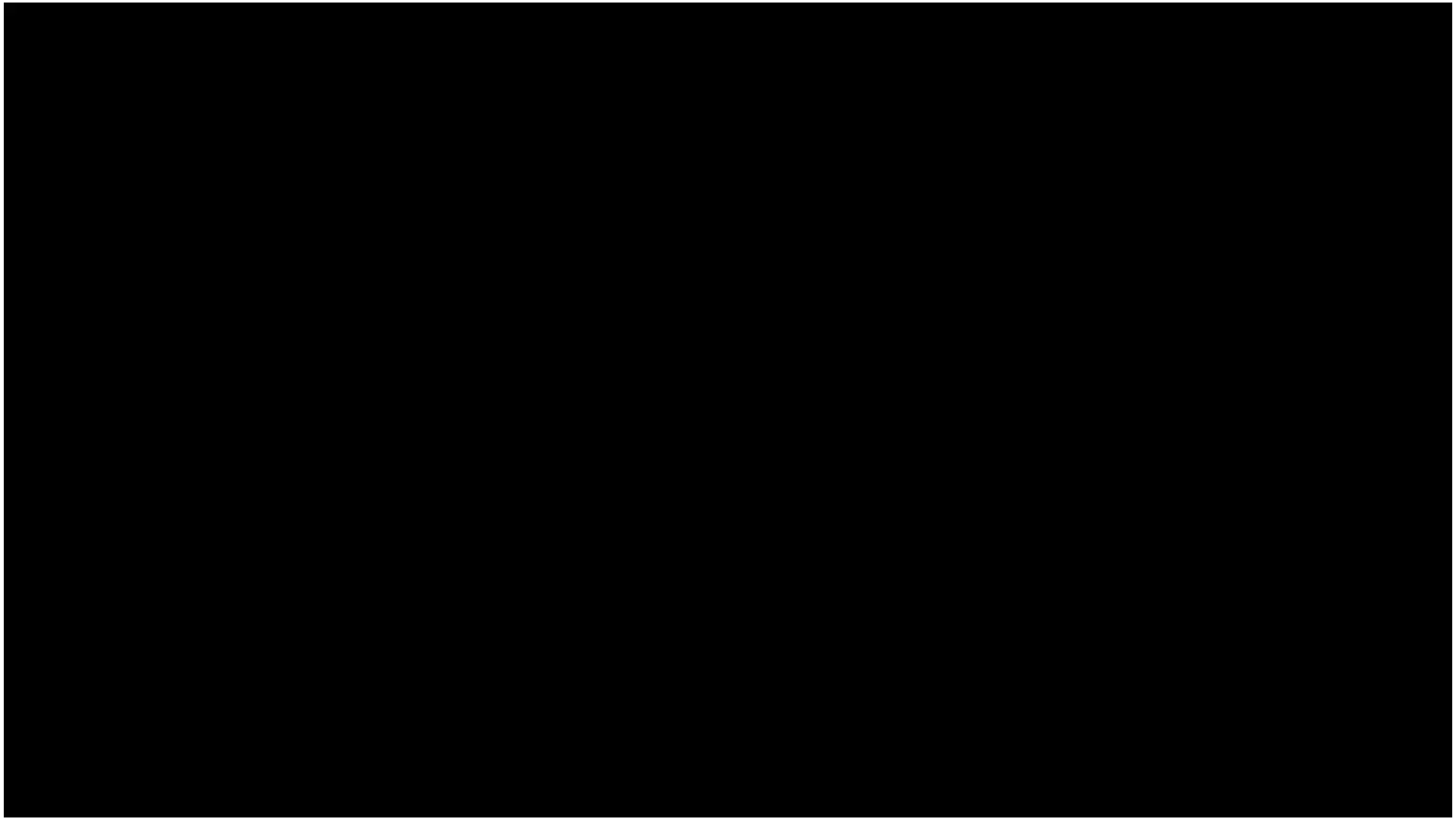
Onboard relative localization for agile aerial swarming in the wild



Martin Saska

Multi-robot Systems group,

Czech Technical University in Prague

http://mrs.felk.cvut.cz   martin.saska@fel.cvut.cz

Multi-Robot Systems at CTU in Prague

45 employees

> 50 MSc. & Bc. Students

> 50 AUTONOMOUS DRONES

3/2017 – MBZIRC 3rd challenge:
1st place $330.000 prize

2019-2021 - DARPA SubT: 2x 1st place among self-funded teams. 2nd place in virtual challenge finals
$200k & $500k & $500k prizes

2/2020 – MBZIRC 2rd challenge:
1st place $250.000, TOTAL WINNERS

- Close collaboration with MRS group at CTU in Prague (spin out)
- 35 R&D engineers for technology transfer from research to products
- 4 new positions starting 8/2024

Long-term motivation: Swarms of micro aerial vehicles in forest

- Swarming in GNSS denied space
- No direct communication
- Strictly decentralized system
- Scalable, large, anonymous groups
- Unknown environment
- Small low-cost aerial platforms
- High density of obstacles
- MAVs are well suited for such task

Petracek Bioinspiration & Biomimetics 2020, Ahmad ICRA 2021, Krizek ICUAS 2022, Saska ISRR 2017, Saska AURO 2017, Brandtner ECMR 2017, Saska JINT 2016, Saska ICUAS 2015, Saska ICRA 2014, Saska IJRR 2014

Relative Onboard Localization of Neighboring UAVs

- CNN (RGB), Stereo (3D cam), 3D lidar, active RGB lights, AprilTags, UWB,…

Saska IJRR 2014, Krajnik…Saska JINT 2014, Faigl…Saska ICRA 2013, Vrba…Saska RAS 2022, Vrba…Saska RAL 2020, Vrba…Saska RAL 2019, Stasinchuk…Saska Field Robotics, 2022

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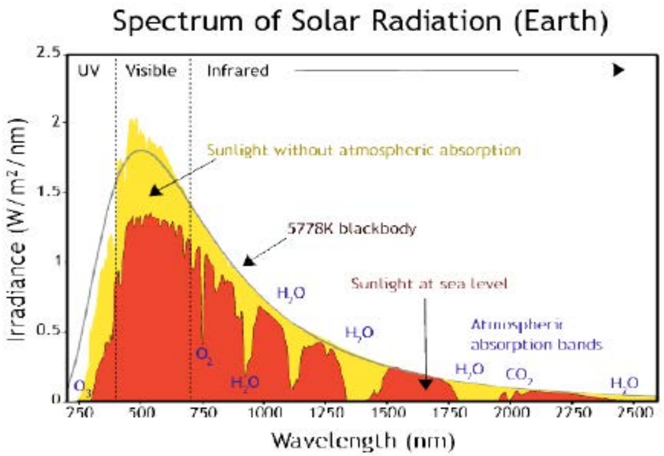
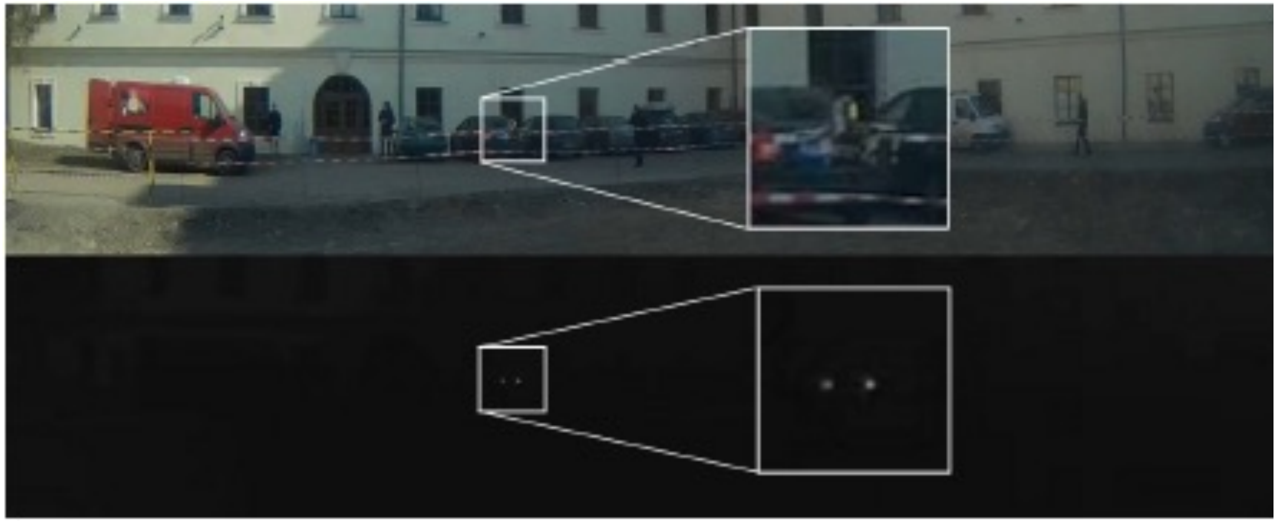
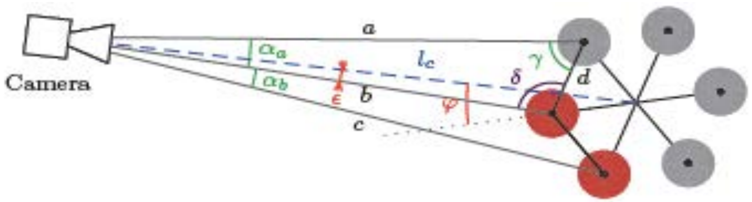
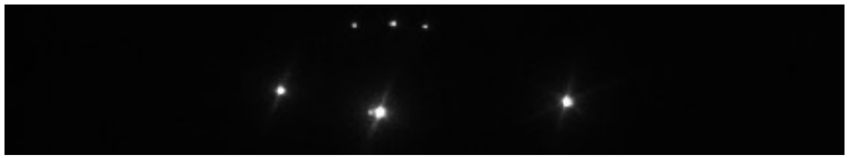
Mutual Localization of UAVs using Ultraviolet Markers

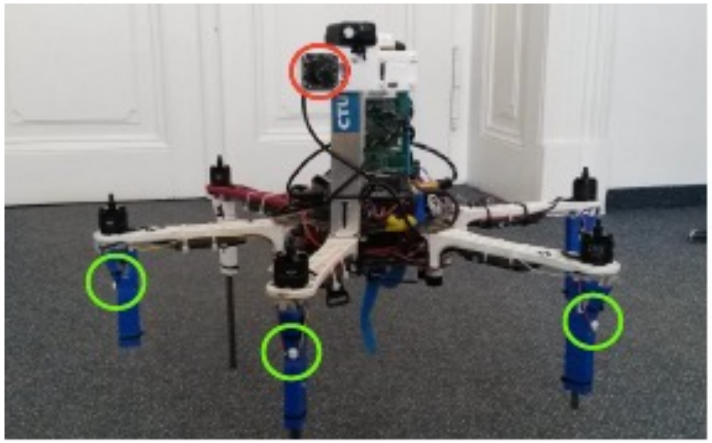
- Reduced size of markers, computational complexity
- Increased reliability







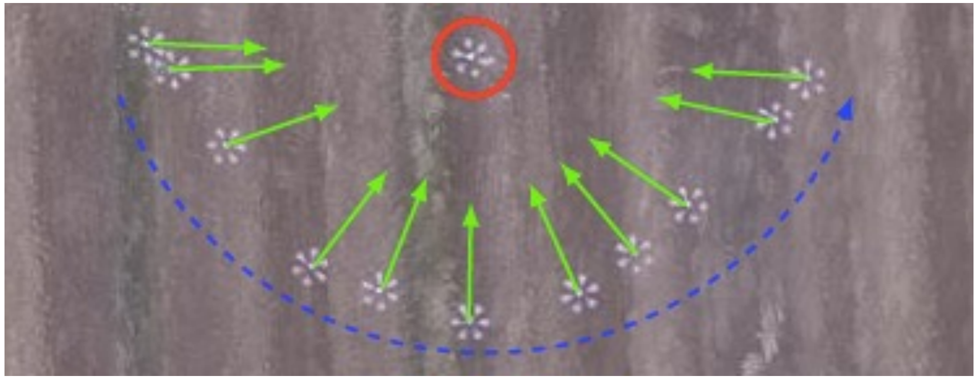


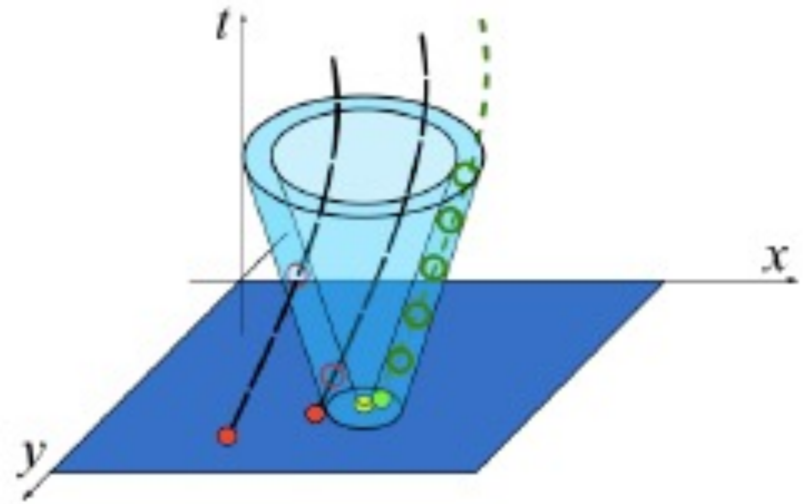


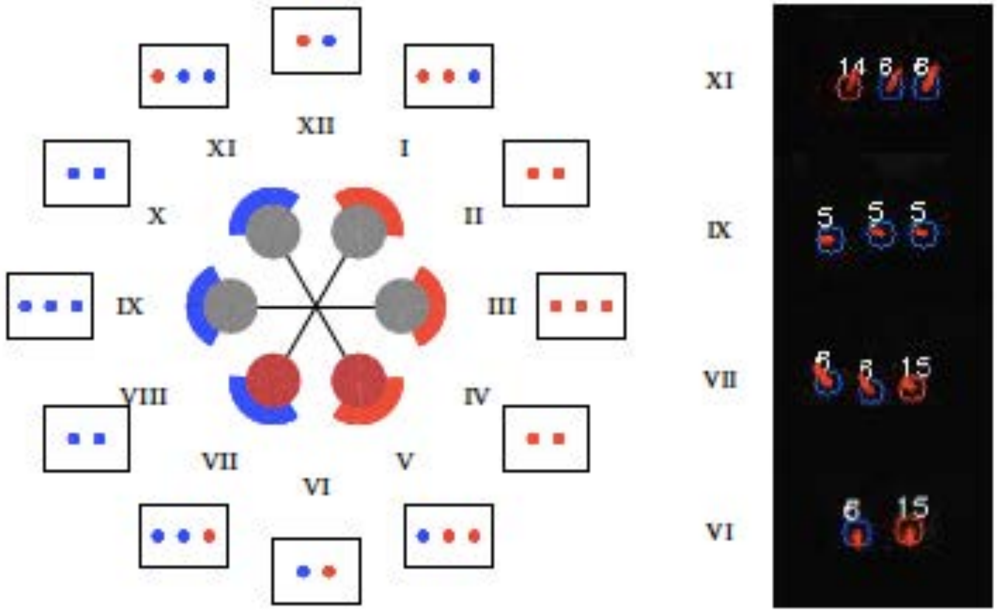
V Walter, N.Staub, M Saska and A Franchi. Mutual Localization of UAVs based on Blinking Ultraviolet Markers and 3D Time-Position Hough Transform. In IEEE CASE 2018.

Blinking UV markers

- ID encoding and observation
- Relative orientation estimation
- Low bandwidth optical communication







V Walter, N Staub, A Franchi and M Saska. UVDAR System for Visual Relative Localization With Application to Leader–Follower Formations of Multirotor UAVs. IEEE RAL, 4(3):2637-2644, July 2019.

Flying Robot for Swarming

With UVDAR and UWB relative localization.

- Open software and ROS in Linux onboard PC
- Modular HW
- Onboard artificial intelligence
- Powerful onboard processing
- Onboard computer vision supported
- Full autonomy in real-world outdoor conditions

- Multi-robot and swarm applications
- Onboard image processing
- Motion and trajectory planning, locomotion generation
- Control, communication, coordination
- Stabilization of groups of ground, aerial, and modular robots, ... and more

fly4future.com/economy

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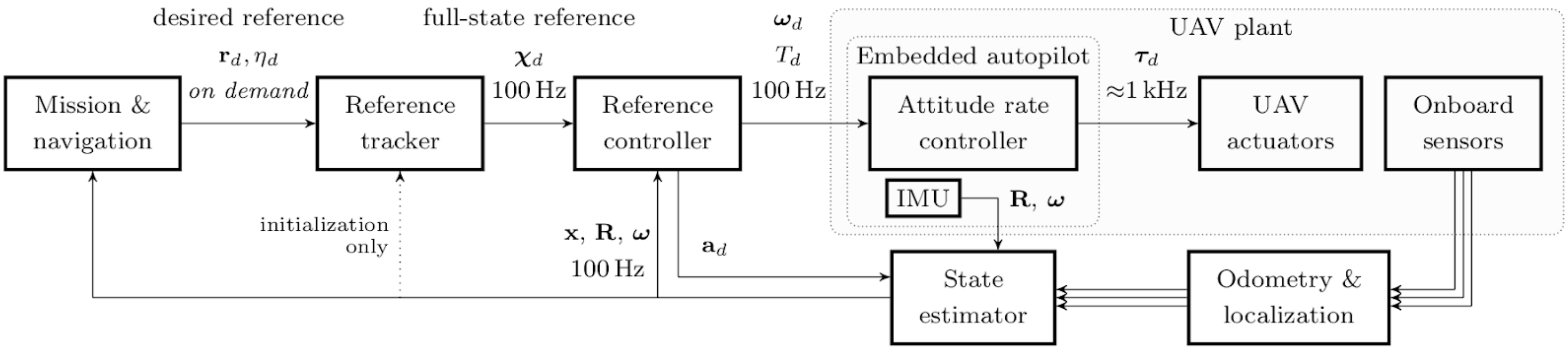
http://mrs.felk.cvut.cz/ martin.saska@fel.cvut.cz

MRS UAV System - Control Architecture

- Mission & Navigation - provides high-level reference (position + heading, 4D trajectory)
- Reference (MPC) tracker - feasible feedforward reference for the feedback controllers
- Reference (MPC or SE(3)) controller - estimates control disturbances and outputs attitude rate command to Pixhawk
- Attitude rate controller - PID loop on attitude rate, creates control commands to individual motors
- Odometry & Localization - UAV position (velocity) based on sensory data, examples: Laser SLAM, Visual SLAM, Optic Flow, …
- State estimator - a bank of estimators and filters produces a set of hypotheses (estimates) of the UAV state; switching between sensor configurations in flight
- Open source: >1000 registered active users

Tomas Baca, Matej Petrlik, Matous Vrba, Vojtech Spurny, Robert Penicka, Daniel Hert and Martin Saska. The MRS UAV System: Pushing the Frontiers of Reproducible Research, Real-world Deployment, and Education with Autonomous Unmanned Aerial Vehicles. JINT 102(26):1–28, May 2021.



Nature-inspired swarming - No GNSS, no communication, fully decentralized

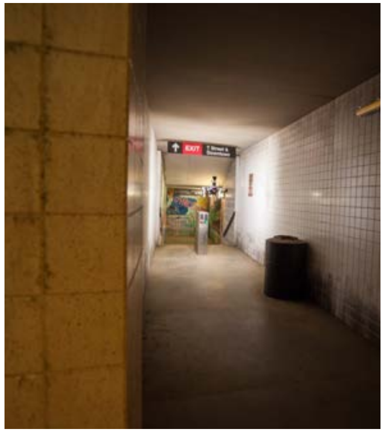
Afzal Ahmad, .. and Martin Saska. PACNav: A Collective Navigation Approach for UAV Swarms Deprived of Communication and External Localization. Bioinspiration & Biomimetics 17:1-19, 2022.

Nature-inspired swarming - No GNSS, no communication, fully decentralized

J. Horyna, … and M. Saska. Decentralized swarms of unmanned aerial vehicles for search and rescue operations without explicit communication. Autonomous Robots, pages 1-17, 2022.

Further challenges of closely cooperating UAV-teams in the wild

- Agility – current swarms are slow
  - nonlinear control
  - fast perception (ego navigation & relative localization)
- Reliability of GNSS-denied localization
  - Degraded environment (no features)
  - Sensors depend on the environment (multi-modal perception required)
- Applications require also global localization
  - Long-range missions (huge maps)
- Scalability in real world (perception)
  - Scalable and secured mesh communication
- Heterogenous systems with different dynamics



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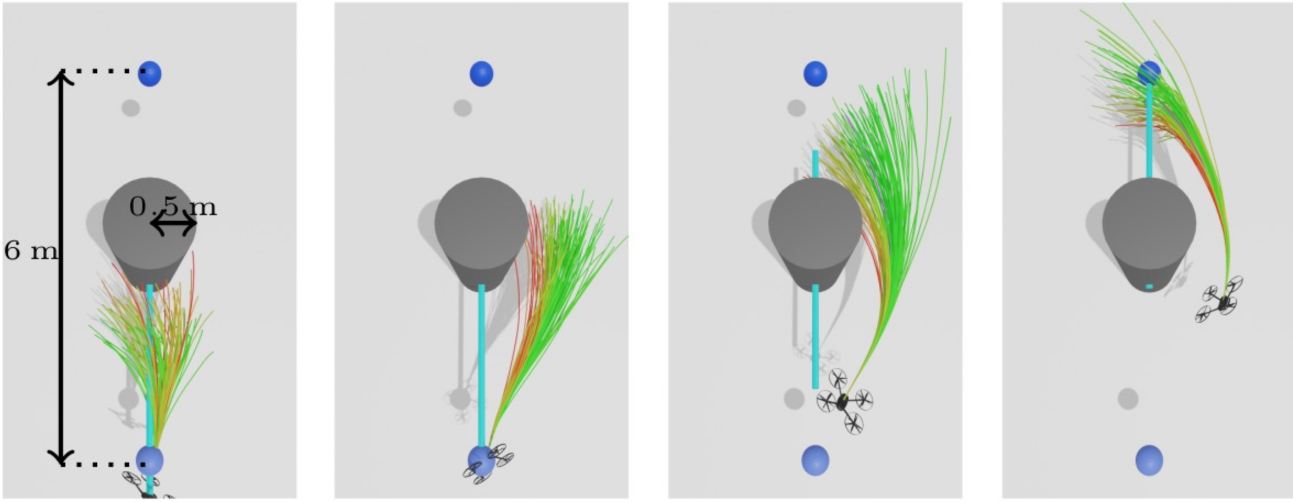
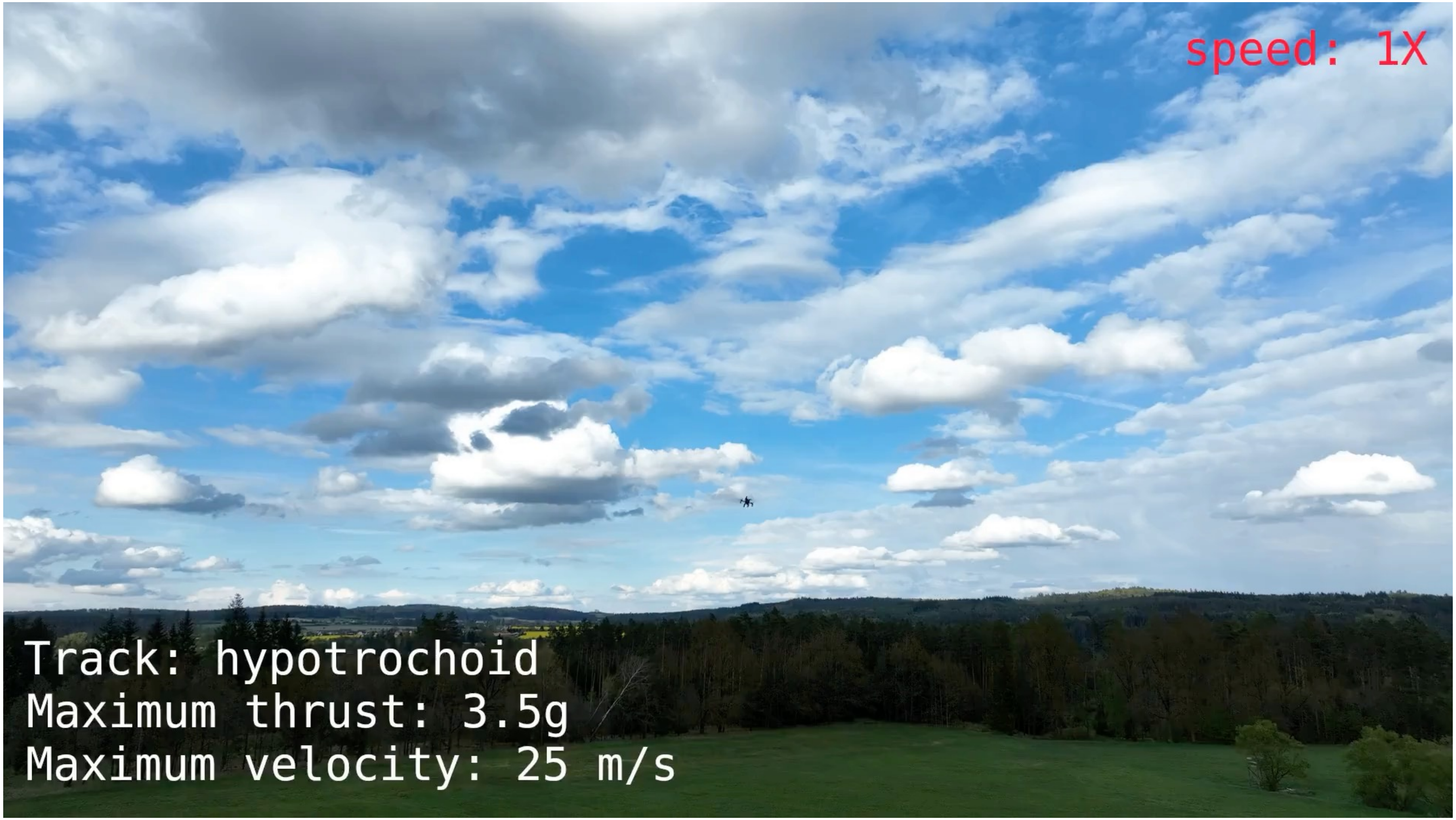
Model Predictive Path Integral Control for Agile UAVs



- Real-time control and dynamic obstacle avoidance for UAVs entirely onboard, leveraging parallelized GPU optimization
- Unlike NMPC, MPPI handles non-convex and non-differentiable cost functions, operates at higher frequencies (100 Hz vs. 10-20 Hz of SOTA MPPI planners), and effectively manages complex, non-convex obstacles.
- For unpredictable outdoor conditions, relying on onboard sensors and GPS for localization, complex tasks in dynamic, cluttered environments.

Michal Minařík, Robert Penicka, Vojtech Vonasek, Martin Saska. Model Predictive Path Integral Control for Agile Unmanned Aerial Vehicles. In IEEE IROS, 2024.

Model Predictive Path Integral Control for Agile UAVs



Michal Minařík, Robert Penicka, Vojtech Vonasek, Martin Saska. Model Predictive Path Integral Control for Agile Unmanned Aerial Vehicles. In IEEE IROS, 2024.

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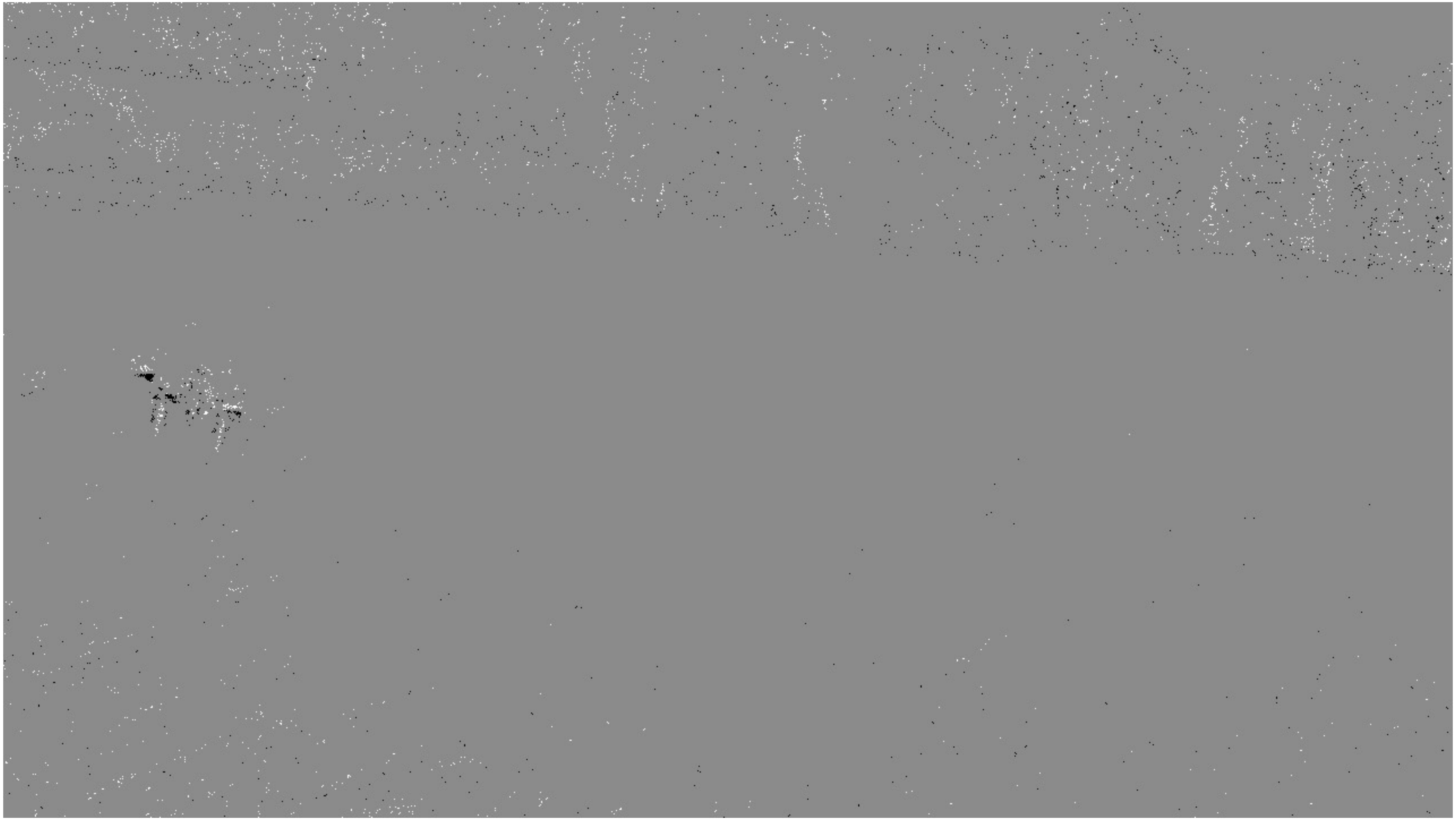
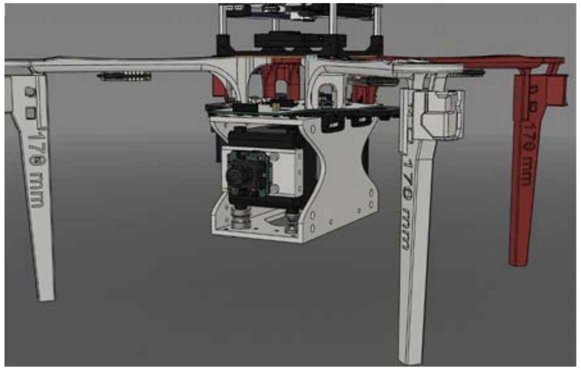
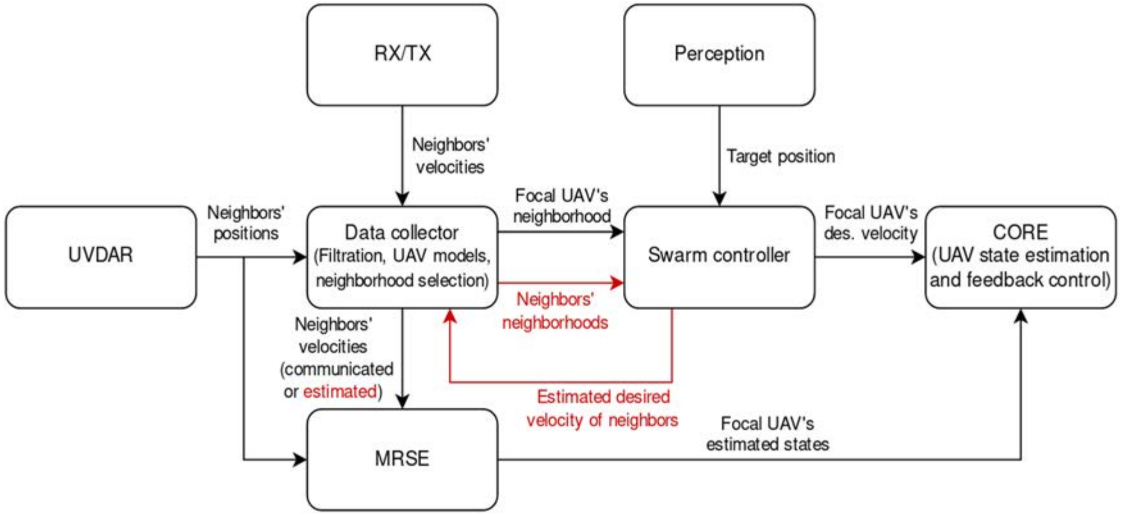
Agile swarms: super fast onboard relative localization



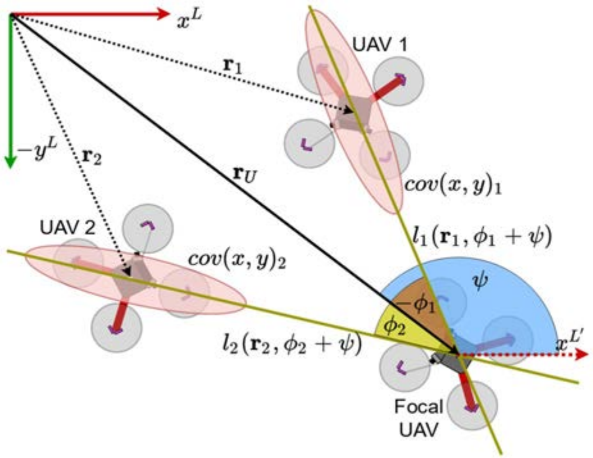
Increasing Reliability: Fast swarming in plain GNSS-denied environment

- Precise onboard only localization and neighbor perception
- VIO for self localization with improved dampening and IMU filtration
- Multi-robot state estimator (MRSE) in case of decrease of localization features
- Model of neighbors fusing UVDAR + velocities





Red parts shows the system used in the case of loss of communication.



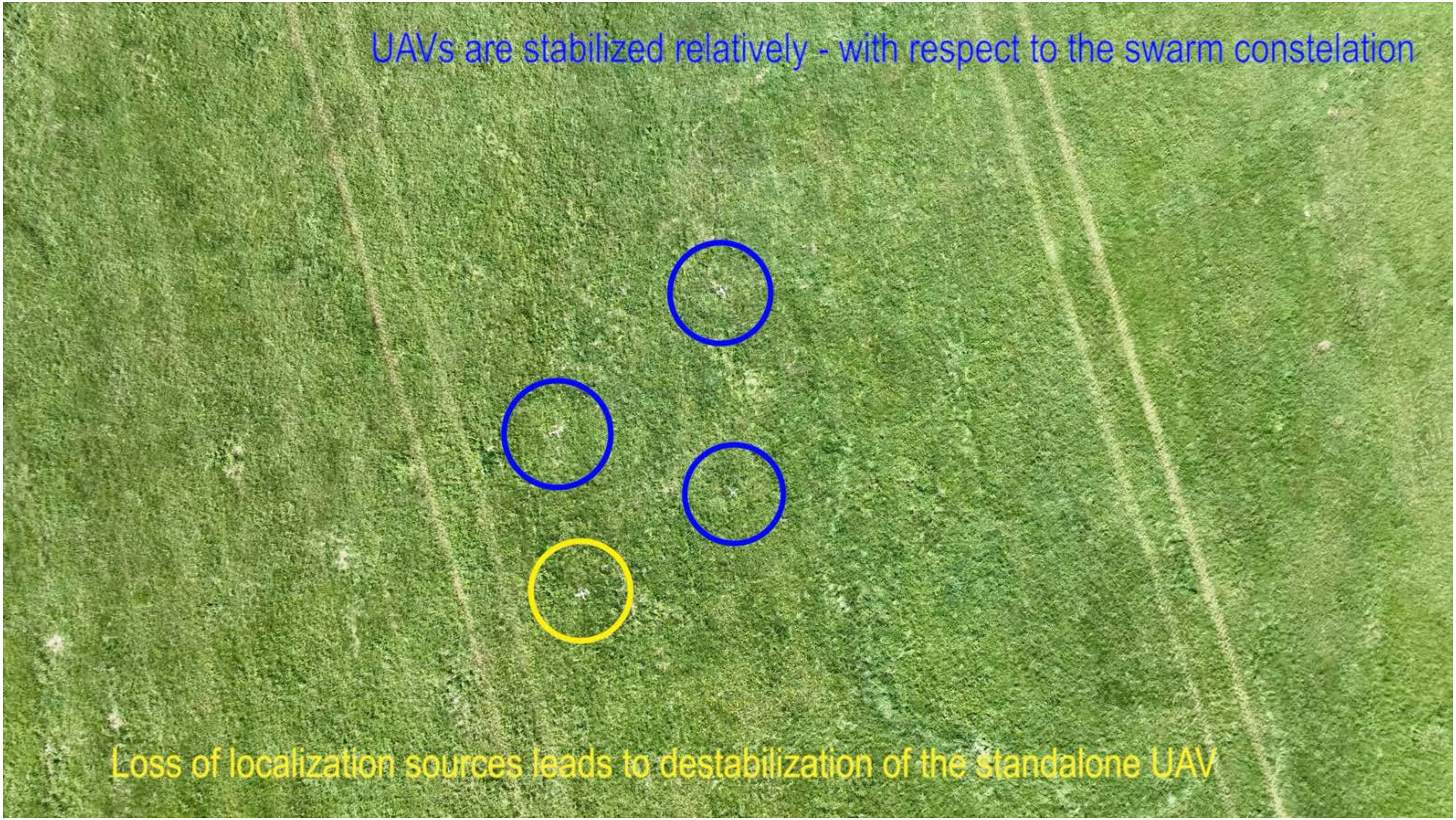
MRSE: UVDAR used for self-localization in the case of decrease of localization features of VIO

Jiri Horyna, Vit Kratky, Vaclav Pritzl, Tomas Baca, Eliseo Ferrante and Martin Saska. Fast Swarming of UAVs in GNSS-denied Feature-Poor Environments without Explicit Communication. IEEE RAL 9(6):5284-5291, April 2024. IROS 2024 presentation.

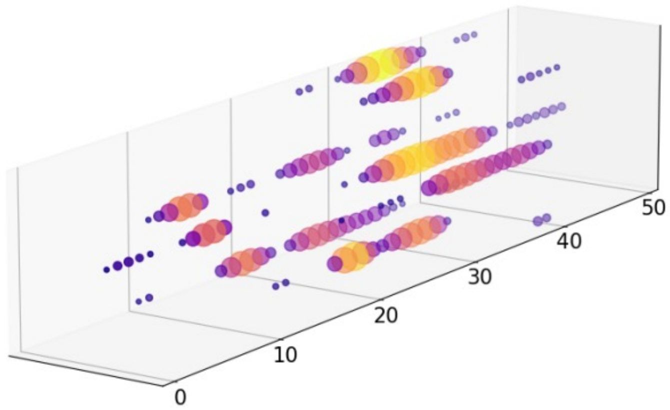
No GNSS. Some UAVs with no velocity measurements.

Jiri Horyna, Vit Kratky, Vaclav Pritzl, Tomas Baca, Eliseo Ferrante and Martin Saska. Fast Swarming of UAVs in GNSS-denied Feature-Poor Environments without Explicit Communication. IEEE RAL 9(6):5284-5291, April 2024. IROS 2024 presentation.

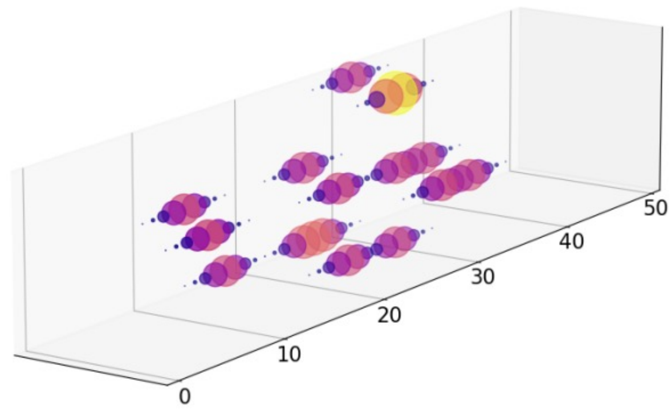
No GNSS. ALL UAVs without velocity measurements.



Towards scalability in wild: relative localization of hundreds



(a) Prediction



(b) Ground truth

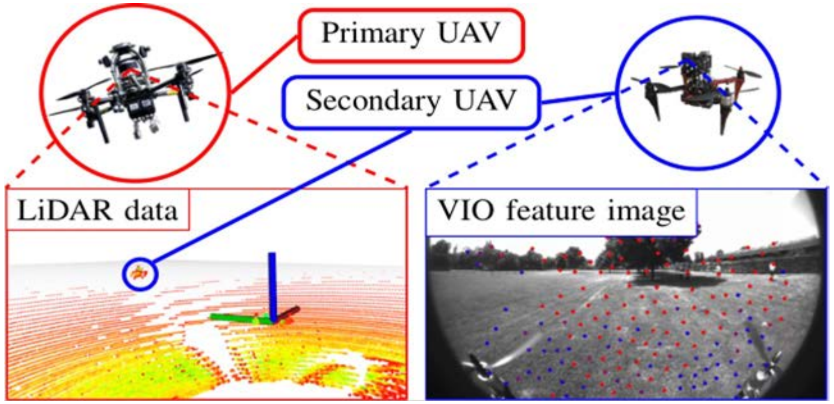
(c) Input

- Inspired by large flocks of birds
- Not relying on detecting of individual neighbors
- Regressing a neighbor density over distance

Martin Křížek, Matouš Vrba, Antonella Barišić Kulaš, Stjepan Bogdan and Martin Saska. Bio-inspired visual relative localization for large swarms of UAVs. In IEEE ICRA, 2024.

Cooperative navigation of a less-equipped UAV by an accompanying UAV

- Primary LiDAR-equipped UAV
- Secondary camera-equipped UAV
- Relative localization using fusion of LiDAR detections and VIO odometry data



- *Vaclav Pritzl, Matous Vrba, Vit Kratky, Jiri Horyna, Petr Stepan, Martin Saska. Drones Guiding Drones: Cooperative Navigation of a Less-Equipped Micro Aerial Vehicle in Cluttered Environments. In IROS 2024.*
- *Václav Pritzl, Matouš Vrba, Claudio Tortorici, Reem Ashour and Martin Saska. Adaptive estimation of UAV altitude in complex indoor environments using degraded and time-delayed measurements with time-varying uncertainties. Robotics and Autonomous Systems 160:104315, 2023.*

http://mrs.felk.cvut.cz/ martin.saska@fel.cvut.cz

Cooperative navigation of a less-equipped UAV by an accompanying UAV

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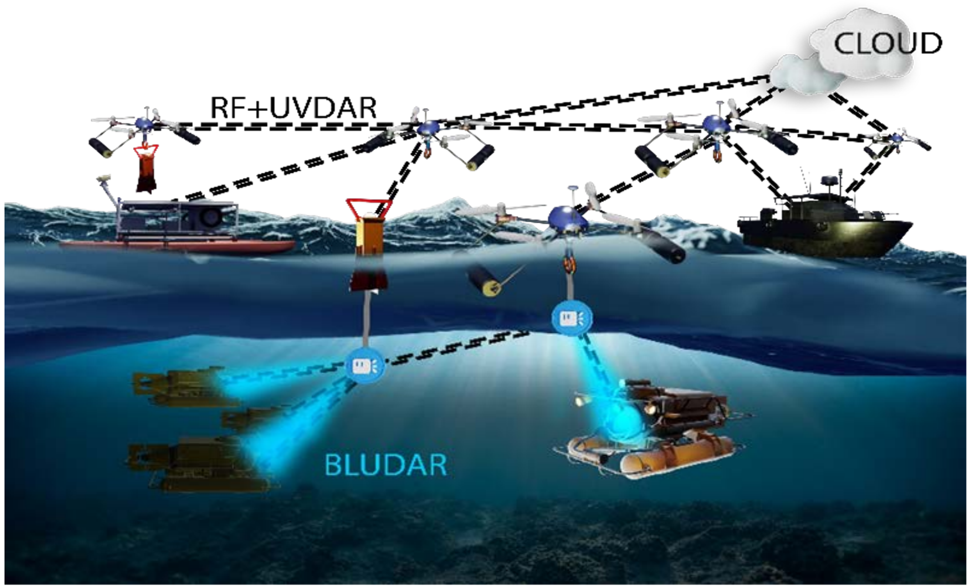
Teams of Cooperating UAVs and autonomous boats (USVs)

Marine operations: cargo delivering to ships, autonomous monitoring and surveillance (on the surface and under water), inspection of ships, water surface monitoring and cleaning

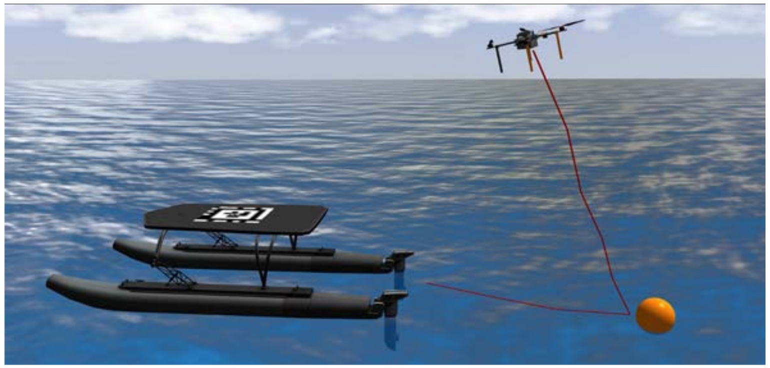


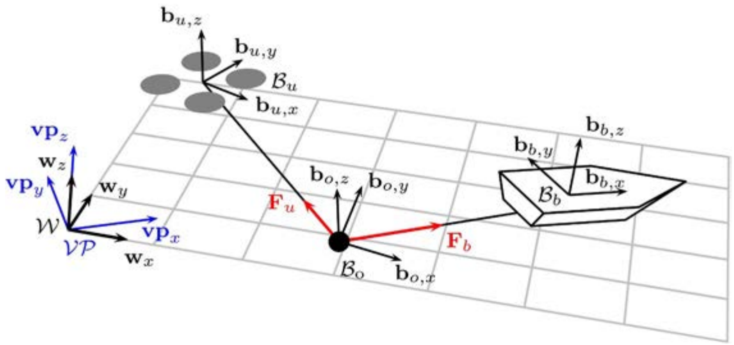
Coordination of robots with different dynamics

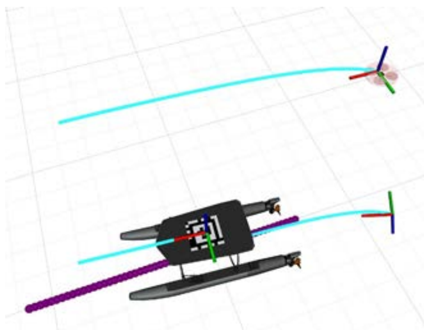
Parakh M Gupta, Èric Pairet, Tiago Nascimento and Martin Saska. Landing a UAV in Harsh Winds and Turbulent Open Waters. IEEE Robotics and Automation Letters 8(2):744-751, 2023.

Collaborative Object Manipulation by a UAV-USV Team Using Tethers

- Novel 6DOF mathematical model of UAV-USV; UVDAR and AprilTag localiz.
- Optimal control using MPC

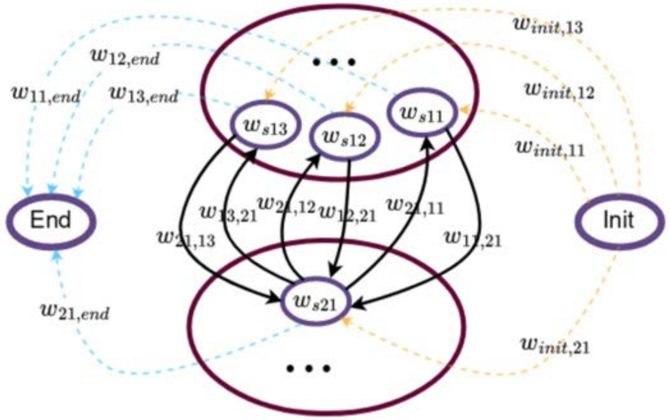




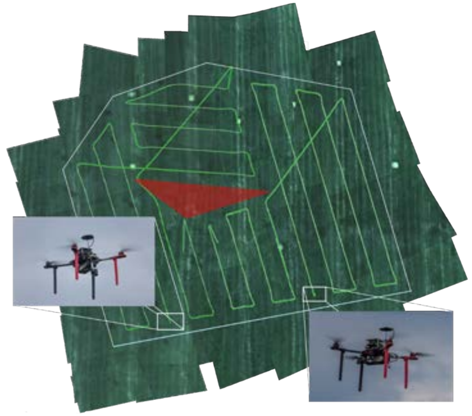


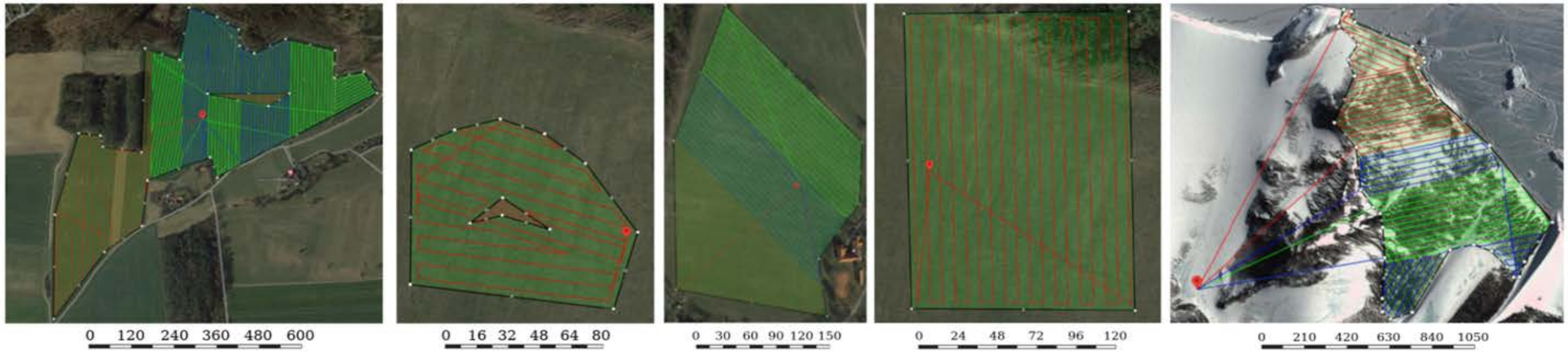
Filip Novák, Tomas Baca, Martin Saska. Collaborative Object Manipulation on the Water Surface by a UAV-USV Team Using Tethers. In IEEE IROS, 2024.

Energy-aware Multi-UAV Coverage Mission Planning with Optimal Speed of Flight



- Energy consumption used as an optimization objective.
- Efficient energy estimation from flight paths during planning
- Coverage Path Pplanning formulated as Multiple Set TSP (MS-TSP)

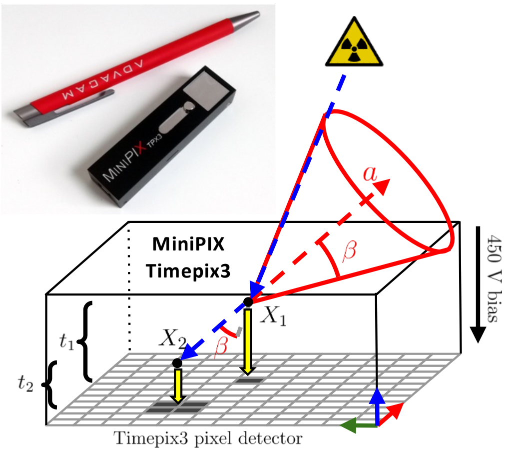


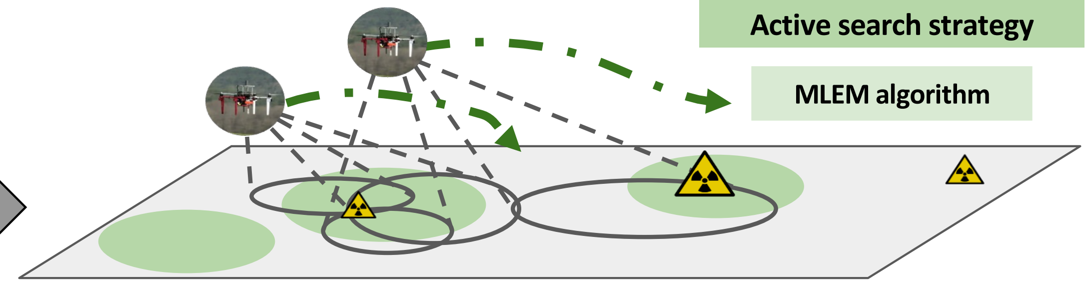


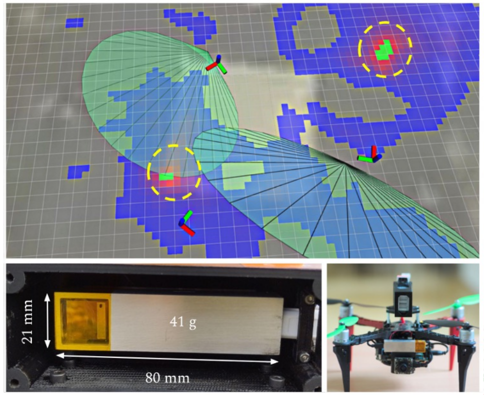
Denys Datsko, Frantisek Nekovar, Robert Penicka and Martin Saska IEEE RAL, 2024. IEEE IROS 2024 presentation.

Autonomous localization of multiple ionizing radiation sources using miniature single-layer Compton cameras onboard a group of MAVs

Compton camera

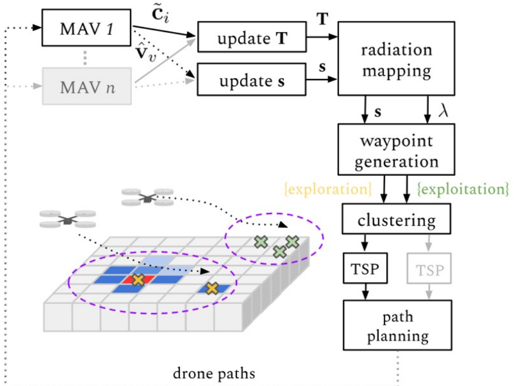






Real-world evaluation using 3 fully-autonomous aerial robots.

Maximum likelihood expectation maximization (MLEM)

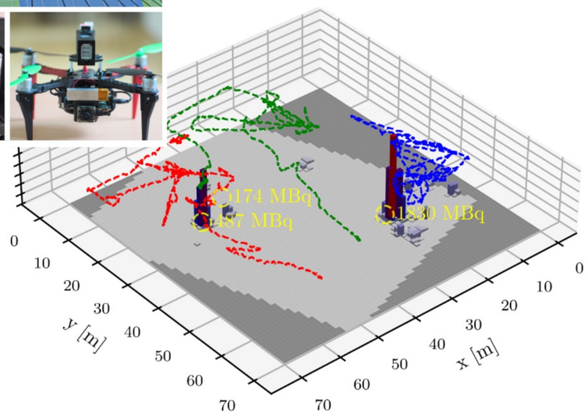


discretize the area of interest into J bins

introduce λ - our hidden parameters

optimize using EM approach

$$\hat{\lambda}_j^{(l+1)} = \frac{\hat{\lambda}_j^{(l)}}{s_j} \sum_{i \in I} \frac{t_{ij}}{\sum_k t_{ik} \hat{\lambda}_k^{(l)}}$$



Michal Werner, Tomas Baca, Petr Stibinger, Daniela Doubravova, Jaroslav Solc, Jan Rusnak, and Martin Saska. Autonomous localization of multiple ionizing radiation sources using miniature single-layer Compton cameras onboard a group of micro aerial vehicles. IEEE IROS, 2024.

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Autonomous localization of multiple ionizing radiation sources using miniature single-layer Compton cameras onboard a group of MAVs

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DEVELOPMENT & PROTOTYPING

Radiation-detecting Drone

A unique miniature drone solution for protecting the population from the adverse effects of radiation

CONTACT US

A Miniature Drone for A Miniature Radiation Camera

Advanced algorithms and artificial intelligence techniques can analyze and process the data collected by the miniature drones. This speeds up decision-making processes and provides valuable insights into potential risks or areas requiring further investigation.

Fly4Future, in collaboration with our valued partner Advacam, co-developed the miniature drone designed to meet the research needs of the RaDron project. Advacam focused on the development of cameras and advanced imaging methods. The miniature drone **can detect and search for stationary and moving sources of ionizing radiation** (e.g., Cs-137, Co-60, Co-57, Eu-152).

The **unique miniature Compton camera sensor** MiniPIX Timepix3, developed by Advacam, facilitates radiation detection. The onboard software is the result of research by our partner, **the MRS group at CTU in Prague**. The drone system has been tested, with the support of the Czech Metrology Institute (CMI), during numerous civil defense exercises with the National Institute for Nuclear, Chemical, and Biological Protection (SUJCHBO) and the National Radiation Institute (NRI) in Řež.

Fly4Future in cooperation with Advacam, is currently working on the commercializing the results of the RaDron research project.

The miniature radiation-detecting drone features a unique, state-of-the-art sensor. It accurately detects radiation even on moving targets.

https://fly4future.com/development-and-prototyping/radiation-detecting-drone/

Autonomous aerial surveillance of workers by a UAV team

- Cooperation of a team of UAVs –surveillance UAVs and UAVs with lights
- Trajectory of the surveillance UAV tackles inspection and cinematography aspects
- Coordination of all UAVs optimized within obstacle-free corridors

Vít Krátký, Alfonso Alcántara, Jesús Capitán, Petr Štěpán, Martin Saska and Aníbal Ollero. Autonomous Aerial Filming with Distributed Lighting by a Team of Unmanned Aerial Vehicles. IEEE RAL, 2021

Autonomous Aerial Filming with Distributed Lighting by a Team of Unmanned Aerial Vehicles

Vít Krátký, Alfonso Alcántara, Jesús Capitán,
Petr Štěpán, Martin Saska, Aníbal Ollero

grvc

FACULTY OF ELECTRICAL ENGINEERING CTU IN PRAGUE

MRS MULTI-ROBOT SYSTEMS GROUP

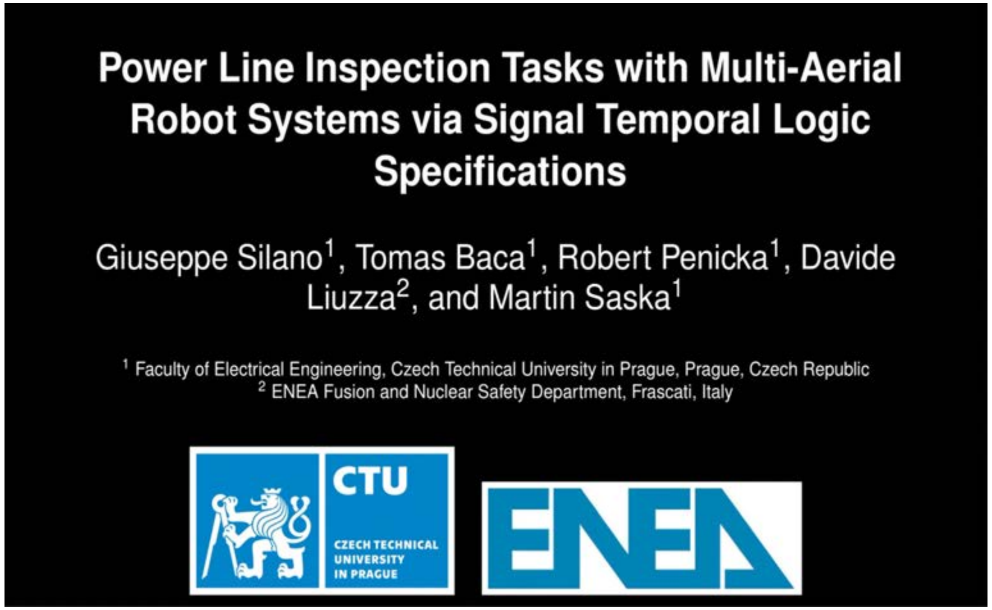
Long-range inspection of power transmission lines by UAVs

- Inspection by multiple UAVs formulated as a Multitour Set TSP
- Inspection of a wire segment in one direction is represented as a vertex in graph

František Nekovář, Jan Faigl and Martin Saska. Multi-Tour Set Traveling Salesman Problem in Planning Power Transmission Line Inspection. IEEE RAL, 2021

Motion planning framework leveraging on Signal Temporal Logic

- Inspection mission encoded as STL specifications for a fleet of UAVs to guarantee feasible trajectories;
- Optimization problem including velocity and acceleration constraints, avoiding obstacles and maintaining a safe distance between drones
- Event-triggered re-planning to tackle disturbances and unforeseen events along the tracking



Giuseppe Silano, Tomas Baca, Robert Penicka, Davide Liuzza and Martin Saska. Power Line Inspection Tasks with Multi-Aerial Robot Systems via Signal Temporal Logic Specifications. IEEE RAL 2021.

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CUSTOM DRONES

Drones for Inspection of Power Lines

A unique SW for flying close to the high voltage poles in power line inspection.

CONTACT US

A Unique SW for Drones Flying Close to the Power Lines from Fly4Future

When it comes to electricity transmission, ensuring the safety and reliability of the network is of utmost importance. One critical aspect of achieving this is through regular inspections of the transmission network elements. Regular inspections play a vital role in the timely detection of defects, helping to prevent potential failures and ensuring uninterrupted power supply.

Traditionally, power line inspection has been performed using helicopters when defects are identified by an onboard expert during flight or by using video recordings afterward. The use of **drones offers numerous advantages**. In terms of safety, it eliminates the need for physical human presence. Thanks to high-resolution cameras and sensors, drones can collect **detailed images and data**, promptly detecting potential issues such as damaged or faulty lines. This enables **more accurate and thorough inspections**.

Drones can fly close to the power line and send real-time data to the operator interface.

https://fly4future.com/custom-drones/drones-for-inspection-of-power-lines/

AEROSTREAM PROJECT

AeroSTREAM Open Science:
Open Remote Laboratory 2023 - 2025

About AeroSTREAM Open Science

AeroSTREAM Open Remote Laboratory is a part of AeroSTREAM's Open Science initiative. Open Science's objectives are to enhance open collaboration between universities and industrial partners in different countries, and to share knowledge, tools and data throughout and after the AeroSTREAM project lifetime, not only with academia, but also with industry, end-users, public authorities, citizens, and society as such.

AeroSTREAM Open Remote Laboratory

AeroSTREAM Open Remote Laboratory aims to provide an open remote laboratory for autonomous unmanned vehicles. Using existing equipment of AeroSTREAM partners, this Laboratory will allow everyone to remotely conduct experiments on real UAVs. A staff member in the open remote lab will prepare the UAV for flight and personally monitor the safety of the experiment being conducted. The data collected will be open for scientists and the general public.

AEROSTREAM

Registration

Before you submit your experiment, please, read our AeroSTREAM Experiment Preparation instructions.

You will also need your CV and your experiment description in pdf ready to upload.

REGISTER HERE

Registration deadline is July 7, 2024.

Funding

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Thank you for your attention

IEEE RAS SUMMER SCHOOL ON MULTI-ROBOT SYSTEMS 2024

https://mrs.felk.cvut.cz/summer-school-2024

JUL 29 - AUG 2, 2024 - Prague, Czech Republic

Martin Saska

Multi-robot Systems group,

Czech Technical University in Prague

http://mrs.felk.cvut.cz   *martin.saska@fel.cvut.cz*

ROBOTICS AND ADVANCED INDUSTRIAL PRODUCTION

ROBOPROX

The ROBOPROX project focuses on cutting-edge research in robotics and optimization algorithms for manufacturing and materials engineering.

CONTROL AND OPTIMIZATION FOR SYSTEMS, MATERIALS AND MANUFACTURING

ROBOTICS AND COMPUTATION METHODS FOR PRODUCTION

Contact – Project Coordinator:
Czech Technical University in Prague
Czech Institute of Informatics, Robotics and Cybernetics (CIIRC CTU)
Jugoslávských partyzánů 1580/3
160 00 Prague 6 – Dejvice, Czech Republic
info@roboprox.eu
Business registration No.: 68407700
VAT No.: CZ68407700
ROBOPROX - Robotics and Advanced Industrial Production
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