Simone D'Angelo

Control techniques for tilting unmanned aerial manipulators for in-contact non-destructive testing

Tutor: Prof. Bruno Siciliano co-Tutor: Prof. Fabio Ruggiero

Cycle: XXXVII Year: Third

Candidate's information

- MSc degree in Automation Engineering
- Group: **PRISMA Lab (UNINA)**
- PhD start – end date: 1/11/2021 – 31/10/2024
- University Scholarship: "**Semi-autonomous Interaction Control of Robotics Systems"** – funded by **DIETI**
- Period abroad: 2 months at **Toronto Metropolitan University** (TMU) and 3 months at **Technical University of Denmark** (DTU)

Summary of study activities

- Some **courses** attended in these 3 years:
  - Statistical data analysis for science and engineering research
  - Academic entrepreneurship
  - Control of Complex Systems and Networks
  - Operational Research: Mathematical Modelling, Methods and Software Tools for Optimization Problems
  - Model Predictive control
  - Semantic artifacts and Multimedia knowledge graphs for biodata integration

- **PhD schools** attended in these 3 years:
  - IEEE RAS Summer School on Multi Robot Systems in Prague
  - 2023 Spring School in Transferable Skills

Summary of study activities

- Some **seminars** attended in these 3 years:
  - IEEE Authorship and Open Access Symposium: Tips and Best Practices to get published from IEEE Editors
  - Game Theory for Information Engineering
  - Is control a solved problem for aerial robotics research?
  - NDT in contesto aeronautico
  - Exploring Advanced Aerial Robotics: A journey into cutting-edge projects and neural control
  - Analytic center selection of optimization-based controllers for robot ecology

Research area(s)

- Compared to the past, today, robot actions are no longer a predetermined sequence of movements

- Their actions are performed automatically thanks to a **control system** that governs motion in relation to what is happening in the environment.

- Robotics defined as:

  Intelligent connection between perception and action

- My research focus is to apply this concept to allow an aerial robot to complete a contact-based inspection task with an interaction surface in an industrial setting

- **Why drones:**
  - Thanks to their agility and dimensions, they can operate in various hard-to-reach environments improving human safety.

Research area(s)

- To this purpose, scientists have devised various methods to enable robots to interact with the environment proposing:
  - **New hardware**
    - Tilting/tilted drones
    - UAM equipped with rigid stick or articulated arms
  - **New control methods**
    - Model-based controller
      - Indirect/direct control laws
      - Optimization techniques
    - Reinforcement Learning
  - **Different onboard sensors**

Research results

- Focus on two main platform with tilting capabilities

Aerobull drone: prototype developed at **DTU**

NDT drone: platform developed at PRISMA Lab

- Investigated and implemented state-of-the-art solutions
- Proposed solutions enhancing shared-control and inspection completion
- Investigated advantages of shared-control over autonomous task execution via Human subjects’ study

Published Research products

[J1]	**Stabilization and Control on a Pipe-Rack of a Wheeled Mobile Manipulator with a Snake-like Arm -** ***Simone D'Angelo****, Antonio Corrado, Fabio Ruggiero, Jonathan Cacace, Vincenzo Lippiello* Journal: *Robotics and Autonomous Systems* - RAS
[C1]	**Development of a Control Framework to Autonomously Install Clip Bird Diverters on High-Voltage Lines** - ***Simone D'Angelo****, Francesca Pagano, Fabio Ruggiero, Vincenzo Lippiello* Conference: *The 2023 Int´L Conference On Unmanned Aircraft Systems* - ICUAS 23
[C2]	**Development of a Semi-Autonomous Framework for NDT Inspection with a Tilting Aerial Platform -** *Salvatore Marcellini,* ***Simone D'Angelo****, Alessandro De Crescenzo, Michele Marolla, Vincenzo Lippiello, and Bruno Siciliano* Conference: *18th International Symposium on Experimental Robotics* - ISER 2023
[C3]	**Efficient Development of Model-Based Controllers in PX4 Firmware: A Template-Based Customization Approach -** ***S. D'Angelo****, F. Pagano, F. Longobardi, F. Ruggiero and V. Lippiello* Conference: *2024 International Conference on Unmanned Aircraft Systems* – ICUAS 24
[C4]	**Horizontal Sustained Force Delivery with an Aerial Manipulator Using Hybrid Force/Position Control -** *H. Ullah****, S. D'Angelo****, F. Ruggiero, V. Lippiello and S. M. Orozco Soto* Conference: *2024 25th International Carpathian Control Conference* - ICCC

Under-review Research products

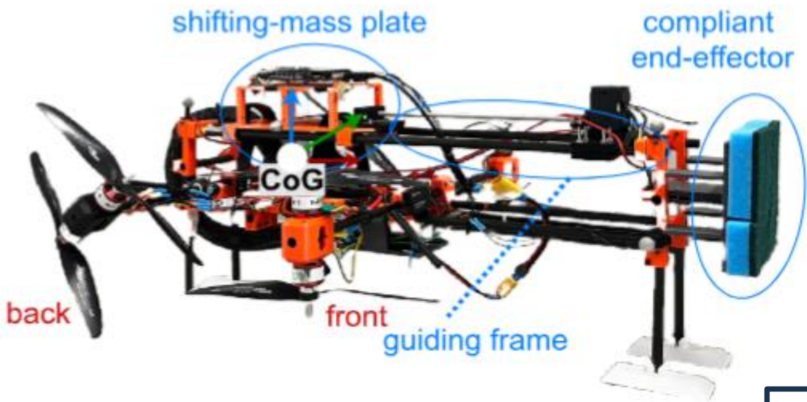
[J2]	**Dynamic Center-of-Mass Displacement in Aerial Manipulation: An Innovative Aerial Vehicle Design -** *T. Hui, S. Rucareanu, E. Zamora,* ***S. D'Angelo****, H. Liu, M. Fumagalli* Journal: *Robotics and Autonomous Systems* - RAS
[J3]	**AEROBULL: A Center-of-Mass Displacing Aerial Vehicle Enabling Efficient High-Force Interaction** - *T. Hui, E. Zamora, S. D'Angelo, S. Rucareanu, M. Fumagalli* Journal: *IEEE/ASME Transaction on Mechatronics* - T-MECH
[J4]	**Semi-autonomous Unmanned Aerial Manipulator Teleoperation for Push–and–Slide Inspection using Parallel Force/Vision Control** - ***S. D'Angelo****, M. Selvaggio, V. Lippiello, F. Ruggiero* Journal: *Robotics and Autonomous Systems* - RAS
[J5]	**A Semi-Autonomous Aerial Platform Enhancing Non-Destructive Tests –** ***S. D'Angelo****, S. Marcellini, A. De Crescenzo, M. Marolla, V. Lippiello and Bruno Siciliano* Journal: *International Journal of Robotics Resarch* - IJRR
[C5]	**Drone-Based Solutions for Asset Integrity: Development of NDT Drone and 3D FPV Payload for Asset Remote Testing and Inspection -** *R. Campaci, V. Lippiello****, S. D'Angelo****, T. Borzone, L. Madia, M. Favaretto, A. Vignali* Conference: *International Petroleum Technology Conference* - IPTC

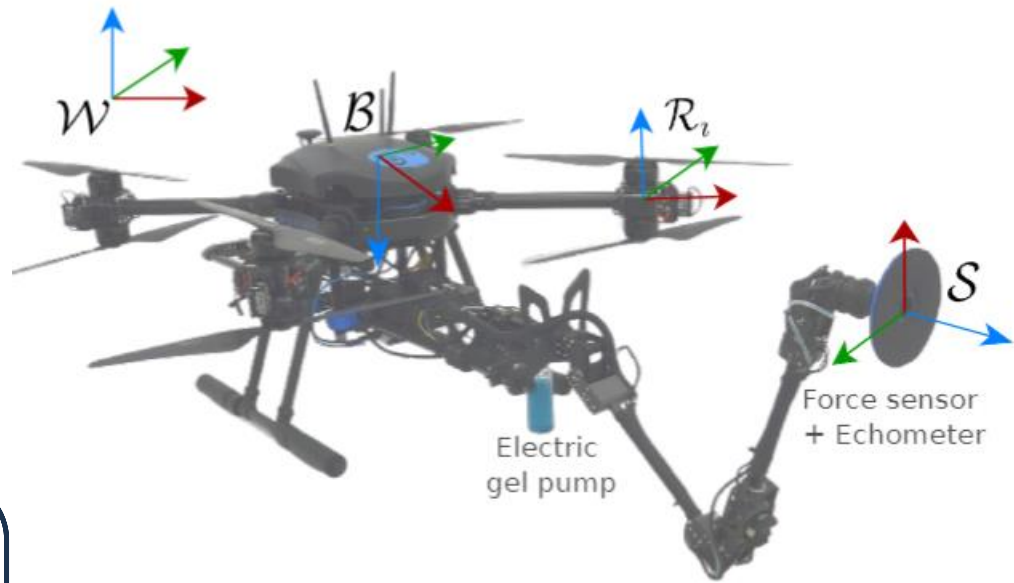
PhD thesis overview

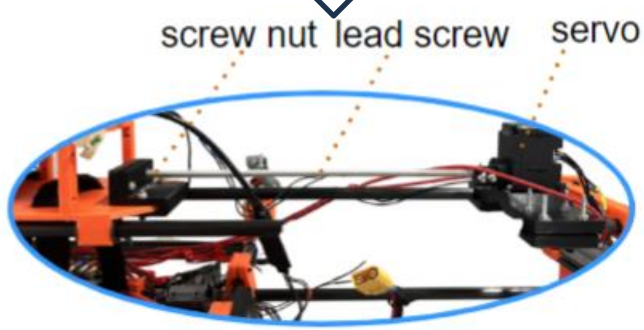
- **Problem statement:**
  Design and implement control strategies to allow a drone to complete a contact-based inspection task (pushing only or push-and-slide)
- **Objective:**
  1. Design and modeling of ad-hoc platforms
  2. Design Implement state-of-the-art solution
  3. Parallel control laws accounting for different sensor fusion
  4. Design optimization techniques accounting for friction constraint during the interaction

- **Methodology:**
  - Combine standard approaches in hybrid and parallel control law
  - Leverage on model predictive control
  - Use of human-guided device in a shared-control paradigm
  - Statistical data analysis to evaluate notable metrics

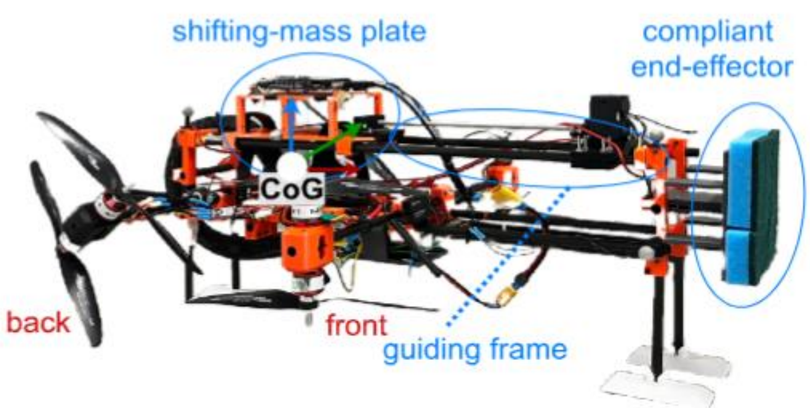
PhD thesis: system description

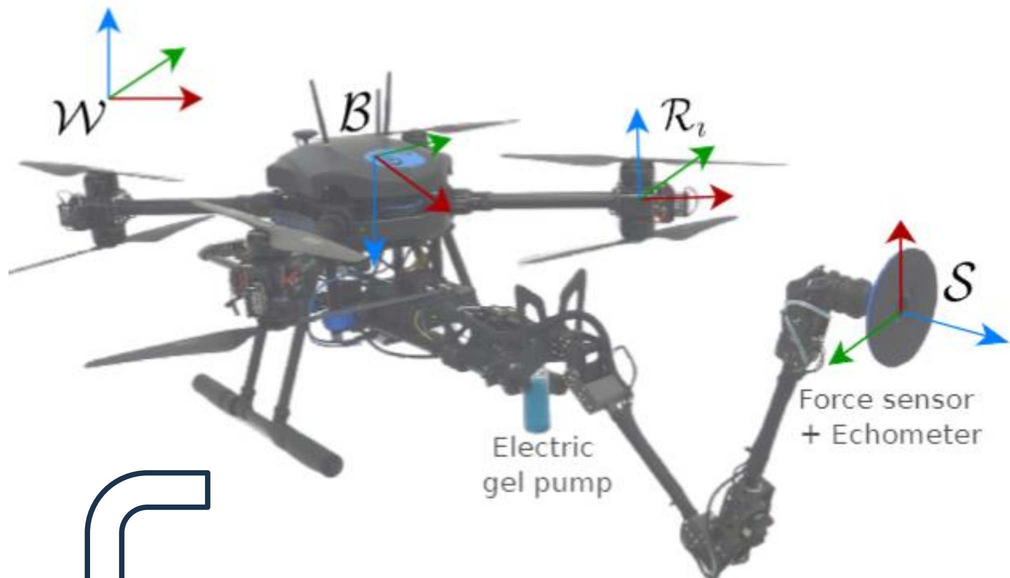


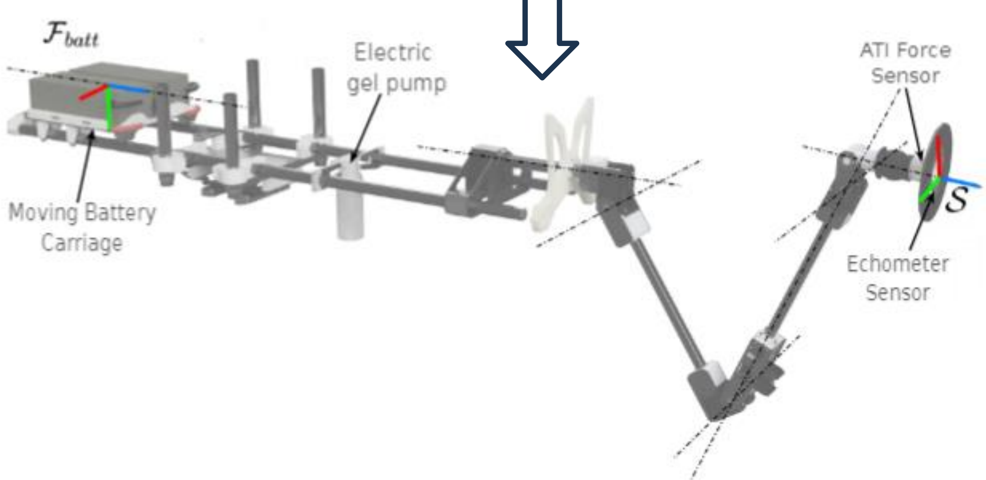




PhD thesis: system description







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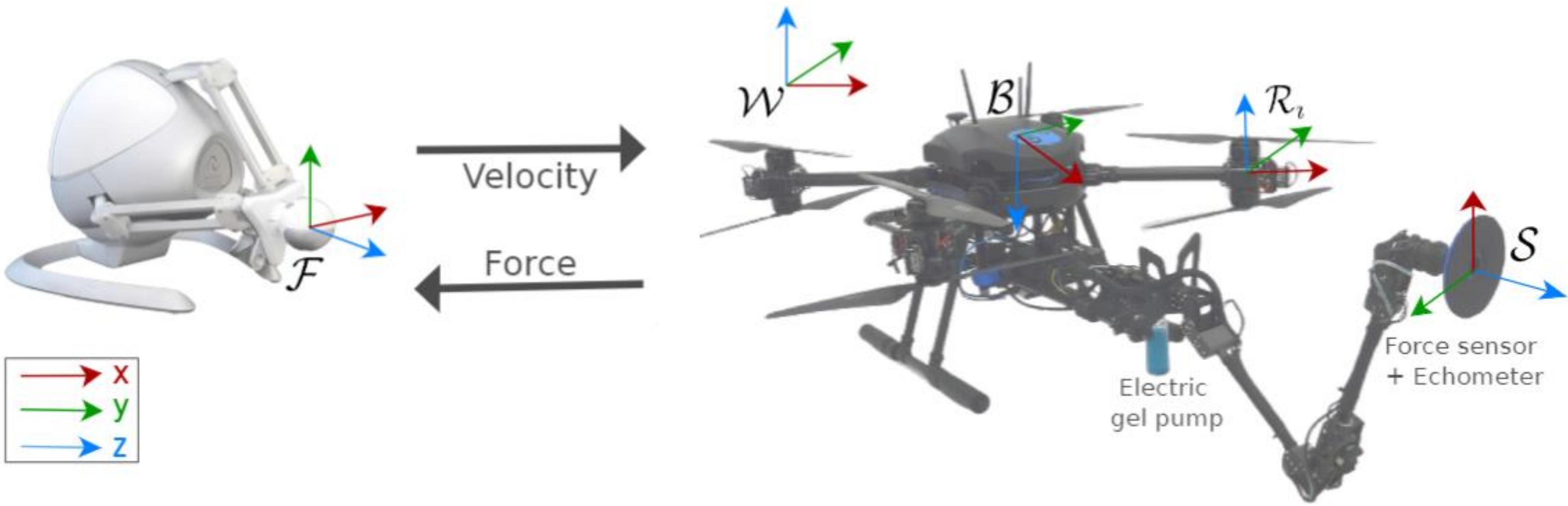
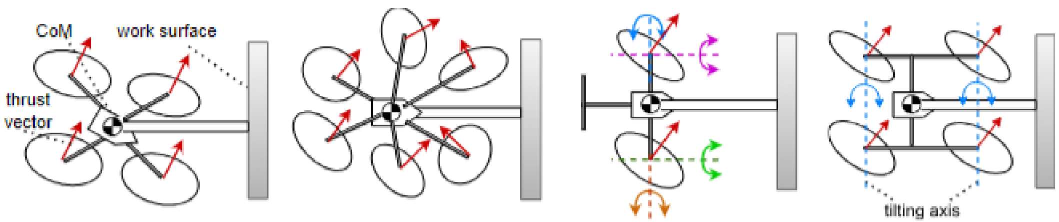
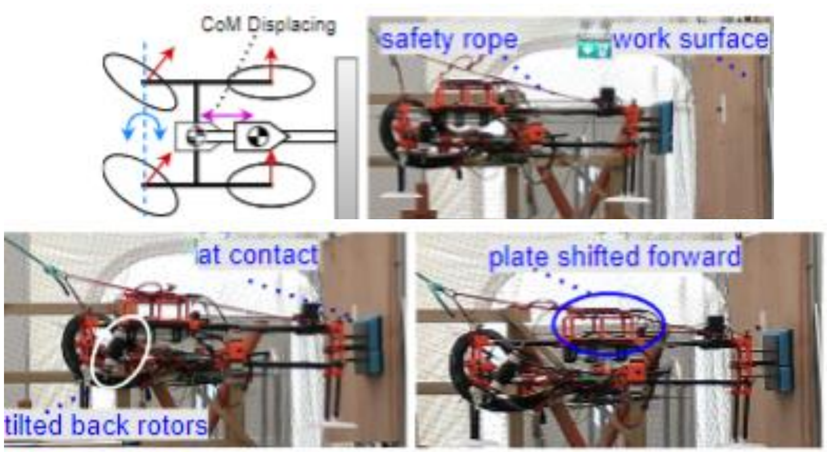


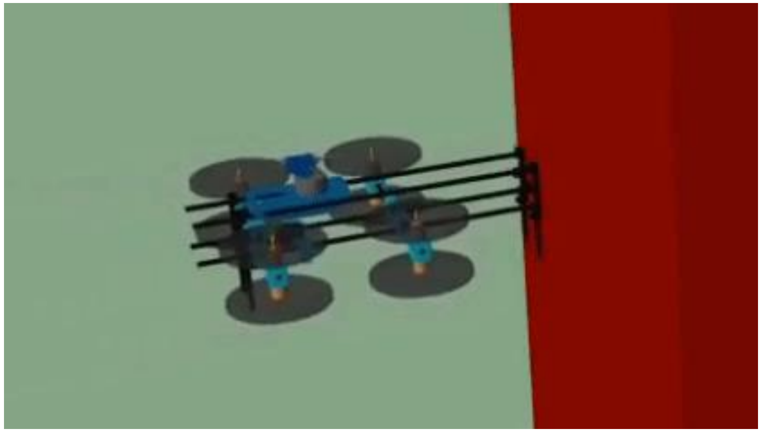
PhD thesis

- Existing flat and tilting/tilted UAV feature a **fixed** center of mass



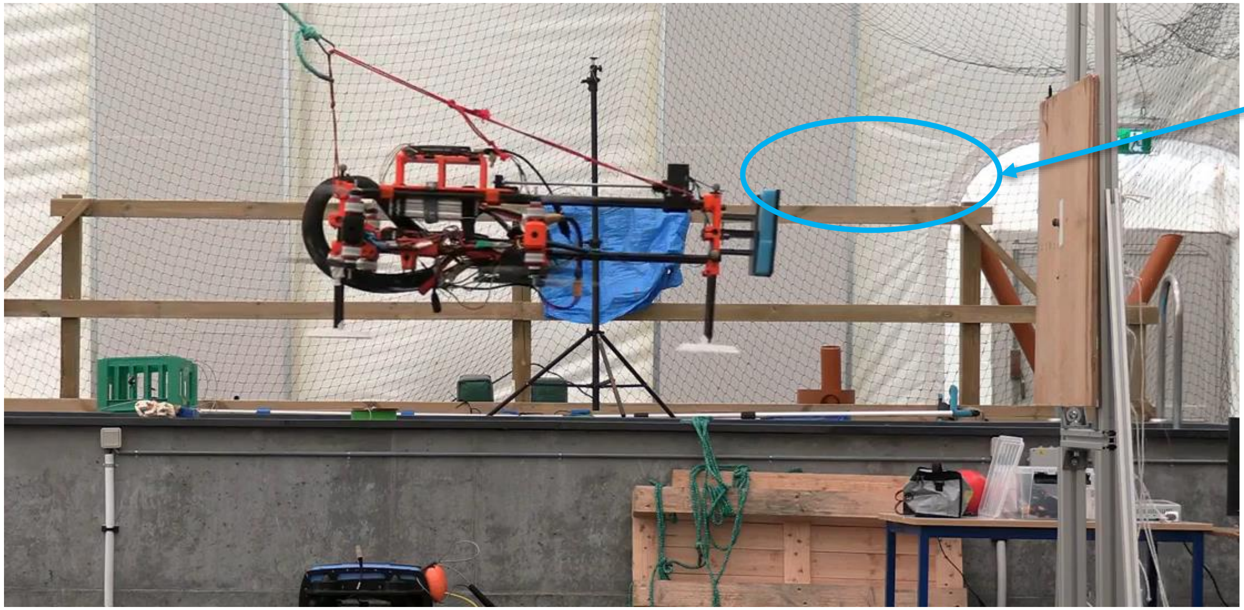
- To decrease the momentum arm, improve stabilization and force exertion the **AEROBULL** drone is introduced





PhD thesis: Impedance control

- No force error loop closure
- Exerted force on the work surface: 28N (drone weight: ≅ 3 kg)
- Exerted force without the shifting-mass procedure: 15N



Shifting-mass procedure

PhD thesis: Parallel techniques

- Fusing motion control and direct force control laws
- Force error loop closure
  - Precise force tracking
- Omnidirectional platform is dexterous, but it increases complexity

Parallel force-position Control

Parallel force-impedance Control

PhD thesis: Force/Vision Control

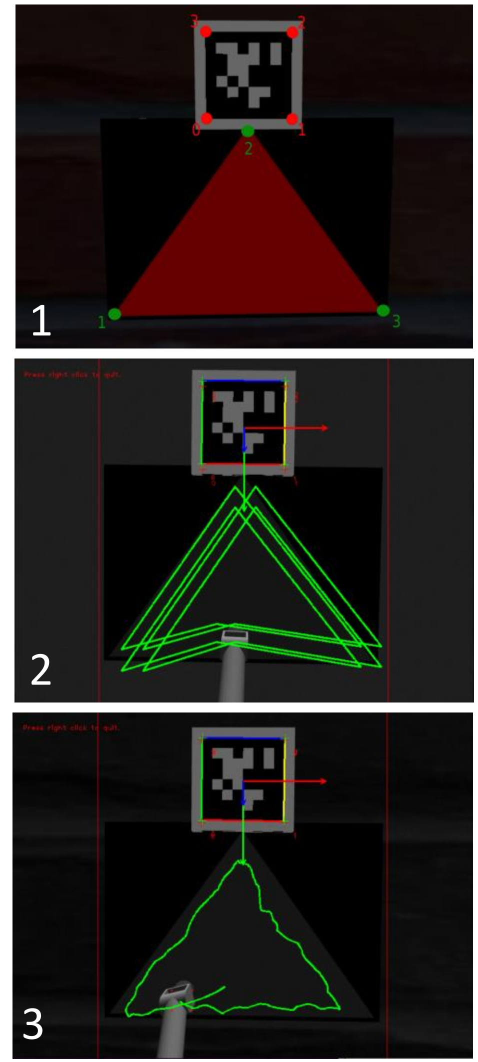
- Visual-servoing outperforms classical Cartesian motion control
- Existing literature focus only on standard drones and indirect force control in the image space
- First time applying parallel force/vision control to tilting UAM with direct force control in a shared-control paradigm
  - Needed for shared-autonomy in real industrial scenario
  - Allowing precise force tracking
  - Use of a dexterous platform
  - Development of a training environment for specialized and non-experienced users
- User study on the effectiveness of the introduced control modalities

PhD thesis: Force/Vision Control

- **Simulated context** is crucial for addressing challenges faced by non-experienced users, who may fail to execute tasks correctly by moving outside the field of view or occluding the vision, thus losing the only available source of information.

Camera point-of-view (PoV):

1. The surface is detected through an **AprilTag** marker. The UAM tracks the triangular shapes while interacting:
2. Tracking results in the **autonomous** control mode
3. Tracking results in the **teleoperated** control mode.



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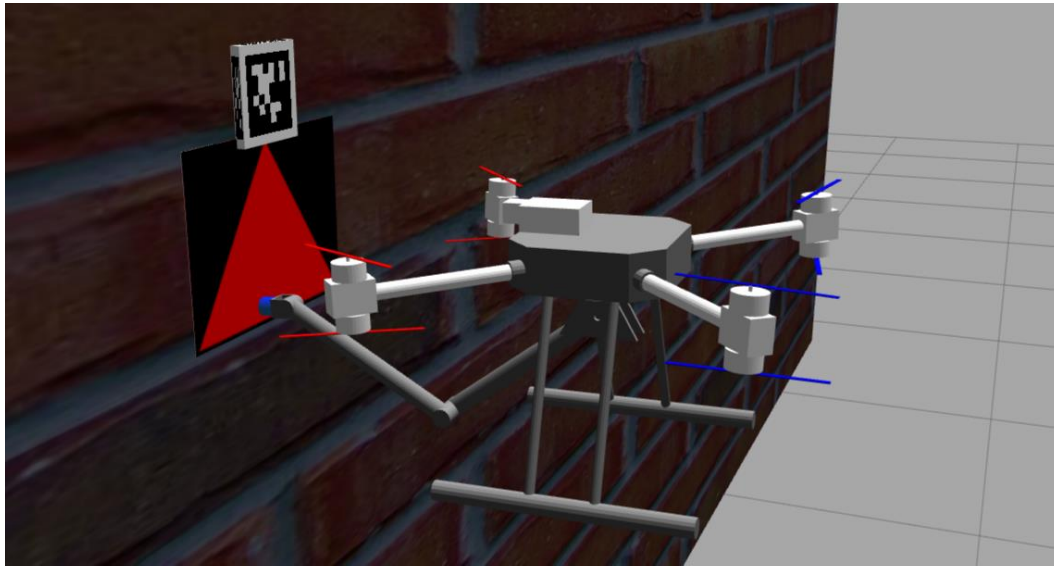
4. Haptic device entering the loop

PhD thesis: Force/Vision Control



Evaluated Control modes:

- **P**: autonomous sliding + teleoperated pushing
- **S**: teleoperated sliding + autonomous pushing
- **PS**: teleoperated pushing + sliding

Haptic feedback modes:

- **VF**: presence of haptic feedback
- **~~VF~~**: absence of haptic feedback

Combining control and haptic modes leads to six conditions:

- P, PVF, S, SVF, PS, PSVF

PhD thesis: Human subject study

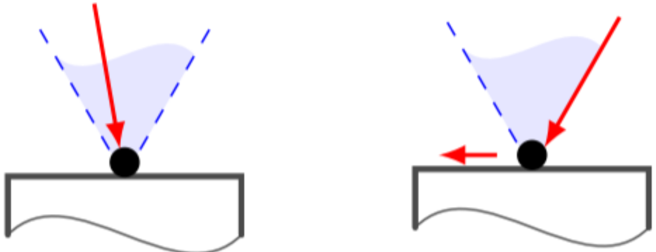
- 20 human subjects (18 male, 2 female)
- Mixed between experienced and beginners in interfacing with the hardware and the simulation
- Randomized sequence of trials
- Evaluated via **quantitative** (logs) and **qualitative metrics** (questionnaire)

ANOVA statistical data analysis results

- Sliding feature identified as the most **challenging** and **time-consuming** to accomplish manually
- Autonomous sliding affects the pushing force mean evaluated along the trajectory
- Adding force feedback during manual control reduces force error compared to autonomous pushing without feedback
- Generation of higher commanded velocities in sliding-based modalities

PhD thesis: extension to parallel MPC

- Model prediction Control techniques allow definition of constraints to be satisfied to achieve the control goal
- Friction Constraints defined as Coulomb Friction Cone:
  - Ensuring contact $F_N > 0$
  - Avoiding slippery on the surface (a) $||F_T|| \leq \mu F_N$
  - Force the sliding remaining on the cone border (b) $F_T = -\mu F_N \frac{v_T}{||v_T||}$



(a) (b)

Thank you
for your attention