Exploiting Vision and External Force Estimation for Aerial Manipulation

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- Introduction
- Interaction control for VToL UAVs + robotic arms
  - Lightweight sensorized robotic arm concept
  - Momentum-based force/moment estimator
  - Impedance control of a VToL UAV (decentralized control)
- Visual servoing for aerial manipulation
  - Point-based visual servoing
  - Moments-based visual servoing
- Conclusion

- From a general point of view, for aerial manipulation we mean the grasping, transporting, positioning, and assembly/disassembly of mechanical parts, measurement instruments, and objects performed with Vertical Take-off and Landing (VToL) Unmanned Aerial Vehicles (UAVs) endowed of a gripper and/or a robotic arm

- Aerial robotics has become a new frontier in service robotics

Why Aerial Manipulation

- Really useful?

Why Aerial Manipulation

- Business opportunity?

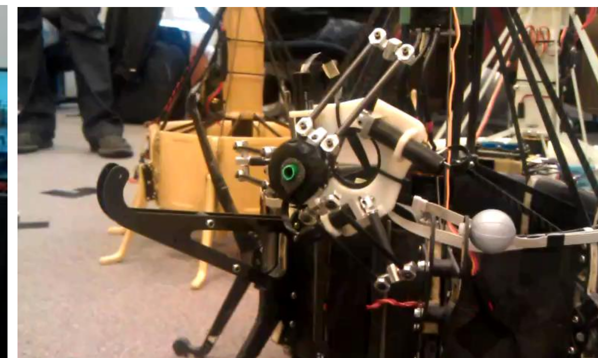
Delivering

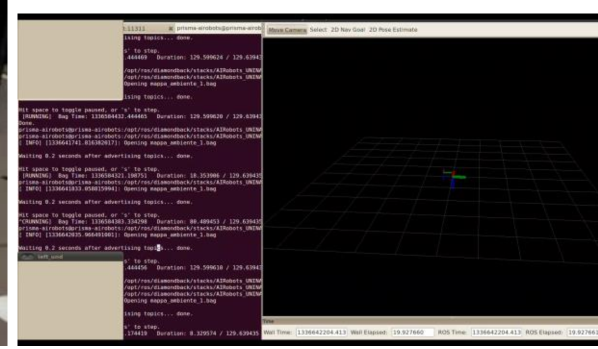
Industry

Marketing

Research in Aerial Manipulation

AIRobots





Research in Aerial Manipulation

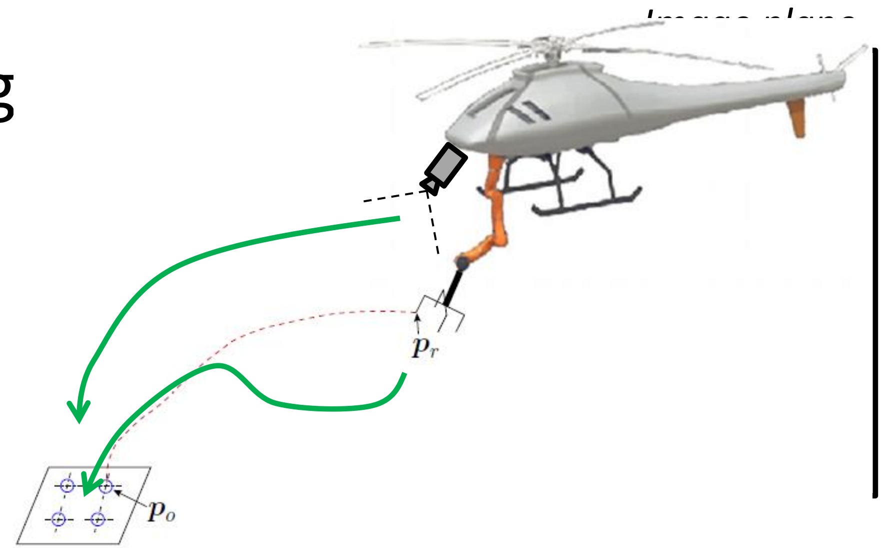
Research in Aerial Manipulation

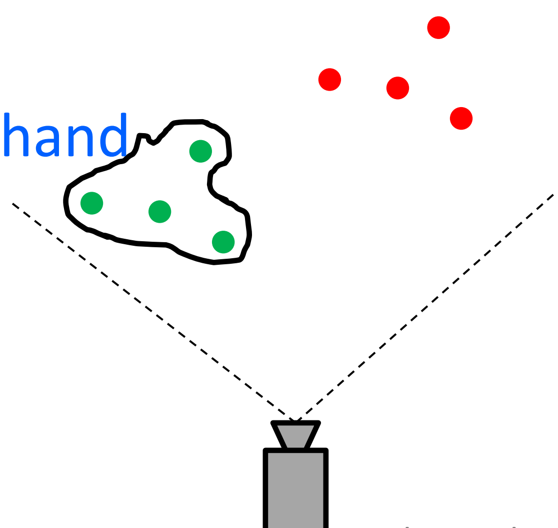
Required Capabilities for Aerial Manipulation

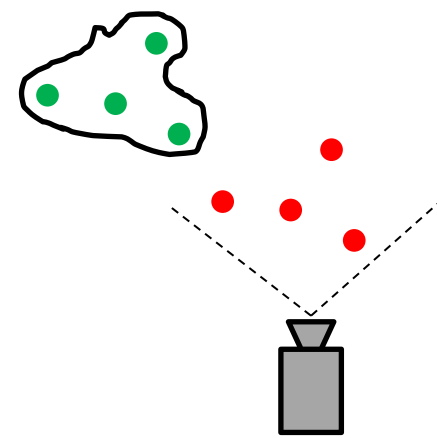
- Vision plays a primary role in grasping and assembly tasks in unstructured environment
- Interaction control is needed during the physical contact to reduce undesired interaction force and moment
  - The measurement/estimation of the interaction force and moment is required for the low-level control of the UAV

Image-based Visual Servoing

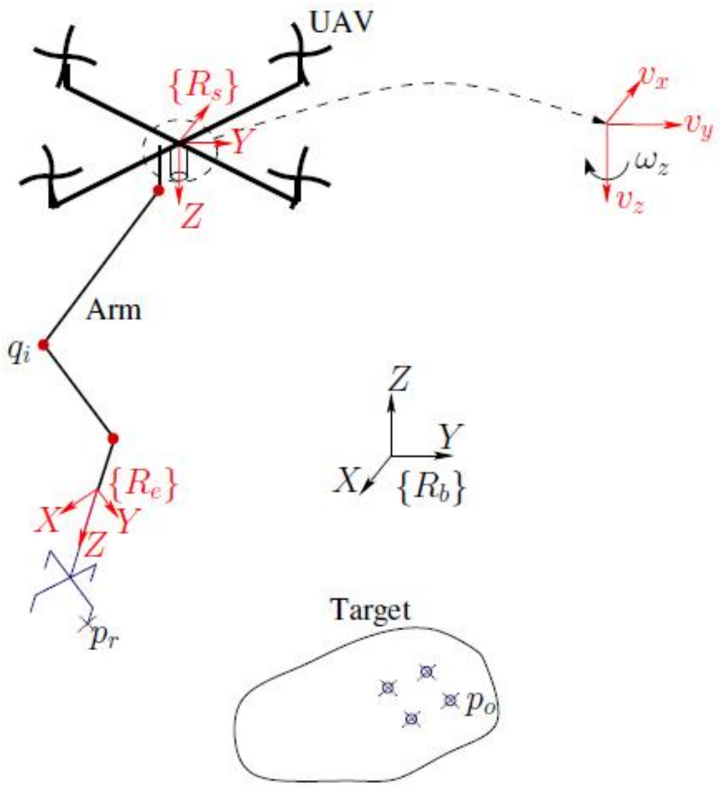
- Image-based visual servoing
  - Control input (control law) defined directly into the image plane of the camera
- Camera configuration
  - Eye-to-hand
  - Eye-in-hand
  - Onboard-eye-to-hand







Kinematics of the Observed Points



- Image point coordinates

$$\boldsymbol{s}_O = (x_O \;\; y_O)^\top \in \mathbb{R}^2$$

- Target image kinematics

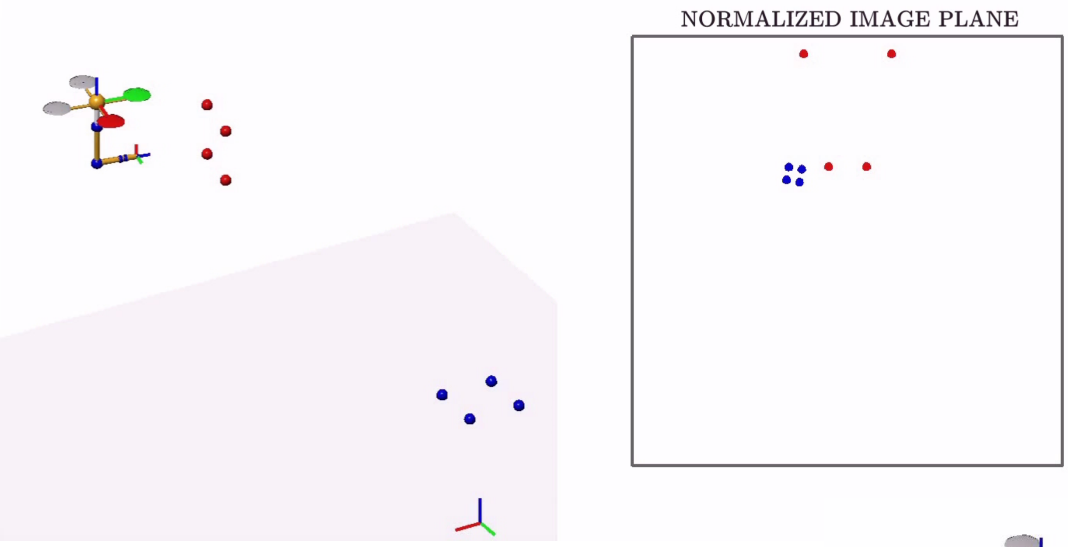
$$\dot{\boldsymbol{s}}_O = \boldsymbol{L}_O \mathbf{v}$$

  - L_O interaction matrix
- Carried points kinematics

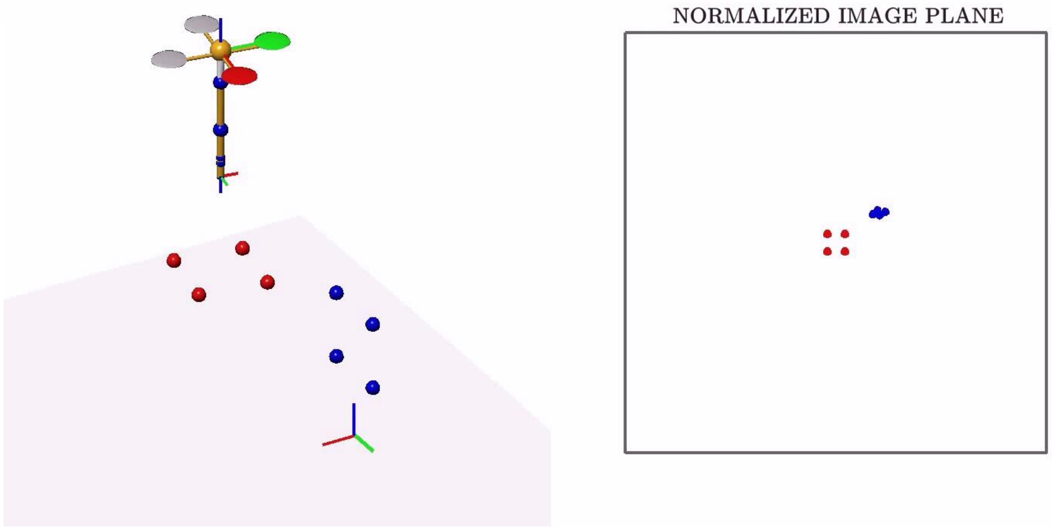
$$\dot{\boldsymbol{s}}_r = \boldsymbol{L}_r \, \dot{\boldsymbol{q}}$$

  - q robotic arm joint vector

Point-based Visual Servoing Examples



Motion of the image features in the image plane is smooth and quite straightforward



Drawback: Cartesian motion in the 3D space can be undesirable and/or unpredictable, that could not be borne in practice

Point-based Image Moments

- Image feature vector of point-based image moments

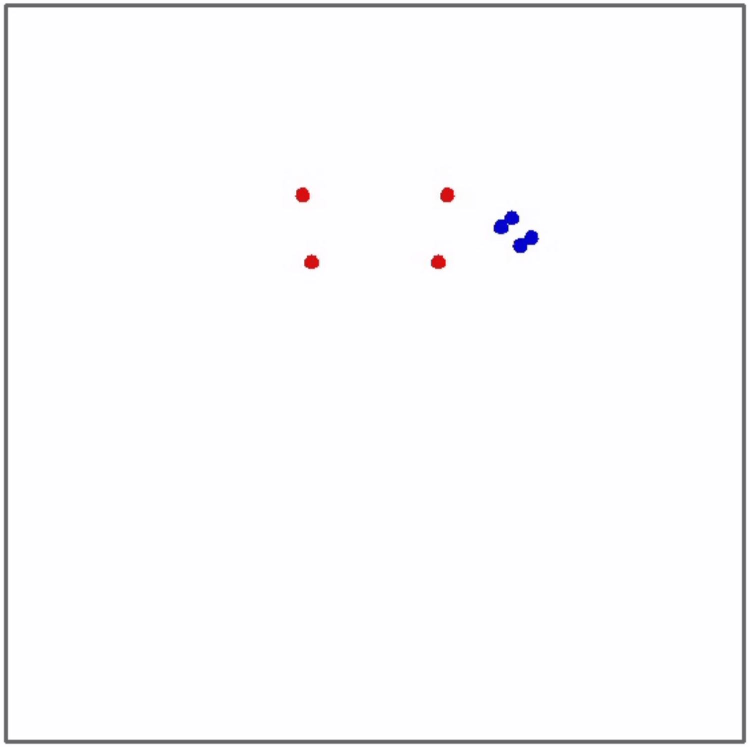
$$s_m = \left(\sqrt{a} \quad x_g \quad y_g \quad \eta_{11} \quad I_1 \quad \sqrt{I_2}\right)^{\top} \in \mathbb{R}^6$$

with

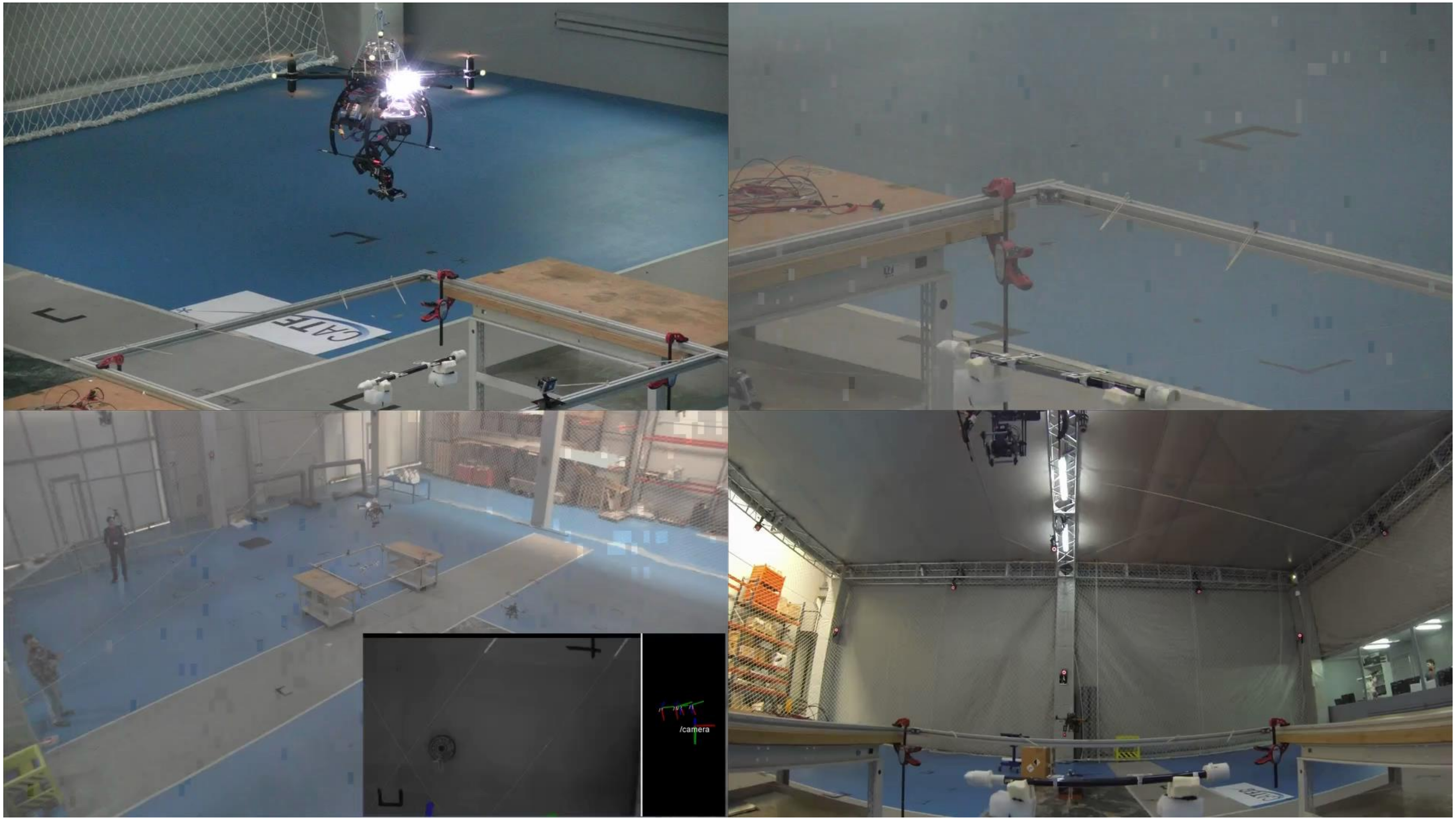
$$\begin{cases} a = m_{00}, \quad x_g = m_{10}/a, \quad y_g = m_{01}/a \\ I_1 = \eta_{20} + \eta_{02}\,, \quad I_2 = 4\eta_{11}^2 + (\eta_{20} - \eta_{02})^2 \end{cases} \qquad \begin{cases} \mu_{pq} = \displaystyle\iint_S (x - x_g)^p \,(y - y_g)^q \,\mathrm{d}x\,\mathrm{d}y \\ \eta_{pq} = \mu_{pq}/a^{(1+\frac{p+q}{2})} \end{cases}$$

  - Area is mainly affected by motions orthogonal to the camera plane
  - The centroid coordinates are affected by the motion parallel to the image plane
  - Term η_{11} is related to the main angle of the prospective points shape section, that strongly depends on the rotation around the optical axis
  - Terms I_1 and I_2 are invariant to both scale, translation, and rotation in the image, thus they should be affected mainly by the remaining motions: the rotations around image x- and y-axis

Example: Orthogonal Assembly



Visual Grasp Results



Control of a VToL UAV + Robotic Arm

- Two main approaches
  - Centralized control
    - The whole dynamic model of the VToL UAV plus the multi-link robot manipulator is considered and the control law is designed on the basis of this complete dynamic model
  - (Partially) Decentralized control
    - The VToL UAV and the robot arm are considered as two independent systems
      - The effects of the robot arm on the VToL UAV are considered as external disturbances, and vice versa
    - This approach could be useful in case of the dynamics of the arm is not enough to compensate the UAV positioning errors and/or in case of an arm with servo motor (torque control not allowed)

Decentralized Control

- On the one hand, the control of a robot arm with external disturbances has been deeply examined in the robotics literature
- On the other hand, the control of a VToL UAV with external disturbances is an appealing recent scenario
- Dynamic model of a VToL UAV

$$m\ddot{\boldsymbol{p}}_b + m\boldsymbol{g} = u\boldsymbol{R}_b(\boldsymbol{\eta}_b)\boldsymbol{i}_3 + \boldsymbol{f}_{ext}$$
$$\boldsymbol{M}(\boldsymbol{\eta}_b)\ddot{\boldsymbol{\eta}}_b + \boldsymbol{C}(\boldsymbol{\eta}_b, \dot{\boldsymbol{\eta}}_b)\dot{\boldsymbol{\eta}}_b = \boldsymbol{Q}(\boldsymbol{\eta}_b)^{\mathrm{T}}\boldsymbol{\tau}_b^b + \boldsymbol{\tau}_{ext}$$

where the generalized (*ext*) forces may represent unmodeled aerodynamics effects, imbalances, motion of the robotic arm placed for aerial manipulation actions, interaction with the environment, wind, and so on

Decentralized Control

- The control aim is to build control inputs u and $\boldsymbol{\tau}_b^b$ so as to guarantee tracking of the planned trajectory at the best in unconstrained directions even in presence of external disturbances or unmodelled dynamics
- Two solutions coming from service robotics have been investigated to be applied in the aerial robotics scenario
  - Impedance control
  - Passivity-based control
- It could be shown that, in case of either constant or slowly-varying external generalized forces, a proper feedback of the estimate of such generalized forces improves performance of the controllers
  - A momentum-based external generalized forces estimator is thus proposed

Momentum-based Force/Moment Estimator

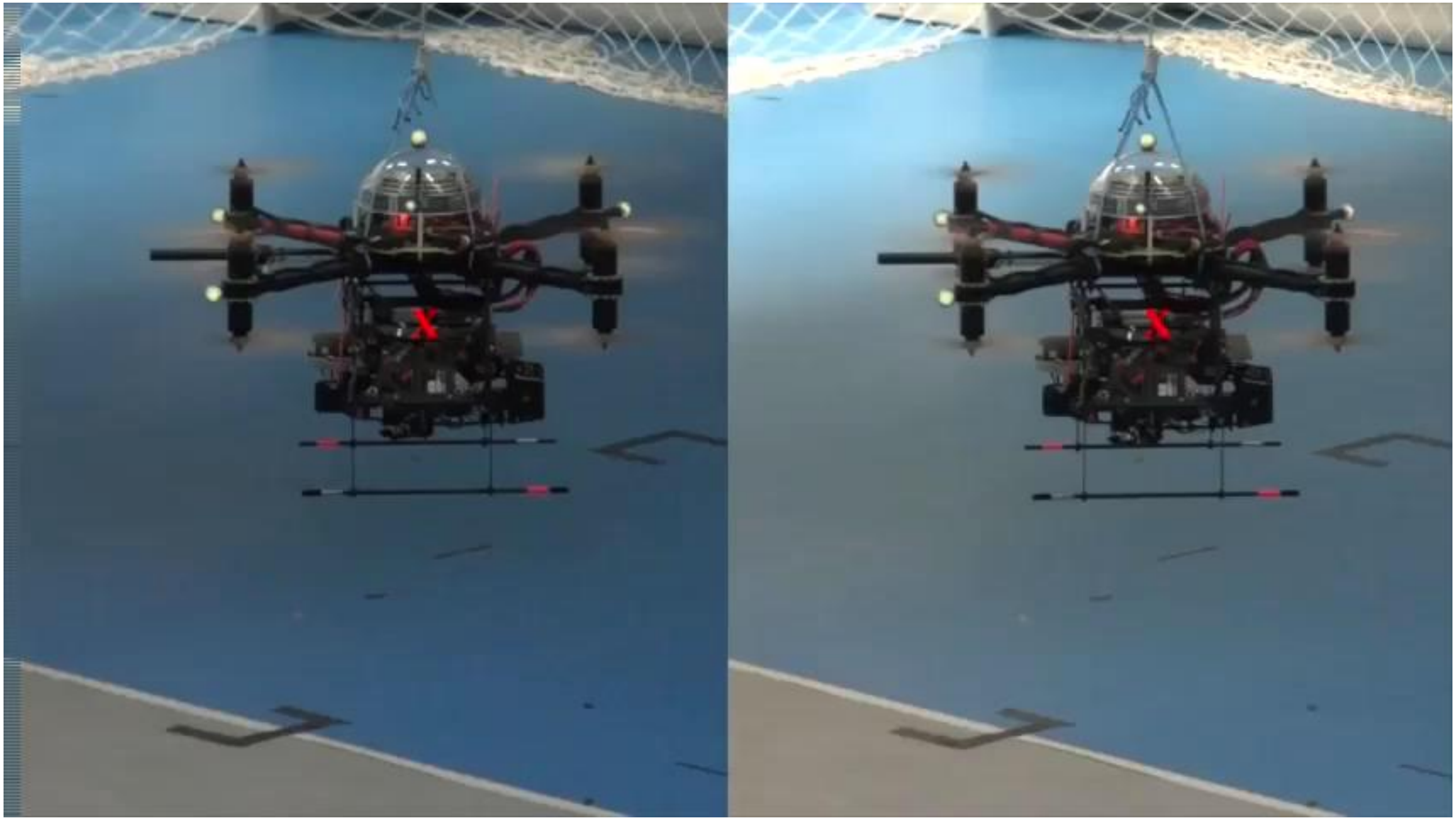
- The expression of the estimated external generalized forces in the time domain is defined as follows

$$\begin{bmatrix} \widehat{\boldsymbol{f}}_{ext} \\ \widehat{\boldsymbol{\tau}}_{ext} \end{bmatrix} = \boldsymbol{r}(t) = \boldsymbol{K}_1 \left(\int_o^t -\boldsymbol{r}(t) + \boldsymbol{K}_2 \left(\boldsymbol{q}(t) - \int_0^t \left(\begin{bmatrix} u\boldsymbol{R}_b(\boldsymbol{\eta}_b)\boldsymbol{i}_3 - m\boldsymbol{g} \\ \boldsymbol{Q}(\boldsymbol{\eta}_b)^{\mathrm{T}}\boldsymbol{\tau}_b^b + \boldsymbol{C}(\boldsymbol{\eta}_b, \dot{\boldsymbol{\eta}}_b)^{\mathrm{T}}\dot{\boldsymbol{\eta}} \end{bmatrix} + \boldsymbol{r}(t) \right) ds \right) ds \right)$$

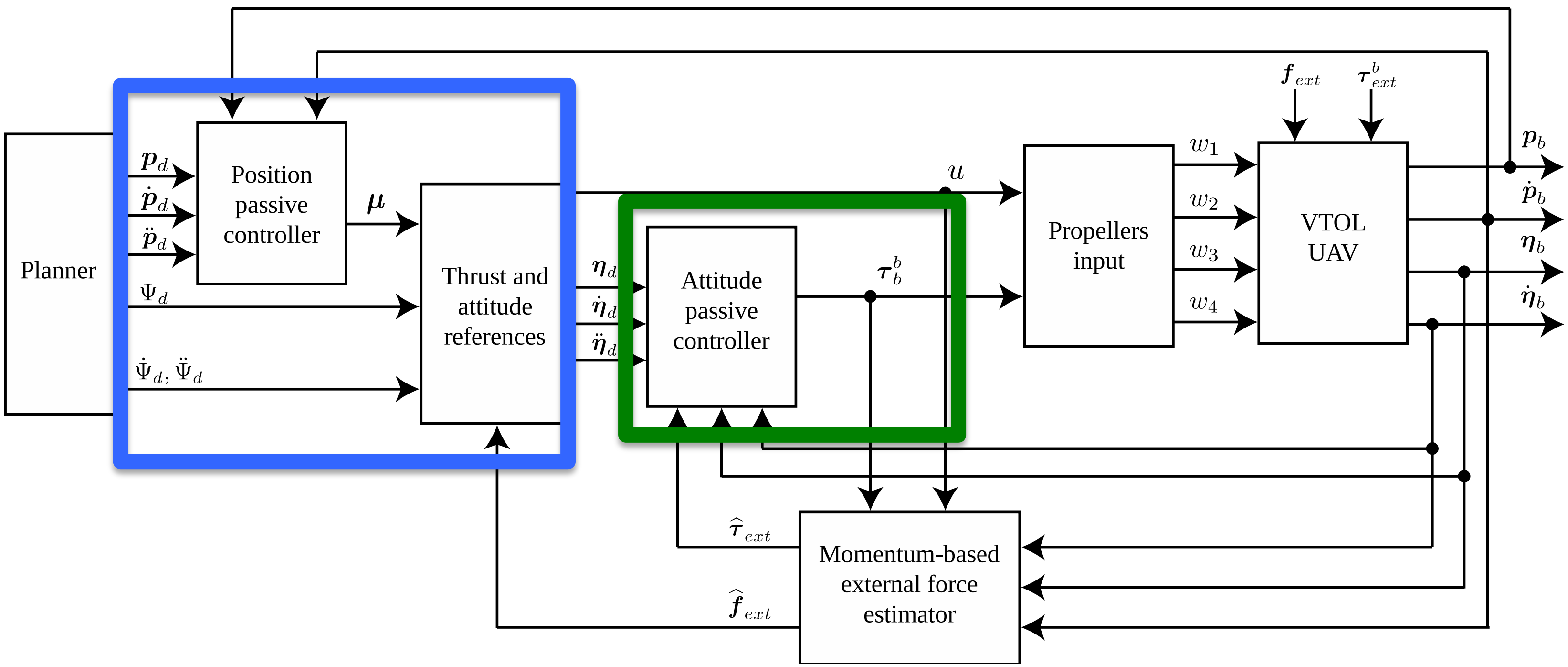
  where $\boldsymbol{q}(t)$ is the momentum of the system
- The estimator is based on the concept of the momentum conservation principle
  - Starting from the known model of the system, all the unmodelled terms and the external forces plus moments are estimated to preserve the system's momentum
- Notice that
  - no inversion of the inertia matrix is required
  - no knowledge of the absolute position of the vehicle is necessary

Control Benefits

EXPERIMENTAL RESULTS

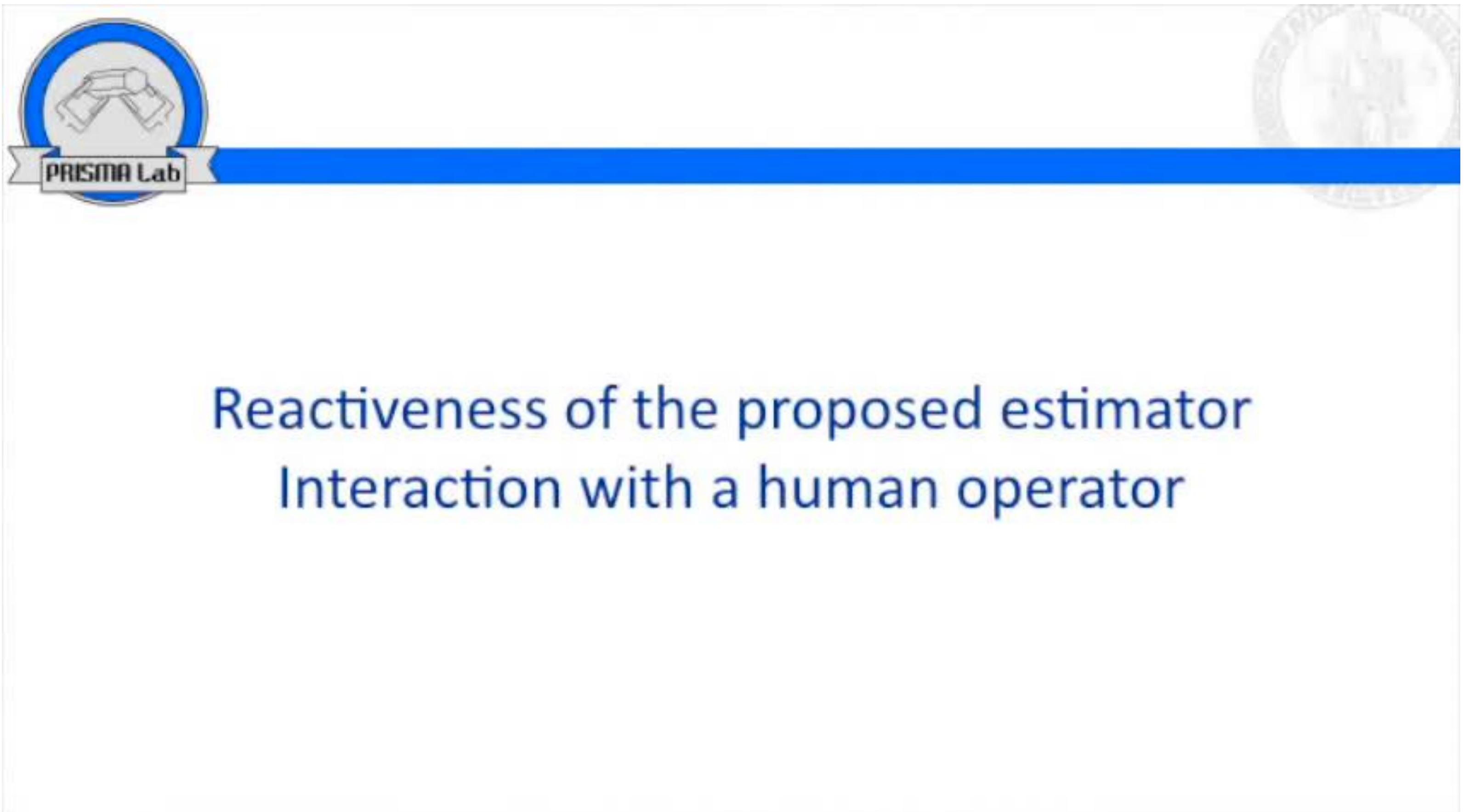


Passivity-based Control



$$m\ddot{\boldsymbol{e}}_p + \boldsymbol{D}_p\dot{\boldsymbol{e}}_p + \boldsymbol{K}_p\boldsymbol{e}_p = u\boldsymbol{\delta}(\boldsymbol{\eta}_d, \boldsymbol{e}_\eta) + \widetilde{\boldsymbol{f}},$$

$$\boldsymbol{M}(\boldsymbol{\eta}_b)\left(\dot{\boldsymbol{v}}_\eta + \boldsymbol{D}_o\dot{\boldsymbol{e}}_\eta + \boldsymbol{K}_o\boldsymbol{e}_\eta\right) + \boldsymbol{C}(\boldsymbol{\eta}_b, \dot{\boldsymbol{\eta}}_b)\boldsymbol{v}_\eta = \widetilde{\boldsymbol{\tau}},$$


Reactiveness of the proposed estimator
Interaction with a human operator

Conclusion

- A new visual-servoing scheme relevant for the onboard-eye-to-hand camera-configuration class has been presented
  - Image moments, thanks to their intuitive and geometrical meaning, have been adopted in order to improve system capability of interacting with the target
  - Undesirable/unpredictable Cartesian motions that could not be borne in practice can be avoided
- A new passivity-based control has been designed to control a VToL UAV in case of interaction with the environment
  - A new momentum-based force/torque estimator has been designed and tested for the UAV control