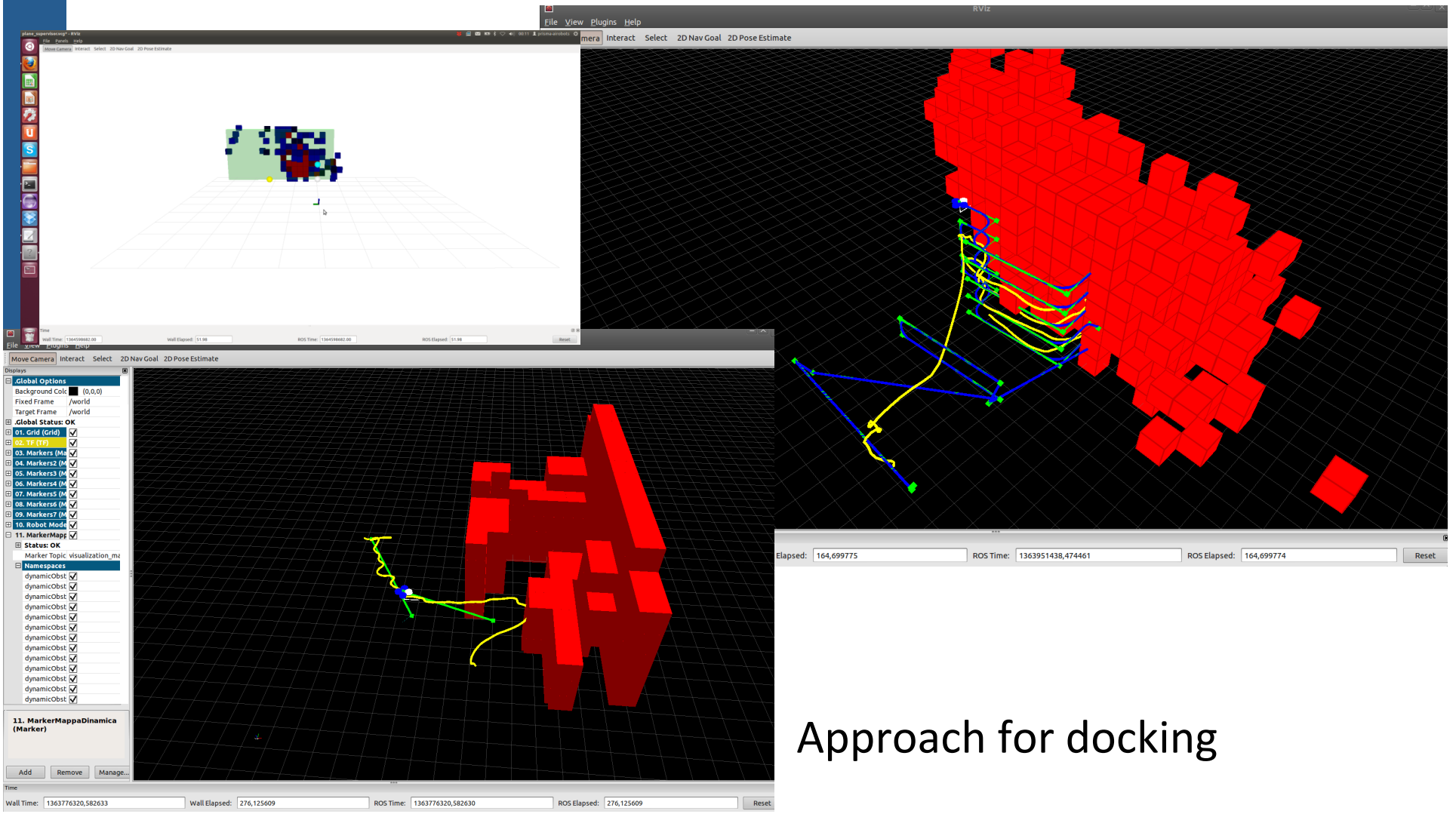
Test: Inspection Tasks

- Docking and physical inspection
- Wall detection and visual inspection



Test: Inspection Task

Strategy for wall detection and visual inspection



Approach for docking

Conclusion

- Aerial Service Robotics is a novel application for plan-based autonomy;
- We presented the challenges of the ASV domain along with the solutions provided within the AIRobot project;
- The proposed high-level system combines hierarchical task decomposition, mixed-initiative control, BDI execution, RRT path planning/replanning to allow reactivity, flexibility, and sliding autonomy;
- Future work:
  - Deeper integration between high-level and low-level system;
  - Learning methods for parameters setting;
  - More complex mixed initiative and sliding autonomy.

SHERPA

Smart collaboration between **H**umans and ground-a**E**rial **R**obots for im**P**roving rescuing activities in **A**lpine environments