PhD Francesca Pagano

Online Optimization-Based Multi-Robot Monitoring

Tutor: Prof. Vincenzo Lippiello

Cycle: XXXVII

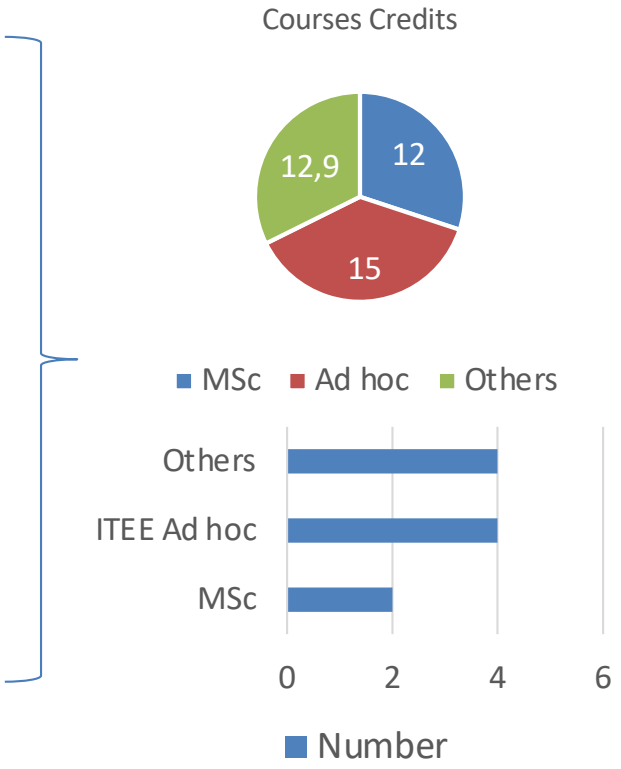
Year: 2022

Candidate's information

- *MSc degree* in Automation Engineering
  University of Naples "Federico II"
- *Research group*: PRISMA Lab – Aerial Robotics
- *PhD start and end date*: 01/01/2022 - 31/12/2024
- *Scholarship type*: PON-Green
- *Company*: Società Agricola "Lenza Lunga" dei F.lli Cacciapuoti
- *Period Abroad*: INRIA-IRISA Rennes, France

Summary of study activities

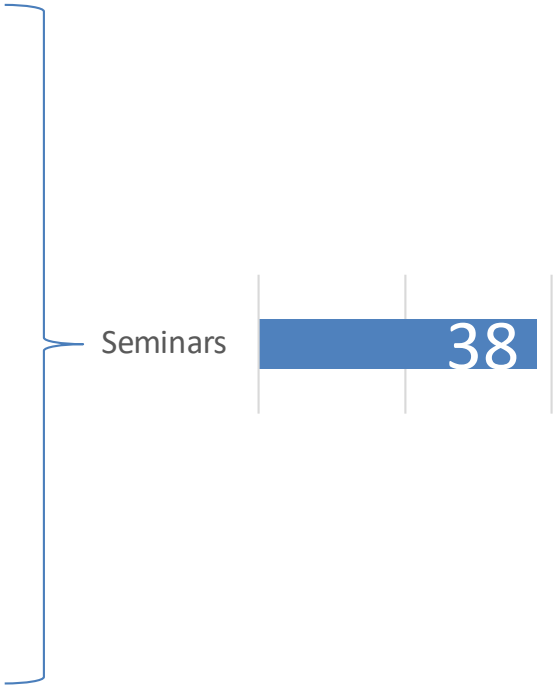
- Attended Courses:
  - Probability calculus and elements of stochastic modelling
  - Operational Research: Mathematical Modelling, Methods and Software Tools for Optimization Problems
  - Robotics Lab
  - Matrix Analysis for Signal Processing with MATLAB Examples
  - Model Predictive Control
  - Control of Complex Systems and Network
  - Theory and Applicationsof Contracting Dynamical Systems
  - Ethics and AI
  - Strategic Orientationfor STEM Research & Writing
  - Innovation and Entrepreneurship



- PhD Schools:
  - 2022 IEEE RAS SummerSchool on Multi-Robot Systems
  - 2023 Spring School onCourse Transferable Skills

Summary of study activities

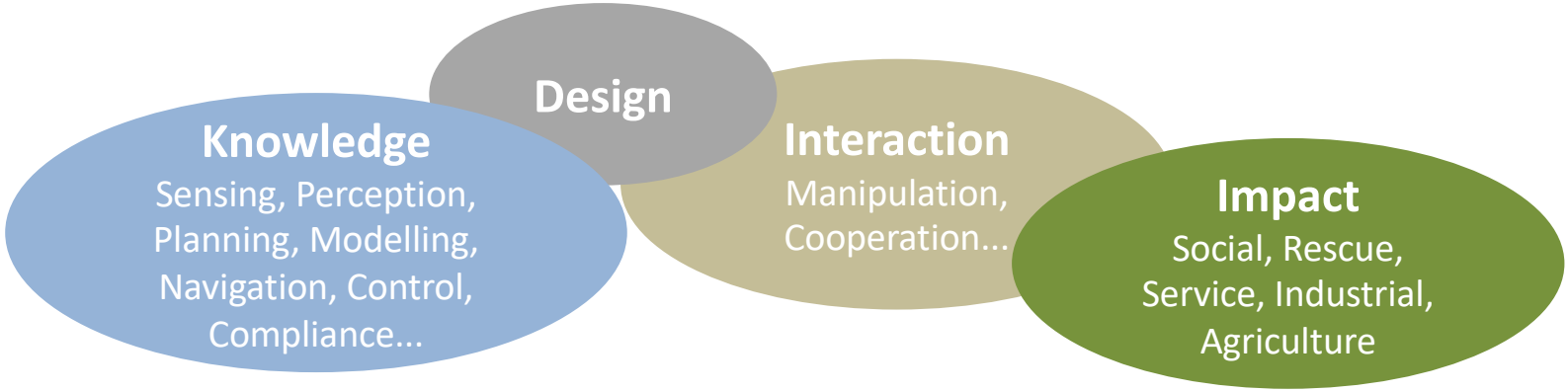
- Some seminars:
  - IEEE Authorship and Open Access Symposium: Tips and Best Practises to Get Published from IEEE Editors
  - Global and cluster synchronization in complex networks and beyond
  - On using simple optimization techniques for tuning of UAVs
  - IEEE-ICRA 2022 workshop: Shared Autonomy in Physical Human-Robot Interaction: Adaptability and Trust
  - IROS 2022 Workshop: Human-Multi-Robot Systems: Challenges for Real World Applications
  - Is control a solved problem for aerial robotics research?
  - Multi-robot Control of Heterogeneous Herds
  - Exploring Advanced Aerial Robotics: A Journey into Cutting- Edge Projects and Neural Control
  - From Romeo & Juliet Seminar to OceanOneK Deep- Sea Robotic Exploration
  - AI, Robots and Society: Challenges and Opportunities for Social Innovation
  - Designing Cooperative Multi-Agent Teams and Socially-Aware Autonomy
  - Learning to optimize dynamic behaviors
  - On Shapes, Robots, and Sensor-Based Controls
  - Agile flight of aerial robots under dynamical uncertainties
  - Analytic center selection of optimization-based controllers for robot ecology
  - Trends and challenges in collaborative robotics: perception, motion planning and control



- Conferences:
  - 2023 - *International Conference On Unmanned Aircraft Systems* **- ICUAS 23** - Warsaw, Poland
  - 2024 - *International Conference On Unmanned Aircraft Systems* **- ICUAS 24** - Chania, Greece
  - 2024 - *6th Italian Conference on Robotics and Intelligent Machines* - **IRIM-3D 202**4 - Rome, Italy

Research area(s)

- Robotics: *"Intelligent connection between perception and action"*



- *Main focus*: implement control approaches for autonomous aerial robots

Research area(s)

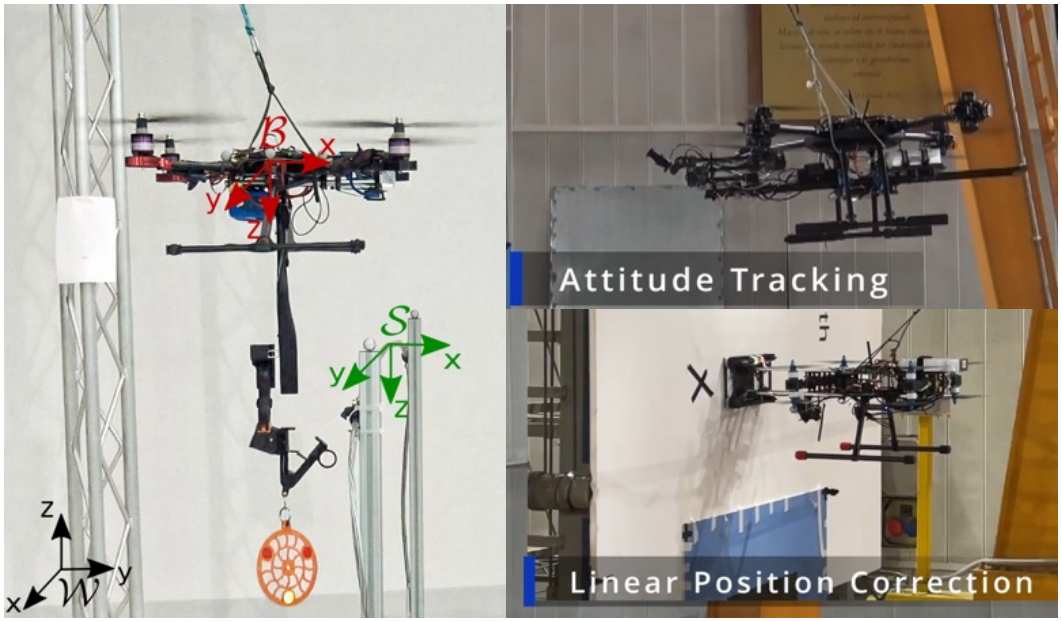
- Aerial Robotics

Research problems

- *Control* of *custom* aerial platforms for *interaction* tasks
- *Impact* in inspection and maintenance operations in hard-to-reach and dangerous environments

Results

- Control Framework to Autonomously Install Clip Bird Diverters on High-Voltage Lines



- Custom flight controller firmware
  - Ease implementation of new control stacks in the standard PX4 firmware for research purposes
  - Tests on multple aerial platforms: flat and tilting drones

Research area(s)

- Multi-robot - Aerial Robotics

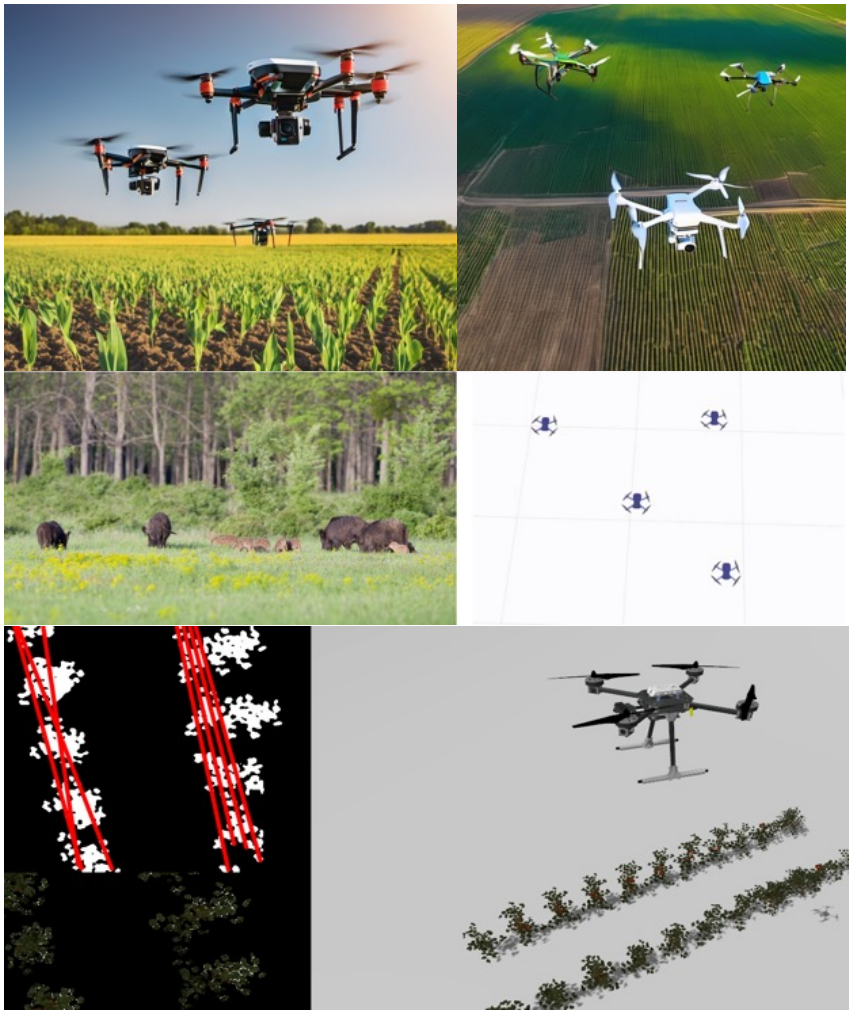
Impact

> ***9.7** billions people by **2050***

- *Robotics* applied to remote sensing and crop monitoring, can play a key role in meeting rising food demands and improving environmental sustainability
- Multi robot teams can reduce time, costs and improve efficiency in real world applications.

Research problems

- Coordinate sensing
- Persistent monitoring
- Heterogeneous robot teams



Research results

- Multi-robot monitoring tasks
  I. Proposed two *novel* multi-robot control methodologies to allow
    I. Persistent monitoring of some points-of-interest with an heterogeneous or homogeneous multi-robot system
    II. Distributed estimation of a diffusive source with a team of drones
- A optimization-based framework for the execution and prioritization of multiple tasks in a redundant robotic system, allowing online insertion and removal of tasks and dynamic switching of task priorities [P1]

Research Products

[P1]	G. Notomista, M. Selvaggio, M. Santos, M. Siddharth, **F. Pagano**, V. Lippiello, C. Secchi *Beyond Jacobian-based tasks: Extended set-based tasks for multi-task execution and Prioritization* *Submitted to IEEE Transaction on Robotics* Status: under review
[P2]	S. D'Angelo*, **F. Pagano***, F. Ruggiero, V. Lippiello *Development of a Control Framework to Autonomously Install Clip Bird Diverters on High-Voltage Lines* International Conference on Unmanned Aircraft Systems (ICUAS), Warsaw, Poland, 2023, pp. 377-382, doi: 10.1109/ICUAS57906.2023.10156403
[P3]	S. D'Angelo*, **F. Pagano***, F. Longobardi, F. Ruggiero and V. Lippiello *Efficient Development of Model-Based Controllers in PX4 Firmware: A Template-Based Customization Approach* International Conference on Unmanned Aircraft Systems (ICUAS), Chania, Greece, 2024, 1155-1162, doi: 10.1109/ICUAS60882.2024.10556938.
[P4]	J. Mellet, **F. Pagano**, F. Ruggiero, V. Lippiello, Simplifying Quadrotor Frame Design: *Toward Scalability with a Modular Robot* 6th Italian Conference on Robotics and Intelligent Machines, IRIM-3D 2024: Rome, Italy, Oct 25-27. 2024 – To appear in proceedings

* co-first authors

PhD thesis overview

- Problem statement

  Design and implement **control** strategies to allow a team of robots to **monitor** large areas and retrieve *measure-based information*

  – Shifting form a *one-to-many* paradigm can improve efficiency reducing costs and time
  – Multi-robot teams can bring enhanced resiliency and leverage *heterogenous* capabilities

- Objective
  – Generate robots' motions that maximize information
  – Enforcing operative and safety constraints
  – Achieve multi-robot coordination
  – Provide **online** and reactive solutions
  – Allow the execution of multiple concurrent and prioritized tasks

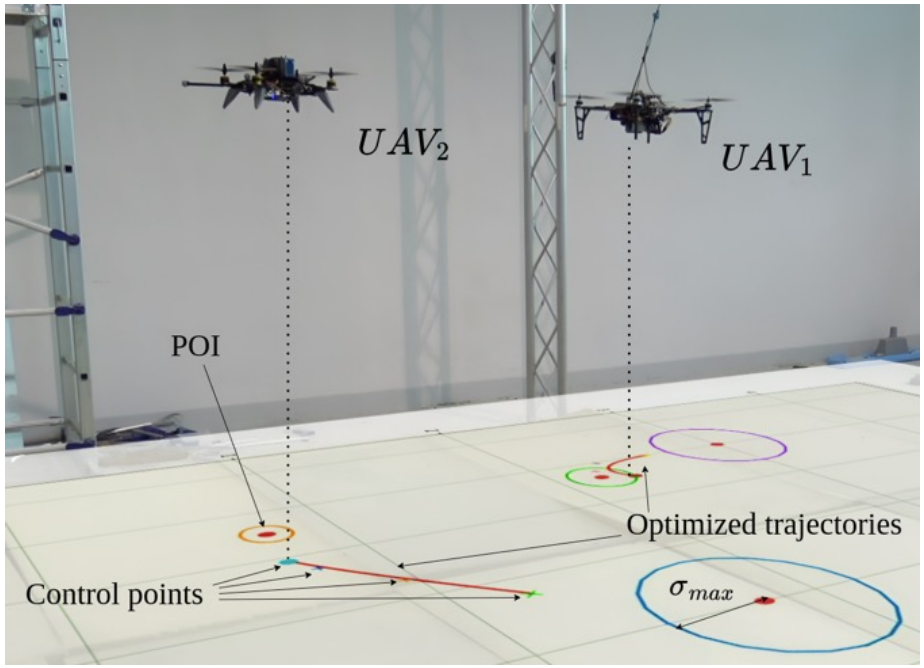
- Methodology
  - Optimal control and model-based approaches
  - Realistic simulations
  - Real experiments
  - Statistical data analysis to evaluate relevant metrics

PhD thesis

Multi-robot Nonlinear Model Predictive Control for Persistent Monitoring

- Problem description
  - Robots persistent monitoring of some point-of-interest within a known area
  - Related to: reconnaissance, surveillance, awareness coverage

- State-of-the-art solutions
  - Mainly employ gradient-based control laws without accounting for dynamical constraints and optimization horizon
  - No real applications to heterogeneous robotic teams



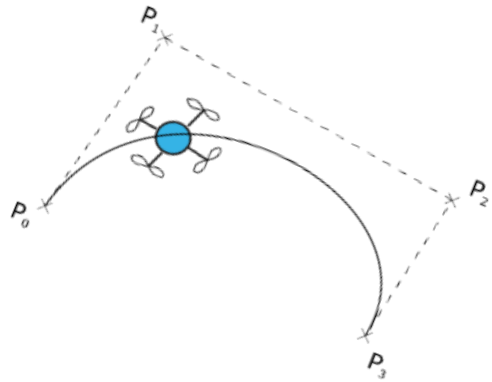
PhD thesis

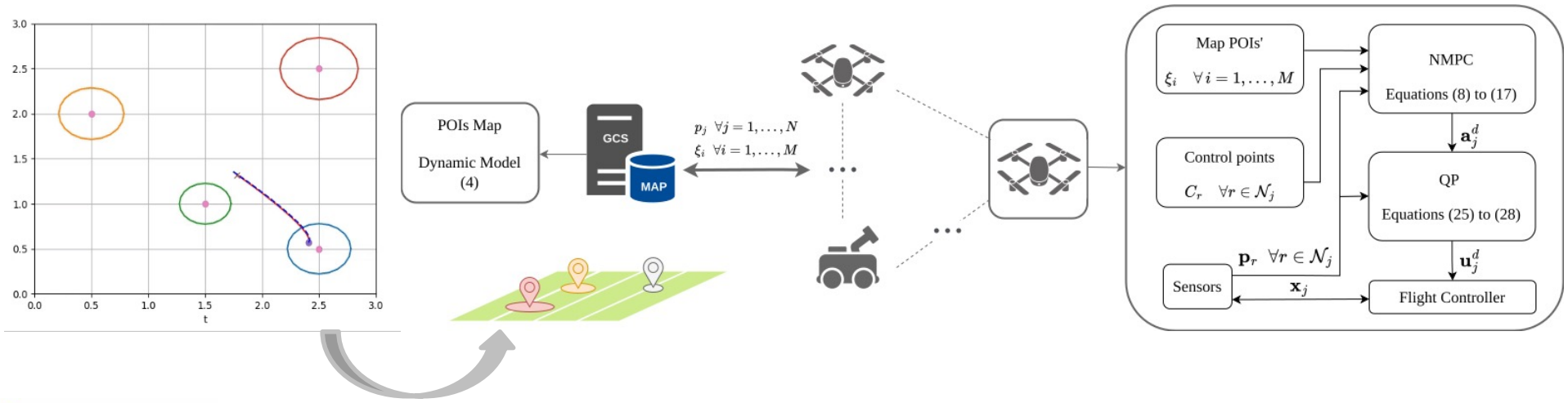
Multi-robot Nonlinear Model Predictive Control for Persistent Monitoring

- Contribution

  Novel methodology using

  - POIs artificial, heat-like, dynamic equation, which depends on the agents' positions
  - Nonlinear Model Predictive Control (NMPC) to compute online feasible motions using Bezier curves
  - QP for safety constraints
  - Decentralized implementation with a central Ground Control Station

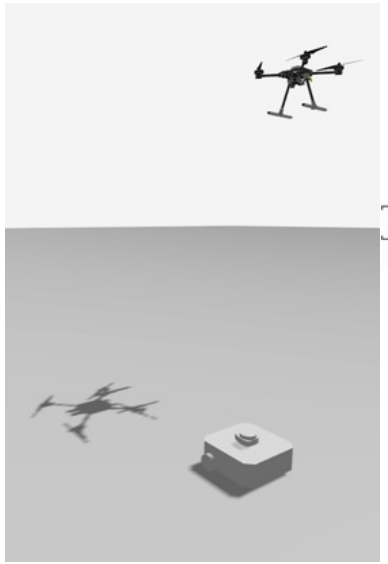




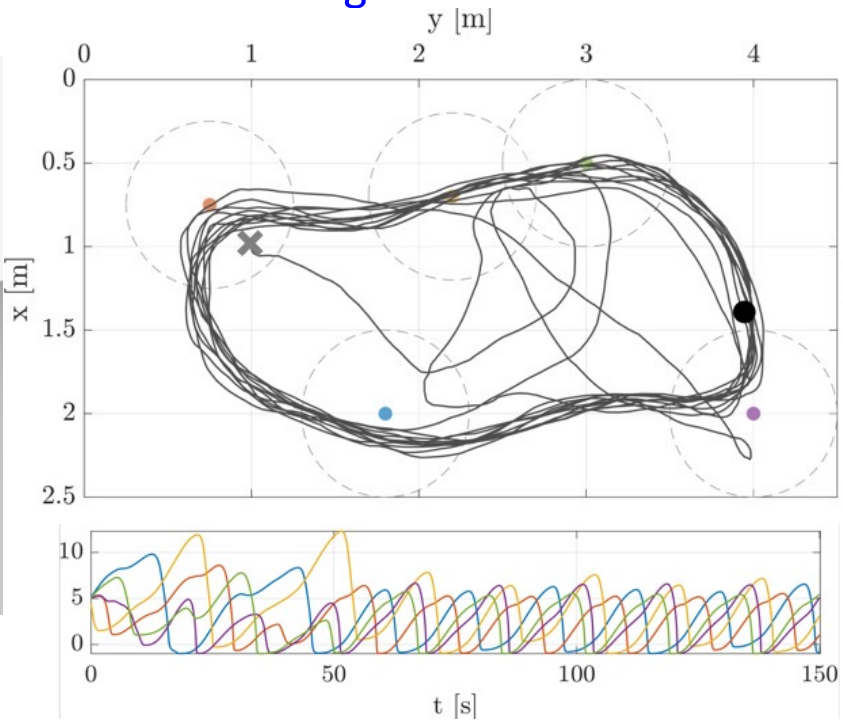
PhD thesis

Multi-robot Nonlinear Model Predictive Control for Persistent Monitoring

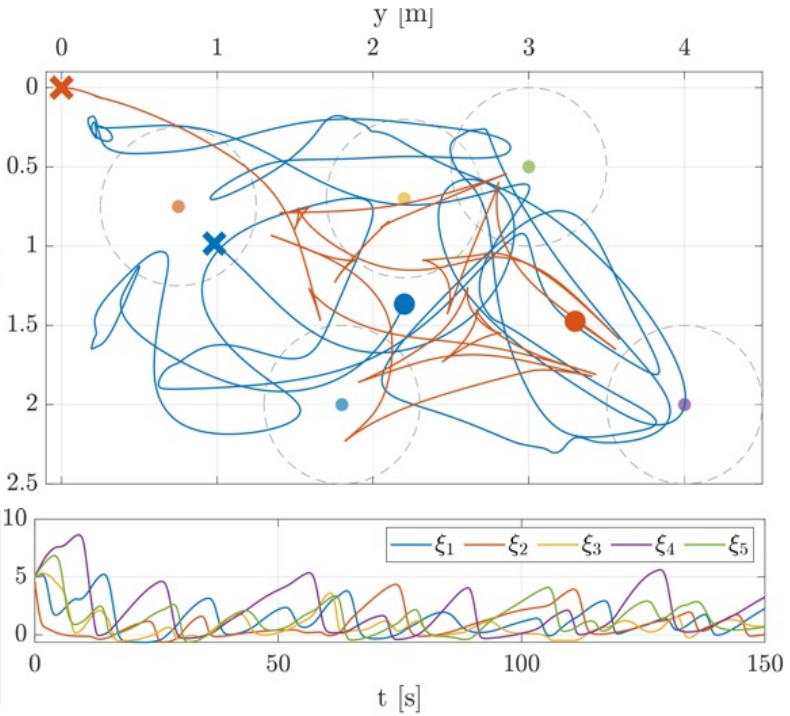
- Simulation Results
  - ROS2-Gazebo/PX4 SITL realistic simulations
  - Single, homogeneous and heterogeneous robots scenarios



Single drone



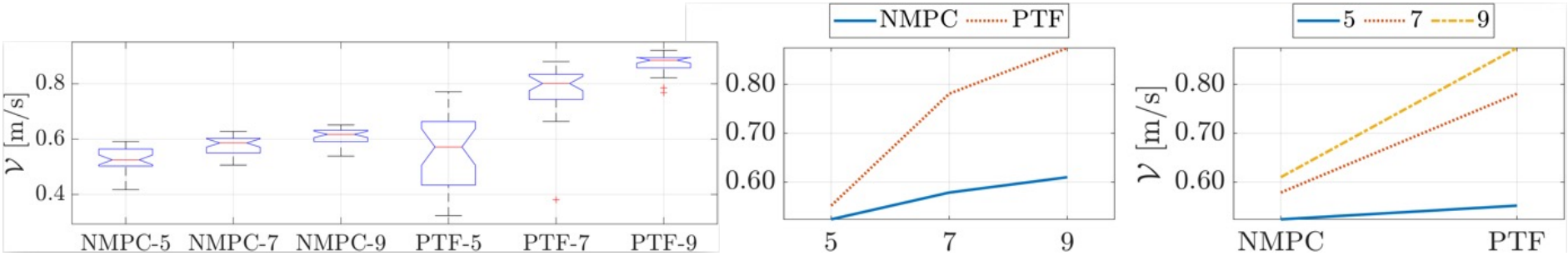
Rover and drone



PhD thesis

Multi-robot Nonlinear Model Predictive Control for Persistent Monitoring

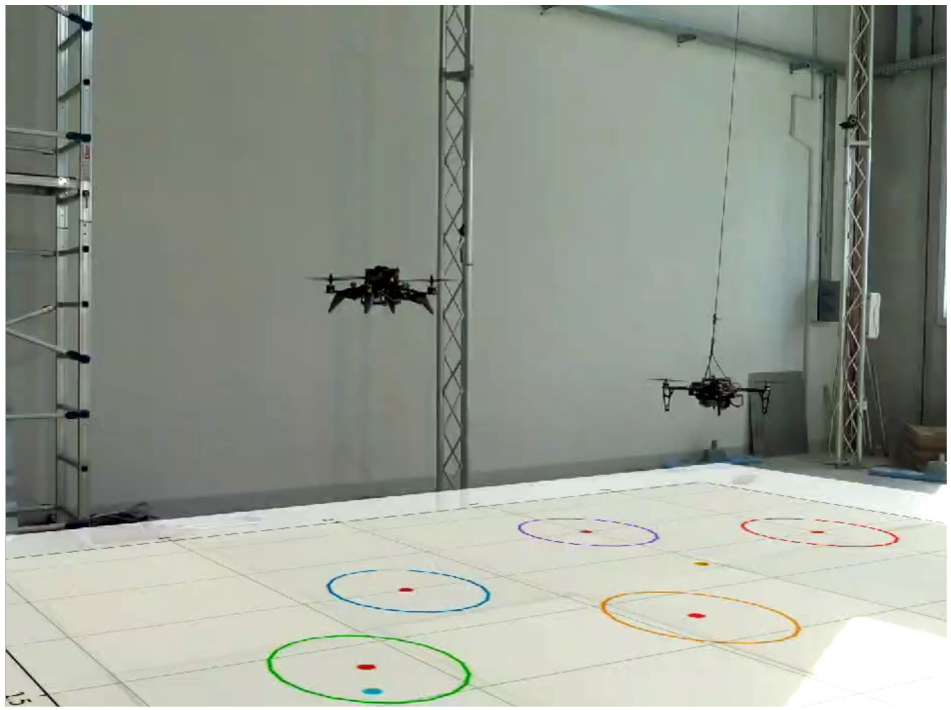
- Statistical comparison results
  - Extensive simulation campaign to compare the performance of the proposed NMPC to a baseline method
  - Evaluation of statistically relevant changes in task-related coverage metrics in 90 randomly generated scenarios with a different number of POIs
  - The NMPC outperforms the baseline along the considered metrics attaining lower values of the robotic system velocities

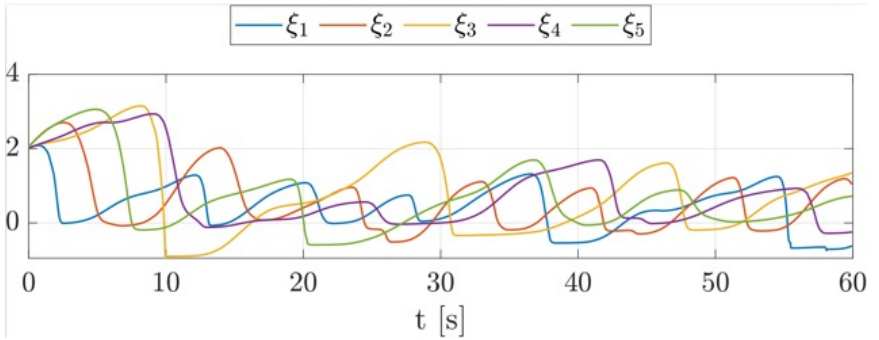


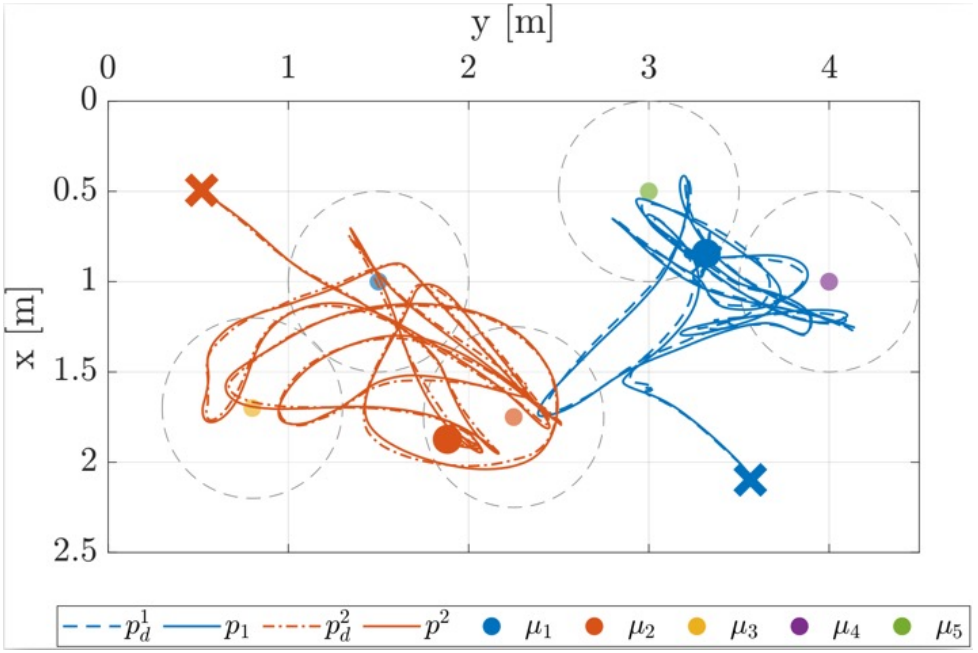
PhD thesis

Multi-robot Nonlinear Model Predictive Control for Persistent Monitoring

- Experimental Results



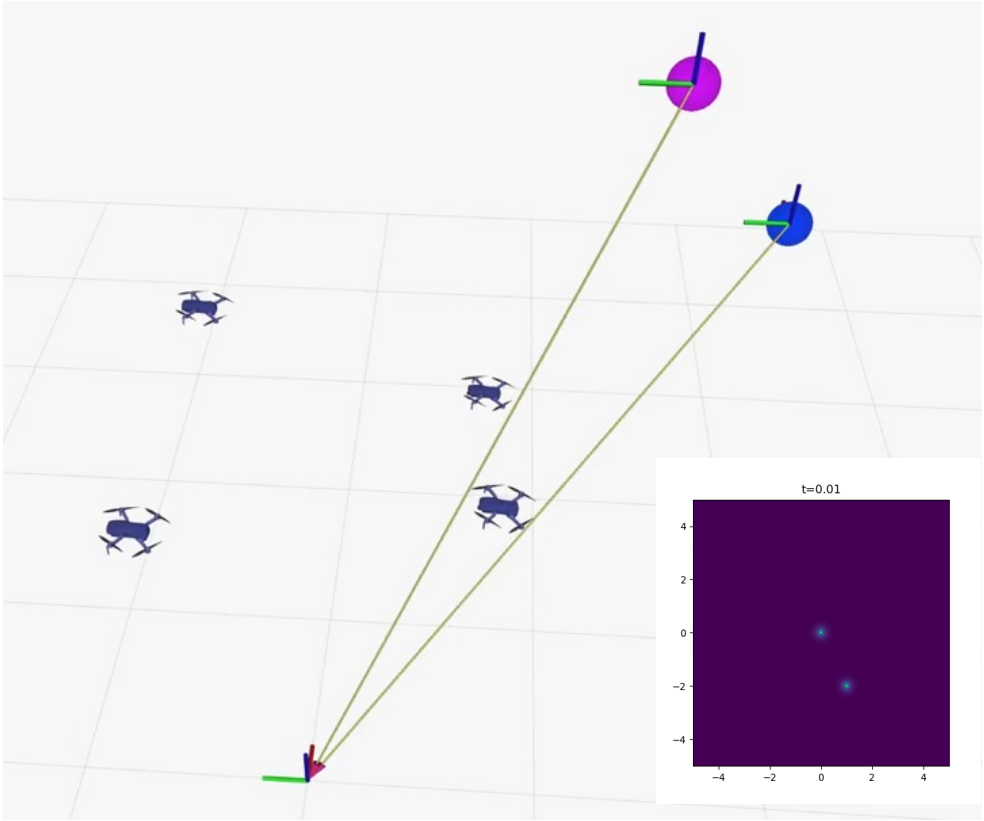




PhD thesis

Multi-robot Diffusive Source Estimation

- Problem description
  - Estimate a diffusive source 3D location and release rate with a team of robots
  - Applications in environmental monitoring
- State-of-the-art solutions
  - Do not address *continuous release* diffusion models



Research activity at

- INRIA, Rainbow Team, Rennes (France)
- *Supervisor:* Dr. Paolo Robuffo Giordano

PhD thesis

Multi-robot Diffusive Source Estimation

- Contribution and proposed methodology
  - Distributed estimation with *consensus-based* Nonlinear Information Filter with forgetting factor
  - Model based approach

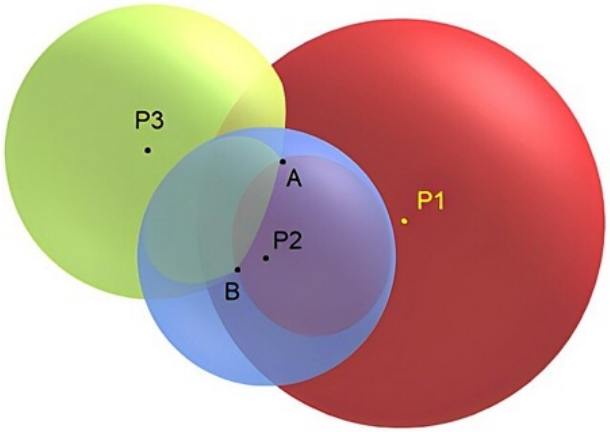
$$y = h(r, q, t) = \frac{q}{4\pi D r}\left[1 - \frac{2}{\sqrt{\pi}}\int_0^{\frac{r}{2\sqrt{Dt}}} \exp\left(-\eta^2\right) d\eta\right]$$

  - **Online** active sensing: agents move to minimize an *A-optimality* criterion based on the collective *Gramian* as information measure

$$\min_u \operatorname{tr}\left(G(p,t)^{-1}\right)$$

  - QP to ensure safety constraint and boundness of the information

$$\begin{aligned}
&\min_{u^i} \|u^i - u^i_{nom}\|^2 \\
&\dot{h}_{src}(p^i, \hat{\mu}) \geq -\alpha(h_{src}) \\
&\dot{h}_{avoid_j}(p^i, p^j) \geq -\alpha(h_{avoid_j}) \\
&\dot{h}_{env}(p^i) \geq -\alpha(h_{env})
\end{aligned}$$

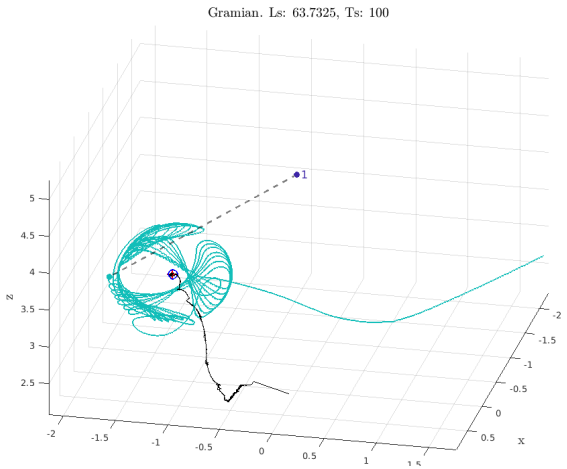


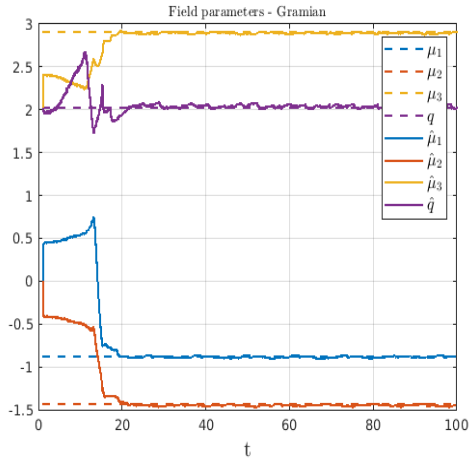
Estimate source location is similar to a trilateration problem

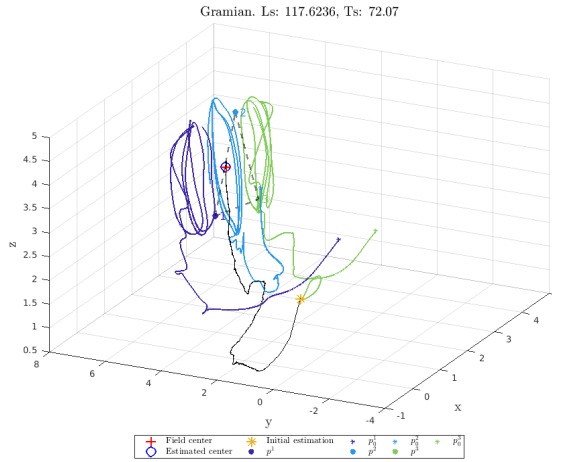
PhD thesis

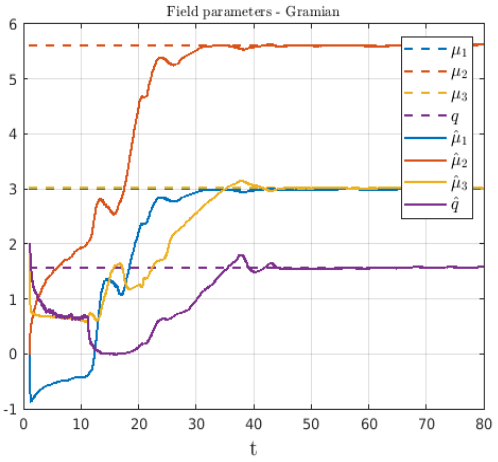
Multi-robot Diffusive Source Estimation

- Simulations
  - Understand how the increase on the number of agents affects the estimation convergence
  - Which motions are more informative
  - Comparison with naïve approaches, varying the agents' number and their velocities









PhD thesis

Multi-robot Diffusive Source Estimation

- Experiments
  - Using simulated measurements
  - Crazyflie drones